Development of Osaka Institute of Technology Nano-Satellite "PROITERES" with Electrothermal Pulsed Plasma Thrusters

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Abstract: In the Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES), a nano-satellite with electrothermal pulsed plasma thrusters (PPTs) will be launched in the end of 2012, because the launching was delayed due to change of schedule of Indian PSLV launcher. The main mission is to achieve powered flight of nano-satellite by an electric thruster and to observe Kansai district in Japan with a high-resolution camera. 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 feature of the satellite FM including EP system. Furthermore, the research and development of the 2nd and 3rd PROITERES satellites with electric thrusters are also introduced.

I. Introduction

THE Project of Osaka Institute of Technology Electric-Rocket-Engine onboard Small Space Ship (PROITERES), as shown in Fig.1, was started at Osaka Institute of Technology in 2007.[1-7] In PROITERES, a nano satellite with electrothermal pulsed plasma thrusters (PPTs) will be launched in 2012, because the launching was delayed from the end of 2011 due to change of schedule of Indian PSLV launcher. The main mission is to achieve powered flight of

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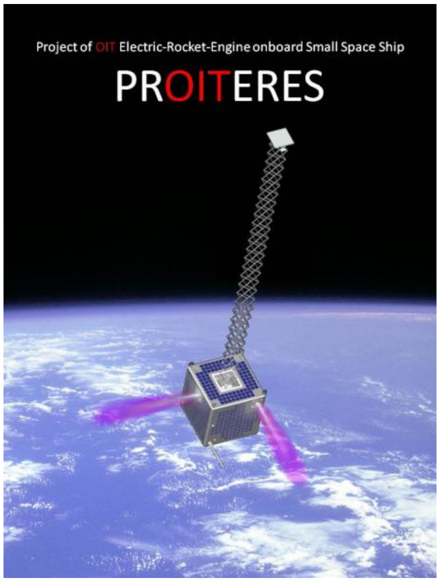


Figure 1. PROITERES satellite on orbit.

nano-satellite by an electric thruster and to observe Kansai district in Japan with a high-resolution camera. The raising in Sun Synchronous Orbit will be carried out by the PPTs.

Our satellite R&D groups are divided into eight sections. We take a student and staff member meeting one time a week and examine the satellite system. Each section developed Bread Board Model (BBM) and Engineering Model (EM) of the satellite in 2007-2009. In this paper, we introduce the final progress of PROITERES Flight-Model (FM) including PPT system. Furthermore, the research and development of the 2nd and 3rd PROITERES satellites with electric thrusters are also introduced.

II. "PROITERES" Satellite Overview

The specification of the satellite, as shown in Table 1 and Fig.2, is as follows. The weight is 15 kg; the configuration is a 0.29 m cube, and the minimum electric power is 10 W. The altitude is 670 km in Sun Synchronous Orbit. The lifetime is above one year. The launching rocket is PSLV in India, and the window will be Oct.-Dec. of 2012.

Table 1. Specification of satellite.

Mass	15kg
Outside dimension	290mm×290mm×290mm (Without extension boom)
Orbit	Orbital inclination: 99.98[deg], Eccentricity：0
Altitude	670km
Commencing time	April, 2007
Life time	1-2 years
Rocket	PSLV（India）
Launch	2012
Attitude control	Magnetic attitude control Gravity-gradient stabilization

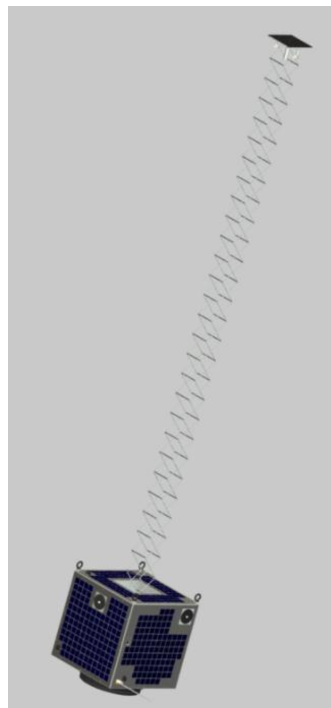


Figure 2. PROITERES satellite.

III. Missions and Their Systems

A. Powered Flight by Electric Thruster

Pulsed plasma thrusters, as shown in Fig.3, 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] We mainly

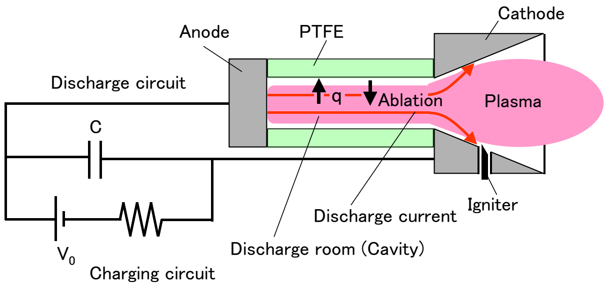


Figure 3. Electrothermal pulsed plasma thrusters.

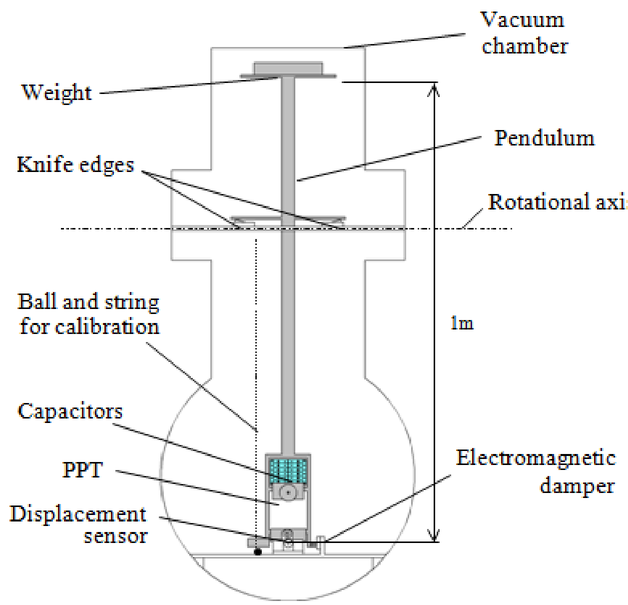


Figure 4. Thrust stand.

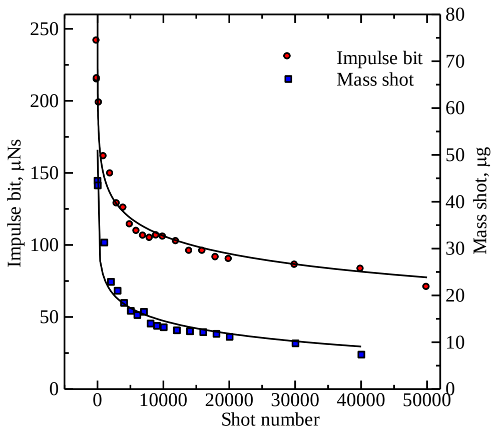
Table 2. Experimental conditions of endurance test.

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

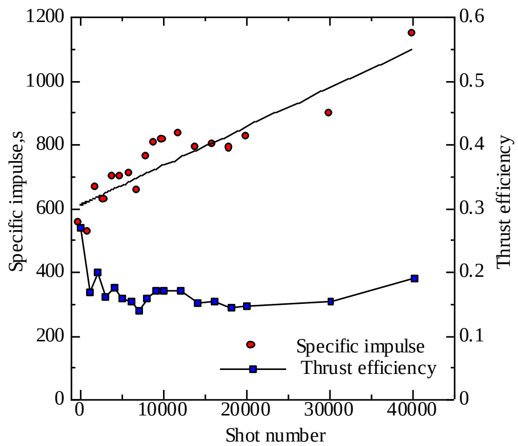
Figure 5. Vacuum chamber.

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



a)



b)

Figure 6. Result of endurance test.
a) Impulse bit and mass shot, b) specific impulse and thrust efficiency.

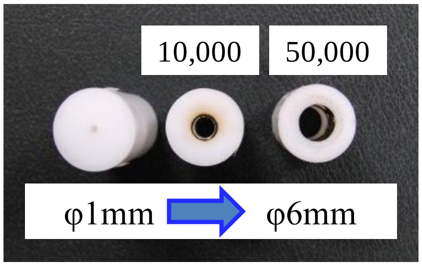
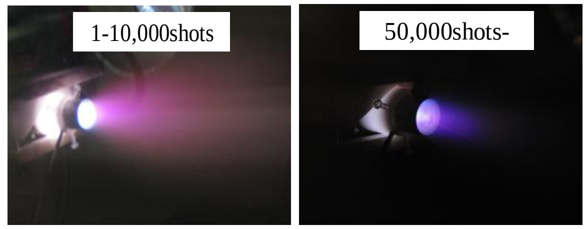


Figure 7. Change of cavity diameter before and after 50,000-shots.



a) b)

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

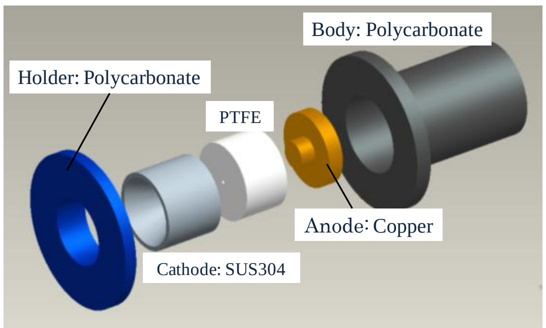
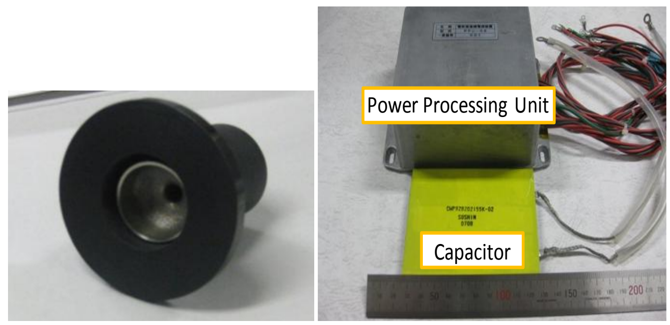


Figure 9. Inner structure of PPT.



a) b)

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.

carried out with the optimum PPT configuration.

Figure 4 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 μm.

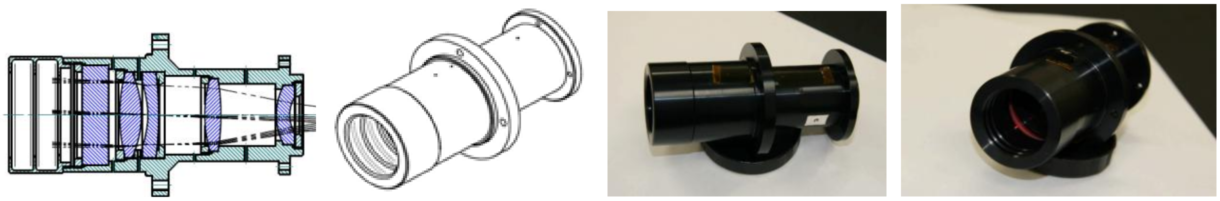
Figure 5 shows a vacuum chamber 1.25 m in length and 0.6 m in inner diameter, which is evacuated using a turbo-molecular pump with a pumping speed of 3,000 l/s. The pressure is kept below $1.0x10^{-2}$ Pa during PPT operation. We carried out endurance tests with the optimum cavity shape 9.0 mm in length 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.

Figure 6 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.7, 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.8, 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.

We designed the flight model of a PPT head and its system. Figures 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.

B. Observation of Kansai District

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



a) **b)** **c)** **d)**

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

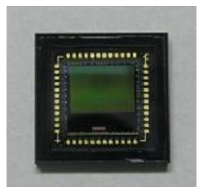


Figure 12. CMOS sensor.

Figure 13. Aliment device.

Figure 14. Photography image of Kansai district in Japan.

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.

IV. Satellite BUS System R&D

A. Structure

Figure 15 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.16, were safe under all vibration tests required from India.

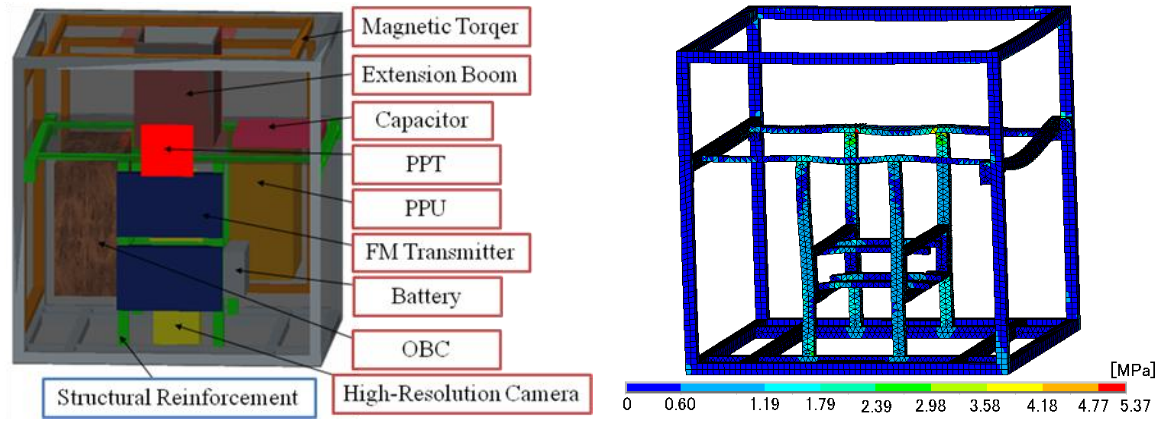
B. Onboard Computer System

Figure 17 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.

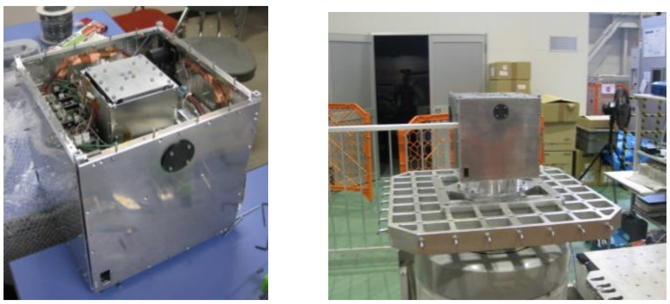
They are all for durability as well as higher performance. Two computers watch each other work properly and each one can reboot the other when it fails. Some of the most important tasks such as attitude control are executed by both computers for redundancy while other tasks are allocated among them for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

Figure 18 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



a) b)

Figure 15. Flight model of PROITERES satellite.
a) Arrangement inside satellite, b) structure under final ANSYS static analysis.



a) b)

Figure 16. Photos of PROITERES FM and vibration test.
a) Satellite FM, b) vibration test.

Prefecture University, and before and after, and during irradiation, running of computer program was checked and completely accepted.

C. Communication System and Ground Station

Figure 19 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

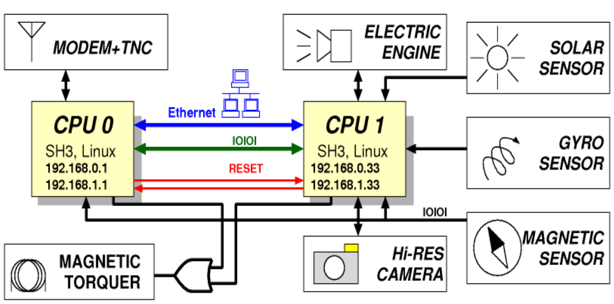


Figure 17. C&DH system of PROITERES satellite.

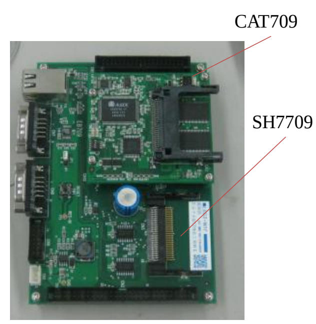


Figure 18. On-Board-computer (OBC).

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 20 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.

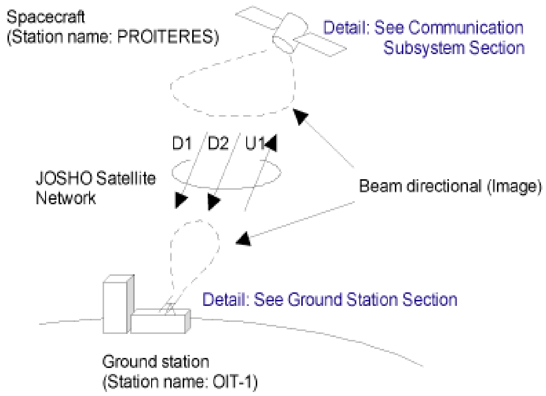


Figure 19. Satellite link overview.

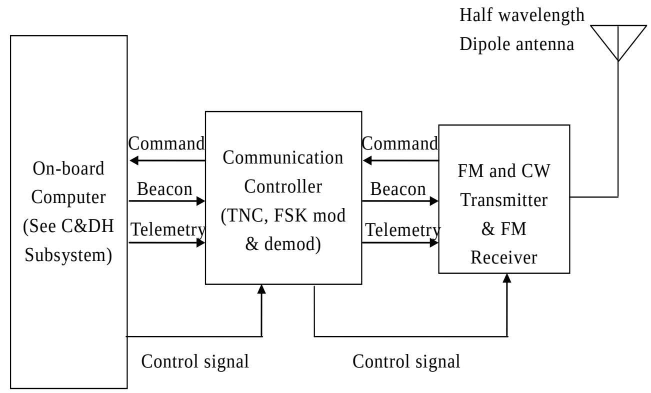


Figure 20. Block diagram of communication subsystem.

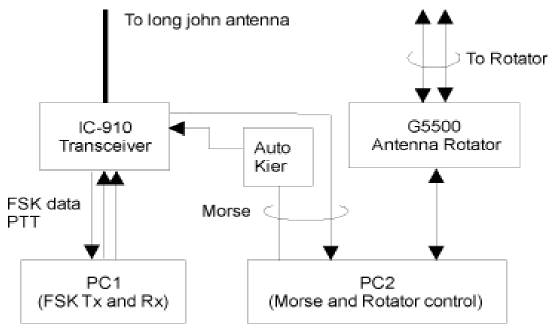
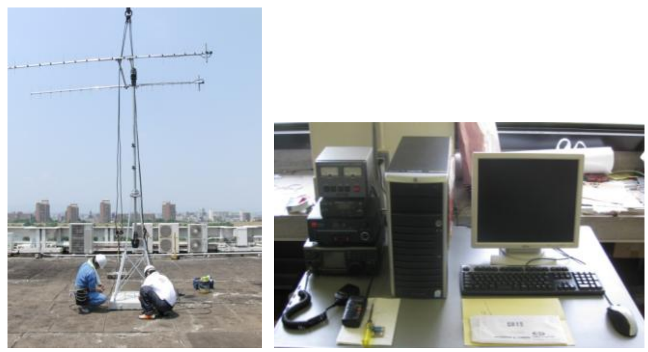


Figure 21. Ground station block diagram.



a) b)

Figure 22. Ground station.
a)Antenna, b)Control PC.

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

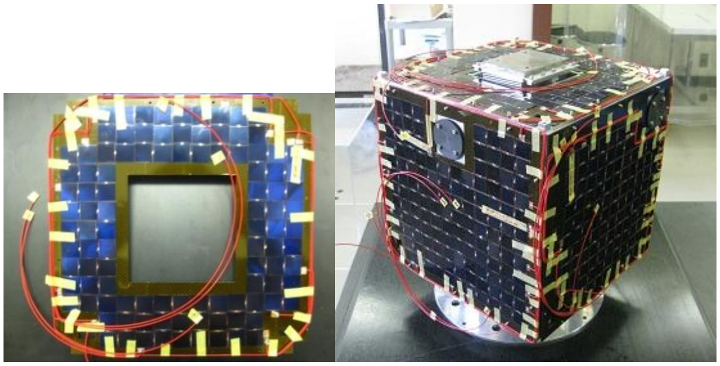
3) Antennas

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.

Figures 21 and 22 show the ground station block diagram and its photo, prepared at Omiya campus, Osaka Institute of Technology, Osaka. This system is one of popular and commercially-available systems in ground.

D. Electric Power System

The electric power system of PROITERES satellite consists of solar panels and a secondary battery, a power supply unit. Figure 23 shows solar panels of 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.



a) b)

Figure 23. Solar array panel of PROITERES. a) Top panel, b) assembled satellite.

Figure 24. Power supply unit of PROITERES.

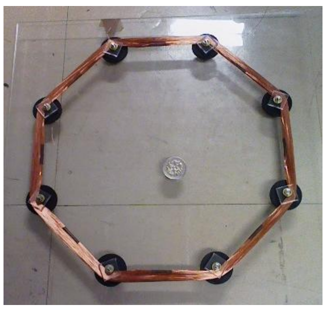


Figure 25. Magnetic torquer.

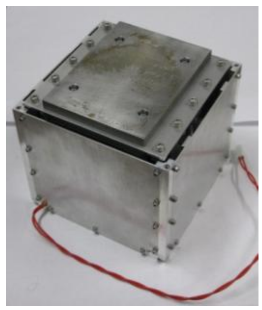


Figure 26. Extension boom.

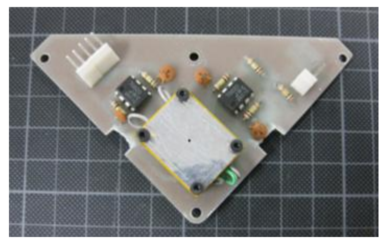


Figure 27. Sun sensor.

The secondary battery is "eneloop" that is the Ni-MH battery of Sanyo Electric Co., Ltd. Figure 24 shows the power supply unit. 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.

E. Attitude Control System

Attitude control systems with magnetic torquers, 3-axis magnetic and gyro sensors, and sun sensors were developed. Figures 25-27 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.

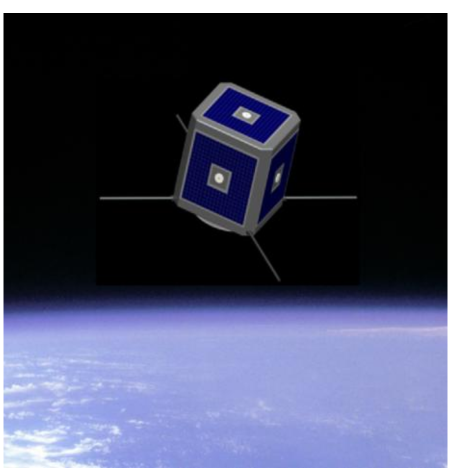


Figure 28. Illustration of 2nd PROITERES satellite.

V. 2nd and 3rd PROITERES Satellite R&D

As next projects, we started the research and development of the 2nd and 3rd PROITERES satellites in Oct. 2010. The 2nd satellite of PROITERES series, as illustrated in Fig.28, 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.[8] 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.

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 with electrothermal pulsed plasma thrusters (PPTs) will be launched in 2012, because the launching was delayed from the end of 2011 due to change of schedule of Indian PSLV launcher. The main mission is to achieve powered flight of nano-satellite by an electric thruster and to observe Kansai district in Japan with a high-resolution camera. 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 and attitude control system etc, in 2007-2009. Finally, we successfully developed the flight model of PROITERES in 2010. The PROITERES satellite FM is under final checking tests.

As next projects, we started the research and development of the 2nd and 3rd PROITERES satellites in Oct. 2010. The 2nd satellite of PROITERES series 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. 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 2nd and 3rd PROITERES satellites are under development.

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