Thruster Parameters Estimation for a Micro Deep Space Explorer: PROCYON

Yosuke Kawabata[(1)] , Chit Hong Yam[(2)], Yasuhiro Kawakatsu[(2)], Yoshihide Sugimoto[(2)], Ryu Funase[(1)], Stefano Campagnola[(2)] , Naoya Ozaki[(1)], Bruno Sarli[(3)], Hongru Chen[(4)] , Satoshi Ogura[(1)], and Shinichi Nakasuka[(1)]

[(1)]The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan, +81-3-5841-6631, ykawabata@ac.jaxa.jp, ozaki@space.t.u-tokyo.ac.jp, ogura.satoshi@ac.jaxa.jp

[(2)]Japan Aerospace Exploration Agency, Institute of Space and Astronautical Science, 3-1-1, Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, 252-5210, Japan, +81-50-336-26364, chithong.yam@ac.jaxa.jp, stefano.campagnola@jaxa.jp, sugimoto.yoshihide@ac.jaxa.jp

[(3)]Japan Aerospace Exploration Agency, Institute of Space and Astronautical Science, The Graduate University for Advanced Studies, 3-1-1, Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, 252-5210, Japan, +81-50-336-23042, sarli@ac.jaxa.jp

[(4)]Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, 819-0395, Japan, hongru.chen@ac.jaxa.jp

Abstract: *This paper presents the results of parameters estimation of a micro deep space explorer. PROCYON (Proximate Object Close flyby with Optical Navigation) is a 50kg-class micro-spacecraft for deep space exploration, which was launched on December 3, 2014 as a secondary payload by an H-IIA launch vehicle along with the Hayabusa-2 spacecraft [1]. The objectives of PROCYON are to demonstrate the technology of micro spacecraft deep space exploration and proximity flyby to asteroids performing optical measurements. The propulsion system can be one of PROCYON's features, which is called I-COUPS (Ion Thruster and Cold-gas Thruster Unified Propulsion System) [2]. The I-COUPS is a combined propulsion system of ion thruster and cold-gas thrusters by sharing the same xenon gas system. This enables both systems to reduce its sizes and to use these 2 thrusters with different characteristics for efficient low-thrust maneuver and high thrust by the cold-gas system. This system is indispensable for the orbit control and unloading the angular momentum of Reaction Wheels. The performance of the I-COUPS is well known by ground tests before the launch. However there is a possibility that the properties change because of the impact at the launch. Generally To perform expected and precise maneuvers, knowledge about the actual thrust performance is absolutely imperative. Unfortunately the ion thruster has the problem and stops its working now. However its estimation method and knowledge are meaningful for PROCYON and the other micro deep spacecraft. This paper presents how to estimate the thrust magnitude of ion thruster and cold-gas thrusters by using the flight data and its validations.*

Keywords: *Micro-Spacecraft, PROCYON, Parameter Estimation, Thruster, In-orbit experiment.*

1. Introduction

PROCYON (Proximate Object Close flyby with Optical Navigation) is the first deep-space micro spacecraft, which is mainly developed by Intelligent Space Systems Laboratory (ISSL) in the University of Tokyo and the Japan Aerospace Exploration Agency (JAXA) [3]. The small-scale and low-cost mission like PROCYON has some characteristics the large-scale mission doesn't have and is preferred. This is because such a small-scale mission eliminates the hesitation to plan and execute challenging and advanced missions and gives us more frequent attempt to test new technology, devices and mission objectives. The mission objective of PROCYON is to demonstrate micro-spacecraft bus technology for deep space exploration and a proximity flyby to an asteroid performing optical measurements. The nominal trajectory of PROCYON includes one Earth flyby and a propinquity flyby to a near-Earth asteroid. However PROCYON experienced the large impact of launch. For the trajectory plan and the mission objective, the grasp of in-orbit performance of the propulsion system is significant and accurate and expected maneuvers are essential. Unfortunately PROCYON cannot arrive at the target asteroid because the ion propulsion system has a problem and stops its working. However the performance estimation method of the propulsion system and its knowledge are meaningful for PROCYON and the other micro deep spacecraft. This paper presents how to estimate the thrust magnitude of ion thruster and cold-gas thrusters by using the flight data and its validations.

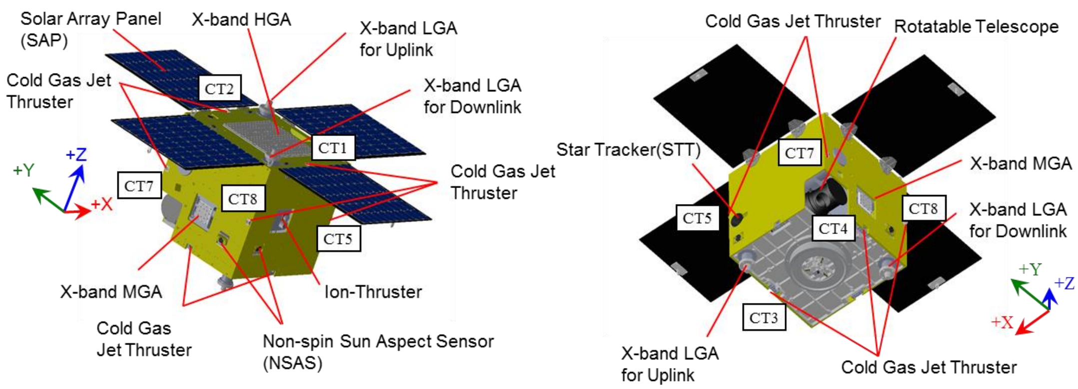

Figure 1.1. Schematic of PROCYON

2. PROCYON Spacecraft Specification

As shown in Figure 1.1 and Table 2-1, PROCYON has four solar array paddles (SAP) for power supply; an Ion Engine propulsion System (IES), eight Cold-Gas-Jet (CGJ) thrusters and three-axis reaction wheels for attitude and orbit control system (AOCS); a high/ middle/ low gain antennas (HGA/ MGA/ LGA) for deep-space communication (see Figure 1.1). Since all the system has to fit in the micro-bus unit, the spacecraft interior is almost fully equipped and, therefore, to maintain the interior temperature, the spacecraft external surface is covered by the Multi-Layer Insulator (MLI) together with heat radiation surface.

In the interplanetary transfer phases, the spacecraft uses commonly-used radio navigation for determining the orbit and miniature ion propulsion system (MIPS) [2], [4] for low thrust guidance; however, around 10km order of proximity flyby requires more accurate orbit determination. Therefore, optical navigation, which allows the spacecraft to determine precise trajectory relative to the target asteroid when the spacecraft approach the asteroid, is applied in the proximity flyby operation phase. The optical navigation can be effectively used in less than a week before the closest approach to the asteroid. Because of this shortage of guidance duration, higher-thrust propulsion system is required. Hence, we developed the combined propulsion system, named I-COUPS, of ion engine and Xenon cold gas jet, which solve not only the mission requirement but also sizing requirement for micro-spacecraft. As shown in Figure 1.1, PROCYON has eight cold-gas thrusters, which are used for momentum unloading of reaction wheels, attitude control and the orbit control at asteroid flyby. Each CGJ is distinguished as shown in Figure 1.1.

Table 2-1 Spacecraft Specification

Structure	SAPs close: 550 x 550 x 670 [mm] SAPs open: 1500 x 1500 x 670 [mm]
Mass	Wet mass: 66.9 [kg] Fuel mass (Xe): 2.5 [kg]
Attitude control system	Sensor Star tracker (STT) x 1 Non-spin Sun sensor (NSUS) x 5 Three-axis fiber optical gyro (FOG) x 1 Actuator Three-axis reaction wheel (RW) x 4 (one for skew)
Propulsion system	Miniature Ion Propulsion System (MIPS) Thrust: 250-350 [μN] Isp: 720-1000 [s] Cold Gas Jet (CGJ) Thrust: 21.3 [mN] Isp: 24.5 [s]
Communication system	X-band TT/C High gain antenna (HGA) x 1 Middle gain antenna (MGA) x 1 Low gain antenna (LGA) x 4
Science payload	1-axis rotatable telescope Lyman alphe imaging camera (LAICA)

3. Method and Results of Parameter Estimation of Cold Gas Jet thrusters

3.1 Parameter Estimation Method of Cold Gas Jet thrusters

This section addresses the parameter estimation of Cold Gas Jet thrusters (CGJ). The thrust magnitude are calculated by following methods.

1) Estimation method by Angular Momentum

As is mentioned above in the section 2, PROCYON has 4 reaction wheels for attitude control. The conservation of angular momentum can be used for the estimation. Hence to estimate the actual thrust magnitude of cold-gas thrusters, Euler's dynamical equation is used on the assumption that the spacecraft and reaction wheels inertia tensor is constant. The flight data, mainly unloading data: the spin rate of reaction wheels and spacecraft, is used for this estimation.
In this section, the objective function is defined by Eq. (3-1). Furthermore there is the transient state of gas ejection when a valve of CGJ opens. It is known that the time span of the transient state is less than 1s. The longer a valve opens, the smaller the influence of the transient state and the error of valve opening time is. Therefore the estimated thrust magnitude is calculated by an average with weight as shown in Eq. (3-2).

$$\text{Objective Function: Minimize } |\boldsymbol{H}_{calculation} - \boldsymbol{H}_{telemetry}| \tag{3-1}$$

$$T = \frac{\sum_i^n (t_i \times T_i)}{\sum_i^n t_i} \quad (3\text{-}2)$$

3.2 Parameter Estimation Results of Cold gas thrusters

The each thrust magnitude is estimated by method mentioned in the section 3.1. The results are shown in Figure.2, based on data from January to August, 2015. The error bar in the Figure 3.1 suggests the standard deviation of the thrust magnitude of all results.
In the cases of single CGJ operation in Figure.3.1, the error bar of estimated thrust magnitude except CT3 include the nominal thrust magnitude of the ground experiment result of the single thruster operation. The standard deviation of ground experiments results is about 1 mN. In terms of this error range, the estimated result of CT3 is consistent with the ground experiments results.
In the cases of pair CGJ operation in Figure.3.1, the estimated values are much lower than the single CGJ operation results because of the reduced back pressure. Though this characteristics is known by the ground experiments, the nominal value of pair CGJ operation on ground experiments is 18 mN and there is the difference between the estimated values from the telemetry and the ground experiments results. Figure.3.2 shows the angular momentum change in a CT5, 7 operation case and Figure.3.3 shows the angular momentum change in a CT7 operation case. Both of CT5 and CT7 generate the torque around z-axis. As shown in Figure.3.2, the pair CGJ operation generates only z-axis torque. However in Figure.3.3, the single CGJ operation changes not only z-axis angular momentum but also both of x-axis and y-axis of angular momentum. As a result of taking into account the sign and axis of accumulated angular momentum and cases of the event occurrence, this is due because the gas of CGJ hits the solar array paddle. That is to say, symmetry property of installation counteract the gas interference on the solar array paddles in the CGJ pair operation case and the gas interference on the solar array paddles occurs in the CGJ single operation case. This interference effects on the operation of trajectory correction maneuver by CGJ and so on because of unexpected angular momentum accumulation. This interference must be investigated in detail.

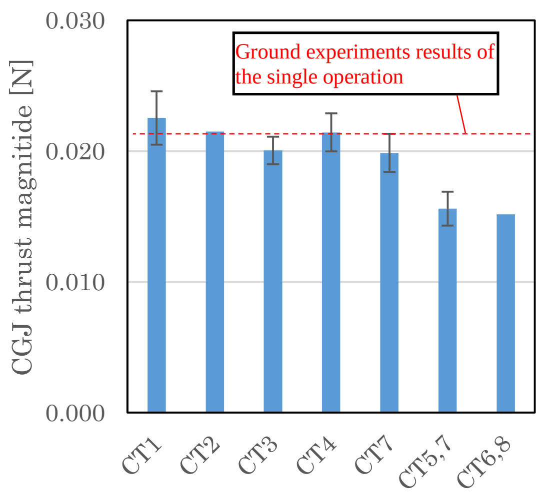

Figure.3.1 Estimation results of each cold-gas thruster

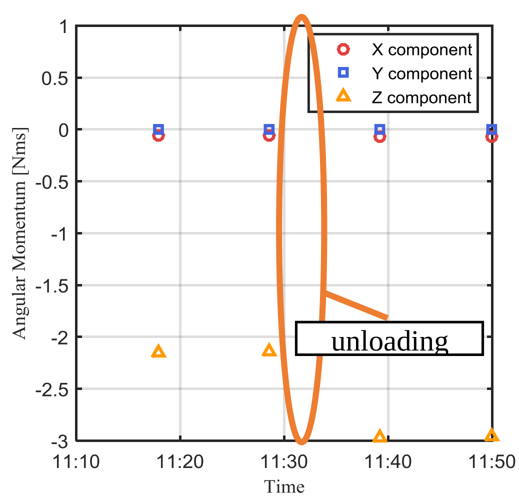

Figure.3.2 Time vs Angular momentum (CT5, 7 operation)

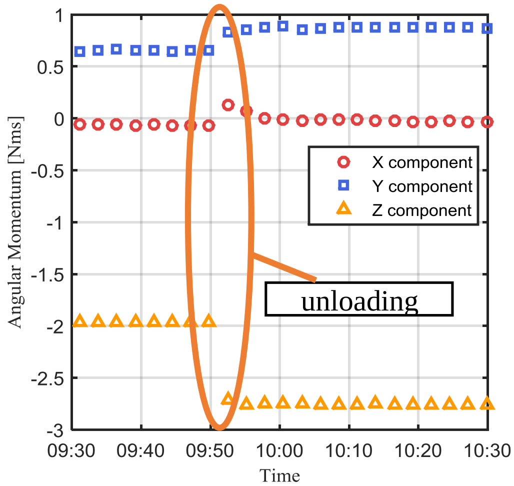

Figure.3.3 Time vs Angular momentum (CT7 operation)

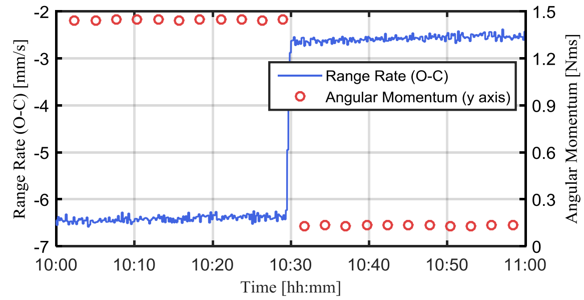

Figure.3.4 Range rate and Angular momentum (CT4 operation)

As another method, the Doppler shift data can be used to estimate the thrust magnitude of CGJ. The velocity of the spacecraft along line of sight (LOS) from the Earth to the spacecraft can be obtained from the Doppler-shift. In addition, from the trajectory and attitude data, the angle between LOS and the Delta-V direction can be known. The estimated thrust magnitude comes from these data. The O-C of Doppler shift data at the CT4 operation is shown Figure.3.4. When the angular momentum reduces, the Range Rate changes significantly. Figure.3.5 gives the result by using Doppler shift data. The error bar means the standard deviation of results. In the CT4 operation case, the estimated value is in good agreement with the ground experiments results. On the other hand, the error bar range of CT3 result is very large. This is because the angle between LOS and Delta-V direction is close to 90 degrees. This leads to the large error.

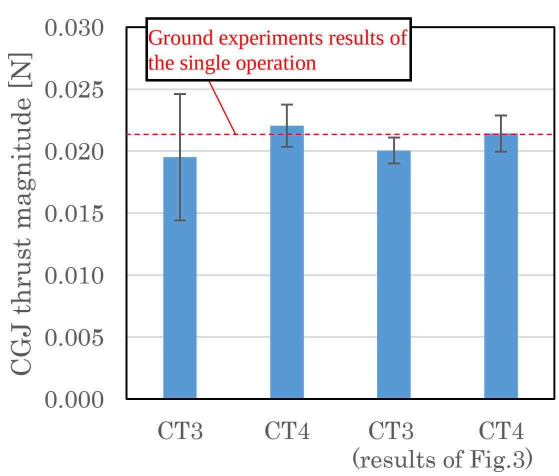

Figure.3.5 Estimation results of each cold-gas thruster by Doppler shift data

4. Method and Results of Parameter Estimation of Ion thruster

4.1 Parameter Estimation Method of Ion thruster

This section addresses the parameter estimation of Ion thruster. The thrust magnitude are calculated by following methods.

The ion thruster performance affects the trajectory plan significantly, as it is the only propulsion system for translational maneuver during interplanetary transfer phase. Taking into account the orbit determination (OD) results and actual thrust and attitude history, the thrust magnitude and specific impulse can be estimated by minimizing the position difference between the OD results and the trajectory propagation with estimated parameters. As shown in Eq. (4-1), the thrust magnitude of an ion thruster is estimated by minimizing the sum of some distances between propagated state of PROCYON and OD results the Fujitsu Company provided.

Table 4-1 gives some parameters in this analysis and Figure.4.1 provides the definition of thrust direction in the body coordinate system. In this section, the error of thrust direction is also estimated by same method. (Thrust direction means the ejection direction of ions)

$$\text{Objective Function: Minimize} \sum_{i}^{n} \left| \boldsymbol{X}_{\boldsymbol{Prop}_i} - \boldsymbol{X}_{\boldsymbol{OD}_i} \right| \quad (4\text{-}1)$$

Table 4-1 Parameters

Period	February 22nd – April 1st , 2015
Dynamics	Sun 8 planets (planetary system for outer planet than Jupiter) The Moon Pluto system Solar Radiation Pressure (Canon ball model)
Thrust timing	Using Telemetry data
Design value of thrust direction	α:-99.2 deg δ: -4.5 deg

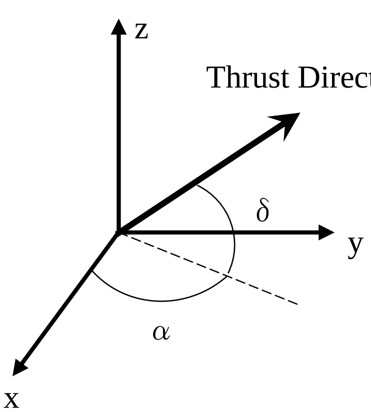

Figure.4.1 Thrust Direction (Body coordinate system)

4.2 Parameter Estimation Results of Ion thruster

In this analysis, the number of OD results to use for the estimation is 3 because the effect of unconsidered parameters is larger if the propagation period is much longer. The period to use for the estimation is from February 22nd to April 1st. The ion thruster operation history is shown in Figure.4.2. The duty cycle means the working time per 3 days of the ion thruster. The duty cycle increases from February 22nd. Though the ion thruster has a problem after March 10th unfortunately, there was enough thrust time to estimate the ion thruster performance.

Table 4-2 gives the estimation results. The first row means the result of the estimating only thrust magnitude. In this case, the thrust direction is fixed to the design parameters shown in Table 4-1 and Figure.4.1 and the estimated thrust magnitude is about 349 μN. The second row indicates the result of the estimation of thrust magnitude and thrust direction. In this case, the estimated thrust magnitude is 355 μN and angle α and δ are -103.3 degrees and -4.9 degrees. The difference between these 2 estimated thrust magnitudes is 6 μN and small. On the other hand, from the standpoint of the conservation of angular momentum, the thrust direction can be estimated when the thrust magnitude is fixed. By way of example, the accumulation of angular momentum by the ion thruster is shown in Figure.4.3. As shown in Figure.4.3, the angular momentum increases during the ion thruster working. In this case, the estimated result of the thrust direction is given in Table 4-2. The result C is closer to the design values than the result B. One possible cause of this is the installation error of the star tracker. The actual attitude history data generated by the star tracker is used in the calculation of the result B. For example, Figure.4.4 shows time constant difference between the sun directions by sun sensor and the star tracker. These kind of errors are confirmed during the operation. The alignment errors must be investigated because these errors cause various problems.

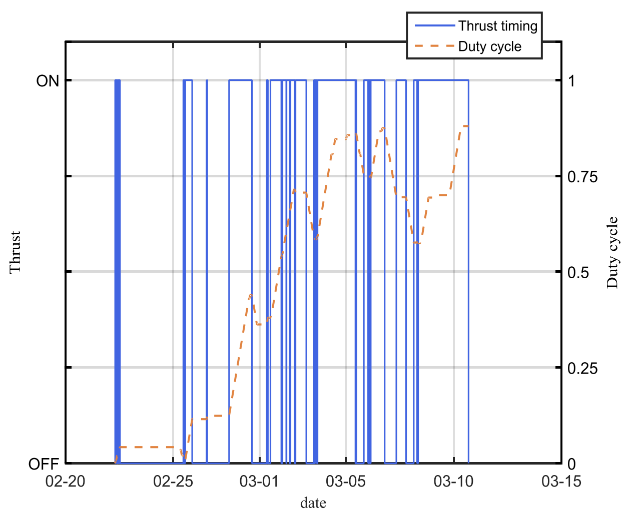

Figure.4.2 Thrust timing and Duty cycle

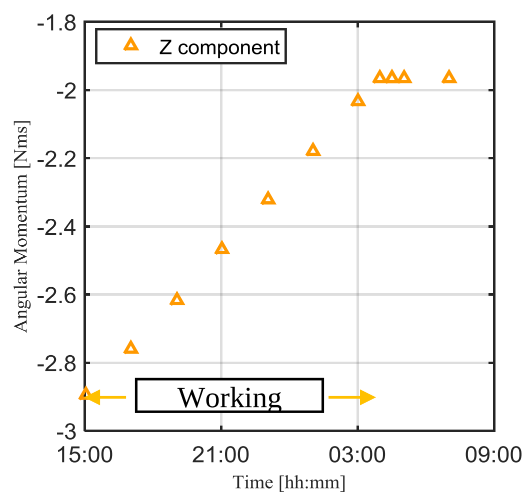

Figure.4.3 Accumulation of Angular momentum by an ion thruster

Table 4-2 Estimated Results

	Estimated Thrust [μN]	α [deg]	δ [deg]
A) Estimation of Thrust magnitude	349	-	-
B) Estimation of Thrust magnitude & Thrust direction	355	-103.3	-4.9
C) Estimation of Thrust direction by the angular momentum	-	-100.6	-4.5

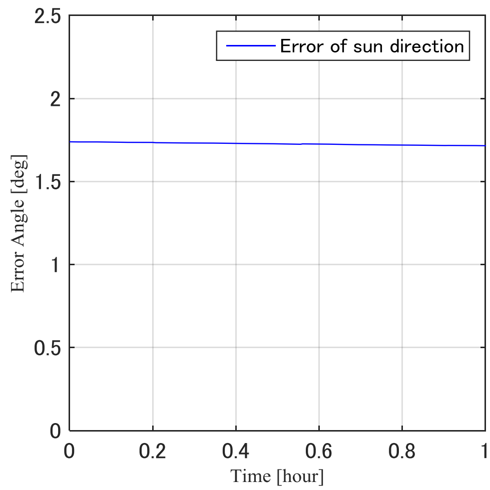

Figure.4.4 Sun direction error between the sun sensor and the star tracker

5 Conclusions

This paper mentioned about thruster parameters estimation for PROCYON.
First the performance of Cold Gas Jet thruster (CGJ) is estimated by using the conservation of angular momentum and the Doppler shift data. The estimated values of single Cold gas jet thruster operations are consistent with the ground experiments results. However the estimated results of pair Cold gas jet thruster operations are inclined to be lower than the ground experiment results. There is a possibility that the plume of CGJ hits the solar array paddle and the unexpected accumulation of angular momentum occurs from the point of view that the only single thruster operation generates this accumulation and the axis and direction of angular momentum can account for the results. These kind of interference have bad effects and we need to take case at the time of a design.
Second the performance of the ion thruster is estimated by minimizing the difference between the orbit determination results and propagation with actual attitude and thrust history obtained from telemetry data. The thrust direction is also estimated. When the thrust direction is fixed to design values, the estimated thrust magnitude is about 349 μN. On the other hand, when the both of thrust magnitude and thrust direction are estimated, the estimated thrust magnitude is 355 μN and angle α and δ are -103.3 degrees and -4.9 degrees. On the other hand, from the standpoint of the conservation of angular momentum, the thrust direction is defined by the angle α of -100.6 degrees and the angle δ of -4.5 degrees. The difference of 2 thrust direction estimation results are possibly

caused by the installation errors. These kind of errors are confirmed during the operation. The alignment errors must be investigated because these errors cause various problems.
In this paper, the method to estimate the thrust magnitude of ion thruster and cold-gas thrusters by using the flight data are described. Unfortunately PROCYON cannot arrive at the target asteroid because the ion propulsion system has a problem. However the performance estimation method of the propulsion system and its knowledge are meaningful for PROCYON and the other micro deep spacecraft. It is important to solve the new problems and improve a series of procedures.

6. References

[1] Tsuda, Y., Yoshikawa, M., and et al, “System Design of Hayabusa2 - Asteroid Sample Return Mission to 1999JU3”, 63rd International Astronautical Congress, IAC-12-A3.4.5. Naples, Italy, 2012

[2] Koizumi, H., Inagaki, T. and et al. “Unified Propulsion System to Explore Near-Earth Asteroids by a 50 kg Spacecraft.”, 28th Annual AIAA/USU Conference on Small Satellites, SSC14-VI-6, Utah, USA, 2014.

[3] Funase, R., Koizumi, H. and et al., “50kg-class Deep Space Exploration Technology Demonstration Micro-spacecraft PROCYON”, Proceedings of the AIAA/USU Conference on Small Satellites, Logan, Utah, USA, 2014.

[4] Kawahara, H., Yaginuma, K. and et al.:“In-Flight Operation of the Miniature Propulsion System installed on Small Space Probe: PROCYON”, Joint Conference of 30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium, 2015.