

Ground Experiment for the Small Unified Propulsion System: I-COUPS installed on the small space probe: PROCYON

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Abstract: To respond to the increasing demand for using satellites, a number of universities and private business develop small satellites. Usage of small satellites continue to expand. Nowadays, small deep space probe has been started to develop. Without thrusters, deep space probes can't complete their missions. A lot of laboratory investigate propulsion systems for small satellites. On the other hand, the method of ground experiment of these thrusters is not established. That is because there are few examples of thrusters installed small satellite flying in space. In this paper, we introduce the ground experiments of the propulsion system: I-COUPS what is installed on small deep space probe: PROCYON and data received from the satellite. It is the first case in the world, so its details would be help to every small space probes developed after this.

Nomenclature

$\dot{m}_i$	= ion mass flow
e	= charge of electron
M	= mass of the ion
I_b	= beam current
I_s	= screen current
I_a	= acceleration current
F	= thrust
v_{ex}	= velocity of ion
V_s	= screen voltage
I_{sp}	= specific impulse
g	= gravity acceleration
$\dot{m}$	= propellant mass flow
η_t	= thrust efficiency

I. Introduction

THERE is a lot of demand for using satellites in academic field and commercial field. However, development of satellites requires hundreds of million dollars and chances to utilize them have been limited. Therefore, small satellites are gathering attentions in the world. Because of short develop period and low cost development, small satellites is much more accessible than the standard ones, and they have provided easier-access to the space for universities and private business. Due to those merits, commercial usage of small satellites have already started. In contrast with a lot of growth of small satellites usage on the low earth orbits, deep space exploration has been limited only for standard-sized spacecraft. Deep space exploration using small satellites requires a lot of advanced

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technologies and one of keys is miniature propulsion system. Developing thruster for small satellites and conducting their ground tests needs lower cost and shorter time than those of standard-sized satellites, because the availability of the facilities for those tests becomes higher as the scale is increasing. Due to these merits, a wide variety of experiments are possible. On the other hand, methods of the ground tests for small propulsion system have not been established. That is because there are few thrusters installed on small satellites flying space and few examples of those ground tests. There is also little sample of ground experiments r these thrusters.

In this paper, we introduce the ground experiments of small unified propulsion system, to which we refer as I-COUPS (Ion thruster and COLd-gas thruster Unified Propulsion System). We propose I-COUPS¹ as propulsion system for small space probe. Ref. 1 described details of I-COUPS. I-COUPS was installed on PROCYON². PROCYON would be the world first space probe less than 100 kg and also it would be the first space probe with RCS and electric propulsion in this class. Details of PROCYON is described in Ref.2. Hence, ground experiments of the thrusters installed on a small space probe would be a rare case and its details are valuable in this field. We have carried out following four experiments. First, we optimize the shape of orifice on the neutralizer by operating flight-model thruster. It was realized because optimize needs a lot of experiments with changing the orifices and operations of the thruster. Secondary, we measured distribution of the ion beam current in the far-field plume. This measurement was carried out to reduce the gap between center of mass and extension line of thrust vector. Vector of thrust is critical for thrusters for small satellites, because installing gimbal on small satellites is difficult. Because of smallness of the thruster, we succeed perform this measurement in small chamber whose diameter is about 1.0 m. Thirdly, we measured thrust of Cold-Gas Jet Thruster (We called CGJT) using a thrust balance. Finally, we estimated performance of the ion thruster after all of the propulsion system was installed on the flight-model spacecraft. The series of above experiments would be world first case of ground test for propulsion systems installed on small satellites, so its details and results would be help to all small space probes developed after this.

II. Experimental apparatus

In this section. We introduce four experimental apparatus, I-COUPS, a chamber with turbo molecular pump, a chamber with diffusion pump, and a thrust balance.

A. I-COUPS

I-COUPS is the system consists of CGJT and micro wave discharged ion thruster. Why CGJT is required is that satellites what have ability for orbital transfer need to have effective method for unloading because main thruster makes larger torque than that made by solar wind. This is due to impossibility adjust center of mass on extension line of thrust vector. The impossibility caused by change of mass of the propellant tank, manufacturing error and absence of gimbal system for small satellites. In addition, unloading device installed on deep space probe is required not to be affected by magnetic field and solar wind. From above reasons, CGJT is suitable for small satellites with a component for orbit transfer. The reason why we unified these two thrusters is cutting down the mass. The mass ratio of gas management system³ is very large, so to unify two thrusters and commonize gas system including a propellant tank result in reduction of total mass of the satellite. We show the schematic of gas line of I-COUPS in Figure 1.

Table 1. Magnetization as a function of applied field.

	Thrust	Specific Impulse	System Power	Number of thruster
Cold Gas Jet Thruster	22 mN	24.5 s	7 W	8
Ion Thruster	300 μ N	1080 s	33 W	1

We show performances of CGJT and ion thruster in Table 1. These performances is measured in ground experiments.

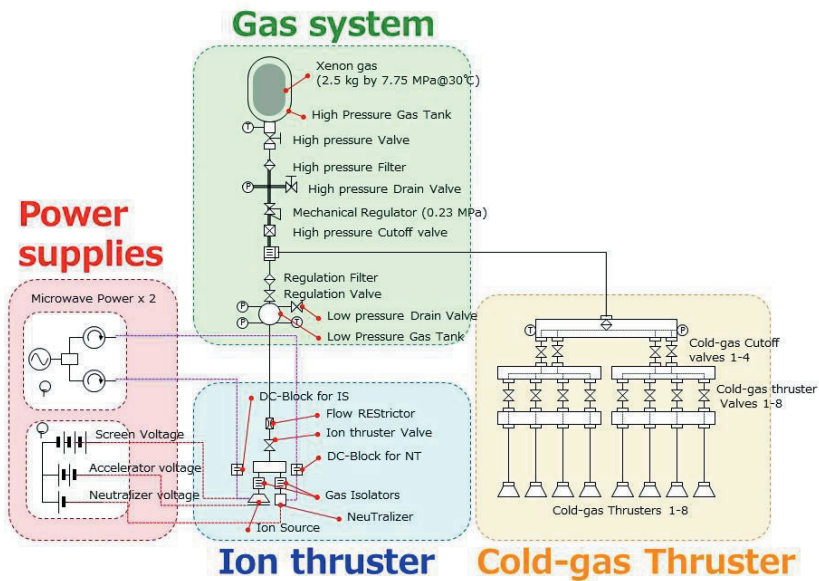


Figure 1. Schematic³ of gas system of I-COUPS.

Next, we explain the concepts of ion thruster and CGJT. We start explanation with the ion thruster. We show the schematic of the ion thruster in Figure 2, and appearance in Figure 3.

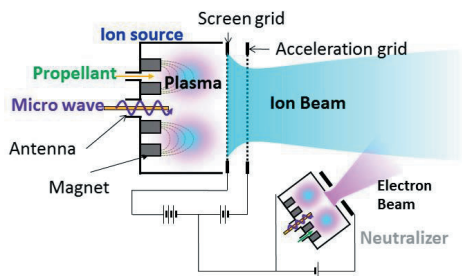


Figure 2. Schematic of thruster head.

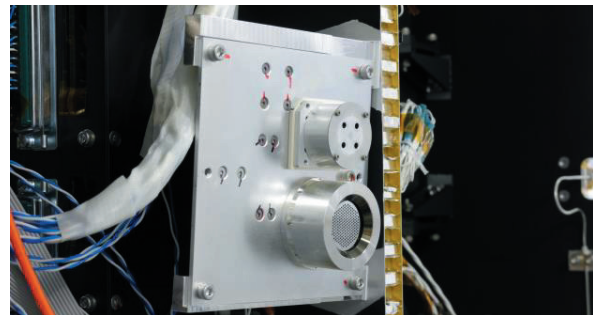


Figure 3. Appearance of thruster head.

Upper cylinder have four holes is neutralizer, and a bigger cylinder under the neutralizer is ion source. .

In ion source, Xenon plasma is produced by the effect⁴ of magnetic field and micro wave. Xe^+ in plasma is drained by the grid charged high voltage called screen grid. Therefore, the ion is accelerated by electric field generated by screen grid and acceleration grid. Neutralizer placed beside ion source and its orifice is charged controlled voltage. This voltage is adjusted to match number of ion flying out of the satellite and electron drained from neutralizer. The role of neutralizer is that stabilize charge of the satellite.

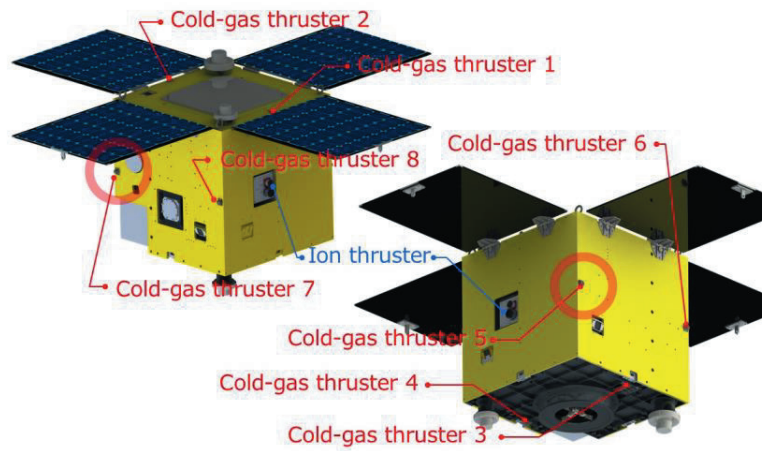


Figure 4. Arrangement³ of CGJT thruster head.

Finally, we explain CGJT. We show the arrangement of CGJT thruster heads in Figure 4. Valves are placed as Figure 1. The thruster heads are placed on edge of the cube as Figure 4. Due to this arrangement, the satellite can generate torques around 3 axis and in 2 directions. To generate torque around Z axis, we prepare 2 thrusters for 1 direction. That is because, torque around Z axis tend to be increased by ion thruster. Pared thrusters also have a role as safety for fault in one of these valves.

B. Chamber with turbo molecular pump

In this session, we introduce the chamber used in CGJT thrust measurement, ion beam distribution measurement and optimizing the shape of orifice on the neutralizer. This chamber is drained by a rotary pump and a turbo molecular pump. We show performance of these pumps in Table 2. This chamber's diameter is 1.2 m, length is 1.7 m. Pressure in this chamber reach to $1.0\text{E-}3$ Pa.

Table 2. Performance of the pumps equipped on small chamber.

	Displacement	Model	Company
Rotary pump	$670 \text{ L} \cdot \text{min}^{-1}$	VD401	ULVAC
Turbo Molecular Pump	$54000 \text{ L} \cdot \text{min}^{-1}$	TG900M	Osaka Vacuum LTD

C. Chamber with diffusion pump

In this part, we introduce the chamber used in performance test for ion thruster. This chamber is drained by two rotary pumps, mechanical booster pump and diffusion pump. We show performance of these pumps in Table 3. This chamber's diameter is 2.0 m, length is 3.0 m. Pressure in this chamber reaches to $1.0\text{E-}4$ Pa. In Figure 5, we show appearance of the chamber. This chamber is large enough to contain a small satellite.

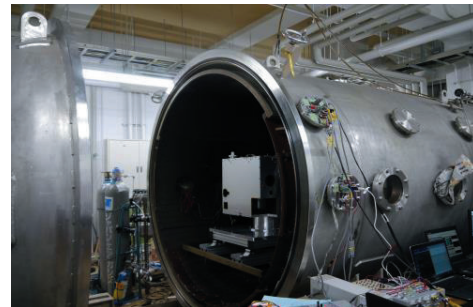


Figure 5. Appearance of the bigger chamber.

Table 2. Performance of the pumps equipped on big chamber.

	Displacement	Model	Company
Rotary pump	15000 L•min ⁻¹	KS-150	ULVAC
Mechanical booster pump	167000 L•min ⁻¹	MB-10000	ULVAC
Diffusion Pump	2220000 L•min ⁻¹	SDP-36	ULVAC

D. Thrust balance

We introduce the thrust balance⁵ used in CGJT thrust measurement in this section. Figure 6 shows appearance of the thrust balance. This thrust balance's motion is horizontal. Dumper, displacement gage, and weight are placed on the stand. To know thrust generated by the thruster on the stand, we read deflection width of the pendulum measured by the displacement gage. As a preparation, calibration to know the relationship between a forth and a deflection width is needed. Details about this thrust balance is described in Ref. 5



Figure 6. Appearance of the thrust balance.

III. Experiments

A. Thrust measurement of Cold Gas Jet Thruster

To measure the thrust, we use the thrust balance introduced in section II-D. Appearance of the BBM of CGJT is showed in Figure 7. To know specific impulse, we estimated mass flow. We measured mass of the accumulation tank before and after the measurement by an electronic balance. Figure 8 shows the schematic of the bread board-model of the CGJT. Regulator is set 0.21 MPa. Two solenoid valves are placed on downstream of the regulator. It simulate flight-model of CGJT gas line. In addition, we adjusted the length of BBM gas line to that of the flight-model by changing length of the line between thruster head and downstream valve. Accumulation tank was placed out of the chamber. The volume of the accumulation tank is 500 cc.

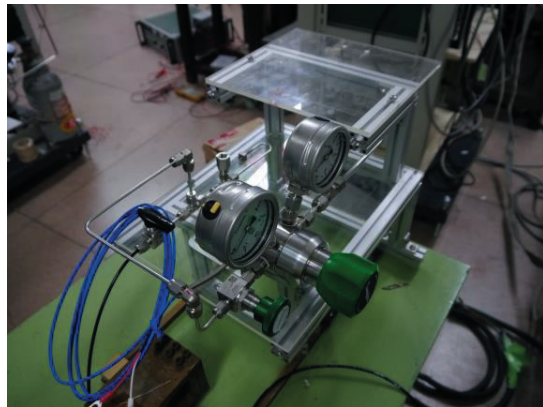


Figure 7. Appearance of CGJT BBM in construction.

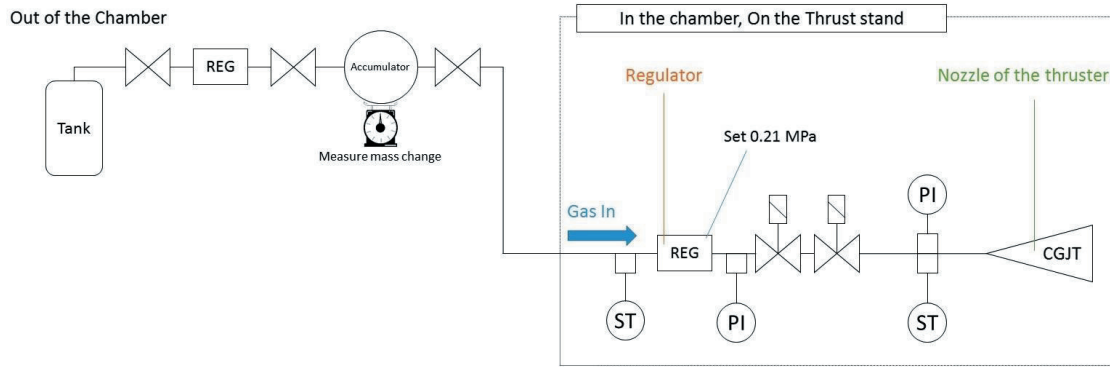


Figure 8. Schematic of the CGJT BBM thrust measurement.

B. Performance test of ion thruster

B-1. Thrust estimating

In this section, we explain how we estimated thrust of ion thruster on the ground. We don't measure the thrust directly. That is because thrust of ion thruster was too low to measure using thrust balance. This measurement is carried out after all propulsion components were installed on the satellite. We measured some currents and voltages showed in Figure 9. We calculated thrust from these currents and voltage using following equations⁶.

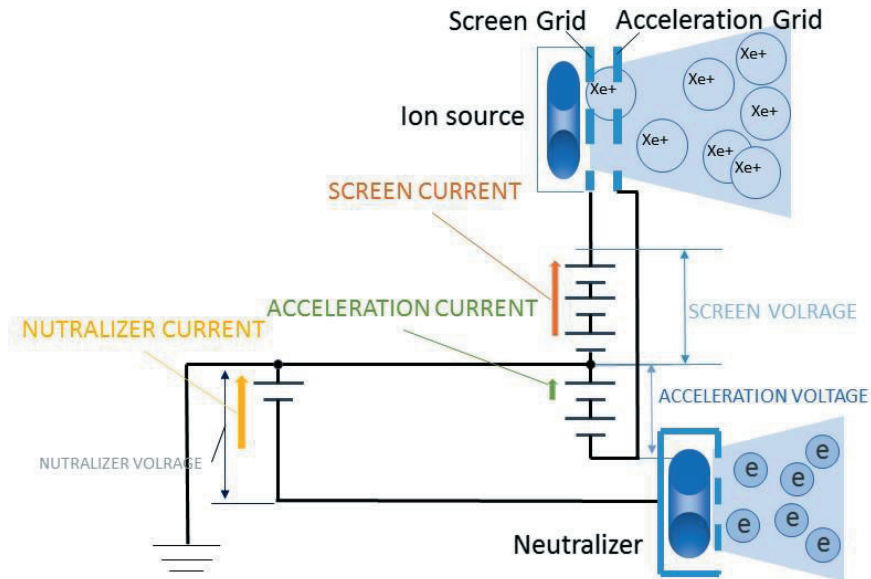


Figure 9. Schematic of current and voltage measurement.

Ion mass flow is described as Eq. (3) from Eq. (1) and Eq. (2)

$$I_b = I_s - I_a \quad (1)$$

$$\dot{m}_i = M \frac{I_b}{e} \quad (2)$$

$$\dot{m}_i = M \frac{I_s - I_a}{e} \quad (3)$$

Emission velocity is described as Eq. (4)

$$v_{ex} = \sqrt{\frac{2eV_s}{M}} \quad (4)$$

Thrust is described as Eq. (5), so from Eq. (3), (4) Thrust is described as equation including I_s and I_a as Eq. (6).

$$F = \eta_t \dot{m}_i v_{ex} \quad (5)$$

$$F = \eta_t (I_s - I_a) \sqrt{\frac{2MV_s}{e}} \quad (6)$$

η_t is a efficiency caused by multi charged ion and diffusion. Following the case of $\mu 10$ on HAYABUSA⁷, we assumed this efficiency as 0.9. We calculated specific impulse using Eq. (7)

$$I_{sp} = \frac{F}{mg} \quad (7)$$

We estimated mass flow of propellant by measuring the pressure at further orifice region. Relationship between measured pressure and mass flow had have been revealed by calibration. Figure 10 shows appearance of Ion thruster in operation.

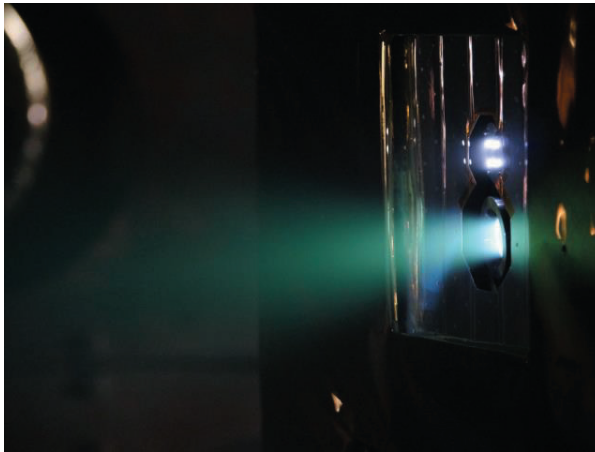


Figure 10. Appearance of the ion thruster in operation.

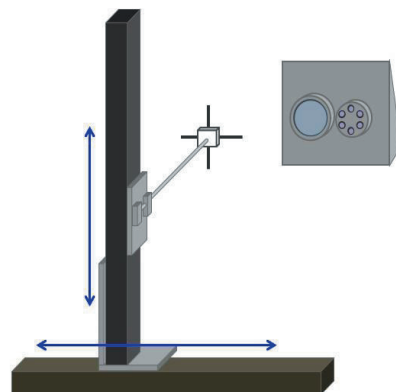


Figure 11. Concept of the probe with two axis stepping motor.

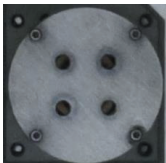
B-2. Ion beam measurement

The aim of this measurement is to reveal the gap between center of mass and extension line of thrust vector and adjust thruster's angle to reduce the gap. That is because large gap generates large torque and a lot of unloading are needed. That means a lot of propellant is used and specific impulse including mass flow of CGJT decrease. This measurement was carried out by using stepping motors what had two axis and single probe. Figure 11 shows the concept of the stepping motors and the probe. Details of this experiment is described in Ref. 8.

B-3. Neutralizer's orifice matching

This experiment was carried out to modify the neutralizer and reduce required propellant for electron emission. Table 4 shows four orifices we tried.

Table 4. Orifices⁸ we tried.

	pattern A	pattern B	pattern C	pattern D
number of holes	6	6	4	4
materials	Al	Al	Al	Mo
thickness	0.8 mm	0.5 mm	0.5 mm	0.5 mm
exposed area	15.27 mm ²	15.27 mm ²	15.21 mm ²	15.21 mm ²
picture				

IV. Results and study

A. Results of Cold gas thruster

In this part, we introduce the result of thrust measurement of CGJT. Figure 12 shows one of the result of the measurement. In this case, average thrust was 23 mN. Other results are different by only 1 mN. We measured the change of mass of the accumulation tank, and calculated specific impulse. Mass flow ratio was $93 \text{ mg} \cdot \text{s}^{-1}$, and specific impulse was about 25 s.

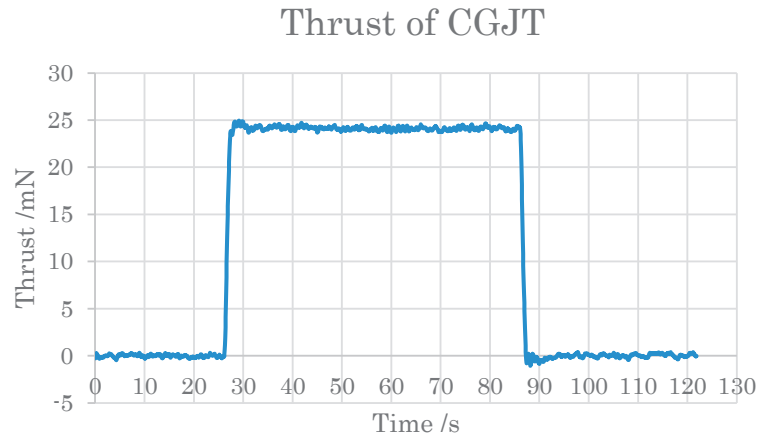


Figure 12. Thrust log of CGJT BBM.

B. Result of ion thruster

B-1. Ion source performance

I-COUPS; last ground test 11:30-15:30 (Sep 26, 2014)

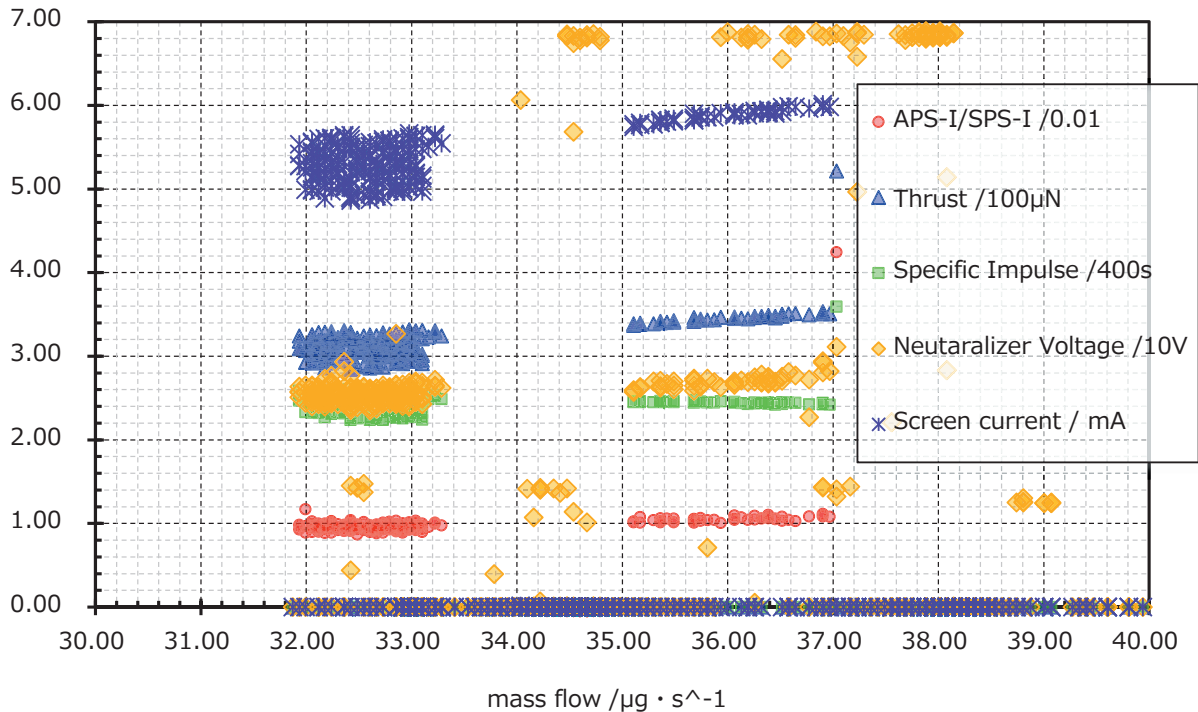


Figure 13. Thrust performance of the ion thruster.

In this section, we introduce the result of performance estimation test for ion thruster. Figure 13 shows performance of the ion source in last configuration on the ground. According to the Figure 13, screen current have tendency to reduce with reduction of the mass flow. The value named APS-I/SPS-I have relationship with thruster's endurance. When mass flow was $35 \mu\text{g} \cdot \text{s}^{-1}$, thrust was $330 \mu\text{N}$. Due to optimizing the orifice on the neutralizer, specific impulse reached 1000 s. We had carried out this experiment when we finished a critical environmental test for the satellite such as thermos vacuum test.

B-2. Ion beam measurement

Due to ion beam measurement, ion beam current distribution as Figure 14 is revealed. We had adjusted the angle of the thruster to match extension line of thrust vector to center of mass following this distribution. Ref 9 describes details of this experiment and result.

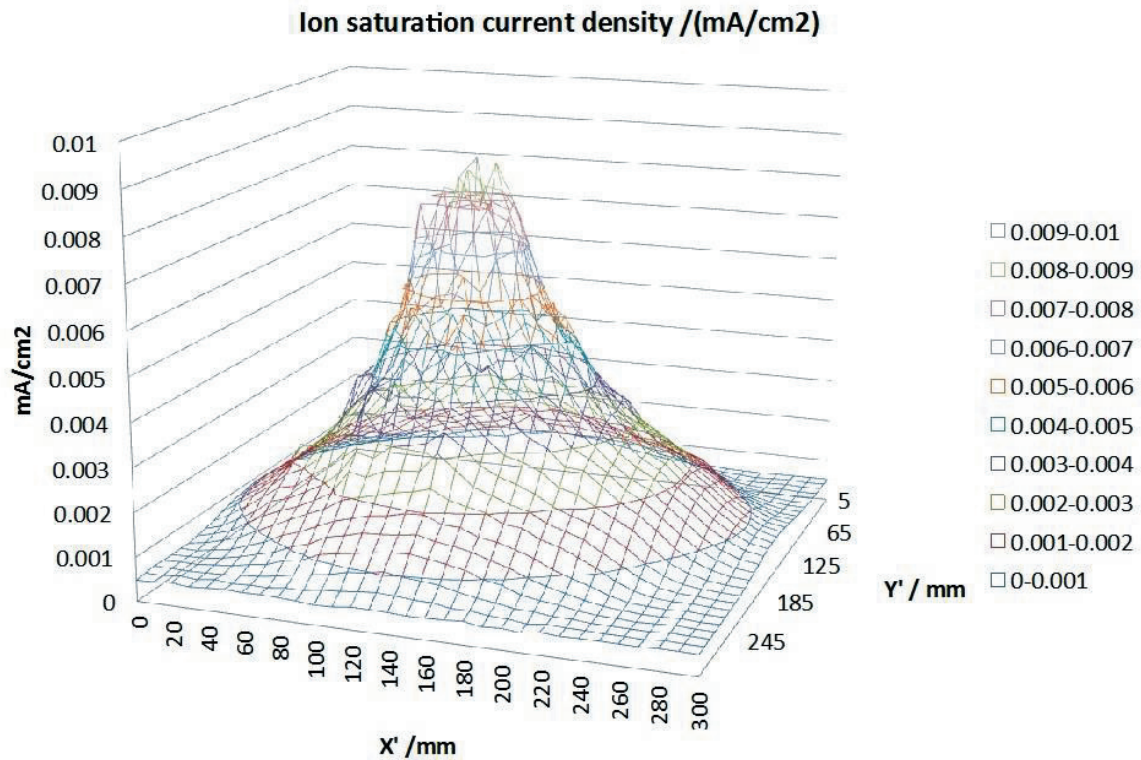


Figure 13. Ion beam current distribution⁹ at 300 mm distance from the thruster

B-3. Optimizing orifice on the neutralizer

The performance of neutralizer for each orifice is shown in Figure 14. Following this result, we chose orifice pattern C. Due to this choice, we could operate the thruster at around $35 \mu\text{g} \cdot \text{s}^{-1}$ and achieve high specific impulse. In case previous setting, pattern A, NPS-V was around 40 V at $35 \mu\text{g} \cdot \text{s}^{-1}$. It would reduce the life time of neutralizer¹². Details of this experiment is described in Ref 8.

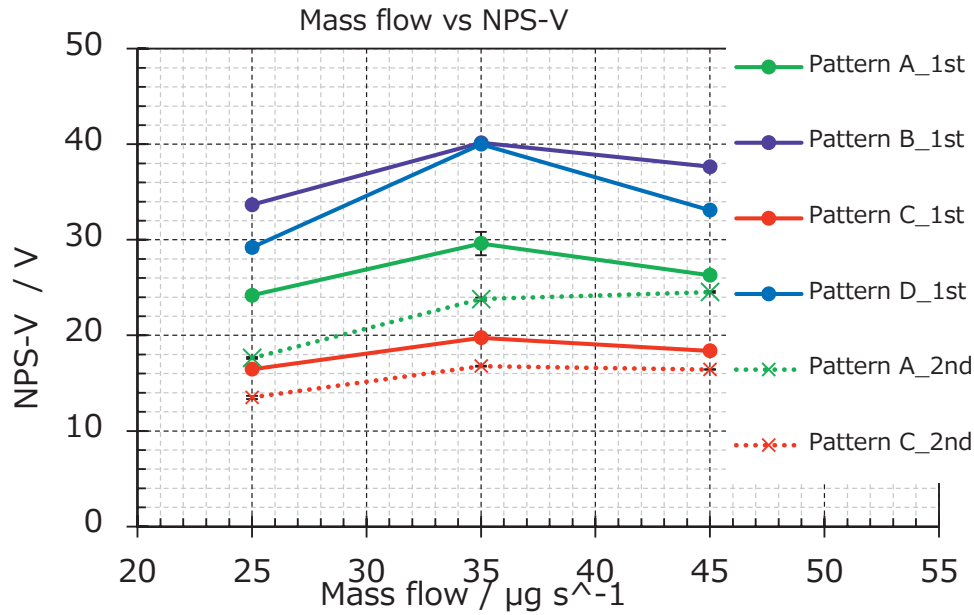


Figure 14. Performance of the neutralizer with each orifices.

C. Results of in-flight operation

In this section, we introduce performance of I-COUS observed in the flight. Details of condition of the satellite described in Ref 10.

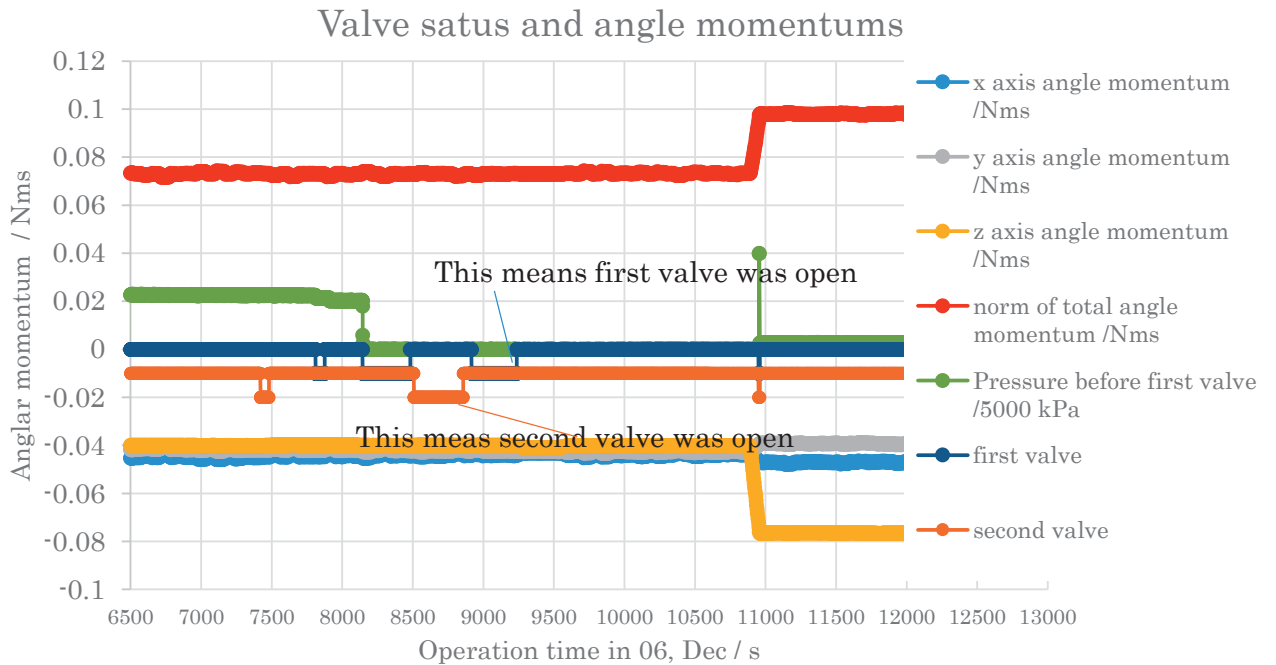


Figure 15. Angle momentums and valve status.

C-1. Operation of CGJT

Figure 15 shows valve status and angle momentums. This figure shows torque was generated when first and second valve were open. We calculated angle momentum from change of rotation speed of the reaction wheels. From this result, torque was generated by CGJT. In addition, we calculated thrust of CGJT from change of angle momentums. According to the calculation, eight CGJTs generated 22 mN in average. These result means CGJT is working successful in space.

C-2. Operation of ion thruster

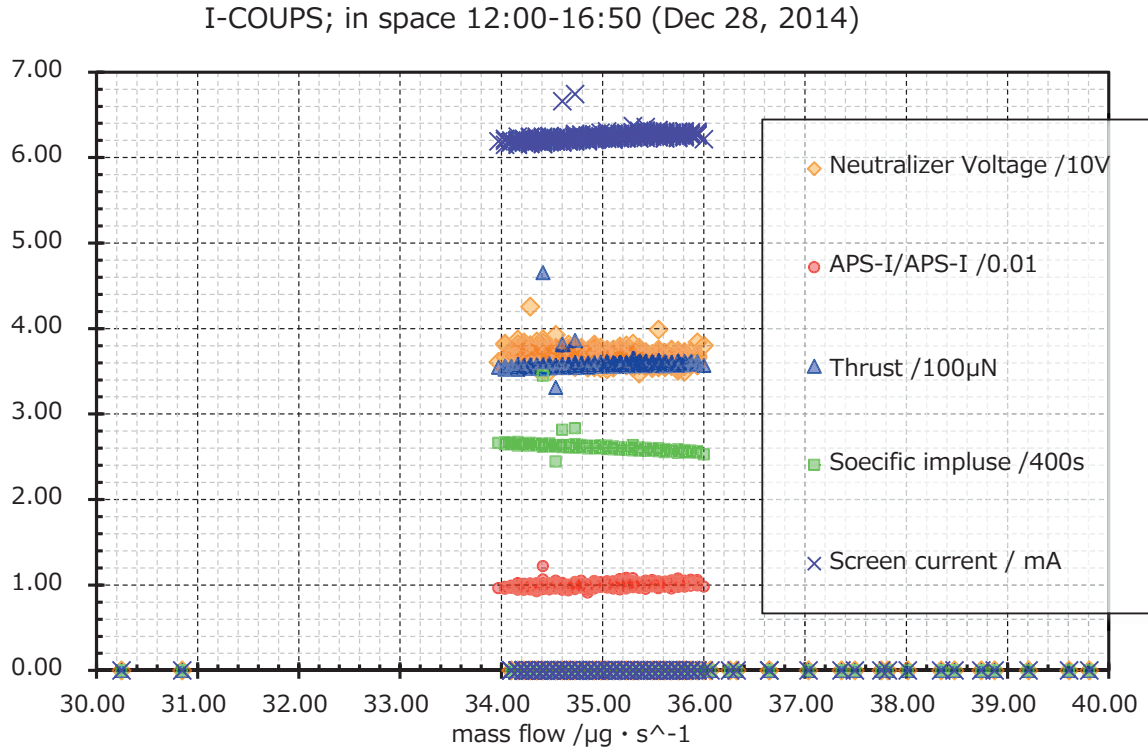


Figure 16. Performance of ion thruster in space.

Figure 16 shows performance of the ion thruster during operated in space. Screen current and Neutralizer voltage were higher than result of ground test. Figure 17 shows Doppler shift measured during ion thruster was operated. This Figure shows the satellite had have been accelerated during screen power source have had been turned on. Taking attitude of the satellite in consideration, generated thrust was $350 \mu\text{N}$. This performance is enough to complete the mission of PROCYON.

V. Conclusion

We proposed the propulsion system, I-COUPS. I-COUPS was installed on PROCYON witch is a small space probe in operation now. We have carried out world first ground experiments of propulsion system for small satellites to estimate performance after installation, and to optimize the design of the system. It is ensured that I-COUPS could generate torque and thrust. This is estimated using the data received during operation of PRROCYON. In addition,

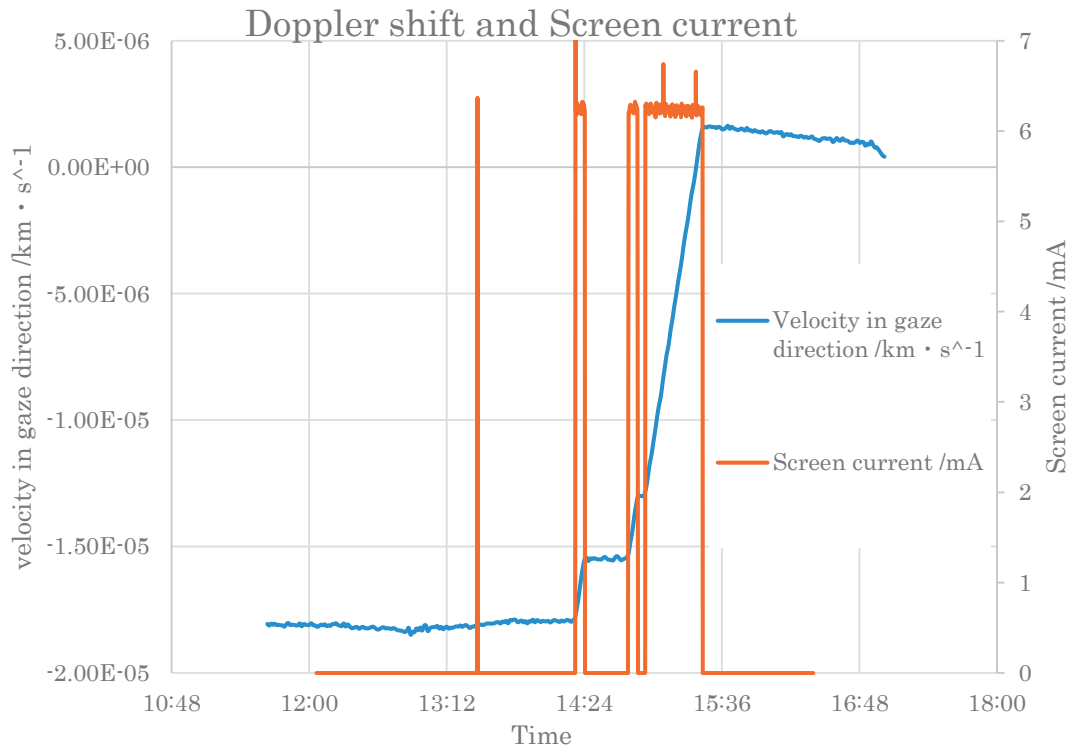


Figure 17. Relationship between acceleration and screen current.

performance of this system in space is enough for PROCYON to complete its mission. From above things, results of the ground tests we had carried out were ensure working in space.

Acknowledgments

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