Deorbit of Space Debris by Exposure of Plasma Flows Exhausted from Electric Thrusters -R&D of the Osaka Institute of Technology 4th PROITERES Nano-Satellite for Deorbiting Space Debris-

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Abstract: The 4th PROITERES satellite is planned as a nano-satellite in order to achieve main mission that space debris makes deorbit by electric propulsion. The principle of deorbiting space debris is exposure of thruster plume to space debris by an electric thruster; that is, reaction impulse is given to debris, and after that debris decreases velocity and deorbits. Accordingly, the 4th PROITERES can deorbit space debris with safety without contacting with space debris and the satellite. Our university is developing four kinds of electric propulsion. These electric thrusters are investigated, and for the 4th PROITERES satellite for deorbiting space debris a suitable electric thruster will be selected. Reaction impulse bit of a pulsed plasma thruster (PPT) is measured on a downstream plate by pendulum method. As a result, a reaction impulse bit is average 1.718mNs. Because a previously directly measured thruster impulse bit of the PPT was about 2.2mNs, a reaction impulse bit is about 30% decrease. Now, the 4th PROITERES is developing all systems for launching in 2019.

Nomenclature

m	=	Total mass of Propellant
t_p	=	Operating time
v	=	Discharge velocity
Δm	=	Exhausted propellant mass at a single act
F	=	Thrust
g	=	Gravitational acceleration
V	=	Orbiting velocity
ΔV	=	Velocity increment
R_0	=	Earth radius
R	=	Orbital radius
M	=	Mass of space debris
E_p	=	Potential energy of unit mass

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E = Total energy of unit mass
m_0 = Initial mass of Propellant
t_0 = Injection time

I.Introduction

Presently, a lot of small/nano-satellites are launched. Accordingly, Space environment showed a deteriorating condition by increase in space debris. In particular, the number of debris has been rapidly increasing by Chinese anti-satellite missile test and iridium cosmos satellite collision. Moreover, new debris is generated by collision between debris. Increasing debris have been accelerating by chain reaction called “Kessler-Syndrome”. Accordingly, many problems occurred such as renewed rocket isn’t able to launch by deteriorating of the space environment. A schematic diagram of a spraying condition of debris is shown in Figure 1.

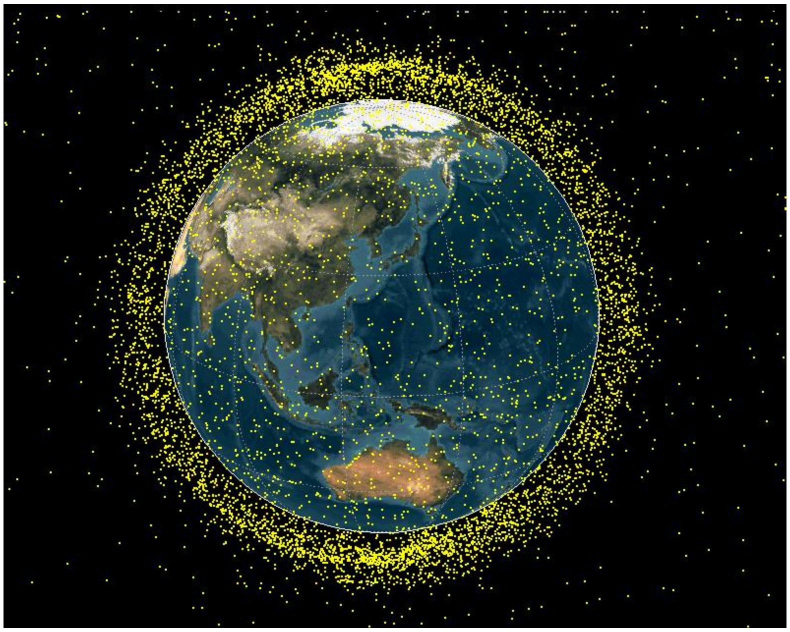

Figure 1. A Schematic diagram of a spraying condition of debris.

II.PROITERES

In the Project of Osaka Institute of Technology Electric-Rocket-Engine onboarded Small Space Ship (PROITERES), the development of nano-satellites with electric propulsion was started in 2007. In the PROITERES, a nano-satellite named the 1st PROITERES satellite with electrothermal pulsed plasma thruster (PPT) was launched by India PSLV C-21 rocket on September 9, 2012. Now, we are developing the 2nd and 3rd PROITERES satellites. The main mission of the 2nd PROITRERES is a long-distance powered flight with changing altitude by Multi-Discharge-Room PPT, and the 3rd PROITERES is lunar exploration by Hall thruster. The 4th PROITERES satellite is planned as a nano-satellite in order to achieve main mission that space debris makes deorbit by electric propulsion. The conceptual diagram of the 2nd PROITERES and 3rd PROITERES are shown in Figure 2 and Figure 3.

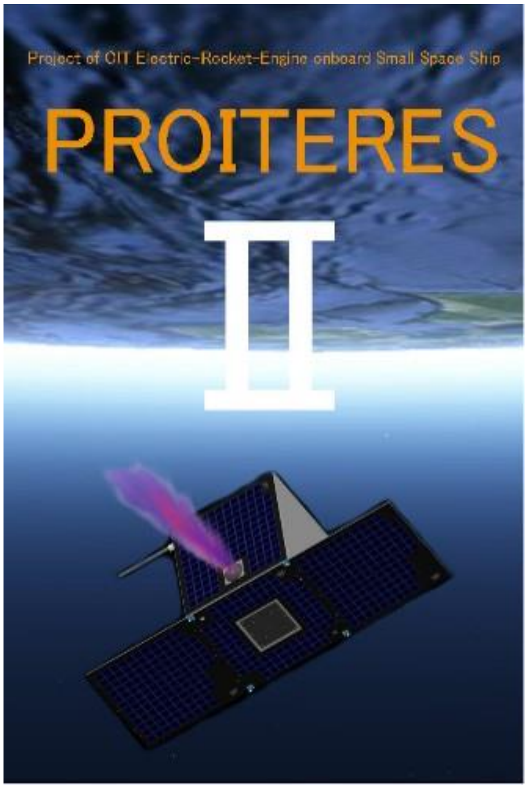

Figure 2. The construal diagram of the 2nd PROITERES.

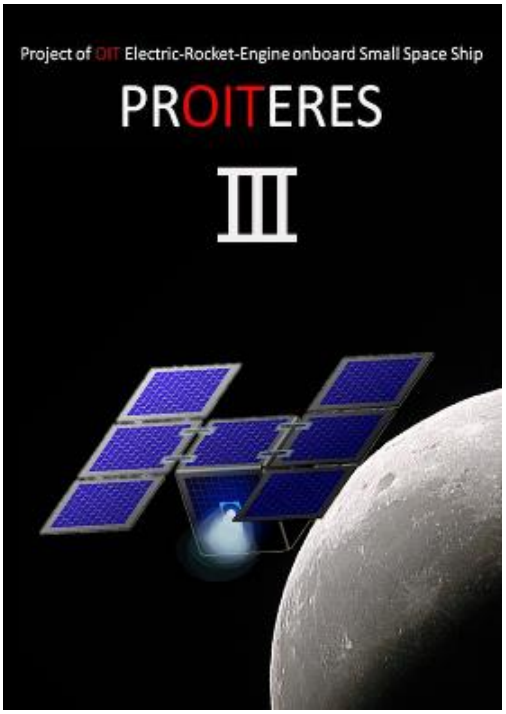

Figure 3. The conceptual diagram of the 3rd PROITERES.

III.The 4th PROITERES

A. Summary

The 4th PROITERES is microsatellite that aimed to remove debris using the PROITERES 2nd technologies now under development. The main mission of the 2nd PROITERES is a long-distance powered flight with changing altitude by using Pulsed Plasma Thruster (PPT). The 1st PROITERES aimed to change altitude of 1km, therefore the 2nd PROITERES is a longer distance powered flight with changing altitude than the 1st PROITERES. Therefore, power is increased and Multi Discharge Room PPT (MDR-PPT) is developed in the 2nd PROITERES. The appearance of MDR-PPT is shown Figure 4.

Satellite attitude control is important for mission execution. For that reason, our project has been developing attitude control rule and attitude control device. It is necessary to consider needing more pattern attitude control rule than the 2nd PROITERES, for that reason, the 4th PROITERES approach to debris and accelerate/decelerate to secure a distance from The 4th PROITERES to debris. Accordingly, the 4th PROITERES attitude is controlled by applying established attitude control system in The 2nd PROITERES.

The 4th PROITERES is supposed 50kg class and 50cm class satellite. Removed debris is supposed 50kg class and 50cm class similar to the 4th PROITERES. As a reason for that universities and companies expanding space development is increase and the number of launched satellite has been increased in recent years. Especially, micro/nano-satellite is lower cost and shorter development time than large satellite. Therefore, micro/nano-satellite development is attention and lots of launched. Many micro/nano-satellites are launched by piggyback type or japan's Kibo laboratory for the international space station (ISS) and thrown into low earth orbit. These satellites life span is 1 to 2 years. After that, satellites are descended gradually by earth gravity and reentered the atmosphere. There are international law the satellites of low earth orbit must be reentered by 25 years. Most of satellites reentered by upwards of ten years. But the number of reentered satellites are greater than the number of launched satellites every year. These are a factor of an increase in debris. The 4th PROITERES is aimed to that finished operation satellites are reentered the atmosphere by electric propulsion and debris are removed in on low earth orbit. Figure 5 shows a conceptual diagram of The 4th PROITERES.

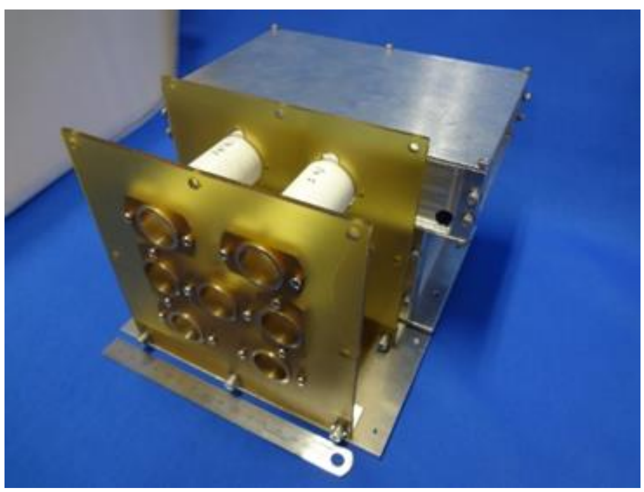

Figure 4. The appearance of MDR-PPT.

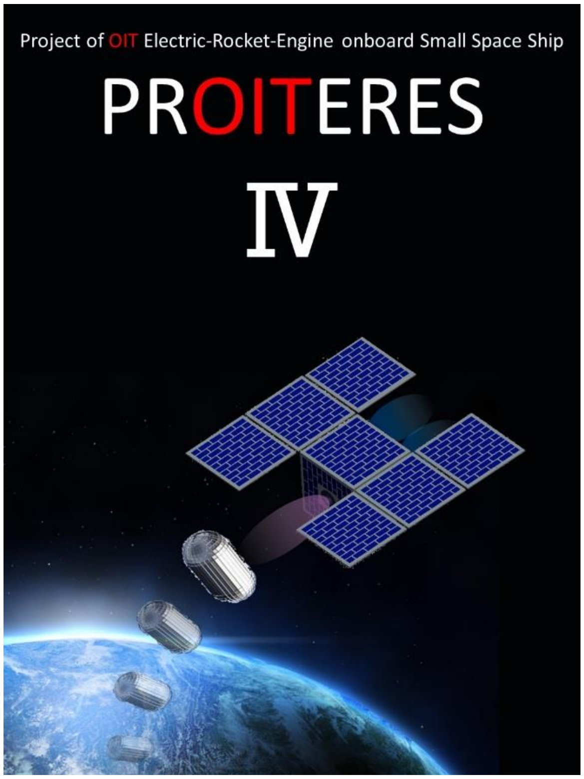

Figure 5. A conceptual diagram of the 4th PROITERES.

B. Principle of deorbiting debris

This section explains principle of descended debris by the 4th PROITERES. Figure 6 shows the relationship between the 4th PROITERES and debris.

Debris are orbiting by balance between gravitational force and centrifugal force. Therefore, the 4th PROITERES navigate forward part of a debris in same speed and expose thruster plume to space debris by an electric engine; that is, reaction impulse is given to debris, and after that centrifugal force of debris decreases by decrease velocity. The balance of the gravity and centrifugal force is lost by decrease centrifugal force. Debris is reentered to pull by gravity. Also at this time, the velocity of debris is decrease. However, the velocity of the 4th PROITERES is increased and the distance from debris is separated. Therefore, the distance in order to keep the distance between the satellite and debris. Therefore, the electric propulsion onboarded to the forward section of the 4th PROITERES and thrust to decrease the same velocity of decreased velocity of debris. Generated impulse of the electric propulsion onboarded the 4th PROITERES is Tt (''T'' is thrust of the electric propulsion, ''t'' is the operation time of the electric propulsion), this impulse is corresponded that thrust impulse given debris is received the reaction impulse (when $0 < \alpha < 1$; $\alpha=1$, all collision status of jet). The 4th PROITERES attempt to acceleration by impulse of "Tt" and the reflection of jet from debris. For that reason, it is necessary to thrust to the forward part of the satellite to given impulse that a same decrease velocity deduct. In brief, the satellite can keep distance by given impulse of "$(1+\beta)$ Tt" to forward part of the satellite (when "$0 < \beta < 2$; $\beta=1$", the plume of the ideal inelastic collision status; when "$\beta=2$", the plume of the ideal perfect collision status).

Debris removal method have been considering, and there are two method, contact type and noncontact type. In this study type, it is not necessary that the satellite contacts to debris. Therefore, this type is very safe and can be thought and attained by the existing state of the technology. Naturally, essential to development electric propulsion system that light and can gain high impulse efficiency, satellite attitude control system and debris tracking system for come off this study.

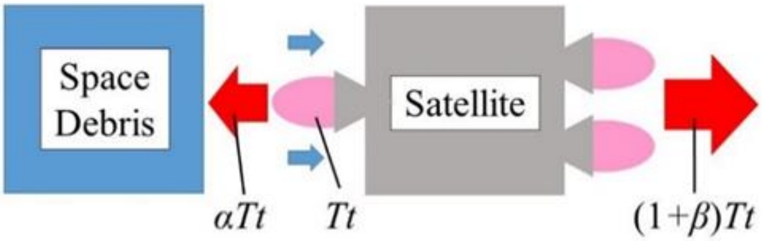

Figure 6. The relationship between the 4th PROITERES and debris.

C. The necessary time for deorbiting

Satellite life span are 1 – 2 years. Therefore, the necessary time calculated by achievement of the mission. Calculates are shown below.

The above-mentioned debris deorbit method is called a spiral orbit transition. It thinks in calculation method that used for changing altitude of the 2nd PROITERES. This thing is increase orbital radius gradually keeping a circular orbit by thrust to orbital velocity direction. Terms are postulated below.

1) Thrust is fixed.
2) Exhausted propellant mass at a single thrust is fixed.
3) Distance of thrust act to tangential direction of flight course.
4) Thrust: $F << mg$ (Orbit is circular orbit).
5) Gravitational acceleration: go ＝0.0098 km/s^2.

Orbiting velocity and velocity increment changing for orbital altitude in each circular orbit altitude shown below are shown below. However, the figure used as a parameter.

・The earth equator radius: 6378.145 km

About debris "m" on orbit, potential energy "PE" for unit quantity of matter is the following equation.

$$PE = \int_{\infty}^{R} g dR = \int_{\infty}^{R} \frac{{R_0}^2}{R^2} g_0 dR = -\frac{{R_0}^2}{R} g_0 \tag{1}$$

Hence all energy for unit of matter are following equations.

$$E = PE + \frac{1}{2}V^2 = -\frac{{R_0}^2}{R} g_0 + \frac{1}{2}V^2 = const \tag{2}$$

$$ER^2 + (g_0 {R_0}^2)R = \frac{1}{2}V^2 R^2 \tag{3}$$

"E" is following equation by law of conservation of angular momentum.

$$E = -\frac{g_0 {R_0}^2}{2R} \tag{4}$$

In addition, velocity of orbital debris is following equations by Equation (3) and (4).

$$V = \left(\frac{g_0 {R_0}^2}{R} \right)^{1/2} \tag{5}$$

Work "dE" is following equation for Propellant consumption during time "dt" by thrust "F".

$$dE = Fds/m = \left(m\frac{dV}{dt}\right)(Vdt)/m = VdV \tag{6}$$

Also, "de" is following equation by Equation (5).

$$dE = \frac{g_0 R_0{}^2}{2}\frac{dR}{R^{3/2}} \tag{7}$$

Equation (5) and (7) is substituted in Equation (6).

$$dV = \frac{dE}{V} = \frac{(g_0 R_0{}^2)^{1/2}}{2}\frac{dR}{R^{3/2}} \tag{8}$$

In addition, "dV" is shown Equation (9) by term 1). "m_o" is total mass of propellant here.

$$dV = \frac{m_p}{t_p}V_j\frac{dt}{(m_0 - m_p t/t_p)} \tag{9}$$

Equivalence Equation (8) and (9), integrate in 0< t < t_p.

$$-\sqrt{g_0 R_0{}^2}\left[R^{-1/2}\right]_{R_1}^{R_2} = -V_j\left[\ln(m_0 - \frac{m_p}{t_p}t)\right]_0^{t_p} \tag{10}$$

$$\left(\frac{gR_0{}^2}{R_1}\right)^{1/2} - \left(\frac{gR_0{}^2}{R_2}\right)^{1/2} = V_j \ln\frac{m_0}{m_0 - m_p} \tag{11}$$

Accordingly, when debris are transferred from orbit "R_1"to orbit "R_2" by spiral movement, the orbit "R_2" that transferred by operation time during spiral movement "t_p" is given by Equation (12).

This relationship is the following. This time, V_1 is navigation velocity on orbit "R_1", V_2 is navigation velocity on orbit "R_2"

$$\Delta V \equiv V_1 - V_2 = V_j \ln\frac{m_0}{m_0 - m_p} \tag{12}$$

By following relationship, necessary velocity increment was calculated to deorbit low earth orbit debris altitude to 100 km. when calculate by Equation (12), result is minus, shown Table 1 as a velocity decrement.

Table 1. Necessary velocity decrement on low earth orbit.

Altitude [km]	Orbital velocity [m/s]	Velocity decrement [m/s]
400	7668.55	57.89
500	7612.60	55.95
600	7557.86	54.74
700	7504.28	53.58
800	7451.83	52.45
900	7400.46	51.37
1000	7350.14	50.31

Moreover, necessary time to deorbit was calculated by following equation (13). "F" is thrust, "Δt" is injection time, "M" is mass of debris, "ΔV" is velocity decrement.

$$F\Delta t = M\Delta V \tag{13}$$

As discussed above, mass of debris is 50 kg. Velocity decrement is calculated injection time "Δt" with velocity decrement of Table 1, when thrust are 1, 5, 10 mN. The result is shown table 2. It was found by the result of Table 2 that the necessary time to deorbited debris is about a month even if thrust is about 1 mN. From this, it was expected that deorbiting debris can be achieved within a month.

The life span of the satellite is considered the period unit the satellite approach to target debris after the satellite launched.

Table 2. Thrust time as changed thrust.

Altitude [km]	Thrust time for each thrust, x 10^5 [s]		
	1 mN	5 mN	10 mN
400	28.95	5.789	2.895
500	27.98	5.595	2.798
600	27.37	5.474	2.737
700	26.79	5.358	2.679
800	26.23	5.245	2.623
900	25.69	5.137	2.569
1000	25.16	5.031	2.516

IV.Considering onboard electric propulsion

D. PPT

PPT is a kind of electric propulsion. There are two kinds: electromagnetic type and electrothermal type. Electromagnetic type has superior has superior specific impulse, electromagnetic type has superior impulse/power ratio. Propulsion efficiency of electrothermal PPT is about 10 %. It is low efficiency compared to other electric propulsion. Therefore, it is often used attitude control. It is thought that since the power is limited in micro/nano-satellite, electrothermal PPT is suited to the powered flight in micro/nano-satellite. Moreover, unlike other electric propulsion, Polytetrafluoroethylene (=PTFE, Teflon®) is used as propellant. Thereby, construction can be simplified as tank and valve can become unnecessary. Therefore, PPT can be reduced in the size, weight. Figure 7 and Figure 8 are conceptual diagram of Electromagnetic PPT and electrothermal PPT.

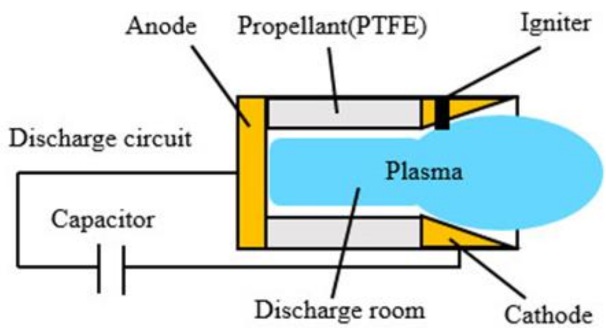

Figure 7. A conceptual diagram of Electromagnetic PPT.

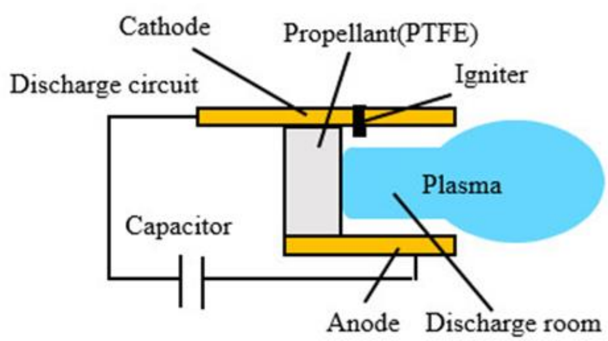

Figure 8. A conceptual diagram of electrothermal PPT.

E. Hall thruster

Hall thruster is Electrostatic acceleration type electric propulsion. The xenon is used for propellant. It has high specific impulse and propulsive efficiency as well as Ion engine mounted on Hayabusa Asteroid Probe. Moreover, it has high thrust force density than ion engine. However, regular hall thruster is not suitable for onboarded for micro/nano-satellite because it is very heavy as it has a complex structure and need high supplying power. For this reason, our university has benn developing small-size hall thruster it called T-CHT. It is planning to be mounted on The 3rd PROITERES that it is aimed to moon probe. Regular hall thruster and T-CHT, a thrusted state of T-CHT are shown in Figure 9, Figure 10 and Figure 11.

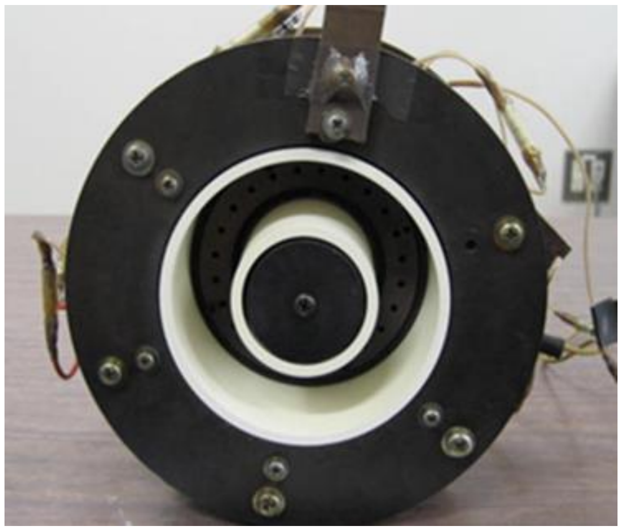

Figure 9. An appearance of the Hall thruster.

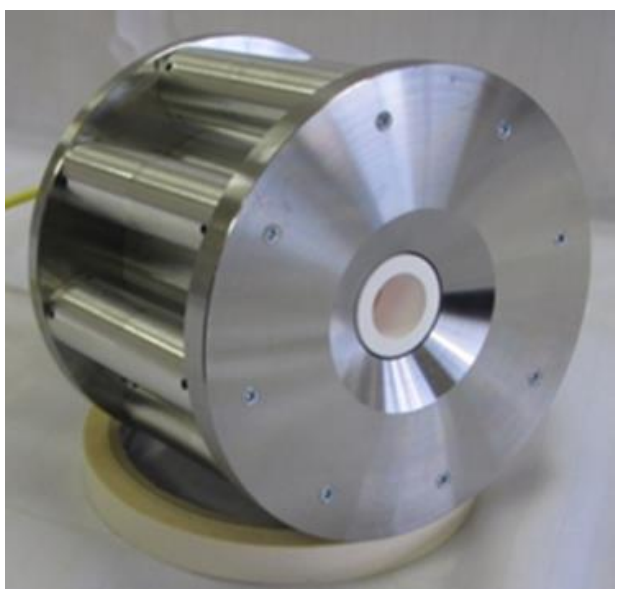

Figure 10. An appearance of the T-CHT.

Figure 11. The thrusted state of the T-CHT.

F. Arc jet thruster

Arc jet thruster is electrothermal type electric propulsion. It is used Hydrazine and Nitrogen for propellant. It can be used together with chemical propulsion. It has the advantage of a simple structure compared to other electric propulsion. However, specific impulse and propulsive efficiency are bad compare to other electric propulsion. An appearance and a jetted state of an arc jet thruster are shown in Figure 12 and Figure 13.

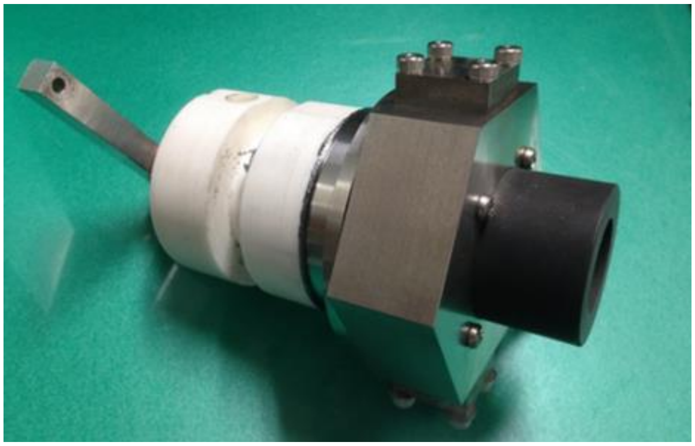

Figure 12. An appearance of the arc jet thruster.

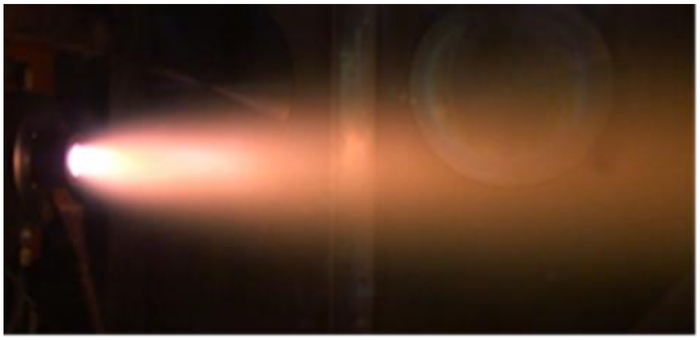

Figure 13. The thrusted state of the arc jet thruster.

V.Reaction impulse measuring experiment

The suitable thruster for removing debris has been considered in and mounted on the 4th PROITERES. In this time, the reaction impulse of PPT was measured electric propulsion in the previous section.

G. Experiment device

The vacuum pumping unit constitute of the vacuum chamber, the rotary pump and the turbo-molecular pump was used in this experiment. This experiment was conducted under the degree of vacuum of 3.0 x 10-2 Pa. The vacuum chamber, the rotary pump and the turbo-molecular pump are shown in Figure 14, Figure 15 and Figure 16. The pendulum was used for measuring the thrust by PPT. The impulse bit was measured from injected to be attached to the tip of a pendulum then shaped width of a pendulum. The experimental equipment of a schematic block diagram is shown Figure 17.

Figure 14. The vacuum chamber.

Figure 15. The rotary pump.

Figure 16. The turbo-molecular pump.

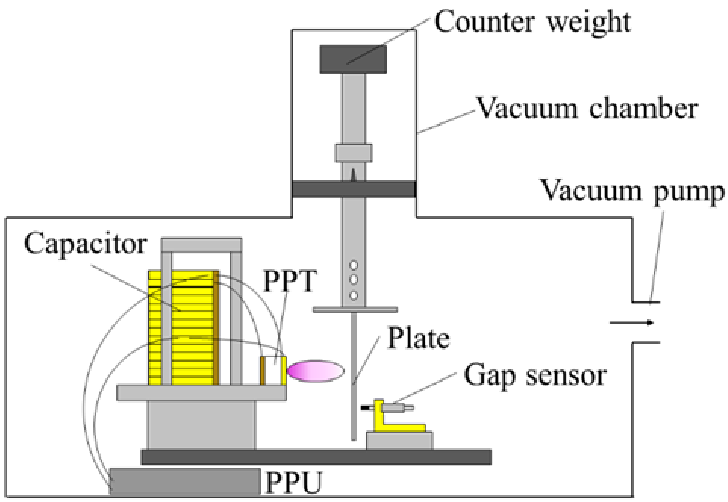

Figure 17. A schematic block diagram.

H. Condition of the experiment

The PPT used in this experiment was a discharge room length of 50 mm, a discharge room diameter of 4 mm similar to onboard it on the 2nd PROITERES. Also, a size of the plate thrusted plume is 200 x 200 mm. The distance between the injection port and the plate is 75 mm. The PPT was injected several times on this condition, impulse bit given to the plate was measured, and the reaction impulse bit in initial performance of the PPT was obtained from their average values. Figure 18 presents the PPT used the experiment. Table 3 presents the experiment condition.

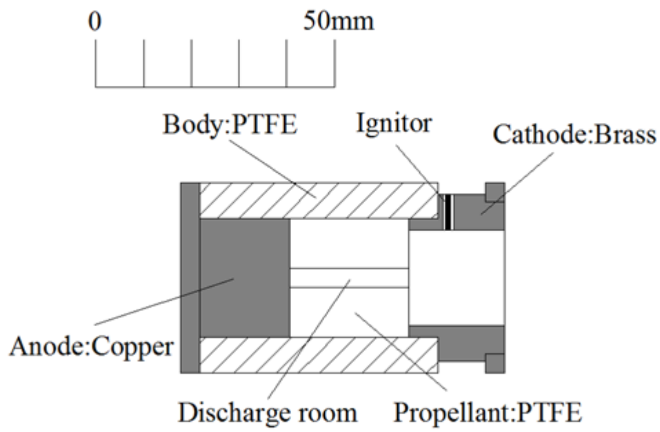

Figure 18. A Schematic diagram of the PPT used this experiment.

Table 3. Experiment condition of PPT.

Items	Value [mm]
Discharge room diameter	4
Discharge room length	50
Nozzle (Cathode) diameter	20
Nozzle (Cathode) length	14
Plate size	200 x 200
Distance between the PPT and the plate	75

I. The result of the study

The result of the experiment, the reaction impulse bit injected to the plate is an average reaction impulse bit of 1.716 mNs. In the initial performance of the PPT. The propulsion impulse bit in PPT itself has been clarified 2.5 mNs from previous research, the impulse bit has decreased by about 30% in the same condition. Also, the impulse bit is gradually decrease when the PPT is operated continuous mode. The measurement result of the impulse bit of continuous operated mode for the PPT in our university is shown in Figure 19. Impulse bit above 2 mNs on commencing operate. However, it decreases to 1 mNs around 30,000 shot. From now on, it is going to research how an impulse bit given the plate with decrease of an impulse bit the PPT itself in order to decreased the impulse bit of the PPT itself is largely concerned. In addition, a total impulse is calculated by obtained dates, it is going to review that how much debris can be deorbited.

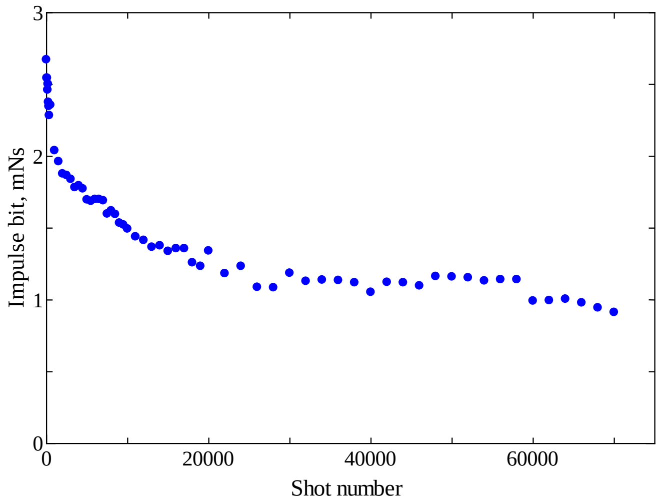

Figure 19. The measurement result of the impulse bit of continuous operated mode.

VI.Conclusion

The following results were obtained:

1) The 4th PROITERES is the satellite that reduce the debris orbital remaining time on low earth orbit by given impulse to an opposite direction to finished operation satellite.
2) The method is noncontact type by irradiate plume of an electric propulsion.
3) The impulse bit that received the plate was measured in initial performance of the PPT. The result is 1.718 mNs, it was seen about 30% decrease from impulse bit of the PPT itself.

The 4th PROITERES is developing all systems for launching in 2019.

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