Micro-thruster Options for the Japanese Space Gravitational Wave Observatory Missions

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100 micro-Newton class thrusters for the Japanese formation flying spacecraft (DECIGO, Deci-hertz Interferometer Gravitational Wave Observatory) are studied. From a conceptual design of the DECIGO pathfinder, which is a small Japanese scientific satellite to demonstrate drag-free technology for the DECIGO mission, requirements for thrust precision (0.5 μN), thrust noise (0.1 μN/Hz$^{1/2}$) are derived. By comparing four thruster options such as field emission electric propulsion (FEEP), colloid thruster, cold gas jet, and small ion thrusters, it is found that FEEP can provide the best capability to control its thrust-level with the lowest thrust noise level.

I. Introduction

FUNDAMENTAL physics experiments in space typically require satellites in purely gravitational orbits. However, a satellite's orbit is disturbed by residual air drag, radiation pressure, micrometeorite impacts, and other small forces that act on its surface. The purpose of drag-free control is to attenuate these non-gravitational forces to acceptable levels in order to provide a dynamically quiet platform for high-precision experiments. A drag-free control system in Fig.1 comprises a proof mass, which is disconnected from the satellite, a sensor to measure any displacements between the proof mass and the satellite, as actuators a number of low-level (ideally proportional) thrusters, and the associated electronics and software (drag-free control algorithms).

Protected inside the satellite, the proof mass follows a purely gravitational orbit. The satellite is disturbed and would be forced against the proof mass if it were not for the drag-free control system. The position of the satellite with respect to the proof mass is measured and fed back to thrusters, which force the satellite to follow the proof mass. In following it the thrusters produce a force, which is on average equal and opposite to the disturbances to the satellite. Thus, there are at least three potential ways to utilize a drag-free satellite for scientific purposes. The first is

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that the instrument or proof mass is unsupported and protected from outside disturbances and therefore is in a particularly benign environment. Secondly, the path of the satellite is purely gravitational providing an improved measurement of the gravitational field. Thirdly, the thrusters produce forces equal and opposite to the disturbances and thus are a measure of these external disturbances with improved bandwidth and accuracy compared with measuring the effect on a satellite's orbit.

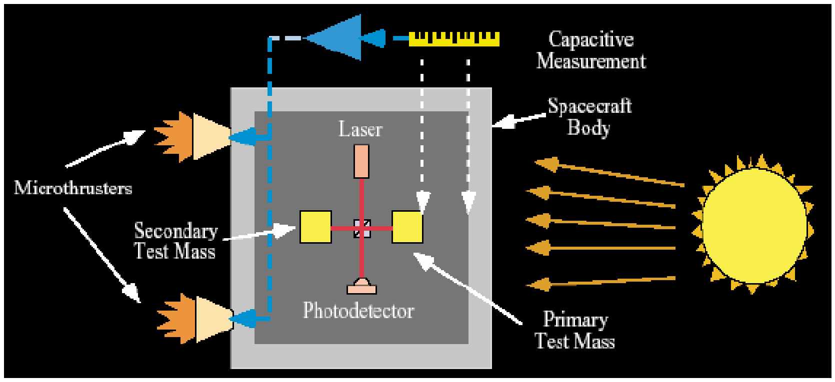


Figure 1. Principle of Drag-Free Spacecraft.

Gravity wave detection requires the determination of extremely small strains, and moving to space provides an opportunity to be free of fundamental limitations from gravity gradient effects on the Earth. Following this idea, some gravity wave detection observatory missions are planned. The LISA mission by NASA and ESA is a prime example[1]. In 2001, Japanese group proposed another gravitational wave observatory space mission, DECIGO[2,3]. To test the key technologies for DECIGO, DECIGO pathfinder mission (DPF) is now studied[4,5]. This paper summarized the DPF spacecraft and its micro-thruster subsystem options, focusing on the requirements and related technology development of the micro-thrusters for the DECIGO/DPF drag-free system.

II. Japanese Gravitational Wave Observatory Spacecraft :DECIGO & DPF

A. DECIGO

DECIGO, a DECi-hertz Interferometer Gravitational wave Observatory, is a space gravitational wave antenna, which is to be launched in 2027[2,3]. The purpose of DECIGO is to observe gravitational waves at the frequency band mainly between 0.1 Hz and 10 Hz, and thus, to open a new window of gravitational wave astronomy. Since the observation band of DECIGO is between LISA (3x10-5-0.1 Hz)[1], and terrestrial detectors such as LCGT[6], it can be a follow-up of LISA by observing inspiral sources that have moved above the LISA band, and can also be a predictor for terrestrial detectors by observing inspiral sources that have not yet moved into the terrestrial detector band. Moreover, since DECIGO's observation band is free from foreground noises caused by unresolved gravitational waves from many galactic binaries, it can play an important role in the observation of stochastic background gravitational waves from the early universe.

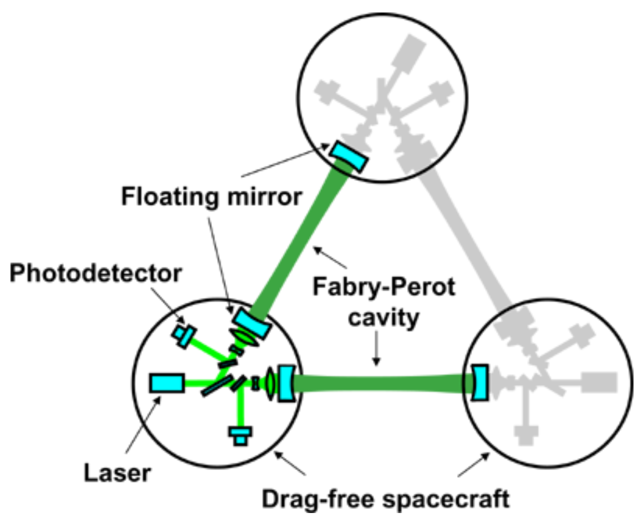


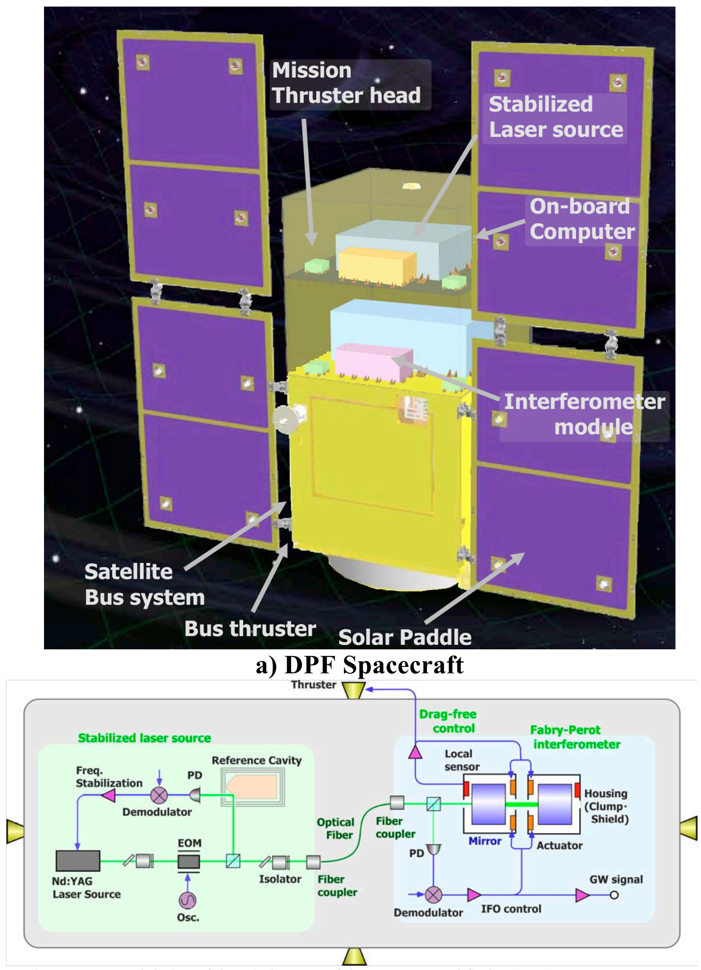
Figure 2. DECIGO[3]. Three drag-free spacecraft keep 1000 km triangular configuration with formation flying technique. Each spacecraft will have light source and two proof masses.

In the pre-conceptual design (Fig.2), DECIGO will be formed by three drag-free spacecraft, which are separated by 1000 km to one another. The gravitational-wave signals are detected by measuring the relative displacements with differential Fabry–Perot interferometers. The mass of the mirror is 100 kg and the laser power is 10 W. Since DECIGO will be an extremely large mission, it is significant to gain the technical feasibility before its launch. Thus, we have a roadmap to launch two milestone missions before DECIGO. DECIGO pathfinder (DPF) is the first milestone mission to test the key technologies with one spacecraft. Pre-DECIGO is supposed to detect gravitational waves with minimum specifications.

B. DECIGO Pathfinder (DPF)

The purposes of DPF are to test the key technologies and to make observations at 0.1-1 Hz frequency band[4,5]. The key technologies tested in DPF will be the followings: (1) low-noise operation and observation with a Fabry-Perot interferometer in space (2) operation of a laser source and its stabilization system, (3) demonstration of a drag-free control system (4) demonstration of a launch-lock system for the test-mass mirrors. All of these technologies are critical in the realization of DECIGO. As for the scientific purpose of DPF, DPF targets at 0.1-1 Hz gravitational waves from intermediate-mass blackhole inspirals. If merger or ringdown events occur at around the center of our galaxy, DPF will have a sufficient sensitivity to detect them.

DPF in Fig.3 will be a small satellite with weight of about 400 kg, orbiting the earth along a sun-synchronous orbit with an altitude of 500 km. The mission part of DPF is designed to be a prototype of DECIGO, being comprised of a short Fabry-Perot (FP) cavity, a stabilized laser source, and a drag-free control system (Fig.3). The FP cavity is formed by two mirrors, which act as free test masses. Each mirror is placed inside a module called housing. The housing has local sensors and local actuators, which are used to monitor and to control the relative motion between the housing and the mirror. In addition, the housing has a function of launch lock, which clumps the mirror at the launch of the satellite and releases it in the orbit with small initial velocity. The cavity has a baseline length of about 30 cm 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. In DPF, we use a Nd:YAG laser source in which the frequency is stabilized using an external reference. The laser source has an output power of 100 mW at a wavelength of 1064 nm.



a) DPF Spacecraft

b) Drag-free System Block Diagram

Figure 3. Spacecraft Configuration and Drag-free System of DECIGO Pathfinder (DPF).[4,5]

The drag-free control of the satellite position works as a shield against external forces such as solar radiations and air drags. The drag-free control is realized by measuring the relative fluctuations between the mirrors and the satellite, and feeding these signals back to the satellite position actuated by low-noise thrusters of the satellite. Thruster options available at this stage are discussed in the preceding sections. With the configuration described above, DPF will have a sensitivity limit of about h~10-15 at around the frequency band of 0.1-1 Hz. Currently, DPF is selected as one of the candidates of small satellite missions of JAXA (Japan Aerospace Exploration Agency). JAXA have a program to launch at least 3 small satellites in this 5 years, using standard bus systems[7]. The standard bus module has a 200 kg weight and a 900mm cubic shape. It will provide a 900 W power with 6 solar-cell paddles at maximum, and a 2Mbps downlink telecommunication ability. A Mission module is attached on the upside of the bus module. The bus and mission modules are connected with power lines and communication lines using the SpaceWire standard. The first mission of the three missions has already 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 the several mission candidates for the upcoming small scientific missions, and might be launched in 2015 in the earliest case.

III. Micro-thruster Options for DPF

The DPF spacecraft has two types of thruster systems. One is conventional reaction control system (RCS, 1-N-class), which is used for orbit insertion and in the case of safe hold operation. Another one is micro-thruster system for a drag-free operation, which is the topic in this paper. For the DPF mission, preliminary design of a micro-thruster system for DPF drag-free control is conducted.

A. Specifications

The specification of the micro-thruster for DPF is summarized in Table 1.

Comparing the specification in Table 1 with that of conventional RCS thrusters, one may find unique features required for the micro-thruster:

- very low thrust level (100 μN) in comparison with standard RCS thrusters (1-20 N)
- wide-range throttling capability (0.1-100 μN)
- fine (0.1 μN) and fast (10 Hz) control of thrust level
- low thrust noise in a frequency range of 0.1 to 10 Hz

Let's take a look at how these specifications are derived. First of all, to keep the DPF spacecraft centered on the proof mass, it is requires for the micro-thrusters to be capable of balancing the solar radiation pressure, including small variations: due to this requirement, a thrust level between 0.1-100 μN should be provided with a resolution of 0.1 μN by a 10 Hz control loop. Such a low thrust level in a fast (10 Hz) control loop is very difficult to obtain with conventional RCS thrusters, and hence, special micro-thruster technology is necessary. Another unique feature required for the DPF mission is the low thrust noise capability. If thrust noise is produced by a micro-thruster, the acceleration noise related to the relative motion of the spacecraft and the proof mass will increase, limiting the observation of gravitational wave. In the measurement bandwidth, the thrust noise should be < 0.1 $\mu N/Hz^{1/2}$.

Table 1. Specifications of Micro-thruster for DPF.

Item	Requirement
Thrust range	5-100 μN
Thrust accuracy	0.1 μN
Thruster unit	8
Thrust noize	0.1 $\mu N/Hz^{1/2}$
Isp	T.B.D
Lifetime	3,000 hrs

For a drag-free mission, four types of throttlable micro-thrusters are considered:

- ion thruster
- cold gas jet
- FEEP
- colloid thruster

Ion thruster technology is, as the reader might know, one of the most matured and flight proven spacecraft propulsion technology. For example, 8-mN thruster were used as a primarily propulsion system onboard HAYABUSA asteroid explorer. In principle, ion thruster has an electrostatic accelerator called 'grid', which extracts a variety level of ion beam from a plasma source; and this grid system can be used to provide variable thrust capability. Scaling down the HAYABUSA's 8-mN thruster to 0.1 mN level is in progress[8,9].

Another type of ion thruster, field emission electric propulsion (FEEP, Fig.4, c)) uses an electric field to extract atomic ions from the surface of a metallic liquid. In these sources a strong electric field is established with a pair of closely (~1 μm) spaced electrodes. The free surface of liquid metal exposed to this field is distorted into a series of conical protrusions in which the radius of curvature at the apex becomes smaller as the field is increased. When the

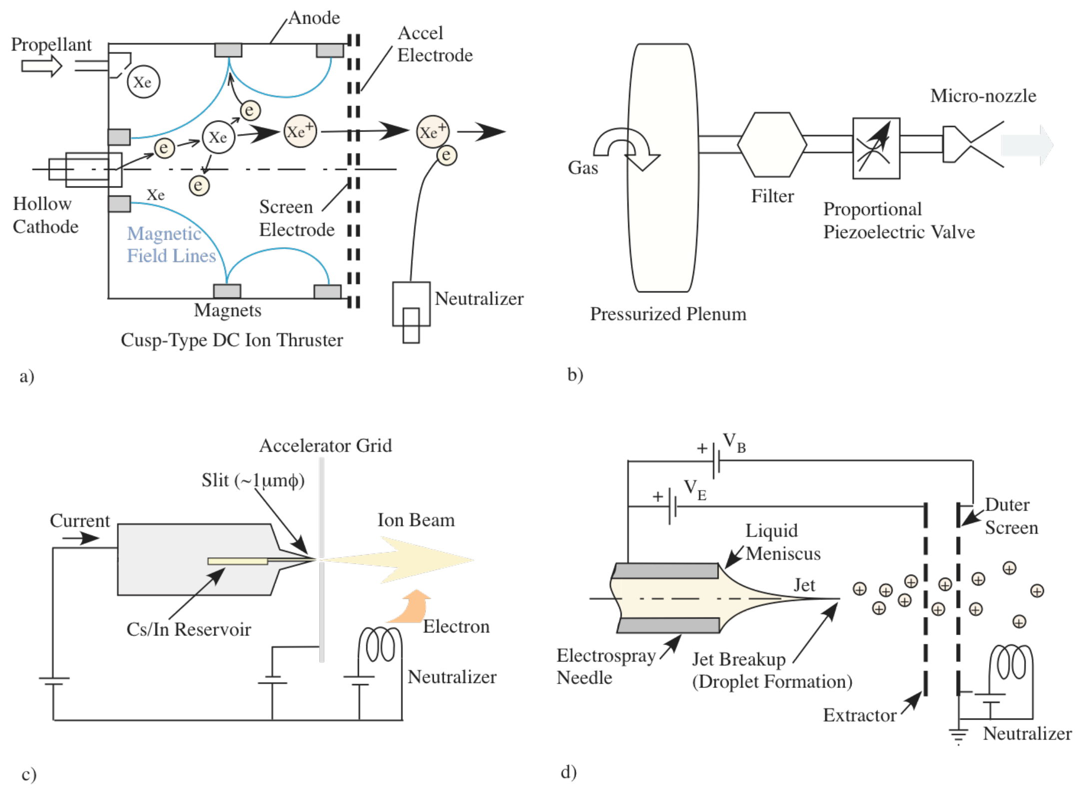


Figure 4. Candidate Micro-thrusters for Drag-Free Spacecraft.

field reaches a threshold value (~ 10^6 V/mm for cesium), atoms on the surface of the tip are ionized and eventually removed. They are then accelerated to high velocity by the same electric field that produced them. Expelled ions are replenished by the flow of liquid propellant in the capillary feed system. This extraction system seems attractive as a drag-free micro-thruster because 1) no mechanical valve is required, and 2) fast control and switching on/off capability following an electronic signal. As standard ion thruster system, a separate neutralizer is required to maintain charge neutrality of the system.

A colloid thruster (Fig.4 d)) produces thrust by elecrostatically accelerating very fine droplets of an electrically charged, conducting fluid. In the more common configuration the droplets are formed by flowing the liquid through a needle with the inner diameter on the order of hundreds of microns. As the liquid exits the needle orifice, a droplet is formed. The needle is biased to a potential of 5–10 kV positive with respect to ground. An accelerating el electrode is pl aced in close proximity to the needle orifice and is biased negatively to a potential of several kilovolts. The electro-static forces on the charged droplet cause it to break off with a net positive charge. In steady-state operation such a needle would emit a stream of such droplets with a very narrow velocity distribution. Although in a development phase, colloid thrusters show promise for delivering the small impulse bits required for precision pointing or a drag-free mission.

Conventional cold gas jet in Fig.4b) may be scaled-down to a micro-thruster for a drag-free mission if its thrust range can be widely changed. In the case of cold gas jet, thrust can be controlled by controlling the pressure and the temperature of a plenum pressure, So, a precise pressure and temperature regulator is necessary to obtain variable thrust level. For such a fast control of its thrust level, pressure regulation by a piezoelectric element is necessary.

B. Trade-off Study

In spite of many R&Ds of micro-propulsion for spacecraft[10], the requirement for the DPF (fast and precise control of thrust with low thrust noise) is difficult for most thrusters; hence, only a few of them are appropriate for the DPF mission. Status of candidate micro-thruster systems for the DPF mission is summarized in Table 2. All the thrusters in Table 2 are in principle considered to meet the requirement for the DPF mission by using electric thrust control, however, only a few thrusters are qualified in terms of thrust level, thrust precision, thrust response, and thrust noise. As a result, TRL level (Table.2) is not so high except for the FEEP and the colloid thruster systems, which are now being developed for the LISA pathfinder mission[11-13]. Since the FEEP system is the most promising

Table 2. Candidate Micro-thruster Systems.

		FEEP	Colloid Thruster	Xe Ion Thruster	Cold Gas Jet
Spec	Thrust per unit	10 μN	30 μN	100 μN	100 μN
	Propellant	Ce,In	Glycerin, Formamide, etc.	Xe gas	N_2, NH_3
	Thrust accuracy	0.1 μN	0.1 μN	N/A	<10 μN
	Thrust response	0.1ms	0.1s	N/A	<0.1s
	Thrust noise	<0.1 μN/(Hz)$^{1/2}$	<0.1 μN/(Hz)$^{1/2}$	N/A	N/A
	Isp	4000-8000s	150-250s	>1000s	70s
	System weight	>14kg	>30kg	>20kg	>15kg
	Lifetime	>4000h	>3,500h	N/A	N/A
	Thrust control	Accel voltage	Accel voltage	Accel voltage	Flow rate
R&D status in the world		Qualified for LISA Pathfinder developed by ARC-Sr (Austria) and ALTA (Itally)	Qualified for LISA Pathfinder developed by Busek (U.S.A.)	R&D by Astrium, NASA JPL, etc	R&D by Marotta and MOOG (U.S.A.) etc.
R&D status in Japan		N/A	Shizuoka Univ.	JAXA, Kyushu Univ., NDA	N/A
Advantages/Uniqueness		No mechanical valve Fast response	Use of ionic liquid for propellant Fast response	Downsizing ion thruster technology Fast response	Piezoelectric flow control
TRL		7	7	3-4	4-5
Technical Issues	Challenge	Electrode fabrication (~1 μm) High voltage power source (~10 kV) Neutralizer	propellant management high voltage power source (~2-10 kV) Neutralizer	Miniaturization of thruster/ propellant supplying unit Neutralizer	Controlling very low flow rate
	Failure mode	Short circuit	Short circuit Valve failure	Short circuit Valve failure Propellant leakage	Valve failure Propellant leakage
	Life limiting factor	Electrode erosion	Electrode erosion	Electrode erosion	-
	Environment	Contamination by propellant Charging	Contamination by propellant Charging	Contamination by eroded electrode Charging	-

from the view point of the system weight, the baseline design of the DPF mission is to employ the FEEP thruster. In addition to adopt a foreign thruster system, the DECIGO/DPF working group is surveying the possibility to develop a new FEEP thruster.

Downsizing xenon ion thruster system for a drag-free mission is a hot topic in electric propulsion community. Currently, ESA, NASA JPL, and some universities are working on their micro ion thruster design. JAXA also continues laboratory experiments on a microwave micro ion source and neutralizer to evaluate their thrust characteristics including thrust noise[9]. When downsizing the ion thruster system, all the components associated with the thruster must be downsized. Among the related components, electronic components are easily miniaturized, but propellant supplying unit (valve, regulator, and so on) is difficult to scale-down. To improve the competitiveness of the ion micro-thruster system should be more lightweight. Lightweight valves and regulators are still challenging technology in a drag-free mission in which xenon leakage is not permitted; this is because even small xenon leakage results in thrust noise, preventing accurate drag-free control by DPF.

The propellant leakage problem also applies to the cold gas jet system. Gas tank for a cold jet is usually heavy, so a lightweight propellant tank as well as a compact and low power valve/regulator are required to make the cold gas jet attractive. Marotta succeeded in developing high pressure but lightweight tank as well as proportional flow controller. The propellant tank was tested in ST-5 mission[14], but proportional flow controller is still under development. Some companies are working on the key component, piezoelectric-actuated regulator, and this is the vital technology to make a fast and precise control of the gas flow.

Another concern for the gas jet system is its large propellant consumption. Propellant consumption of the DPF mission for various Isp is plotted in Fig.5.

Assuming 3000 hours operation, required propellant weight for nitrogen gas jet (whose Isp is typically 70s) is about 1.5 kg. System weight of the cold jet is estimated, and at least 5-6 kg thruster and valve/tube weight may necessary for the DPF mission. So the cold gas jet is a quite reasonable option for a relatively short-term mission.

For the ion and FEEP thruster systems, propellant weight is as much as 0.15 kg for 3000 hours operation. In the case of colloid thruster, propellant weight is about 0.6 kg. Most of the system weight is therefore thruster body, electronics, and propellant supplying unit. Designs of these devices should be carefully optimized and tested. One interesting idea is proposed for neutralizer. In contrast to conventional type neutralizer using xenon gas, carbon nanotube neutralizer seems attractive because of its no propellant consumption. Busek and JAXA are developing carbon nanotube neutralizers, and this type of neutralizer will be beneficial to further improve the competitiveness of FEEP/ion thrusters for the DPF mission.

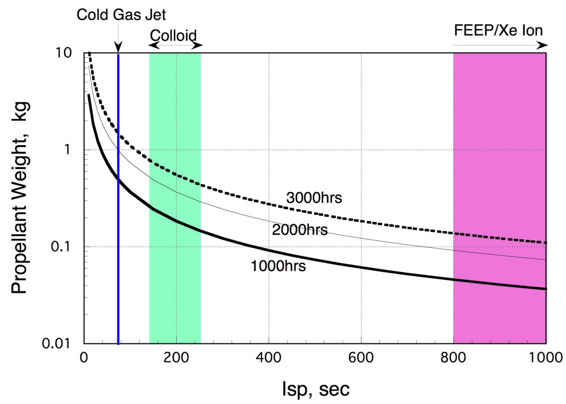


Figure 5. Propellant Consumption for Various Thrusters and Operational Time.

IV. Summary

Preliminary design of a micro-thruster system for the Japanese gravitational wave antenna missions (DECIGO and DECIGO pathfinder, DPF) was conducted. To realize a drag-free DPF spacecraft (~400 kg wet weight) with a small proof mass inside, 12 thrusters, each in 100 μN range, are necessary. As a candidate thruster system, ion thruster, FEEP thruster, cold gas jet, as well as colloid thruster are studied, and they are expected to satisfy the requirement of low-noise and fine control of its thrust level, but only FEEP and colloid thrusters are well qualified at this stage. Considering weight budget of each thruster, FEEP thruster seems the best candidate due to its low subsystem weight. Next step is to design the detail of thruster subsystem that is compatible with the DPF's drag-free subsystem.

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