This paper presents the development and initial operation results of 50kg-class deep space exploration micro-spacecraft PROCYON (PRoximate Object Close flyby with Optical Navigation), which was jointly developed by the University of Tokyo and Japan Aerospace Exploration Agency (JAXA). The primary mission of PROCYON is the world’s first demonstration of 50kg-class deep space exploration bus system which includes the demonstration of high-efficiency GaN-based SSPA (Solid State Power Amplifier) for communication and high-precision navigation by a novel method of DDOR (Delta Differential One-way Range) observation. PROCYON also has some secondary advanced missions, which are deep space flight to a Near-earth asteroid and high resolution observation of the asteroid during close and fast flyby, and the wide view scientific observation of geocorona by a Lyman alpha imager from a vantage point outside of the Earth’s geocoronal distribution. PROCYON was developed at very low cost (a few million dollars) and within very short period (about 1 year), taking advantage of the heritage from Japanese Earth-orbiting micro satellite missions. PROCYON was launched into an Earth departure trajectory together with Japanese second asteroid sample return spacecraft Hayabusa-2 on December 3, 2014, and it has achieved its primary mission and some of the secondary missions.

MISSION OF PROCYON

The primary mission of PROCYON is the world’s first demonstration of micro-spacecraft bus system for deep space exploration, which is intended to show that the spacecraft of this scale (~50kg) can conduct deep space mission by itself. The secondary missions consist of engineering mission and scientific mission to advance or utilize deep space exploration. Engineering mission includes low-thrust deep space maneuver to perform
Earth swingby and change the trajectory to flyby a Near-Earth asteroid, and high-resolution observation of the asteroid during close (<30km) and fast (~10km/s) flyby. Scientific mission is the wide-view observation of geocorona with a Lyman alpha imaging camera (LAICA) [6] from a vantage point outside of the Earth’s geocoronal distribution.

Fig. 1 shows the trajectory of PROCYON. PROCYON is launched with Hayabusa-2 and initially inserted into an Earth resonant trajectory that allows the spacecraft to come back to the Earth by solar electric propulsion. Within several months after the launch, the first mission (demonstration of the bus system) is conducted. Then, DSM (Deep Space Maneuver) using its miniature ion propulsion system is conducted so that the spacecraft will come back to the Earth from Earth swingby [7]. The Earth swingby will direct the spacecraft trajectory to its target asteroid. PROCYON is intended to perform close flyby trajectory guidance by optical navigation and will pass within 30 km distance from the asteroid. Flyby velocity will be 5 to 10 km/s relative to the target asteroid. During the close flyby, automatic tracking observation of the asteroid is conducted using a camera with a scan mirror and onboard image feedback control which enables LOS (Line Of Sight) maneuver while maintaining the spacecraft attitude (Fig. 2).

**Figure 1: Trajectory of PROCYON**
(Top: Sun-centered J2000 EC, Bottom: Sun-Earth fixed rotating frame)

**Figure 2: Asteroid close flyby observation by onboard image feedback control**

**PROCYON SYSTEM CONFIGURATION**

The external view of PROCYON is shown in Figs. 3, 4 and 5. Fig. 6 shows the system block diagram of PROCYON. The specification of the spacecraft is shown in Table 1. Most of the bus system of PROCYON is based on that of 50kg-class Earth-orbiting micro satellite, excluding the communication system [8] and propulsion system [9], which were newly developed for deep space mission.

**Figure 3: External view of PROCYON (top view)**

**Figure 4: External view of PROCYON (bottom view)**
**Communication System**

The communication system of PROCYON [8] consists of X-band transponder (XTRP), high-power (15 W output) GaN-based solid state power amplifier (SSPA), tone generator for DDOR (Delta Differential One-way Range) orbit determination, isoflux low gain antennas (LGAs), flat antennas (MGA and HGA) and other passive components (switches, diplexer and band pass filters). XTRP and SSPA are newly developed for this mission. Miniaturization was achieved by utilizing COTS (Commercial Off The Shelf) components. The communication system of PROCYON is compatible with Japanese deep space antenna, as well as JPL’s DSN (Deep Space Network).

**Table 1: Specification of PROCYON**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td><strong>Structure</strong></td>
<td>Size 0.55m x 0.55m x 0.67m + 4 SAPs (Solar Array Panels)</td>
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<tr>
<td></td>
<td>Weight &lt;70kg (wet)</td>
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<tr>
<td><strong>Power</strong></td>
<td>SAP Triple Junction GaAs, &gt;240W(1AU,θs=0,BOL)</td>
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<tr>
<td></td>
<td>BAT Li-ion, 5.3Ahr</td>
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<tr>
<td><strong>AOCS</strong></td>
<td>Actuator 4 Reaction Wheels (RW), 3-axis Fiber Optic Gyro (FOG)</td>
</tr>
<tr>
<td></td>
<td>Sensor Star Tracker (STT), Non-spin Sun Aspect Sensor (NSAS)</td>
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<td></td>
<td>Performance &lt;0.002[deg/s], ~0.01[deg] (pointing stability)</td>
</tr>
<tr>
<td><strong>Propulsion</strong></td>
<td>RCS Xenon cold gas jet thrusters x8, ~22mN thrust, 24s Isp</td>
</tr>
<tr>
<td></td>
<td>Ion propulsion Xenon microwave discharge ion propulsion system</td>
</tr>
<tr>
<td></td>
<td>0.3 mN thrust, 1000s Isp, 500m/s ΔV capability</td>
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<tr>
<td></td>
<td>Propellant 2.5 kg Xenon (shared by RCS and ion propulsion)</td>
</tr>
<tr>
<td><strong>Communication</strong></td>
<td>Frequency X-band (for deep space mission)</td>
</tr>
<tr>
<td></td>
<td>Antenna HGA x1, MGA x1, LGA x2 (for uplink), LGA x2 (for downlink)</td>
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<tr>
<td></td>
<td>Output power &gt;15 W, &gt;30%</td>
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</table>
**Propulsion System for Attitude and Orbit Control**

Micro propulsion system named I-COUPS (Ion thruster and Cold-gas thruster Unified Propulsion System) was also newly developed for PROCYON [9]. I-COUPS is a propulsion system that unifies an ion thruster called MIPS (Miniature Ion Propulsion System) and multiple cold-gas thrusters. The ion thruster provides 300 μN of thrust with a specific impulse of about 1000 s, which is used for DSM. The cold-gas thrusters, which provide about 20 mN of thrust with 24 s of specific impulse are used for both the reaction wheel desaturation and the asteroid flyby trajectory correction maneuver. The weight of the propulsion system is less than 10 kg including about 2.5 kg of propellant (Xenon). Such lightweight property was realized by sharing the gas system for both ion thruster and cold-gas thrusters.

**DEVELOPMENT OF SPACECRAFT**

The spacecraft was developed primarily by the University of Tokyo and JAXA, in cooperation with a number of Japanese universities such as Hokkaido University (thermal design), Nihon University (SAP hold & release mechanism), Tokyo Science University (OBC), Meisei University (asteroid observation telescope) and Rikkyo University (geocorona imager). All of the system integration and electrical tests were conducted at the University of Tokyo. System level environmental tests such as vibration test and thermal vacuum test were conducted at CENT (Center for Nanosatellite Testing) at Kyushu Institute of Technology, which is located in the west part of Japan.

The piggyback launch of PROCYON together with Hayabusa-2 was approved on September 2013, and the development of spacecraft started at that time.

After a couple of months of the spacecraft system design phase, we built STM (Structure and Thermal Model) to verify the mechanical and thermal design of the spacecraft. Vibration test (March and May 2014, Fig. 7. The improved design was tested at the second test) and thermal vacuum test (April 2014, Fig. 8) was successfully conducted. Parallel to the STM test, fabrication of the onboard equipments was proceeded.

The integration and test of flight model started on July 2014 (Fig. 9), and it completed at the end of October 2014, taking about four months to conduct I/F test, ion thruster end-to-end test (in vacuum chamber, Fig. 10), thermal vacuum test, vibration test (Fig. 11), and separation shock test. The spacecraft was delivered to JAXA at the beginning of November 2014, which was the end of the one year of the spacecraft development.
INITIAL OPERATION RESULTS

PROCYON’s command and telemetry operation is conducted mainly via Japanese deep space stations (64m and 34m antenna). We receive international cooperation from JPL and ESA when we perform DDOR experiments, which is an international collaboration experiment between JAXA, NASA, and ESA.

PROCYON was successfully launched into an interplanetary trajectory together with Hayabusa-2. The spacecraft conducted very smooth autonomous control sequence during the four hours of critical phase until the beginning of the first pass. The spacecraft successfully conducted SAP deployment, detumbling control, sun search control, and sun pointing control (Fig. 12).

During the subsequent initial operation for a couple of months, the demonstration of the deep space micro-spacecraft bus system was successfully conducted. All of the following functions were verified, which demonstrated that the micro-spacecraft has a capability to conduct deep space exploration mission by itself.

- Power generation/management (>240W)
- Thermal design to accommodate wide range of Solar distance (0.9~1.5AU) and power consumption mode (IES on/off) [10]
- 3-axis attitude control with high stability (~0.01deg) [11]
- World’s first deep space micro communication & navigation system [8]
  - High efficiency (GaN SSPA, >30%)
  - High output (>15 W)
  - Precise navigation by “Chirp DDOR” method
- World’s first demonstration of micro propulsion system in deep space [12,13], which has both of
  - RCS for attitude control/momentum management (8 thrusters)
  - Ion propulsion system for trajectory control (Isp=1000s, thrust=300uN)

Also, the scientific observation mission (wide-view observation of geocorona) was successfully conducted on January 5, 2015.

CONCLUSION

University of Tokyo and JAXA developed a 50kg-class micro-spacecraft PROCYON for deep space exploration. The primary mission of PROCYON is the demonstration of micro-spacecraft bus system for deep
space exploration, and the secondary advanced missions are low-thrust deep space maneuver to perform Earth swingby, high-resolution observation of a Near-Earth asteroid during close (<30km) and fast (~10km/s) flyby, and wide-view scientific observation of geocorona from a vantage point outside of the Earth’s geocoronal distribution. Most of the bus system of PROCYON is based on the heritage from 50kg-class Earth-orbiting micro satellite missions, which enabled extremely quick (~1 year) and low-cost (~a few million dollars) spacecraft development. COTS-based deep space micro communication system and miniature propulsion system were newly developed for PROCYON mission.

PROCYON was successfully launched into an interplanetary trajectory together with Hayabusa-2, and it succeeded in the demonstration of the micro-spacecraft bus system for deep space exploration and scientific observation mission. The goal of the PROCYON project was achieved, which is to demonstrate that a low-cost small-scale spacecraft can be a useful tool of deep space exploration. The success of PROCYON mission will contribute to the realization of high-frequent and challenging deep space exploration.

References

6. Kameda, S., Yoshikawa, I. and et al., “Observation of Geocorona using Lyman Alpha Imaging Camera (LAICA) onboard the very small deep space explorer PROCYON”, 40th COSPAR Scientific Assembly, D2.3-23-14, Moscow, Russia, August 2014.