LOW-THRUST TRAJECTORY DESIGN AND OPERATIONS OF PROCYON, THE FIRST DEEP-SPACE MICRO-SPACECRAFT

Stefano Campagnola[(1)], Naoya Ozaki[(2)], Yoshihide Sugimoto[(3)], Chit Hong Yam[(3)], Hongru Chen[(4)], Yosuke Kawabata[(5)], Satoshi Ogura[(5)], Bruno Sarli[(5)], Yasuhiro Kawakatsu[(3)], Ryu Funase[(2)], and Shinichi Nakasuka[(2)]

[(1)]*ISAS/JAXA, Yoshinodai 3-1-1, Sagamihara, Kanagawa 252-5210, Japan, +81 70 6912 1162, stefano.campagnola@jaxa.jp*

[(2)]*The University of Tokyo, Japan*

[(3)]*ISAS/JAXA, Japan*

[(4)]*Kyushu University, Japan*

[(5)]*The Graduate University for Advanced Studies,, Japann*

Abstract: *PROCYON is the first deep-space micro-spacecraft; it was developed at low cost and short time (about one year) by the University of Tokyo and JAXA, and was launched on December 3rd, 2014 as a secondary payload of the H-IIA launch of Hayabusa2. The mission primary objective is the technology demonstration of a micro-spacecraft bus for deep-space exploration; the second objectives are several engineering and science experiments, including an asteroid flyby. This paper presents PROCYON high-fidelity, very-low-thrust trajectory design and implementation, subject to mission and operation constraints. Contingency plans during the first months of operations are also discussed. All trajectories are optimized in high-fidelity model with jTOP, a mission design tool first presented in this paper. Following the ion engine failure of March 2015, it was found the nominal asteroid could not be targeted if the failure was not resolved by mid-April. A new approach to compute attainable sets for low-thrust trajectories is also presented.*

Keywords: *PROCYON, micro-spacecraft operation, low-thrust*

1. Introduction

PROCYON [1] is a micro-spacecraft by the University of Tokyo and ISAS/JAXA that was launched on Dec 3rd, 2015. PROCYON is the world's first deep-space micro-spacecraft, and the world's first deep-space mission by an university. The mission primary objective is the technology demonstration of a micro-spacecraft bus for deep-space exploration; secondary objectives include a number of engineering and science experiments, most of which have been successfully executed. One secondary objectives has not been achieved: the flyby of the binary asteroid 2000 DP 107, which is enabled by low-thrust orbit control and an Earth flyby, cannot currently be attained because of a failure of the Ion Engine System (IES).

Despite this accident, PROCYON demonstrated that deep space exploration by a micro-spacecraft is feasible, and especially, that such a spacecraft can be developed in a little more than a year. Short development times enable frequent and low-cost access to deep-space exploration, with a tremendous impact to the space community, for both scientists and engineers. For this reasons, in the last year both ESA, JAXA and ESA released announcements of opportunities for interplanetary cubesat; the first interplanetary cubesat MARCO will be launched in 2016.

Deep-space micro-spacecraft design and operation present many challenges. Efficient, miniaturized, low-cost components are needed for communication, power, and in nearly all the subsystems. In particular, orbit design and maneuver planning must deal with limited orbit control capabilities, and unfrequent passes over ground stations for orbit determination. Also, the trajectory design and optimization must be carried in high-fidelity models and is subject to several mission constraints.

This paper discusses the trajectory design and implementation of PROCYON, from before launch to the IES failure. The paper also introduces jTOP , a trajectory optimization program that has been used in the past for a number of application, but is first presented here. jTOP was upgraded to model multi-body dynamics and precise maneuver planning for PROCYON operations. Surprisingly, multi-body dynamics enabled a new solution for the nominal launch date, that was deemed unfeasible during the preliminary design. It was found that the low acceleration of PROCYON is sufficient to target a 500,000 km-altitude Earth flyby on the way to 2000 DP 107, but would not be enough to target the Earth center of mass, as required by the patched-conics model typically used during preliminary design. Finally, we briefly introduce a new approach to compute attainable set of low-thrust trajectories, and its implementation to PROCYON mission.

2. Background

2.1. PROCYON mission

PROCYON mission was approved on September 2013 as a secondary payload of the H-IIA launch of Hayabusa2[2]. After a development time of just about one year, PROCYON was launched on December 3rd, 2014 into an Earth escape trajectory and will return to the Earth vicinity in December 2015. Procyon trajectory is shown in Figure 1 in the ecliptic frame, and in Figure 2 in a Sun-Earth rotating frame, centered at the Earth. Low-thrust arcs are marked in red. Table 1 shows the spacecraft specification and Figures 3-4 show the top and bottom view of the spacecraft.

Shortly after launch, PROCYON successfully performed solar array panel deployment, detumbling control, Sun search control, and Sun pointing control (see Funase et al. for detailed information [3]); in the following months, the main mission objective was accomplished by demonstrating the capabilities of a micro-spacecraft bus for deep space missions, including attitude control [4], thermal control[5], operation of the world's first deep-space micro communication and navigation system [6], and of the world's first demonstration of micro-propulsion system in deep space [7]. In addition, engineering and scientific experiments were conducted: VLBI navigation using chirp-DDOR and combined Hayabusa2 and PROCYON one-way measurements; and wide-view observation of geocorona with a Lyman alpha imaging camera (LAICA) [8] . The ground stations used for command and telemetry operations are the Japanese Usuda station (64 m antenna, available during weekends) and Uchinoura station (32 m antenna, available typically one time per week).

The advanced mission objective of PROCYON is an asteroid close-flyby observation and optical navigation. The asteroid flyby is the main objective of the low-thrust trajectory design presented both in this paper, and in previous papers [9, 10, 11]. Unfortunately, on March 2015 a failure in the Ion Engine System (IES) system has caused the spacecraft to drift away from its nominal trajectory, and currently no asteroid flyby is planned for PROCYON.

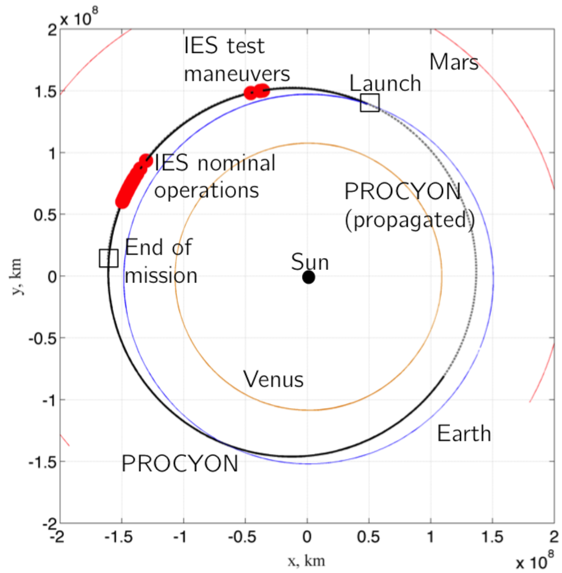


Figure 1. PROCYON trajectory in the ecliptic J2000 reference frame.

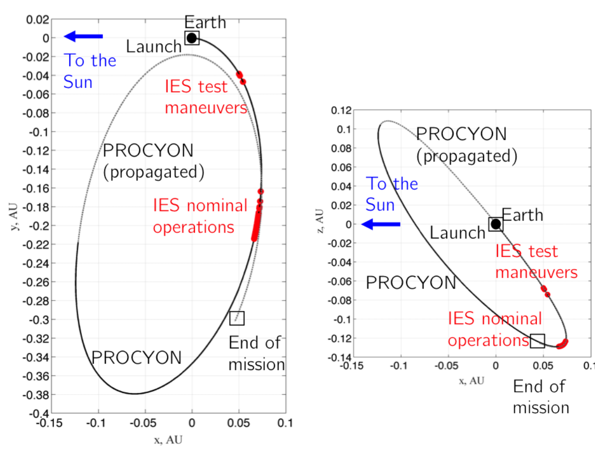


Figure 2. PROCYON trajectory in the Sun-Earth rotating frame.

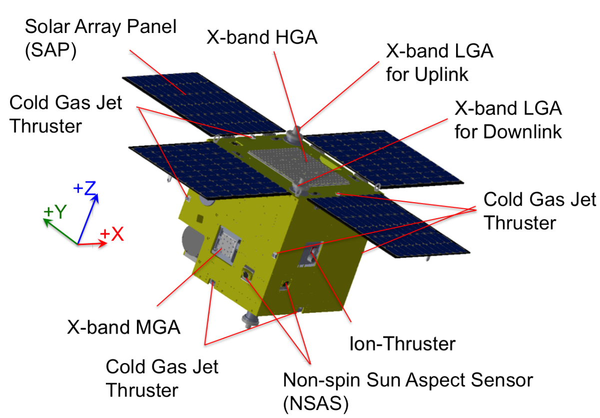


Figure 3. Top view of PROCYON.

Structure	Size	0.55m x 0.55m x 0.67m
		+ 4 SAPs
	Weight	66.9 (Wet)
Power	SAP	Triple Junction GaAs¿240W
		(1AU,$\alpha_s = 0$,BOL)
	BAT	Li-ion, 5.3Ah
AOCS	Actuator	4 Reaction Wheels,
		3-axis Fiber Optic Gyro
	Sensor	Star Tracker, Non-spin
		Sun Aspect Sensor.
		Telescope (for opt. nav.)
Prop.	RCS	Xenon CGJ x8,
		~22mN thrust, 24s Isp
	Ion Propulsion	Xenon microwave
		discharge ion prop. system
		0.3 mN thrust, 1000s Isp
	Propellant	2.5 kg Xenon
Comm.	Frequency	X-band
	Antenna	HGAx1, MGAx1, LGAx2
		(for UL), LGAx2 (for DL)

Table 1. PROCYON specification.

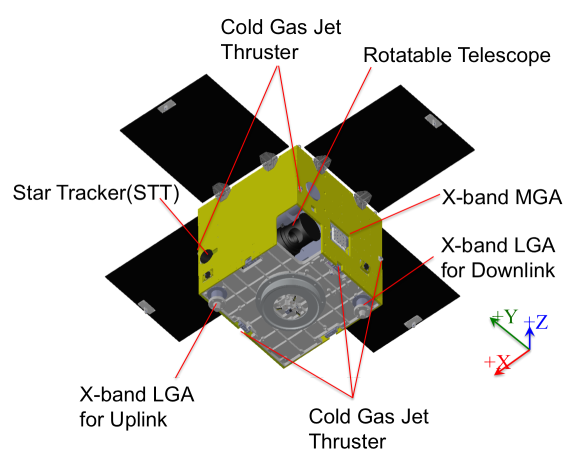


Figure 4. Bottom view of PROCYON.

Propellant Mass	IES $\leq$ 1.0 kg (about 150 m/s) CGJ $\leq$ 1.5 kg (about 5 m/s)
Operation	IES duty cycle $\leq$ 0.7 Coast arcs 1month after launch, 1 month before Earth flyby
Communications	Earth Distance ¡0.57 AU at ast. FB Decl. from Usuda ¿-56.13 deg
Thermal	Sun distance betw. 0.9AU and 1.5 AU
Optical Navigation	ast. observable 3 d before the c.a. Rel. vel. to the ast. ¡ 30 km/s Asteroid not on the Milky Way
Power (*)	$E_s \geq 812[\mathrm{W/m^2}]$ (IES) $E_s \geq 585[\mathrm{W/m^2}]$ (CGJ)

Table 2. PROCYON trajectory constraints. (*) The power constraints were enforced only in the high-fidelity optimization (see next section).

2.2. Preliminary mission design

This section is an overview of the preliminary mission design; details can be found in [9, 10, 11].

The preliminary design was performed in the zero-radius sphere-of-influence ("patched-conics") model, where the spacecraft is subject to the gravity of the Sun only, and the Earth flyby is modeled with an impulsive change of velocity. At the end of the study, two near-Earth asteroids were selected : the binary 2000 DP107 and the Aten-type 1992 FE. Trajectories to these asteroids included low-thrust arcs and one Earth flyby one year (for 2000 DP 107 options) or two years (for 1992 FE options) after launch, and were optimized with GALLOP[**?**]. Table 2 shows the mission constraints (all but last were implemented in the preliminary design optimization). In the table, the duty cycle is the fraction of the nominal thrust allowed during the optimization. A 30% margin was used, for contingency and precise orbit determination (OD).

The main challenges to PROCYON trajectory design is the very-low thrust capability, and the initial launch orbit, which is almost, but not exactly, a 1-year orbit. In fact, the Hayabusa team included some engine test maneuvers during the first year of operations, and for this reason, the launch trajectory does not return to the Earth ballistically. PROCYON is launched into the same orbit as Hayabusa , but because of the much lower orbit control capabilities (the initial acceleration is about $4\mu m/s^2$ for PROCYON and about $50\mu m/s^2$for Hayabusa2), the short test maneuver for Hayabusa becomes a very long thrust arc for PROCYON. In fact, on certain launch dates PROCYON cannot retarget the Earth in just one year, and therefore a second revolution around the Sun is introduce before the Earth flyby. Figure 5 shows the result of the launch window analysis from Yam et al. [10].

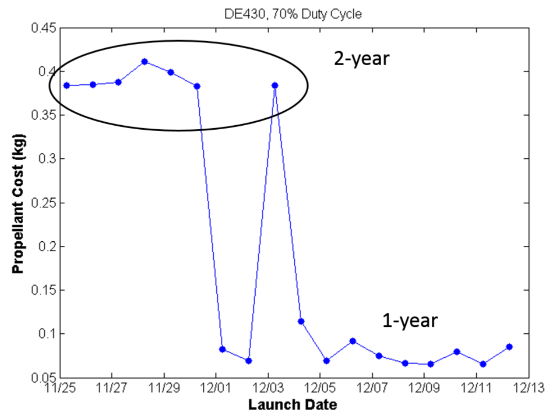


Figure 5. Launch window (from [10]).

3. High-fidelity trajectory optimization

The nominal trajectory must be re-optimized in a higher-fidelity model for validation, refinement, and for detailed maneuver planning. For this purpose, the trajectory optimization tool jTOP was equipped with a low-thrust, high-fidelity module, and shortly before launch [1], the nominal trajectory was recomputed for selected launch dates. Surprisingly, a one-year solution to 2007 DP107 was found for the nominal launch date of December 3rd, for which the preliminary design could only find two-year solutions (see Figure 5). The new , one-year solution includes a very-high altitude flyby at the Earth (at about 500,000 km), which provided the right Δv to target 2000 DP 107. This section presents the tool jTOP and the nominal trajectory optimization and implementation.

3.1. jTOP

jTOP is a mission design tool that can optimize a variety of trajectories with multiple flybys, with impulsive or low-thrust maneuvers, in low-fidelity or high-fidelity models. Although presented for the first time in this paper, jTOP has already been used in number of applications, summarized in Table 6.

jTOP trajectories are split in phases; each phase is defined by an optimization vector y that typically includes a central state x_C and time t_C; backward and forward propagation time intervals T_B, T_F; and a number of additional parameters (for example thrust vectors at selected times). For a given merit function, set of constraints, and dynamical systems acting on each phase, the parameters are optimized using the non-linear programming tool SNOPT[15]. Although jTOP is mostly implemented in Matlab, the propagation of the equations of motion is performed with a Fortran 90 library, which improve the computational speed by 20 times. The derivatives of the boundary states with respect to the optimization parameters $dx_{B,F}/dy$ (where $x_{B,F} = x(t_C + T_{F,B})$) are computed by propagating a system of partial derivatives, also in Fortran90. The constraint and merit function derivatives are computed using the chain rule, analytical derivatives, and the matrix of sensitivities $dx_{F,B}/dy$, which improves the optimization robustness and computational speed.

[1] We recall that the development time for the mission was only one year.

Application	Prop.	Dynamics	#FB
NASA 2010 Europa orbiter and lander[12]	CH	Multi-body (planets and Galilean moons)	˜20
Neptune Orbiter for ESA L2-L3 mission[13]	CH + EP	Patched-conics, LT modeled as small DVs	3˜4
JAXA Mars Moons sample return	CH + EP	Multi-body, piecewise constant LT	0˜1
PROCYON	EP	Multi-body, SRP, piecewise constant LT	0˜1
GTOC7	CH + EP	Patched-conics, piecewise constant LT	0
GTOC8	CH + EP	Patched-conics, piecewise constant LT	0
JAXA's DESTINY proposed mission[14]	EP	Multi-body, piecewise constant LT	˜4

Figure 6. Main applications of jTOP up to date.

3.2. Nominal trajectory optimization and implementation

The nominal trajectory for December 3rd launch was computed in a high-fidelity model, with a dynamical system consistent to the propagator of the Orbit Determination (OD) tool by Fujitsu[2]. The trajectory and thrust profiles are shown in Fig 8-10. The dynamics include the gravity from the planets and the Moon, and solar radiation pressure with a cannonball model (area = 1.25 m^2, reflectivity parameter 1.5). Planetary ephemerides are from JPL DE430 files, and the origin of the reference frame in the propagation is the Solar System baricenter - small but not negligible errors were found when the propagation is centered at a planet, and the relative accelerations are computed with restricted n-body problem equations.

One of the main differences between the new analysis in high-fidelity and preliminary design in patched conics, are the effect of multi-body dynamics. PROCYON interplanetary trajectory is perturbed by the Earth gravity, even when the spacecraft cannot get too close to the Earth. While the patched-conic solution for December 3rd could not bring the spacecraft back to the Earth after one year, the solution in jTOP exploited the Earth gravity with a very-high-altitude flyby at about 500,000 km to target DP107.

Another difference between the high-fidelitty and the preliminary design results comes from the inclusion of the power constraint during thrust operations:

$$\frac{E_{1AU}\cos\alpha}{r_{Sun}^2} \geq 812$$

where α is the Sun aspect angle, i.e. the angle between the spacecraft-Sun vector and the normal

[2]Fujitsu was contracted with the OD operation for Hayabusa2 and for PROCYON.

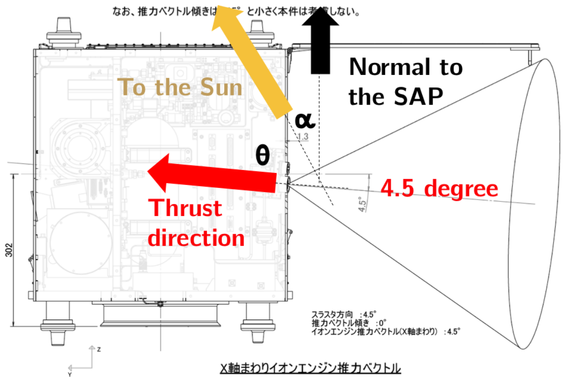


Figure 7. Power constraint and thrust direction.

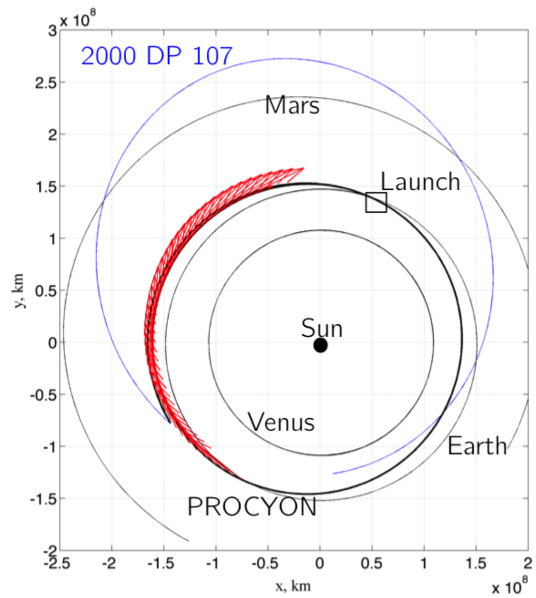


Figure 8. Nominal trajectory to 2000 DP 107 in the ecliptic J2000 reference frame.

to the solar panel, which in general depends on the attitude. However, if we maximize the input power while keeping the thruster aligner with required thrust direction, the spacecraft-Sun vector, the thrust direction, and the normal to the panels belong to the same plane, as shown in Figure 7. In this case , α is simply $(85.5^o - \theta)$, where θ is the angle between the thrust direction and the Sun-pointing vector, and can be computed explititely without using attitude equations. Finally, since the constraint is active only during thruster operation ($T > 0$), the equation was smoothed using the hyperbolic tangent function:

$$\frac{E_{1AU}\cos(\theta+\delta)}{r_{Sun}^2} \geq 812\tanh(100T)$$

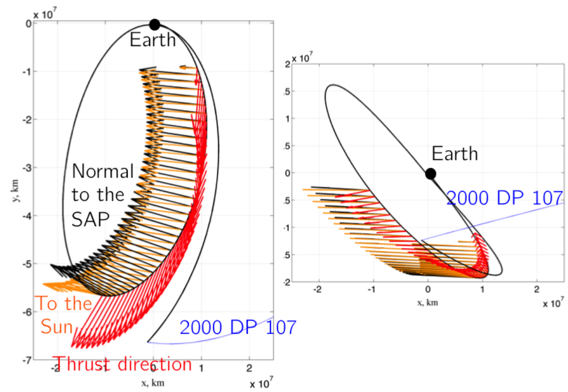


Figure 9. Nominal trajectory to 2000 DP 107 in the Sun-Earth rotating frame.

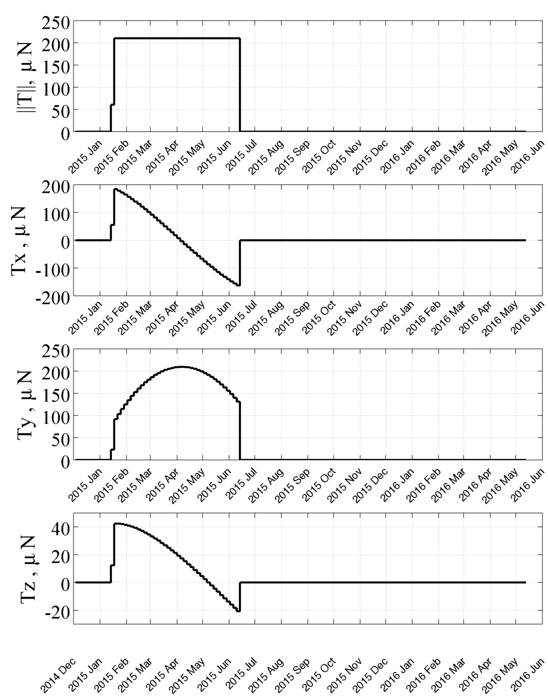


Figure 10. Trajectory profile of the nominal trajectory to 2000 DP107.

4. Operations

Since Usuda ground station is available every weekends, it was decided that the thrust direction would be changed weekly between inertially fixed directions. More precisely, it was planned that new OD data (if any) would be available on Wednesday; then the new trajectory would be re-optimized the same day, and during the next weekend , if needed, the thrust direction for the week starting 7 days after would up updated. Precise OD was scheduled about once per month, and would require at least three passes with no thrusting in between. Because of the limited ground station availability, it was estimated that every month we would need about five days of coasting. The duty cycle was then kept at 70% for most of the trajectory, for OD and contingency, except for the upcoming week , where duty cycle was increased to ˜90%.

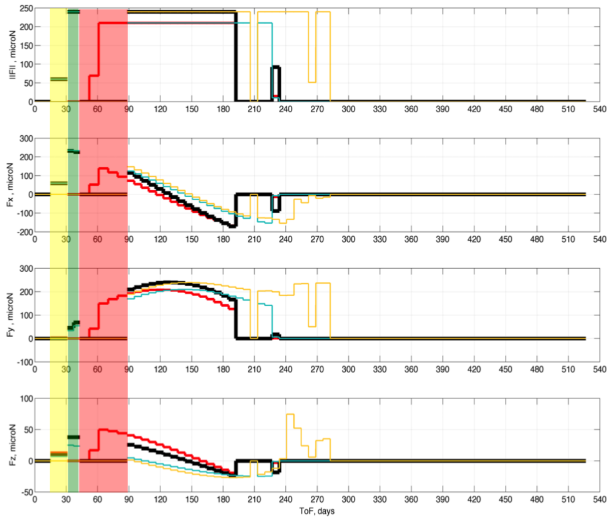
In practice, a number of contingencies changed the operation plan, except for a few weeks of nominal operations between February and March 2015.

4.1. Uchinoura ground station maintenance

Soon after launch, a number of challenges were encountered that required re-planning the nominal trajectory. The first challenge was the Uchinoura station shutdown for maintenance between end of January and end of February, 2015. Without the Uchinoura station, the spacecraft could only be tracked during weekends by Usuda station. Week-long thrust arcs without communication is too risky, especially at the beginning of the nominal operations. However, postponing the beginning of nominal operations is also critical, because of the high sensitivities of the Earth closest approach to the early thrust arcs. Therefore , new trajectories were optimized with a coast arc during ground station maintenance, but with thrust arcs in January, one month after launch and just before the ground station shutdown. Different scenarios were analyzed, by increasing the duty cycle in the rest of the mission or by optimizing the thrust directions of the tests maneuver during LEOP, so that they would also contribute to the Earth flyby targeting. The different scenarios are summarized in Figure 11. Eventually, case 6 in the figure was selected as new nominal.

4.2. Delay of nominal operations and IES failure

LEOP took more time than planned, and therefore, is was not possible to start nominal IES operations on January 3rd. However, it was found that the IES thruster could provide $330\mu N$ of thrust - a 10% improvement over the nominal thrust level. A new trajectory was computed where nominal operations were delayed until end of February, and 70% duty cycle could be maintained throughout the rest of the mission. Figure 12 shows three thrust profiles, where we checked the effect of further delaying nominal operations. Even a two week delay would compromise the Earth flyby , assuming 70% duty cycle. Nominal operation started on February 22nd and continued until March 10th, when the failure of the IES occurred. Currently, the ion engine cannot produce any acceleration, probably because of a contamination that caused a shortcut between accelerating grids.



Case ID	Duty cycle during (a)IES tests (b) first nominal operation	Max duty cycle during Uchinoura maintenance	Max duty cycle after Uchinoura maintenance	Propellant mass
4	20% 80%	70%	70%	0.257 kg
5	20% 80%	0%	80%	0.260 kg
6	20% 80%	0%	70%	0.278 kg
7	0% 0%	0%	80%	0.385 kg
8	0% 0%	0%	<80%	CURRENTLY UNFEASIBLE!

Figure 11. Ground station shutdown and recovery plans.

5. Recovery analysis by attainable set method

After IES failure, a new approach was used to quickly assess neighboring traectory options. In the linear approximation, the set of points attainable at any given time with limited thrust is bounded by a polyhedron with M polygons, defined by the M equations $A\delta x \leq b$, where δx is the deviation from the ballistic trajectory. The matrix A and the vector b are computed with a quadrature formula, involving the coefficients of the state transition matrix of the linear system. Details on this approach will be presented in the journal version of this paper.

The attainable set approach was used to compute the latest time for restating IES operations and still being able to target 2000 DP 107. Figure 13 shows the attainable sets at time of the Earth flyby, assuming IES operation would restart on April 1st and on April 15th. When IES operation starts on April 1st, the attainable set encloses the target closest approach to reach 2000 DP 107. However, when IES operation starts on April 15th, the attainable set shrinks and the conditions for the asteroid flyby cannot be reached anymore. These results were confirmed by jTOP optimization in the full model. The attainable set method will also be used to find alternative target asteroids in the neighborhood of the nominal trajectory, should the failure be recovered before the end of the mission.

Case ID	Duty cycle during the first week of March	Duty cycle during the second week of March	Duty cycle in the rest of the mission	Propellant mass
20	**70%**	**70%**	**70%**	**0.419 kg**
21	**0%**	**70%**	**70%**	**0.651 kg**
22	**0%**	**50%**	**70%**	**0.782 kg**

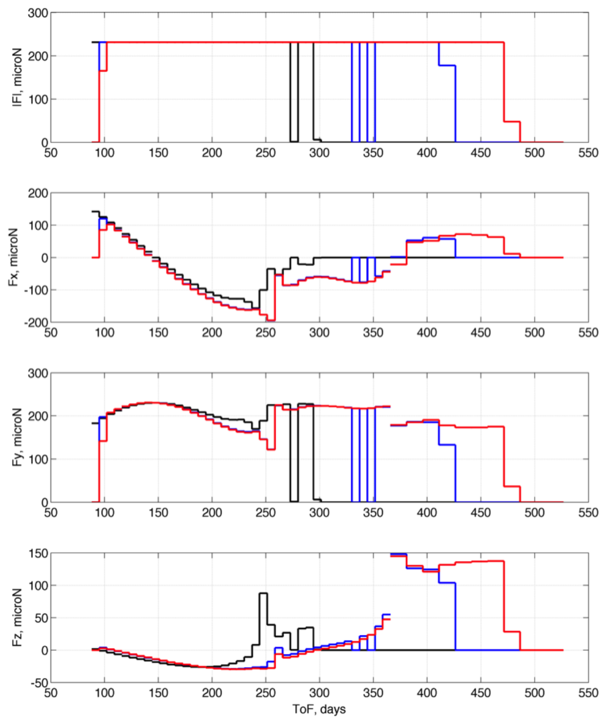


Figure 12. Trajectory options for delayed operations after ground- station reopening.

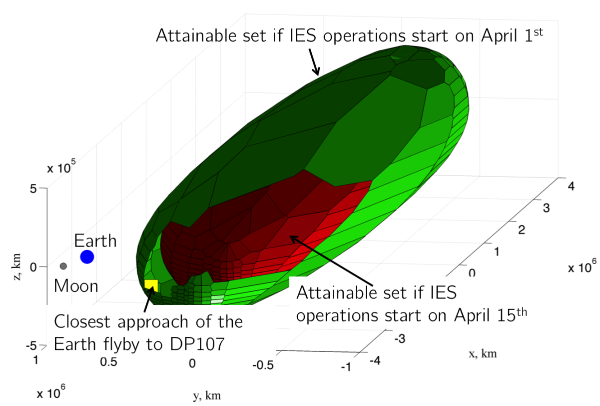


Figure 13. Attainable set method used to compute the latest time of IES recovery to reach asteroid 2000 DP 107.

6. Conclusions

This paper presents the low-thrust trajectory design of PROCYON in high-fidelity model, and the trajectory implementation for flight operations. A new nominal trajectory was found shortly before launch, exploiting a high-altitude (500,000 km) Earth flyby which would have enabled a flyby of the binary asteroid 2000 DP 107. A number of contingencies during the first months of the mission were resolved computing alternative thrust profiles, also presented in this paper, until the IES failure of March 10, 2015.

The trajectory optimization tool jTOP was used to compute all the trajectories in high-fidelity model, and is first presented in this paper. Also, a new method to quickly asses attainable sets for low-thrust propulsion trajectories is applied to find the latest time to restart IES operations and reach the asteroid.

7. Acknowledgment

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