R&D and Final Operation of Osaka Institute of Technology 1st PROITERES Nano-Satellite with Electrothermal Pulsed Plasma Thrusters and Development of 2nd and 3rd Satellites

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Abstract: The Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES) was started at Osaka Institute of Technology in 2007. In PROITERES, a nano satellite named the 1st PROITERES satellite with electrothermal pulsed plasma thrusters (PPTs) was launched by Indian PSLV C-21 rocket on September 9, 2012. We developed Bread Board Model (BBM) and Engineering Model (EM) of the satellite, including electrothermal PPT system, high-resolution camera system, onboard-computer system, communication system and ground station, electric power system, attitude control system etc, in 2007-2009. Finally, the development of the satellite Flight-Model (FM) was completely finished in 2010. In this paper, we introduce the R&D feature and final operation of the satellite FM. Furthermore, the research and development of attitude control devices of the 2nd PROITERES and 3rd PROITERES satellites with high-power electric thrusters, i.e., high-power electrothermal PPT, magnetic torquer and cylindrical Hall thruster are also introduced.

I. Introduction

THE Project of Osaka Institute of Technology Electric- Rocket-Engine onboard Small Space Ship (PROITERES) was started at Osaka Institute of Technology in 2007. In PROITERES, a nano satellite named “1st PROITERES” with electrothermal pulsed plasma thrusters (PPTs) was successfully launched on a Sun-synchronous orbit of 660 kilometers in earth altitude by PSLV C-21 launcher at Satish Dhawan Space Center (SDSC), Indian Space Research Organization (ISRO) on September 9th, 2012. Figure 1 shows photographs of the launch feature of the PSLV C-21 rocket.

We developed Bread Board Model (BBM) and Engineering Model (EM) of the satellite, including electrothermal PPT system, high-resolution camera system, onboard system and etc, in 2007-2009. Finally, the development of the satellite Flight-Model (FM) was completely finished in 2010. Now, the 1st PROITERES was blackout, and we are sending FM telemetry on thruster firing and continuing observation.

We are developing the 2nd PROITERES. The R&D of the 2nd PROITERES was started in 2010. The main mission of the satellite is to change orbital altitude by high-power electrothermal PPT and to perform operation tests for reaction wheels designed for micro-satellites.

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In this paper, we introduce the R&D and launch processes, and operation history of the 1st PROITERES. Furthermore, the R&D of attitude control devices of the 2nd PROITERES and 3rd PROITERES with high-power electric thrusters, i.e., high-power electrothermal PPT, magnetic torquer and cylindrical Hall thruster are also introduced.

Figure 1. Launch of PSLV C-21 rocket.
(Photo Courtesy of ISRO)

II. Overview of the 1st PROITERES

Figures 2 and 3 show the Flight model (FM) of the 1st PROITERES satellite and its overall view, respectively.

The specification of the satellite is shown in Table 1. The weight is 14.5 kg, the configuration is a 0.29 m cube, and the minimum electric power is 10 W. The altitude is 660 km in Sun-synchronous orbit. The lifetime is above one year.[1-3] The main mission of the satellite are to achieve powered flight of nano-satellite by an electric thruster and to observe Kansai district in Japan with a high-resolution camera.

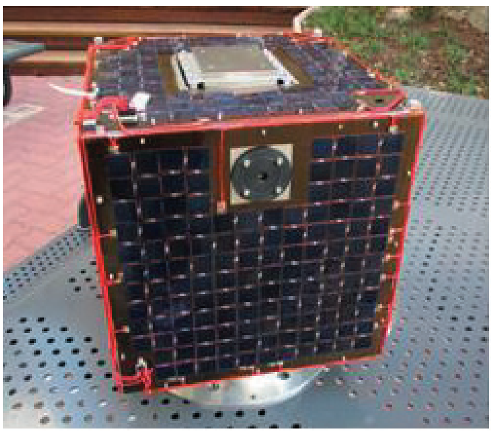


Figure 2. Flight model of 1st PROITERES.

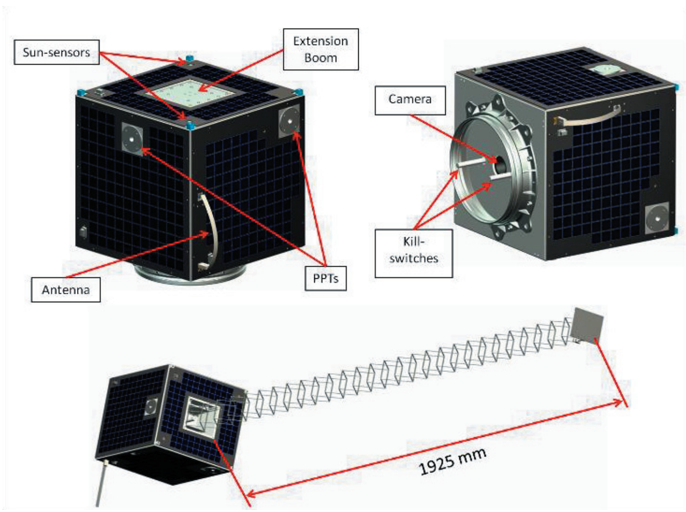


Figure 3. Overall view of 1st PROITERES.

Table 1. Summary of 1st PROITERES.

Mass	14.5kg
Outside dimension	290mm x 290mm x 290mm (Without extension boom)
Orbit	Orbital inclination: 99.98deg, Eccentricity : 0
Altitude	660km
Commencing time	April 2007
Life time	1-2 years
Attitude control	Magnetic attitude control Gravity-gradient stabilization

A. Electrothermal pulsed plasma thruster

Pulsed plasma thrusters, as shown in Fig. 4, are expected to be used as a thruster for small/nano satellites. The PPT has some features superior to other kinds of electric propulsion. It has no sealing part, simple structure and high reliability, which are benefits of using a solid propellant, mainly Teflon® (poly-tetrafluoroethylene: PTFE). However, performances of PPTs are generally low compared with other electric thrusters.

At Osaka Institute of Technology, the PPT has been studied since 2003 in order to understand physical phenomena and improve thrust performances with both experiments and numerical simulations.[4-6]

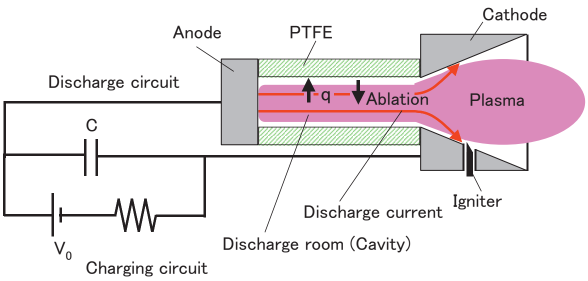


Figure 4. Electrothermal pulsed plasma thrusters.

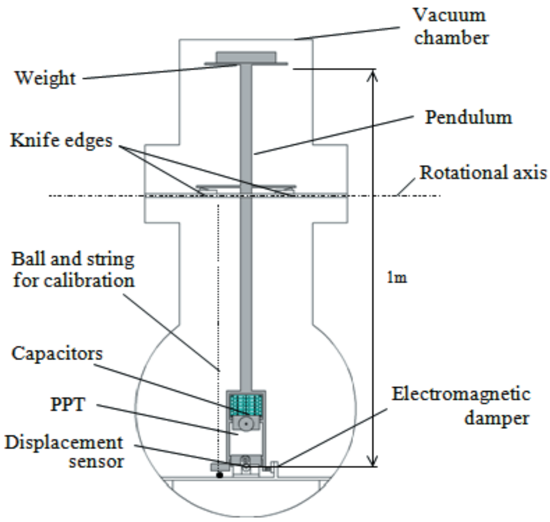


Figure 5. Thrust stand.

Figure 6. Vacuum chamber.

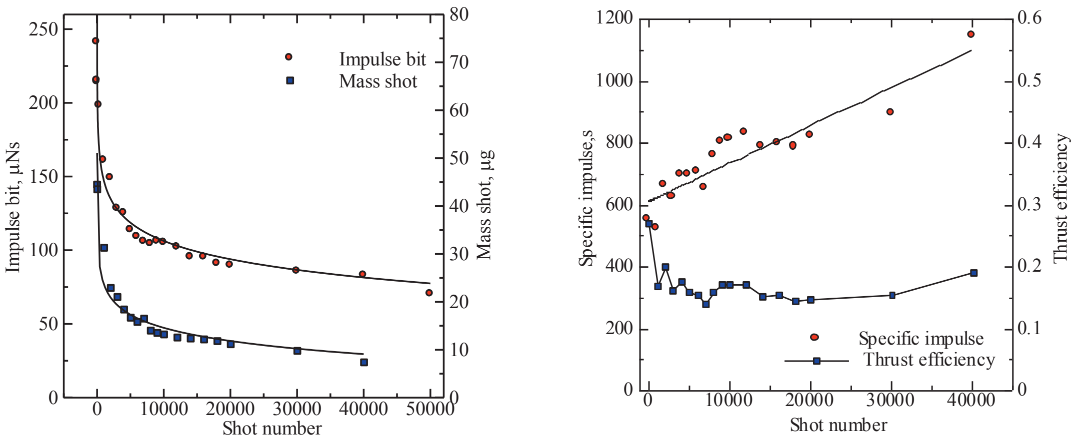
Table 2. Experimental conditions of endurance test.

Capacitor, μF		1.5
Charging voltage, V		1800
Stored energy, J		2.43
Cavity	Length, mm	9.0
	Diameter, mm	1.0
Nozzle	Length, mm	23
	Half angle, degree	20

We mainly studied electrothermal-acceleration-type PPTs, which generally had higher thrust-to-power ratios (impulse bit per unit initial energy stored in capacitors) and higher thrust efficiencies than electromagnetic-acceleration-type PPTs. Although the electrothermal PPT has lower specific impulse than the electromagnetic PPT, the low specific impulse is not a significant problem as long as the PPT uses solid propellant, because there is no tank nor valve for liquid or gas propellant which would be a large weight proportion of a thruster system.

In our study, the length and diameter of a Teflon discharge room of electrothermal PPTs were changed to find the optimum configuration of PPT heads in very low energy operations for PROITERES satellite. Initial impulse bit measurements were conducted, and long operations and endurance tests were also carried out with the optimum PPT configuration. Fig. 5 shows a thrust stand in a vacuum chamber for precise measurement of an impulse bit. The PPT and capacitors are mounted on the pendulum, which rotates around fulcrums of two knife edges without friction. The displacement of the pendulum is detected by an eddy-current-type gap sensor (non-contacting micro-displacement meter) near the PPT, which resolution is about ±0.5 m.

Figure 6 shows a vacuum chamber 1.25 m in length and 0.6 m in inner diameter, which is evacuated using a turbo-molecular pump with a pumping speed of 3,000 l/s. The pressure is kept below 1.0x10-2 Pa during PPT operation. We carried out endurance tests with the optimum cavity shape 9.0 mm in length and 1.0 mm in diameter at a discharge energy per one shot of 2.43 J/s. Table 2 shows the operational condition of endurance test. The repetitive frequency is 1.0 Hz.



a) b)

Figure 7. Result of endurance test.
a) Impulse bit and mass shot, b) specific impulse and thrust efficiency

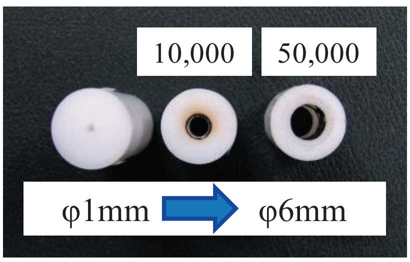
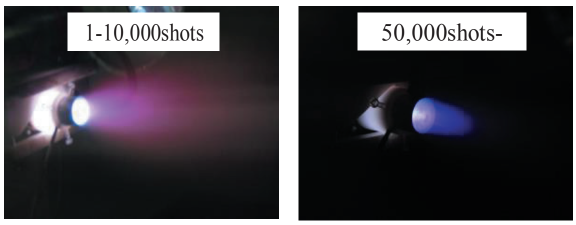


Figure 8. Change of cavity diameter before and after 50,000-shots.



a) b)

Figure 9. Feature of plasma plume.
a) 1-10,000 shots, b) 50,000shots.

Figure 7 shows the shot-number history of impulse bit, mass loss, specific impulse and thrust efficiency. Both the impulse bit and the mass loss, as shown in Fig. 7(a), rapidly decrease with increasing shot number. Specially, the impulse bit decreases from 250 μNs at initial condition to 75 μNs after about 50,000 shots. Although a few miss fires occurred around 53,000-shot, a total impulse of about 5 Ns was achieved. As shown in Fig. 7(b), the specific impulse increases with increasing shot number, and the thrust efficiency is around 0.2 during the repetitive operation. The cavity diameter, as shown in Fig. 8, increases from 1.0 mm to about 6.0 mm of the anode diameter after 50,000 shots. The discharge feature, as shown in Fig. 9, changes from a long plasma plume with intensive emission light at

1-10,000 shots to a very short plume with weak emission. This is expected because of lowing pressure and ionization degree in the cavity when enlarging cavity diameter.

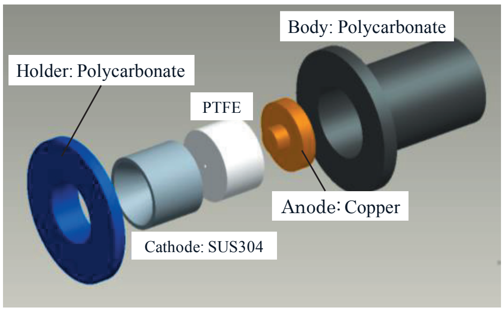
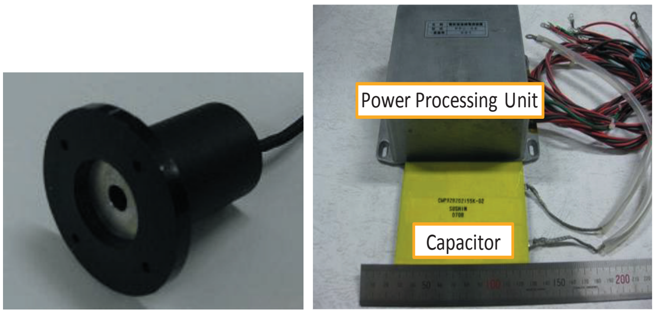


Figure 10. Inner structure of PPT.



a) b)

Figure 11. PPT flight-model parts.
a) Photos of PPT head, b) power processing unit and 1.5-μF capacitor of flight model of PPT.

We designed the flight model of a PPT head and its system. Fig. 10 and 11 show the structure, illustrations, and photos. The PPT head has a simple structure, and two PPT heads are settled on the outer plate of PROITERES satellite. As shown in Fig. 11(b), the power processing unit and the 1.5-μF capacitor are mounted in the satellite. The final endurance test of the PPT system was successfully finished.

III. Final Checking at SDSC, ISRO

The 1st PROITERES satellite and its mass-dummy were carried to SDSC, ISRO by air transportation to Chennai International Airport, India from Kansai International Airport, Osaka, Japan on July 18, 2012, and final checking tests of the satellite, as shown in Fig. 12, were conducted in July-August 2012. After those, the PROPTERES satellite was installed to the PSLV C-21 rocket.

The satellite was attached to the satellite deck of the PSLV C-21 launcher with five degrees in inclination shown in Fig. 13. An interface ring was used to give an inclination of five degrees. Finally, as shown in Fig. 14 we prayed to Japanese God by Japanese style for success of launch on the satellite deck just before launching.

Figure 12. Features of final checking tests at SDSC, ISRO.

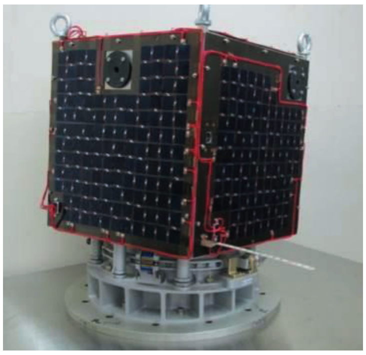


Figure 13. 1st PROITERES with separation device and interface ring.

Figure 14. 1st PROITERES Satellite on PSLV C-21 satellite deck and Japanese style praying for success of launch.

IV. Operation after Launch

Table 3 shows the operation history of 1st PROITERES in 2012 and 2013. The launch on September 9th succeeded, and after that we could receive telemetry data of Morse signals from the satellite nine hours later at the ground station, Omiya campus, Osaka Institute of Technology, Osaka, Japan. The receiving operational data of current and voltage values of the power supply system are shown in Fig. 15 and 16. From these data, the discharging current is stable between 0.2 and 0.31 A. The voltage was lower than 11.5 V at the time of charging and higher than 9.8 V at the time of discharging. These data show that the satellite works normally.

Then we could keep receive of Morse signals between the satellite and the ground station during about a week. However, the communication was blackout. After that, the satellite is repeating receive of Morse signals of revival and communication blackout. As shown in Fig. 17, we conducted a ground experiment to find a cause of this malfunction. As a result, the communication system of transmitter and receiver on the satellite was inferred to be not so good, i.e. electrically unstable.

Furthermore, we received the warning information that two debris approached the satellite with about 100 m in distance and 15 km/s in relative velocity in the end of December 2012 from the Joint Space Operations Center (JSOC), USA. However, because we succeeded in the communication with the satellite later than that accident, the satellite works now. Just now we are sending mission signals of FM telemetry at fixed intervals on thruster firing and continuing observation.[7-9]

Table 3. Operation history of the 1st PROITERES

Date	Time(JST)	Details of history
Sep. 9, 2012	13:23	We succeeded to launch satellite.
	16:36	We received reports that German ham operator received Morse of the PROITERES.
	22:48	We succeeded to receive morse of the PROITERES at OIT.
Sep. 10-13		We succeeded to receive data of power supply.
Sep. 14	10:36	We could not gradually receive morse of the PROITERES.
	10:36	The communication was blackout.
Sep. 21	10:25	The other station received Morse of the PROITERES. (Then the night path could not receive.)
Sep. 23	21:41	We succeeded to receive again morse of the PROITERES at OIT. Then the morse of PROITERES was abnormal.
	21:42	The communication was blackout again.
Dec. 4	00:16	We received warning from JSOC that approaching two debris.
Dec. 5	00:01	A debris was closest to the PROITERES. (First debris) Then we didn't receive clashing of the PROITERES and the debris.
Dec. 6	03:27	A debris was closest to the PROITERES. (Second debris) Then we didn't receive clashing of the PROITERES and the debris.
Apr. 11, 2013	09:00	We succeeded to receive again morse of the PROITERES only morning path at OIT. But the morse of PROITERES was abnormal.
Apr. 12	09:00	We succeeded to receive again morse of the PROITERES only morning path at OIT. But the morse of PROITERES was abnormal.
Apr. 13		The communication was blackout again. Now that still continues. We are sending FM telemetry on thruster firing and continuing observation.

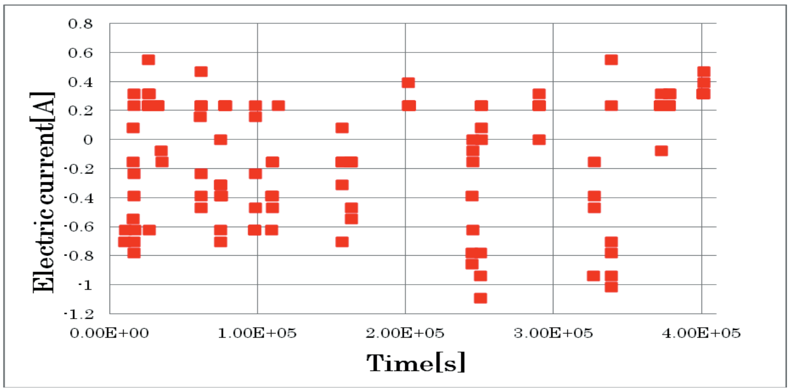


Figure 15. Current history data of power supply.
(Plus values present discharging, and minus values present charging)

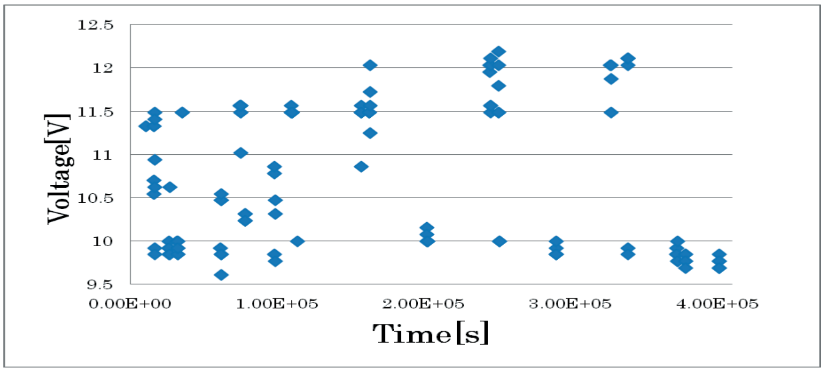


Figure 16. Voltage history data of power supply.

Figure 17. Ground experiment on malfunction of satellite.

V. R&D of the 2nd PROITERES

As next projects, we started the research and development of the 2nd PROITERES satellites in October 2010. The 2nd satellite of PROITERES series, as illustrated in Fig. 18, is a 50 kg-class satellite with high-power and large-total-impulse pulsed plasma thruster system for practical use. The PPT system with 10-15 kg is provided with four thruster heads with Teflon feeding mechanisms, and the total impulse per one thruster head is 2500 Ns at an input power of 25 W. As a result, we will be able to change the altitude of the satellite.[10,11]

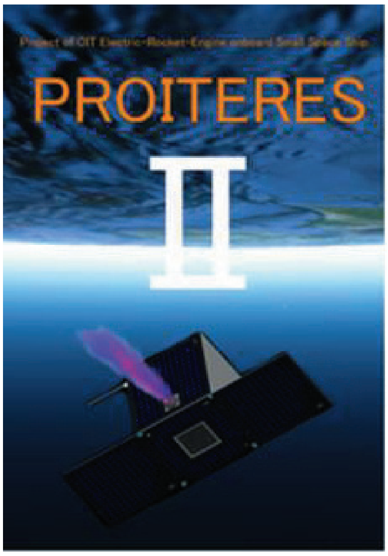


Figure 18. Illustration of 2nd PROITERES satellite.

A. Overview of the 2nd PROITERES

The specification of the 2nd PROITERES satellite is shown in Table 4. The weight is 50.0 kg, the configuration is a 0.5 m cube, and the minimum electric power is 60 W. The 2nd PROITERES have two paddles. The lifetime is a year and over. The main mission of the satellite is to change orbital altitude by high-power electrothermal PPT. The sub-mission is to perform operation tests for reaction wheels designed for micro-satellites.

Table 4. Specification of the 2nd PROITERES.

Mass	50.0kg
Outside dimension	500mm x 500mm x 500mm (Without extension paddles)
Starting time	April 2010
Electric power	62W
Life time	1-2 year
Attitude control	Magnetic attitude control
Main mission	Powered flight by multi discharged PPT
Sub mission	Demonstration of Reaction Wheel

B. Multi-Discharge-Room Electrothermal PPT

The PPT system for the 2nd PROITERES satellite will be expected to establish a longtime operation for 200-400 km orbital transfer. Therefore, a new PPT system with Multi-Discharge-Room electrothermal PPT (MDR-PPT) was developed. The MDR-PPT has seven discharge rooms. An ignitor, a nozzle and an anode are established in each discharge room. The structure is shown in Fig.19, and the photograph is shown in Fig. 20. A repetitive 1000 shot operation test was performed using the MDR-PPT at an input energy of 31.59 J and a frequency of 0.5 Hz.

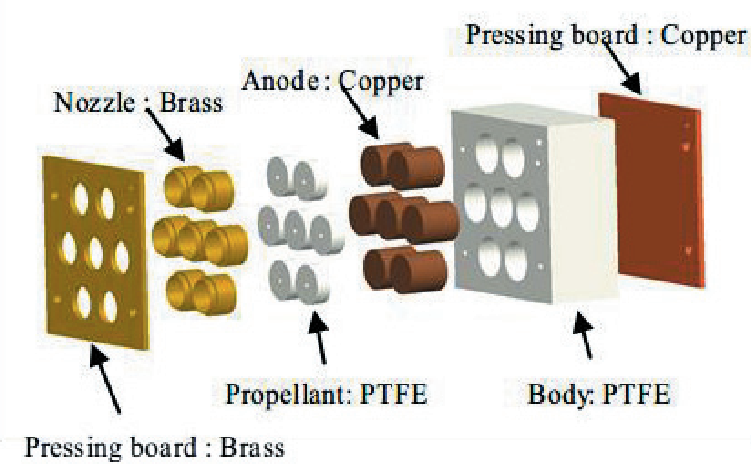


Figure 19. Structure of the MDR-PPT.

(a) (b)

Figure 20. Photograph of the MDR-PPT.
a) Thruster overview, b) Operation.

C. Reaction Wheel

A small reaction wheel for micro/nano satellites is manufactured by Mitsubishi Precision Co. in our sub-mission. The reaction wheel is shown in Fig. 21, and specification is shown in Table 5.

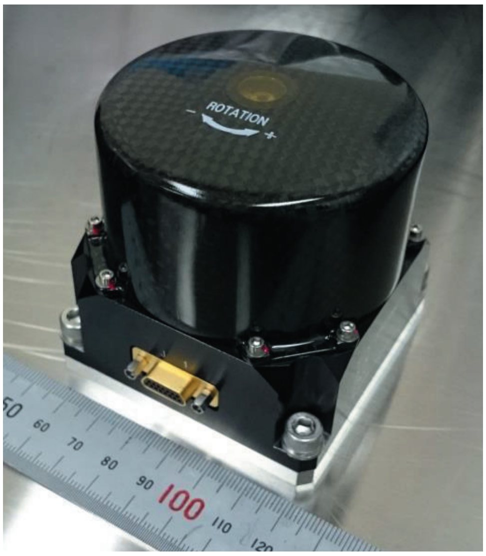


Figure 21. Reaction wheel manufactured by Mitsubishi Precision Co.

Table 5. Specification of reaction wheel.

Design Specification	Capability
Maximum momentum	0.2~0.4Nms(selectable)
Maximum output Torque	0.010Nm
Power consumption PeakTorque ±6000rpm, Maximum torque Steady state ±6000rpm	<25.5W <6W
Size	72mm x 72mm x 78mm
Mass	1000g
Operation Temperature Range	258.15 ~ 333.15K
Bearing Life	>3.2x10^{9} Revolution

D. Magnetic torquer

The main factors that the attitude of the satellite is disturbed are geomagnetic torque, gravity gradient torque, solar radiation torque and aerodynamic torque. These environment disturbance of the 2nd PROITERES are shown in Fig. 22. We scheduled the altitude of the 2nd PROITERES of 600 km. The geomagnetic torque and gravity gradient torque are most dominant in 600 km by Fig. 22. Then, the total disturbance torque is $3.09\text{x}10^{-5}$Nm. The magnetic torquer is required to generate over this torque. The magnetic moment of minimum requirement of the magnetic torquer is 0.65 Am^2. We determined requirement of magnetic moment to 6.0 Am^2 in a margin, and electricity consumption is 0.5W or less. The developed magnetic torquer is shown in Fig. 23, and the specification is shown in Table 6.

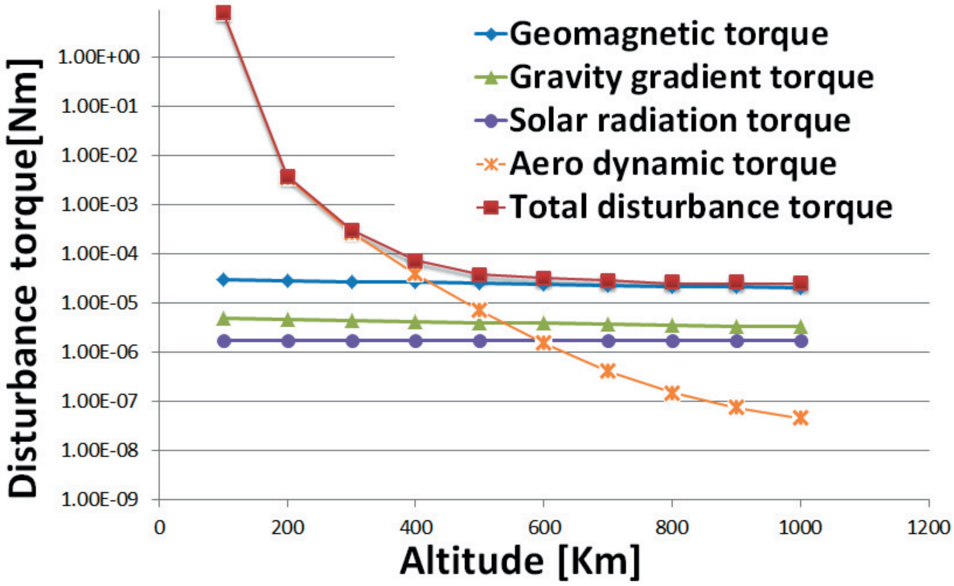


Figure 22. Environment disturbance of the 2nd PROITERES.

Figure 23. Magnetic torquer.

Table 6. Specification of magnetic torquer.

Material of core	Permalloy PB
Diameter of core	8mm
Length of core	300mm
Material of lead	Copper 0.5mm
Number of turns	2400 (600x4)

We applied an electrical current to the developed magnetic torquer and measured magnetic moment. The result is shown in Fig. 24. We confirmed that the experimental value and the theoretical value were more than 6.0Am^2 in 0.2A. Then, the electricity consumption is 0.2W. We achieved requirement of the magnetic torquer. In the future, we will develop a control driver of the magnetic torquer.

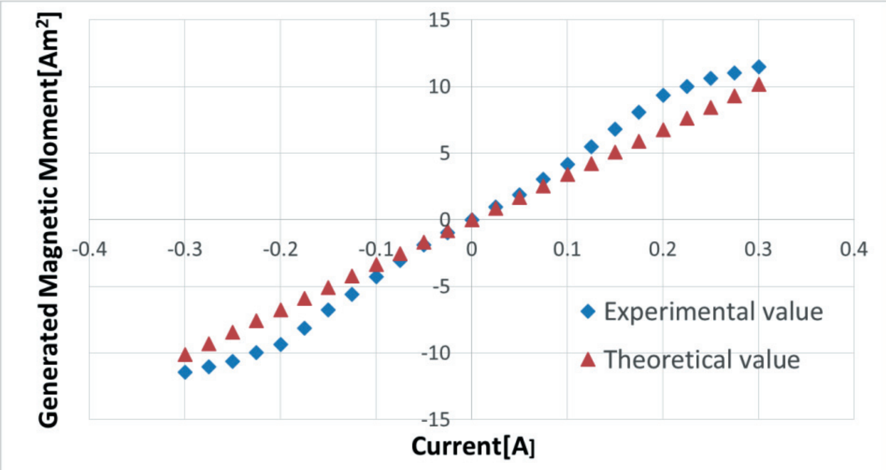


Figure 24. Experimental result.

VI. 3rd PROITERES

The 3rd satellite of PROITERES series is a 50-kg moon-exploration satellite as shown in Fig. 25, with cylindrical-type Hall thruster system for powered flight from the low earth orbit to the moon orbit. The Hall thruster system will produce specific impulses of 1500-2000 sec at xenon mass flow rates of 0.1-0.3 mg/s with an input power of 30W. The trip time to the moon is within 3 years. Now, we are developing the cylindrical-type Hall thruster.

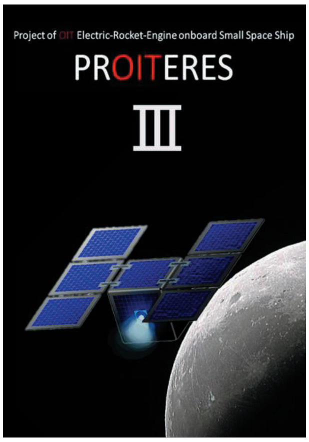


Figure 25. Illustration of 2nd PROITERES satellite.

VII. Conclusion

The Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES) was started at Osaka Institute of Technology in 2007. In PROITERES, a nano satellite named the 1st PROITERES satellite with electrothermal pulsed plasma thrusters (PPTs) was launched by Indian PSLV C-21 rocket on September 9, 2012. And, we succeeded the communication with the satellite in ground station of our university nine hours later. However, the communication with the satellite was cut off a few days later. After that, the satellite repeats revival and communication blackout and reaches it at the present. Therefore, we experimented it to find a cause of this malfunction. As next projects, we started the research and development of the 2nd PROITERES satellites in Oct. 2010. We developed high-power electrothermal PPT systems for powered-flight of the 2nd PROITERES and magnetic torquers as attitude control devices, and achieved requirement of it. In the future, we will develop a control driver of magnetic torquer and other devices. Furthermore, the 3rd PROITERES satellite of moon exploration by powered-flight to moon from the low-earth mission is under development.

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