

R&D, Launch and Initial Operation of the Osaka Institute of Technology 1st PROITERES Nano-satellite with Electrothermal Pulsed Plasma Thrusters and Development of the 2nd Satellite

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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 successfully launched by Indian PSLV C-21 rocket on September 9th, 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 checking, launch process and initial operation of the satellite FM including EP system. Furthermore, the research and development of the 2nd and 3rd PROITERES satellites with high-power electric thrusters, i.e., high-power electrothermal PPT and cylindrical Hall thruster, respectively, 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-computer system, communication system and

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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. The satellite's main mission are to achieve powered flight of nano-satellite by an electric thruster and to observe Kansai district in Japan with a high-resolution camera.

In this paper, we introduce the R&D feature and final checking, launch process and initial operation of the satellite FM including EP system. Furthermore, the research and development of the 2nd and 3rd PROITERES satellites with high-power electric thrusters, i.e., high-power electrothermal PPT and cylindrical Hall thruster, respectively, are also introduced.



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

II. Overview of the 1st PROITERES

Figure 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.¹⁻⁵

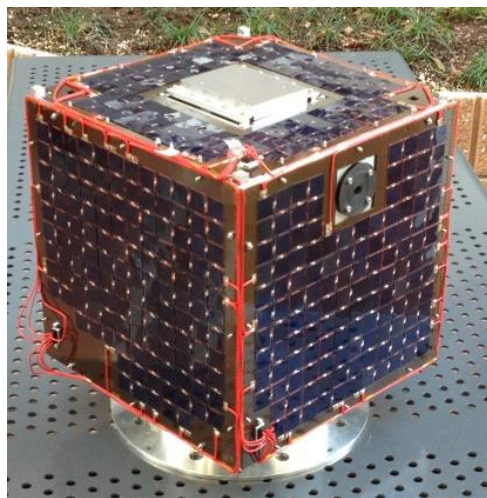


Figure 2. Flight model of 1st PROITERES.

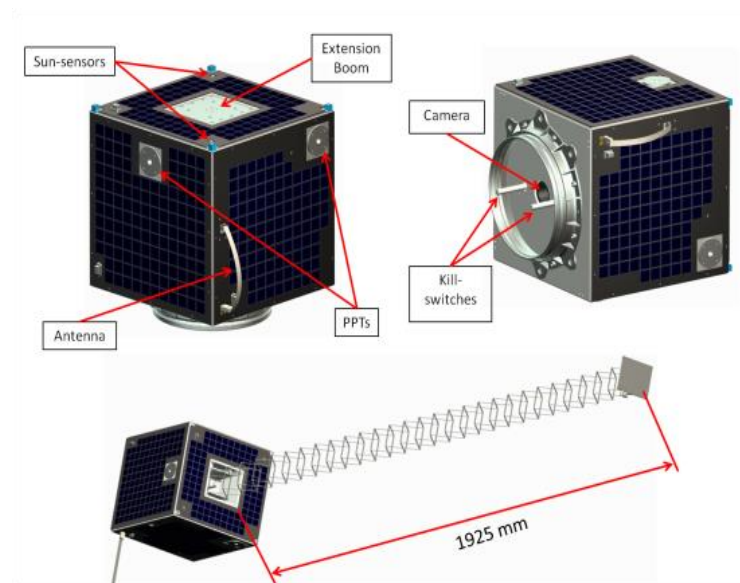


Figure 3. Overall view of 1st PROITERES.

Table 1. Summary of 1st PROITERES.

Mass	14.5kg
Outside dimension	290mm×290mm×290mm (Without extension boom)
Orbit	Orbital inclination: 99.98[deg], 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.^{3,5-7}

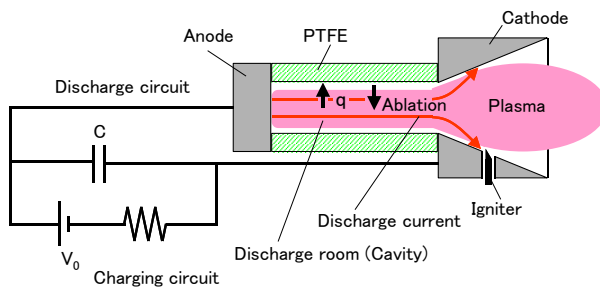


Figure 4. Electrothermal pulsed plasma thrusters

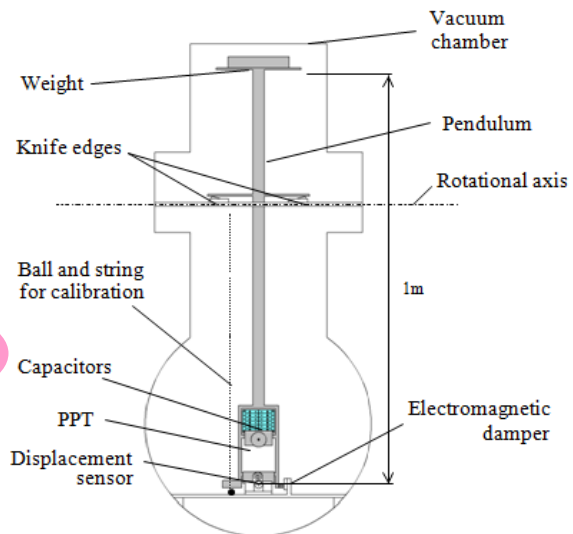


figure 5. Thrust stand



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. Figure 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 $\pm 0.5 \mu\text{m}$.

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 1.0×10^{-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.

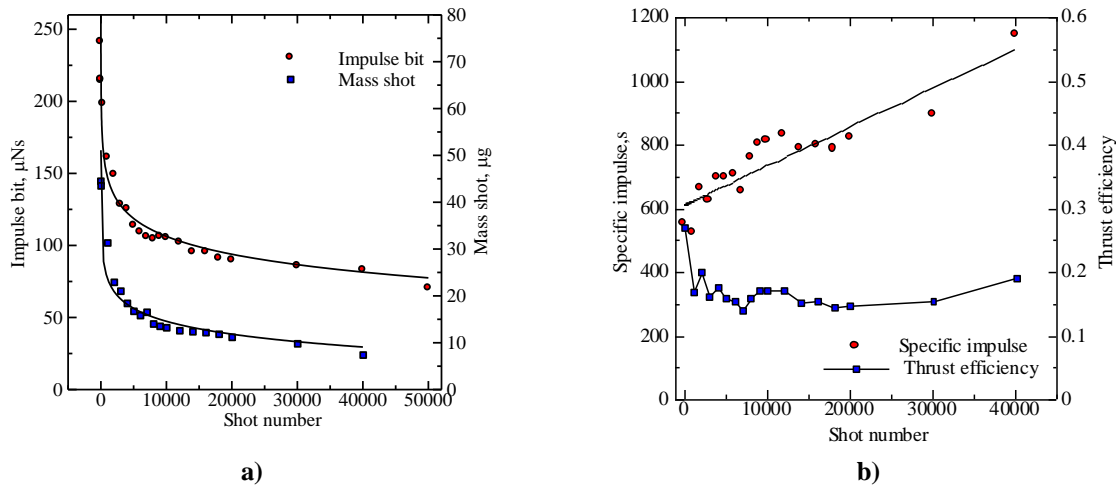


Figure 7. Result of endurance test.
a) Impulse bit and mass shot, b) specific impulse and thrust efficiency

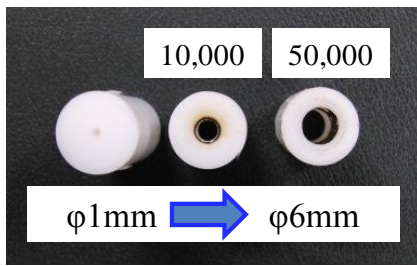


Figure 7. Change of cavity diameter before and after 50,000-shots.

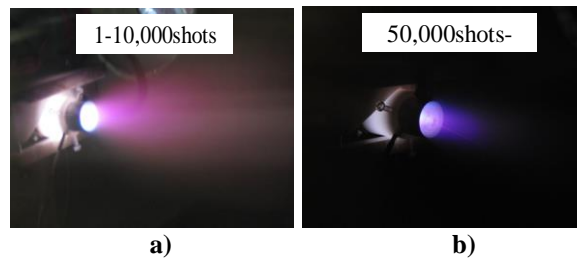


Figure 8. Feature of plasma plume.
a) 1-10,000 shots, b) 50,000 shots.

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.6(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.6(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 lowering pressure and ionization degree in the cavity when enlarging cavity diameter.

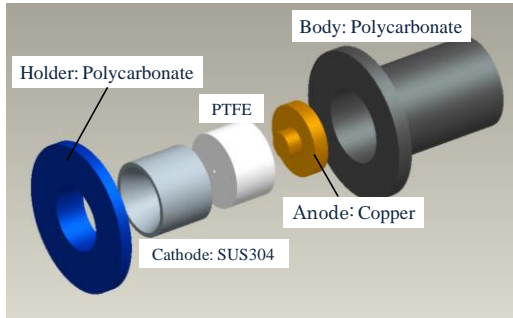


Figure 9. Inner structure of PPT.

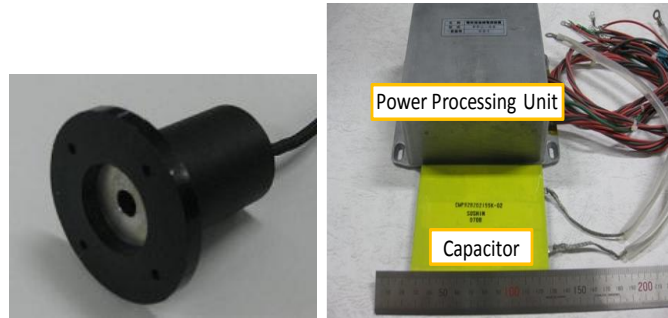


Figure 10. PPT flight-model parts.
a) Photos of PPT head, b) power processing unit and 1.5-μF capacitor of flight model of PPT.

We designed the flight model of a PPT head and its system. Figure 9 and 10 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.10(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.⁶⁻⁸

B. High-resolution camera system

A high-resolution camera system was developed for PROITERES satellite. Figures 11 and 12, and Table 3 show the flight model of the optical system, the CMOS sensor, and the specification. The optical system has five-lens system with a focal length of 85.3 mm and a F number of 3.6. The mass is 230 g, and the length and diameter are 109 mm and about 50 mm, respectively. Accordingly, the optical resolution is 30 m for the CMOS sensor. After accurate alignment between the optical system and the CMOS sensor with a special facility shown in Fig.13, the camera system was onboard the satellite. As shown in Fig.14, we will be able to observe the Kansai district with Yodo River from PROITERES satellite.

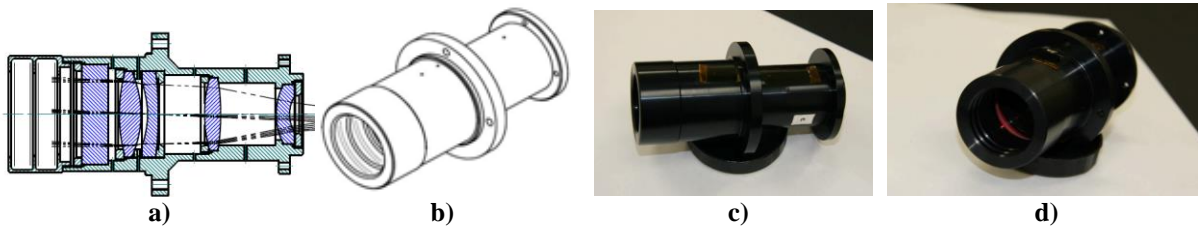


Figure 11. High-resolution camera optical system.
a) Cross-sectional drawing of optical system, b) outline view of optical system, c) side view of optical system, d) front view of optical system.

Table 3. Flight model of the optical system.

Parameter	Typical Value
Model number	MT9T001
Size	14.22mm × 14.22mm
Active imager size	6.55mm(H) × 4.92mm(V) 8.19mm(Diagonal)
Active pixels	2048H × 1536V 3-Mega pixels
Pixel size	3.2μm × 3.2μm



Figure 12. CMOS sensor.



Figure 13. Aligent device.



Figure 14. Photography image of Kansai district in Japan.

C. Attitude Control System

Attitude control systems with magnetic torquers, 3-axis magnetic and gyro sensors, and sun sensors were developed. Figures 15-17 show these device FMs. Three magnetic coils are used for generation of magnetic fields. The attitude of PROITERES satellite can be controlled by magnetic torque, which is created by interaction between the geomagnetic field and the magnetic field generated with the coils in the satellite. The sun sensor detects the direction of the Sun with arrangement of a linear photo sensor and a slit. The extension boom which produces gravity gradient is mounted to assist attitude control.



Figure 15. Magnetic torquer.

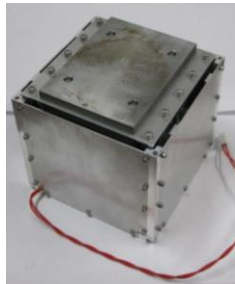


Figure 16. Extension boom.



Figure 17. Sun sensor.

D. Structure

Figure 19 shows the flight model of the satellite structure under final ANSYS analysis. Main satellite frames and walls are made of duralumin A7075. Both a mass dummy and the flight model of the satellite, as shown in Fig.20, were safe under all vibration and shock tests required from India.

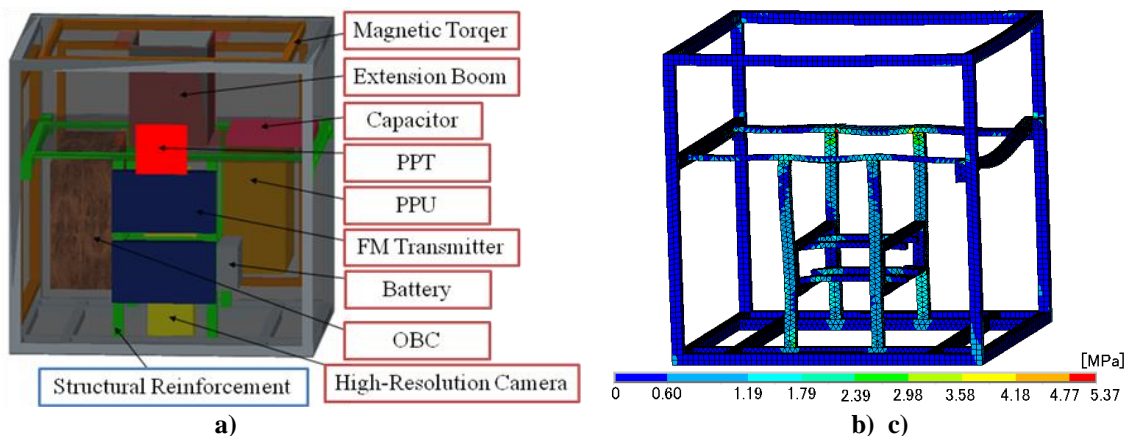
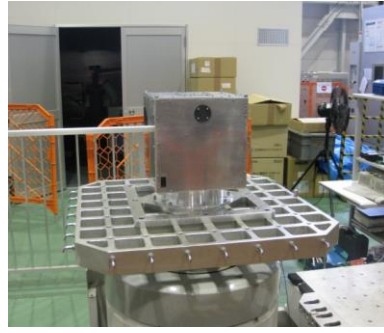


Figure 19. Flight model of PROITERES satellite.

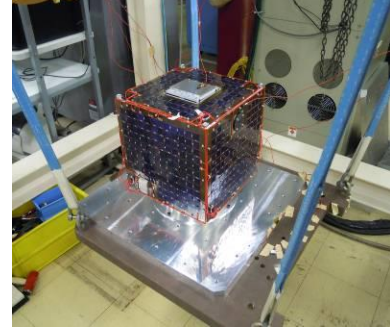
a) Arrangement inside satellite, b) structure under final ANSYS static analysis, c) Interior photo.



a)



b)



c)

Figure 20. Photos of PROITERES FM; vibration and shock tests.

a) Satellite FM, b) Vibration test, c) Shock test.

E. Onboard-computer system

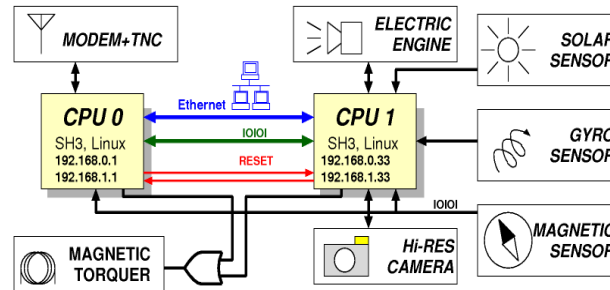


Figure 21. C&DH system of PROITERES satellite.

Figure 21 shows the system diagram of PROITERES satellite. The command and data handling system of the satellite is characterized by these features that

- 1) it has 2 main computers;
- 2) the computers run under Linux operating system, and
- 3) the computers make TCP/IP based local area network.

They are all for durability as well as higher performance. Two computers watch each other work properly and each one can reboot the other when it fails. Some of the most important tasks such as attitude control are executed by both computers for redundancy while other tasks are allocated among them for load balancing.

Figure 22 shows a commercially-available computer board selected for PROITERES satellite. The board computer of SH7709 and CAT709 was irradiated to Gamma rays 64 krad, at Radiation Research Center, Osaka Prefecture University, and before and after, and during irradiation, running of computer program was checked and completely accepted. Attitude control system.

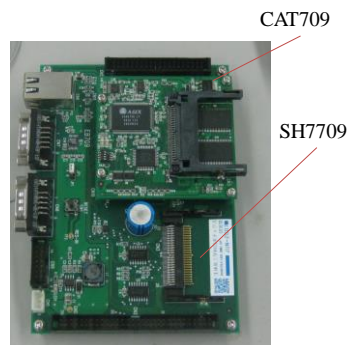
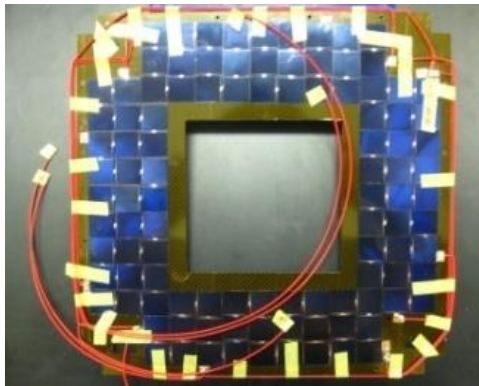


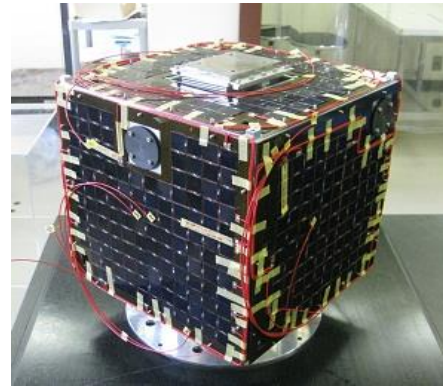
Figure 22. On-board-computer(OBC).

F. Electric power system

The electric power system of the 1st PROITERES consists of solar panels and a secondary battery, a power supply unit. Figure 23 shows solar panels of the PROITERES. Silicon solar cells are connected in 26-series and 4-6 parallel connection per one solar panel. Five solar panels are mounted except the bottom surface of the satellite. The minimum electric power of 10 W will be generated by each surface. Two bus voltages of 5 and 12 V are provided, and that of 12 V is used for electrothermal PPT operation. The secondary battery is "eneloop" that is the Ni-MH battery of Sanyo Electric Co., Ltd. Figure 24 shows the power supply unit including the secondary battery system. This unit was developed by collaboration with AstreX Co., Ltd. As charging mode we selected the battery-solar cell direct-charging method because power loss is minimum.



a) Top panel.

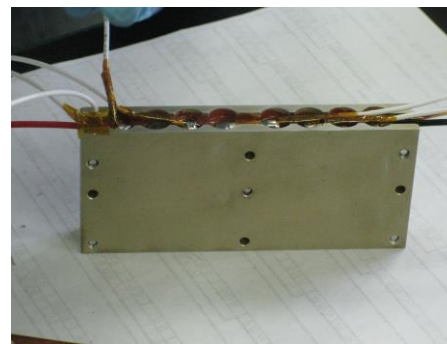


b) Assembled satellite.

Figure 23. Solar panels of 1st PROITERES.



a) Main power supply unit.



b) Secondary power unit (battery).

Figure 24. Power supply unit of 1st PROITERES.

G. Communication system and ground station

Figure 25 shows the satellite link overview. The satellite communication system is equipped for the following purposes:

- 1) Mission data transmission
- 2) Control and maintenance of the satellite
- 3) Support to tracking of the satellite

The PROITERES satellite network has three beams listed as follows:

- 1) Down-link: D1 beam (Telemetry: FM/BFSK)
- 2) Down-link: D2 beam (Beacon: CW/Morse)
- 3) Up-link: U1 beam (Command: FM/BFSK)

All communications are scheduled to be executed in the frequency of 430MHz.

Figure 26 shows the subsystem block diagram. The components are follows:

- 1) Transmitter and receiver (Nishi RF Lab. Custom made module)

This module transmits AX.25 packet (telemetry data) to the ground station by FM method with speed of 1200bps via the dipole antenna. The module also transmits Morse codes (beacon signal) to the ground station. As for the

receiver function, this module receives FM signal (command) and send AX.25 packet to TNC in communication controller.

2) Communication controller (UNISEC Custom made module)

The communication controller mediates onboard computer and the Nishi RF Lab. module. Functions of this unit are follows:

- i) Capsulation of AX.25 packet (Terminal Node Controller),
 - ii) Modulation and demodulation of binary FSK (BFSK) data,
 - iii) Configure the phase lock loop and frequency, PTT of Nishi RF Lab. Module.
- ## 3) Antennas

In PROITERES satellite, the same frequency, 430MHz band, is used for the transmission and the reception. Thus one antenna was installed in the satellite. As for installation antenna type, we used antennas of half wavelength dipole antenna and inverted L antenna.

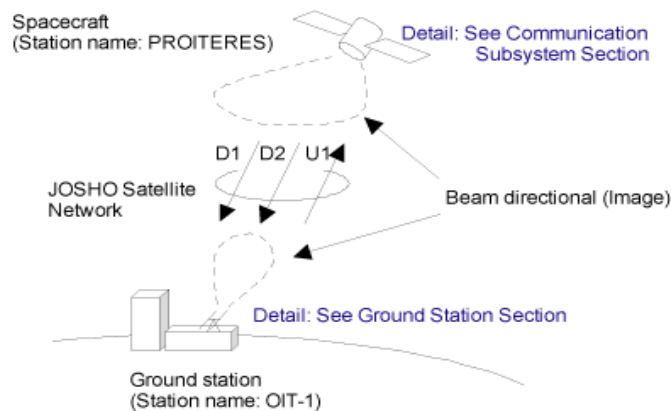


Figure 25. Satellite link overview.

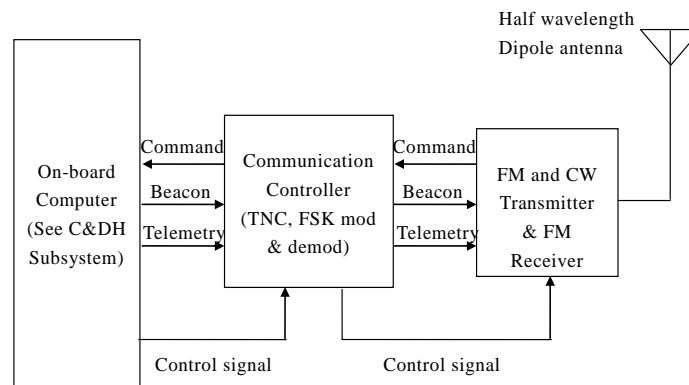


Figure 26. Block diagram of communication subsystem.

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Figure 27 and 28 show the ground station block diagram and its photo, respectively, prepared at Omiya campus, Osaka Institute of Technology, Osaka, Japan. This system is one of popular and commercially-available systems in ground.⁹

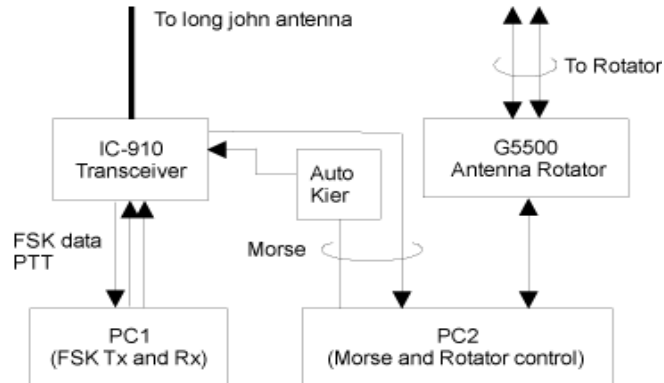


Figure 27. Ground station block diagram.



a) Antenna.



b) Control PC.

Figure 28. Ground station located at Omiya campus, Osaka Institute of Technology.

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.29, 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 Figs.30 and 31. An interface ring was used to give an inclination of five degrees. Finally, as shown in Fig.32 we prayed to Japanese God by Japanese style for success of launch on the satellite deck just before launching.

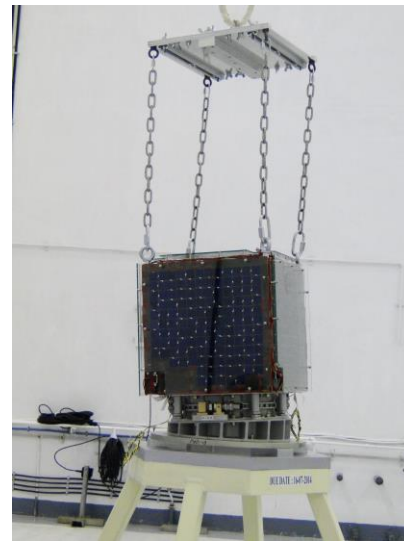


Figure 29. Features of final checking tests at SDSC, ISRO.

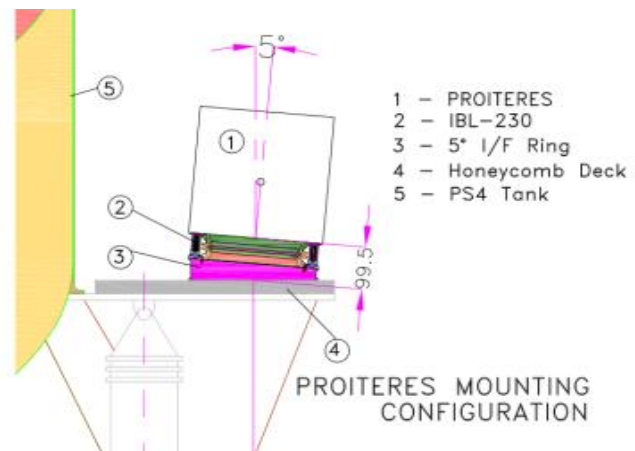
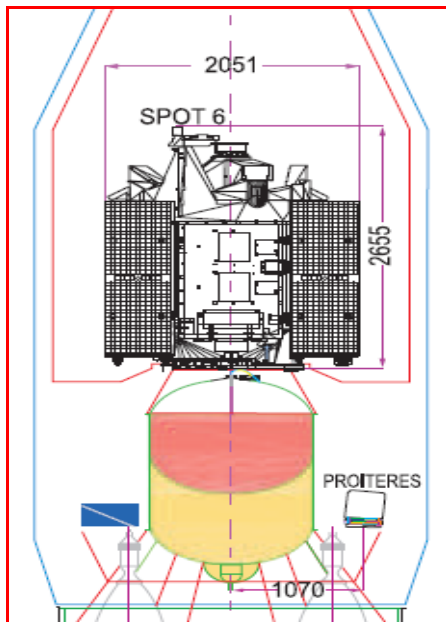


Figure 30. Image after installation of PROITERES.

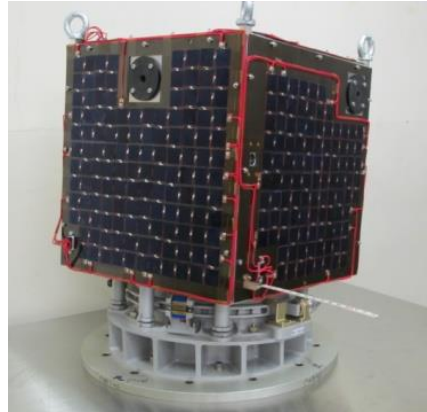


Figure 31. 1st PROITERES with separation device and interface ring.



Figure 32. 1st PROITERES Satellite on PSLV C-21 satellite deck and Japanese style praying for success of launch.

IV. Operation after Launch

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 Figs. 33 and 34. 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 two weeks. However, the communication was cut off. After that, the satellite is repeating receive of Morse signals of revival and communication blackout. As shown in Fig. 35, 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 some 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 Consolidated Space Operations Center (CSOC), 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 on thruster firing etc to the 1st PROITERES satellite.¹⁰

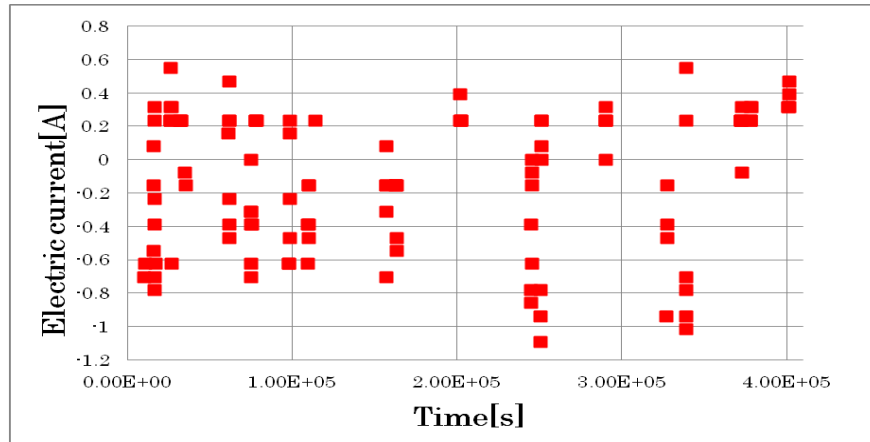


Figure. 33 Current history data of power supply.
(Plus values present discharging, and minus values present charging)

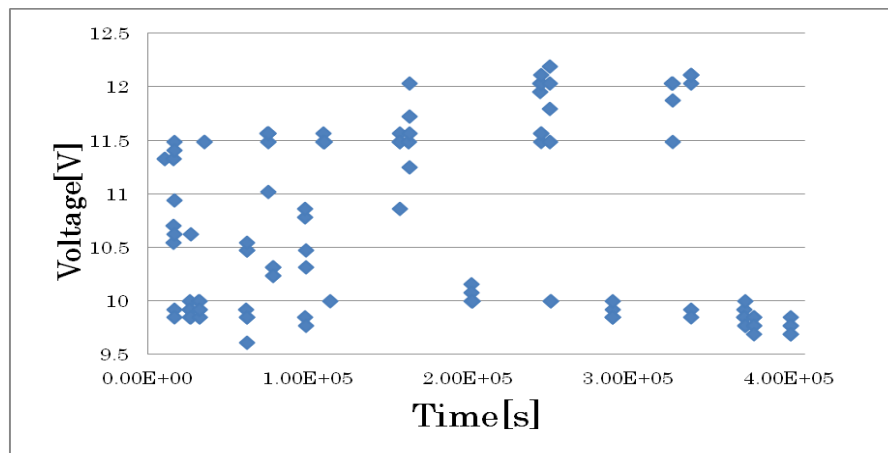


Figure. 34 Voltage history data of power supply.



Figure 35. Ground experiment on malfunction of satellite.

V. R&D of 2nd and 3rd PROITERES Satellites

As next projects, we started the research and development of the 2nd and 3rd PROITERES satellites in October 2010. The 2nd satellite of PROITERES series, as illustrated in Fig. 36, is a 50-kg earth-observation 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 can change totally the altitude of the satellite up to 400 km, and on the lower orbit of 200 km we can keep the altitude up to one month.

The 3rd satellite of PROITERES series is a 50-kg moon-exploration satellite 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 30 W. The trip time to the moon is within 3 years.

The 2nd and 3rd PROITERES satellites are under development.¹¹

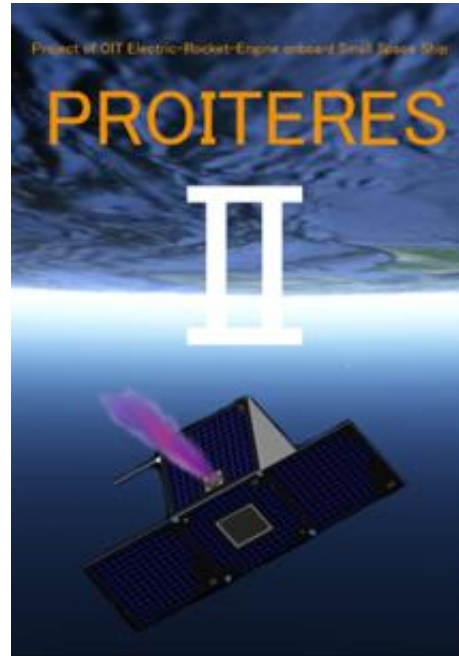


Figure 25. Illustration of 2nd PROITERES satellite.

VI. 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 successfully launched by Indian PSLV C-21 rocket on September 9, 2012. After launch we succeeded the communication with the satellite at the ground station, Osaka Institute of Technology, Osaka, Japan, nine hours later. However, the communication with the satellite was cut off about two weeks later. After that, the satellite is repeating receive of Morse signals of revival and communication blackout. The communication system of transmitter and receiver on the satellite was inferred to be not so good, i.e. electrically unstable. Just now we are sending mission signals of FM telemetry on thruster firing etc to the 1st PROITERES satellite.

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