TRAJECTORY NAVIGATION AND GUIDANCE OPERATION TOWARD EARTH SWING-BY OF ASTEROID SAMPLE RETURN MISSION "HAYABUSA2"

Yuichi Tsuda[(1)], Takaaki Kato[(2)], Masakazu Shiraishi[(3)], and Masatoshi Matsuoka[(4)]

[(1)] *Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency*
3-1-1, Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, Japan, 252-5210,
Phone: +81-50-3362-4411, Email: tsuda.yuichi@jaxa.jp
[(2)(3)(4)]*Mission Design Department, Space System Division, NEC Corporation*

Abstract: *The Japanese new asteroid sample return mission Hayabusa2 was successfully launched in December 3, 2014. The continuous thrust trajectory control by solar electric propulsion combined with one Earth gravity assist, planned in December 3, 2015, enables the spacecraft to reach the C-type asteroid 1999 JU3 in 2018 and return back to the Earth in 2020. This paper describes how the interplanetary guidance and navigation operation has been made incorporating ion engine-specific considerations in the first one-year of cruising operation. An effort to minimize the chemical propellant consumption while improving the guidance accuracy toward the gravity assist has been made by making full use of the ion engine maneuvering, which is also be introduced in the present paper.*

Keywords: *Solar Electric Propulsion, Trajectory Control, Earth Gravity Assist*

1. Introduction

This paper describes the first one-year inorbit operation of Hayabusa2. Hayabusa2 is a Japanese interplanetary probe (Fig.1) launched in December 3, 2014 to visit a NEA (Near Earth Asteroid) 1999 JU3.[1] It is a round-trip mission, scheduled to reach 1999 JU3 in the middle of 2018, and will perform an asteroid proximity operation for 1.5 years. Three touch downs for sample collection and one 2m class-crater generation by kinetic impact are planned during the asteroid proximity operation. The sample is to be brought back to the Earth by the re-entry capsule in 2020. The mission enablers for this round-trip cruise is a high-specific ion engine system, capable of producing >2km/s delta-V with very small amount of xenon propellant.

The outward trajectory to 1999 JU3 incorporates an Earth gravity assist (EGA) after one-year interplanetary cruise. There are multiple purposes to use the EDVEGA technique, which will be described later in this paper. The resulting velocity gain by the Earth gravity assist is +1.6km/s with the swing-by altitude of around 2700km.

After the successful insertion to an interplanetary orbit by the H2A launch vehicle on December 3, 2014 from Tanegashima Space Center in Japan, several ion engine commissioning operations have been successfully conducted, which was followed by two long-term ion engine maneuvers and one small ion engine TCM maneuver to direct the spacecraft onto the EGA corridor.

The ion engine continuous-thrust trajectory is generated by a trajectory design software developed by the authors based on optimization theories.[2] The software effectively incorporates spacecraft-specific constraints so as to derive feasible trajectories taking into account power, thermal, communication and attitude constraints of the spacecraft at once. The last two months before EGA, on the other hand, is planned to be guided using chemical reaction control system (RCS).

This paper describes how the guidance/navigation operation is conducted in the EDVEGA phase of Hayabusa2 and shows how the trajectory correction maneuvers are made toward EGA by combining the ion engine and the RCS delta-Vs.

Fig.1. Artist's Image of Hayabusa2

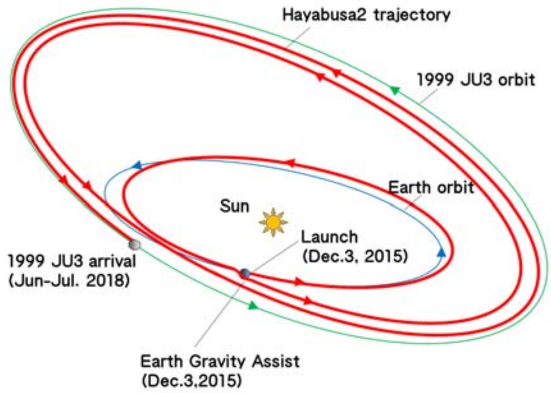


Fig.2. Hayabusa2 Trajectory from the Earth to 1999 JU3

2. Hayabusa2 Trajectory Design

The trajectory design of Hayabusa2 is characterized by continuous-thrust (non-ballistic) fuel-optimum orbit, realized by micro-wave discharged ion engine system [3]. The round-trip mission with ~600kg-class spacecraft is realized owing to this solar electric propulsion technology.

The trajectory sequence is as follows; (i)EDVEGA phase (Earth to Earth), (ii)Transfer phase (Earth to 1999JU3 phase), (iii)Mission Phase (1999JU3 proximity operation), (iv)Return Phase (1999 JU3 to Earth).

The objective of the EDVEGA phase for the Hayabusa2 mission is to connect smoothly with the transfer phase via EGA while (i)enlarging the operational margin of the ion engine (as the EDVEGA phase has long non-operation duration of the ion engine), (ii)isolating the launch constraints and asteroid reachability constraints (which in turns leads to the enlargement of the launch window), (iii)providing back up windows (as we have several EDVEGA options, i.e. 1year /0.5year / Direct transfer options, theoretically.)[2]

Two types of optimization methods are used for the Hayabusa2 trajectory generation. One is based on the Nonlinear Sequential Quadratic Programming (NLSQP)[2], and another is based on the indirect optimization taking advantage of a mission-specific formulation.[4] Since available power for driving the ion engine varies depending on the solar distance, the spacecraft model for the trajectory design incorporates ion engine thrust/power/specific impulse model as well as solar array panel performance model and spacecraft bus power consumption model.

Figure 2 shows the resulting trajectory design of Hayabusa2. The spacecraft was launched on December 3, 2014 by the Japanese H2A202-4S launch vehicle to the EDVEGA loop at $C3=21km^2/s^2$, and then performs EGA on December 3, 2015 to fly along the 1999JU3 transfer orbit. The arrival at 1999JU3 is in around June-July 2018. After staying for 1.5years, the spacecraft will leave 1999 JU3 in December, 2019, and fly back to the Earth in December 2020 at the atmospheric re-entry interface velocity of 11.6km/s.

3. Cruising Operation

3.1. LEOP and Commissioning Phase[5-7]

Hayabusa2 was launched at 04:22:04 UTC on December 3, 2014. The second stage of the H2A launch vehicle flew 1 revolution around the Earth on the 250km-altitude parking orbit (i.e. "long-coast" parking orbit, Fig.3). After the second burn of the second stage, Hayabusa2 was separated from the second stage at 06:09:25 UTC and injected to interplanetary space at the characteristic

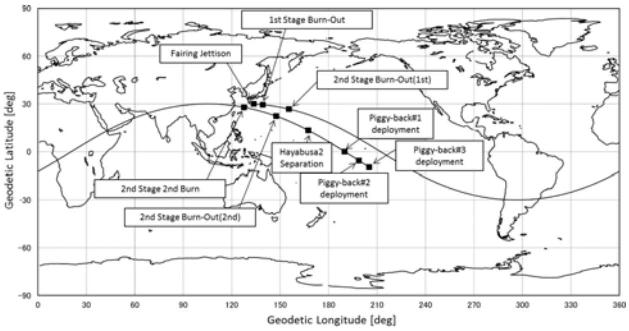


Fig.3. Launch Trajectory of Hayabusa2 Aboard H2A Launch Vehicle F26

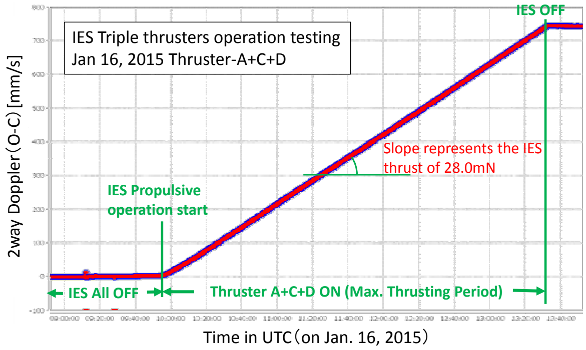


Fig.4. 2way Doppler Measurement at Ion Engine Maximum Thrust Operation

Table 1. IES Operation and TCMs in EDVEGA Phase

Event	Period	ΔV amount	Note
IES ΔV #1	Mar.3-9, 2015	44m/s	Ion Engine A+D, 409hrs
IES ΔV #2	Jun. 2-7, 2015	11m/s	Ion Engine A+D, 102hrs
IES-TCM	Sep. 1-2, 2015	1.3m/s	Ion Engine A+D, 12hrs

energy of C3=21km^2/s^2. The "long-coast" parking orbit enables us to have the initial acquisition at the NASA/DSN Goldstone and Canberra tracking stations very early, only about 20 minutes after the separation from the rocket, increasing operational reliability in such a critical operation as the initial acquisition. The Hayabusa2 navigation team of JAXA concluded that the post-launch injection error was below 1σ of the nominal trajectory, resulting in no need for emergency trajectory correction.

After the separation, the spacecraft autonomously started Sun-pointing maneuver and deployed the solar array paddles. The spacecraft then went into a spin stabilized attitude, waiting for commands from the ground. The DSN Goldstone and Canberra stations acquired the spacecraft signal on time at 6:28 and 6:33 UTC, respectively, and the JAXA's Uchinoura station acquired the signal at 10:13 UTC as planned.

The commissioning phase of the Hayabusa2 operation continued from the launch until March 2, 2015, during which the ion engine system (IES) was turned on for the first time on December 23-26. The four thrusters (IES Thruster-A/B/C/D) were turned on one-by-one. It was confirmed that all the thrusters were healthy and the thrust level of ~9.8mN each was confirmed accomplished in orbit. One of the critical inter-subsystem testing was the IES/AOCS-coordinated operation, in which the two-axis IES gimbal should be controlled so that the thrust vector should align with the spacecraft center of mass, and thence the reaction wheels should keep their rotation speed, compensating for fluctuating IES thrust level. The multiple thruster drive operations were conducted from January 12-16, 2015, and the maximum thrust test using three engines was completed successfully (Fig.4). As the final IES test in the commissioning phase, 24 hours continuous thrust operation was conducted successfully on January 19-20 using Thruster-A+D.

The rest of the commissioning phase was dedicated to the solar radiation pressure modeling. Hayabusa2 employs a special type of attitude keeping called "Solar Sail Mode"[8], which actively utilizing the SRP perturbation torque to keep the almost-Sun pointing attitude. This technique does not require any thruster firing for reaction wheel desaturation and Sun retargeting.

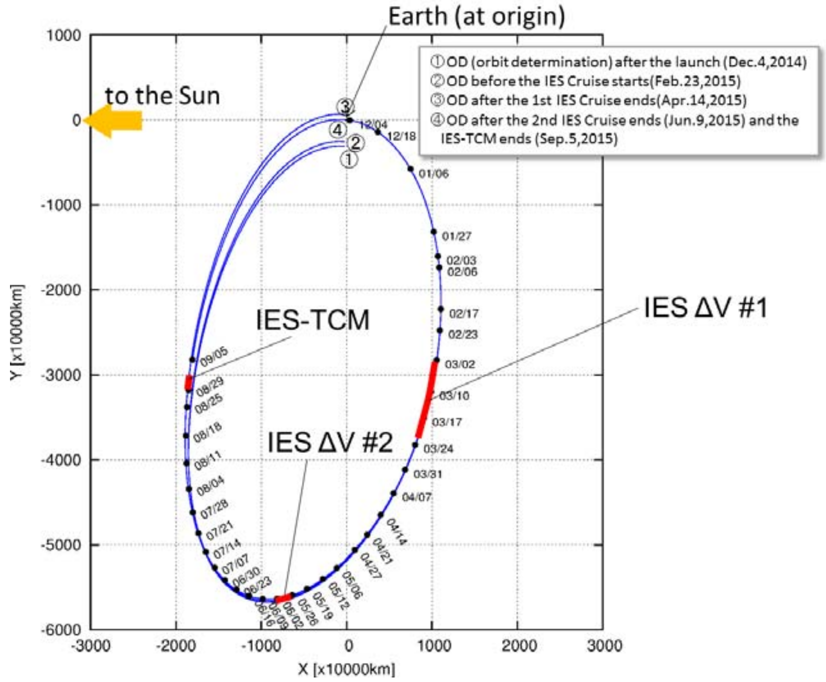


Fig.5. Ion Engine Trajectory Maneuver toward Earth Swing-by

Drawn in Sun-Earth line fixed rotating frame. Each line corresponds to a free celestial motion propagated forward from each OD result. Dates corresponds to when new orbit determination results are released.

Adopting this technique contributes much to fuel saving and obtaining precise orbit determination results easily, free from unpreferable noise.

3.2. Ion Engine Operation in EDVEGA Phase

Hayabusa2 started its cruising phase on March 3, 2015, following the completion of the commissioning phase. Major Ion Engine System (IES) operation was conducted in March and June 2015, and small trajectory correction maneuver using IES was done in September. Total of 523 hours of propulsive operation using Thruster-A and Thruster-D has produced 57.3m/s delta-V (Tab.1). A series of trajectory correction maneuvers (TCMs) using RCS is planned in the last one month before EGA on December 3, 2015.

Figure 5 shows how the trajectory has been evolved by the IES operation since launch toward EGA. The planned swing-by altitude of about 3000km increases the orbital velocity by 1.6km/s and changes the orbital plane. Then a high-duty IES-powered cruise will be started in April 2016 to head for the asteroid rendezvous in 2018.

3.3. Routine Operation for Continuous Thrust Trajectory Guidance and Navigation

Since the Hayabusa2 mission is based on continuous thrust trajectory, frequent trajectory navigation and guidance are essential. The spacecraft is operated with one-week cycle. The range and range rate (RARR) measurement is conducted every week, which is used for the orbit determination (OD) process. Sometimes Delta Differential One-way Ranging (DDOR) is conducted to further refine the OD result. The ion engine thrusting schedule (with the optimum continuous thrust trajectory solution) is then generated by the orbit planning (OP) team based on the latest OD result (usually an OD result produced a week before). The updated OP is used to generate the operation plan (command list) for the next one-week operation (Fig.6).

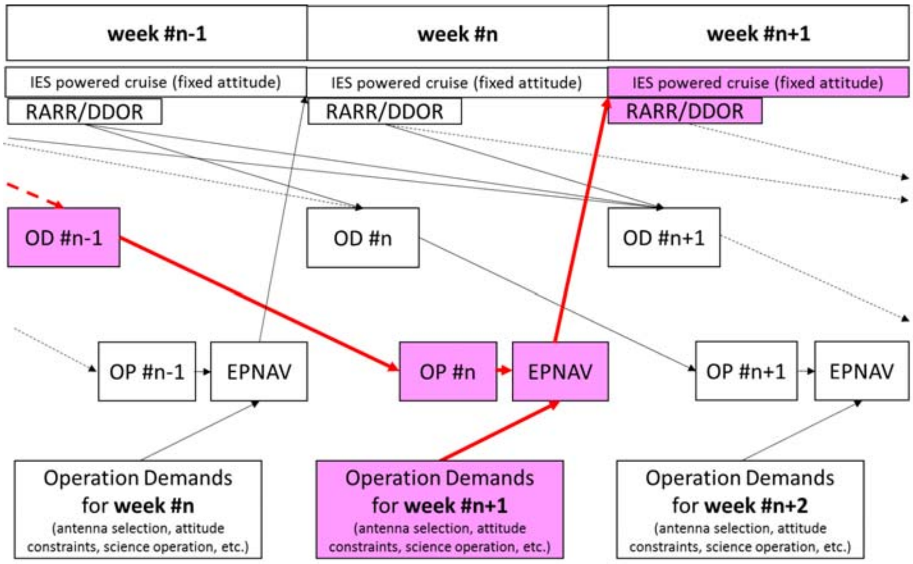


Fig.6. Routine Trajectory Navigation/Guidance Operation of Hayabusa2
RARR: Range and Range Rate Measurement, DDOR: Delta Differential One-way Ranging, OD: Orbit Determination, OP: Orbit Planning (Optimum Trajectory Recalculation), EPNAV: Automated Operation Panning Tool for Hayabusa2.

The command list generation is automated by a software called EPNAV which was originally developed for Hayabusa1 and has been upgraded for the Hayabusa2 mission. There are many constraints and operation limits on the ion engine operation. Given the tracking schedule, the orbit plan including round-trip time for each tracking pass and operation demands such as scientific instruments operation, EPNAV generates feasible commanding schedule and command list, including the ion engine operation, while taking into account operational constraints for the attitude, communication and the other spacecraft hardware limits.

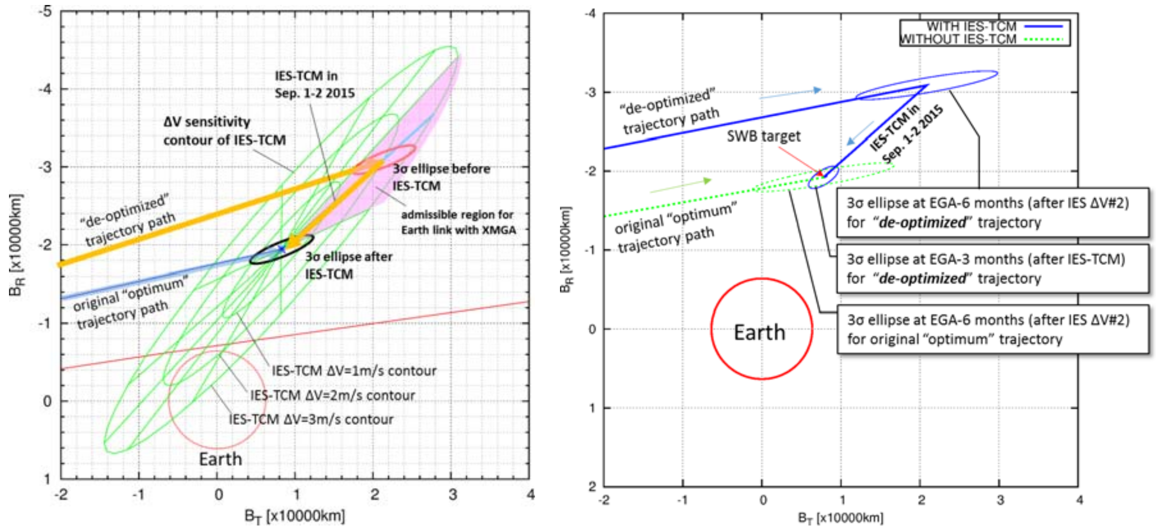
4. Guidance Operation toward Earth Swing-by

4.1. Trajectory De-Optimization for Precision Guidance

It is essential for the Hayabusa2 mission to reserve as much RCS fuel as possible for the asteroid proximity operation, and therefore, it is preferable to conduct the cruising trajectory guidance using IES rather than using RCS. A small deterministic trajectory correction maneuver by IES (IES-TCM) is added 3 months before the EGA for this purpose. It is expected that the IES-TCM can reduce the guidance error produced in the prior IES ΔVs.

Unlike the RCS thrusters (which realize full six degree-of-freedom motion), the IES of the Hayabusa2 spacecraft provides a fixed thrust vector, which results in limited directional capability to correct the trajectory error. Moreover, the IES operation requires high speed communication link using the X-band middle gain antenna (XMGA). Although XMGA is two axis-gimballed, it provides limited Earth-link coverage.

To be adaptive against any potential guidance error with using IES, a trajectory de-optimization strategy was employed. The trajectory is intentionally offset from the fuel-optimum nominal trajectory so that arbitrary 3σ guidance error at the IES ΔV #2 could be compensated by limited-directional IES-TCM with XMGA Earth link secured (Fig.7(a)). The resulting de-optimized trajectory required additional 1.3m/s acceleration by IES, which was conducted on September 1-2, 2015. This IES-TCM operation has successfully reduced the guidance error ellipse by around one fifth (Fig.7(b)).



(a) (b)

Fig.7. Ion Engine Maneuver Plan Projected on Earth B-Plane

(a) B-plane based IES-TCM design, showing efficient Δ V direction and the admissible region to secure the XMGA Earth link result in almost unique TCM plan, (b) Error ellipse on the B-plane, showing that adding the IES-TCM results in shrinking the size of the guidance error ellipse.

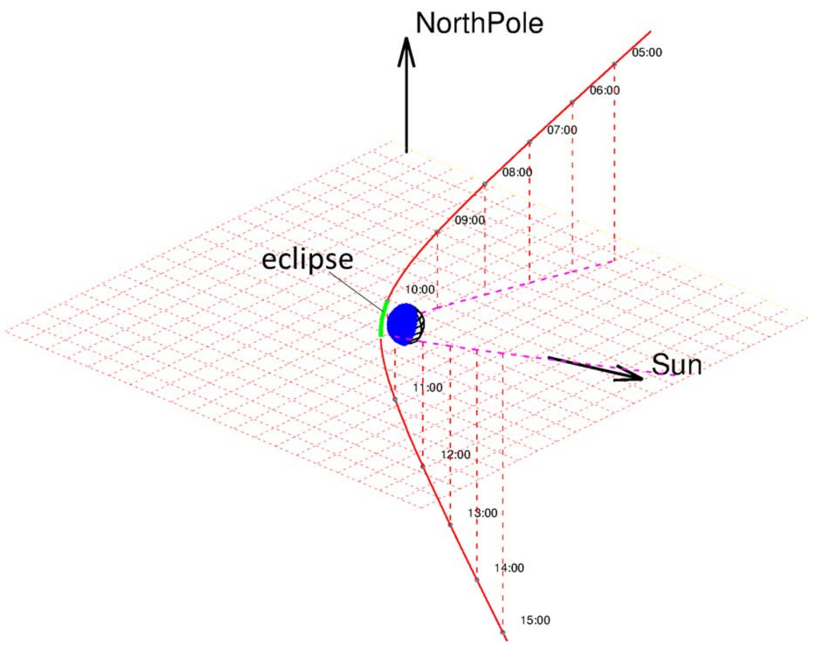


Fig.8. Earth Swingby Trajectory of Hayabusa2

4.2. Earth Swingby Trajectory and Operation

The Earth closest approach is planned to be approximately at December 3, 2015, 10:00UT over the Pacific Ocean (Fig.8). The closest distance is approximately 2700km (from the Earth surface) and the flyby deflection angle (angle between incoming and outgoing velocity vector in ECI frame) is 80deg. The interplanetary velocity increment by this Earth gravity assist is 1.6km/s.

The spacecraft will experience eclipse for about 20minutes, which is the longest battery-powered operation for Hayabusa2 throughout its mission.
The last one month before EGA is dedicated to precision guidance. Maximum three trim maneuvers by RCS are planned, all of which are pure stochastic burns. Owing to the insertion of the IES-TCM as described above, the expected amount of ΔV for each RCS maneuver is reduced to negligible level in terms of the fuel consumption.

5. Conclusion

This paper described the first one-year navigation and guidance operation of Hayabusa2, an asteroid sample return mission to 1999 JU3. Use of ion engine as the main propulsion system requires frequent and cyclic navigation and guidance evaluations, which has been considerably automated using "EPNAV" operation planning software. The guidance toward the Earth gravity assist (EGA) is planned so as to minimize the chemical fuel consumption, by strategically inserting an additional small ion engine burn three month before the EGA. This "de-optimization" shrinks the B-plane error ellipse by one fifth and improves the spacecraft-Earth link geometry. Hayabusa2 is now flying normally toward the EGA in December 3, 2015, and will have three additional RCS trajectory correction maneuvers in November.

7. References

[1] Tsuda Y., Yoshikawa M., Abe, M., Minamino H., Nakazawa S., System Design of The Hayabusa 2 – Asteroid Sample Return Mission To 1999 JU3, ActaAstronautica, Vol.90, pp.356-362, doi: 10.1016/j.actaastro.2013.06.028, 2013.
[2] Tsuda Y., Saiki T., Ogawa N., Morimoto M., Trajectory Design for Japanese New Asteroid Sample Return Mission Hayabusa-2, 23rd International Symposium on Space Flight Dynamics, IMD-1-1, Pasadena, October 29, 2012.
[3] Nishiyama K., Hosoda S., Ueno K., Tsukizaki R., Kuninaka H., Development and Testing of the Hayabusa2 Ion Engine System, ISTS-2015-b/IEPC-333, 30th International Symposium on Space Technology and Science, Kobe, June 4-10, 2015.
[4] Kato, T., Matsuoka, M., Tsuda, Y., "Orbit Plan of Hayabusa2", 22nd JAXA Workshop on Astrodynamics and Flight Mechanics, B-2, July 30, 2012.
[5] Tsuda, Y., Nakazawa, S., Kushiki, K.,, Yoshikawa, M., Watanabe, S., Kuninaka, H., Flight Status of Robotics Asteroid Sample Return Mission Hayabusa 2, 9th IAA Symposium on the Future of Space Exploration: Towards New Global Programmes, IAA-FSE-15-11-01, Torino, Italy, July 9, 2015.
[6] Kuninaka H., Hayabusa2 Project, Deep Space Exploration of Hayabusa-2 Spacecraft, ISTS-2015-k-61, 30th International Symposium on Space Technology and Science, Kobe, June 4-10, 2015.
[7] Hosoda S., Nishiyama K., Tsukizaki R., Kuninaka H., Initial Checkout after Launch of Hayabusa2 Ion Engine System, ISTS-2015-b/IEPC-334, 30th International Symposium on Space Technology and Science, Kobe, June 4-10, 2015.
[8] Tsuda. Y., Ono, G., Akatsuka, K., Saiki, T., Mimasu, Y., Ogawa, N., Terui, F., "Generalized Attitude Model for Momentum-Biased Solar Sail Spacecraft", AAS Astrodynamics Specialist Conference, AAS15-656, Vail, CO, August 12, 2015.