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Mission Design of DESTINY$^+$: Toward Active Asteroid (3200) Phaethon

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Abstract

DESTINY$^+$ is an upcoming JAXA Epsilon medium-class mission to be launched in 2024. The spacecraft will demonstrate advanced technologies, including highly efficient solar electric propulsion to enable deep space missions with lower costs and higher frequency. As the nominal science mission, the spacecraft will perform a high-speed flyby observation of (3200) Phaethon. Visits to several other asteroids are part of the extended mission. This paper presents the mission design and flight operation overview of the DESTINY$^+$ mission. Epsilon S launch vehicle has the capability to insert the spacecraft into a near geostationary transfer orbit. The spacecraft will raise its orbit by solar electric propulsion in a spiral-shaped trajectory that will take it to the vicinity of the Moon. A number of lunar gravity assists will allow the spacecraft to fly to an interplanetary orbit that will take it to multiple asteroid flybys. In addition to the mission analysis, this paper includes an operational feasibility study, as it is highly coupled with system constraints.
Keywords: DESTINY$^+$, Phaethon, Asteroid Flyby, Low-Thrust Trajectory, Gravity Assist, JAXA

1. Introduction

Low-cost and high-frequency deep space exploration missions are revolutionizing deep space exploration. To advance the deep space exploration technologies that enable such missions, JAXA is developing the DESTINY$^+$ (Demonstration and Experiment of Space Technology and INterplanetary voYage, Phaethon fLyby and dUSt analysis) mission to be launched by Epsilon S launch vehicle in the mid-2020s. The advanced technologies that DESTINY$^+$ will demonstrate include highly efficient solar electric propulsion employing an upgraded version of the μ10 ion thruster mounted on the Hayabusa2 spacecraft [1] and light-weight solar array panels. For the nominal science mission, the spacecraft will perform a high-speed flyby observation of the active asteroid (3200) Phaethon, the parent object of the Geminids meteor shower. As an extended mission, several other asteroid flybys are currently under consideration.

Epsilon S launch vehicle has the capability to insert the DESTINY$^+$ spacecraft into a near geostationary transfer orbit. The spacecraft will raise its orbit by solar electric propulsion in a spiral-shaped trajectory that will take it to the vicinity of the Moon. A number of lunar flybys will put the spacecraft on interplanetary course to multiple asteroid flybys. DESTINY$^+$'s trajectory design is made possible thanks to the use of advanced orbital control techniques, including low-thrust trajectory control, Moon and Earth gravity assists, and multi-body effects.

DESTINY$^+$ is the world's first mission to escape from Earth orbit into interplanetary space using a low-thrust propulsion system. The mission design of DESTINY$^+$ includes a number of challenges. For the spiral orbit raising operation around the Earth, we need to solve a multi-revolution low-thrust trajectory optimization problem with hard operational and efficiency constraints [2]. In this phase, we also need to consider the robustness against operational uncertainties. Unlike ESA's SMART-1 mission [3], which also relied on spiral orbit raising to conduct an exploration of the Moon, DESTINY$^+$ will perform the lunar flyby at the right time to achieve desired escape conditions. To do this efficiently, we are planning to perform multiple lunar flybys exploiting multi-body gravitational effects [4]. During interplanetary cruising, we adopt Earth gravity assists to fly by multiple asteroids with small ΔV [5, 6]. The asteroid flyby will be performed at a relative velocity of 36 km/s and a distance of 500 km from the surface. The spacecraft is equipped with a single-axis rotatable telescope that will track the asteroids during the high speed flybys.

This paper presents the preliminary mission design of the DESTINY$^+$ mission. We tackle the trajectory design by dividing the whole mission into three phases. In the first phase, the spiral orbit-raising phase, we adopt a multi-objective evolutionary algorithm that minimizes flight time and fuel consumption. We also consider system and operation constraints in this analysis. In the second phase, the moon flyby phase, we generate a high-fidelity moon flyby database by backward propagation from the escape condition. In the third phase, the interplanetary phase, we employ a free-return trajectory design method and Lambert's problem solutions to generate the initial guess trajectories and we perform low-thrust optimization to translate them to full ephemeris. This paper also shows the strategy to handle operational flight uncertainties, particularly in the spiral orbit-raising phase.

Our paper is structured as follows: In Section 2, we show an overview of the mission and the spacecraft, along with requirements and specifications on the operations and spacecraft systems. In Section 3, we describe the results of the design of the current baseline mission. In Section 4, we present our trajectory design approach. Finally, in Section 5 we discuss the detailed flight operation plan and provide a summary of the practical issues involved.

2. DESTINY$^+$

2.1 Mission Objectives

The primary science objective of DESTINY$^+$ mission is to fly by the asteroid (3200) Phaethon (formerly 1983 TB), shown in Fig.1, and at least one of its child bodies (e.g., 2005 UD or 1999 YC) as the extra mission. Phaethon is an active asteroid observed ejecting dust near its perihelion and is believed to be the origin of the Geminid meteor shower and the parent body of the Phaethon–Geminid complex [7]. Two onboard cameras, a Telescopic Camera for Phaethon (TCAP) and a Multi-band Camera for Phaethon (MCAP) [8], will perform optical observations during flybys at 500 km closest approach distance. The former uses a motor to drive the telescope mirror to follow the target, whereas the latter has no moving parts and has a wide field of view. At least two weeks before the asteroid flyby, the TCAP will be used during the optical navigation part of the mission. The spacecraft will observe the asteroid's dust ejection processes [9] and interplanetary dusts throughout its journey in space. The DESTINY$^+$ Dust Analyzer, developed by the University of Stuttgart, will count the dust collected along with its impact state [10].

Engineering objectives of DESTINY$^+$ mission includes, development of space navigation technology by ion engine propulsion and expand the range of its utilization, and expanding opportunities for small celestial body exploration by acquiring advanced flyby exploration technology.

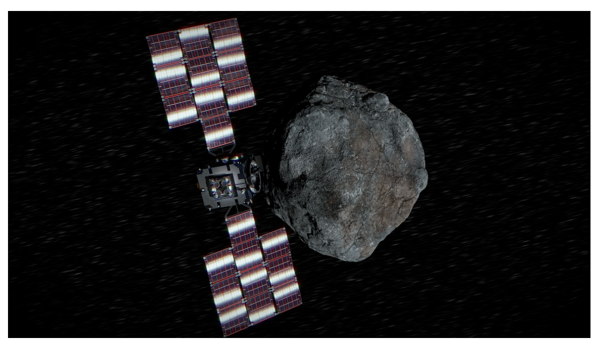

Fig. 1: DESTINY$^+$spacecraft overview.

2.2 Spacecraft System Overview

DESTINY$^+$ is a 480 kg spacecraft that can be launched by Epsilon S launch vehicle to a near geostationary transfer orbit. The spacecraft has a capability of 4 km/s ΔV for free space navigation, including escape/entry from gravitational objects. This capability can be achieved a newly developed solar electric propulsion system that includes the upgraded version of μ10 ion engines, installed in Hayabusa and Hayabusa2 [1], and light-weight solar array panels. The spacecraft can achieve 40 mN thrust magnitude by operating four μ10 ion engines simultaneously. Unlike conventional solar array panels, DESTINY$^+$ employs a thin-film lightweight solar array panel technology. By attaching a thin and flexible solar cell to a sheet of carbon fiber reinforced plastic (CFRP), and supporting it with a lightweight frame structure, the output density (W/kg) is more than double that of the conventional solar arrays. The overall specifications of the spacecraft's systems are shown in Table 1.

Table 1: DESTINY$^+$ specifications

Spacecraft	
Initial mass (wet)	480 kg
Power generated	2.6 kW @ EOL
	thin-film lightweight SAP
	single-axis gimbal
Attitude control	3-axis stabilization
Electric Propulsion	
Thrust	40 mN (4 units in operation)
	36 mN (3 units in operation)
Specific impulse I_{sp}	3,000 s
Propellant mass	approx. 60 kg
Scientific Instruments	
TCAP	1-axis rotatable telescope
Bandwidth	$\lambda = 400$ to 800 nm
FOV	0.80 deg$\times$0.80 deg
Image sensor pixel	2048$\times$2028
MCAP	Multiband camera
Bandwidth	$\lambda = 425/550/700/850$ nm
FOV	6.5 deg$\times$6.5 deg
Image sensor pixel	2048$\times$2028
DDA	Dust analyzer
Measurement range	10^{-16} to 10^{-6} g
Launch Conditions	
Launcher	Epsilon + 4-stage kick stage
Launch date	2024

3. Baseline Mission Design

3.1 Mission Phase

To tackle the complex trajectory design, we divided the whole mission into three phases:

1. Spiral orbit-raising phase
2. Moon flyby phase
3. Interplanetary transfer phase

The first phase starts from a near geostationary transfer orbit into which the launch vehicle inserts the spacecraft, and continues until the spacecraft performs the first flyby of the Moon. In the first phase, we solve multi-revolution low-thrust trajectory optimization problems by applying a newly developed multi-objective evolutionary algorithm that minimizes flight time and fuel consumption and explores affordable launch windows. The second phase involves multiple Moon flybys that raise the spacecraft's departure V_∞ with respect to the Earth. In the second phase, we search multiple lunar flyby trajectories under a high-fidelity dynamical system. Lunar flybys, assisted by solar perturbation, increase the Earth escape V_∞ up to 1.5 km/s. In the third phase, we solve low-thrust trajectory optimization problems so that the spacecraft performs flybys of Phaethon and other asteroids through Earth gravity assists. Figure 2 summarizes the mission scenario for DESTINY$^+$.

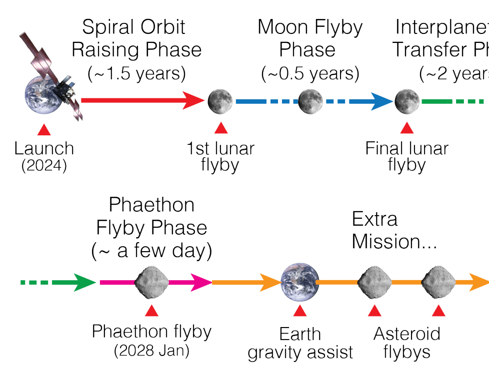

Fig. 2: Mission scenario of DESTINY$^+$.

(3200) Phaethon has a highly inclined elliptical orbit with an inclination of 22.26 deg, a perihelion distance of 0.14 au, and an aphelion distance of 2.4 au. Therefore, it is more efficient to fly by the asteroid at either the descending or the ascending node of its orbit. The ascending node is inside Mercury's orbit and is difficult to access with the spacecraft's capabilities. Hence, we perform the Phaethon flyby near the descending node. The flyby epoch can be calculated as follows

$$t_{CA} = \text{06-January-2028} + m \times 523.5 \text{ day} \quad (1)$$

where m is an arbitrary integer. Because of the communication requirements, the spacecraft can fly by Phaethon in January 2028 or November 2030 in the coming ten years. The geometry of the Sun, Earth, Phaethon, and DESTINY$^+$ is illustrated in Fig. 3. Figure 4 depicts the mission scenario tree for possible launch windows [6].

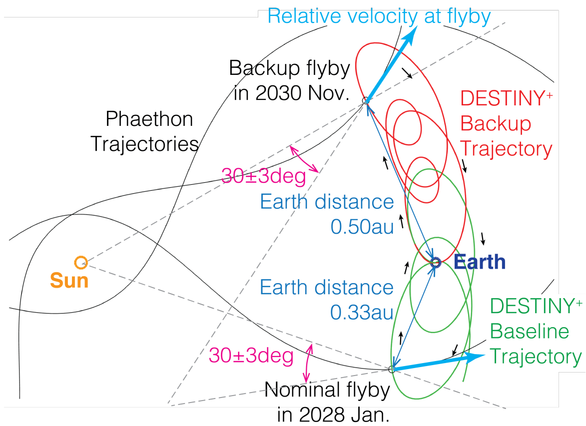

Fig. 3: Geometry of Sun, Earth, Phaethon, and DESTINY$^+$ (Sun-Earth line fixed rotational frame).

3.2 Baseline Trajectory

Figures 5 and 6 illustrate the baseline trajectory of DESTINY$^+$, and Table 2 describes the sequence of events along this baseline trajectory. The spacecraft consumes 80% of the propellant in the spiral orbit-raising phase.

4. Trajectory Design Approach

We initially set the interface condition between phases as summarized in Table 3. We first create initial guess trajectory under this condition and optimize the patched low-thrust trajectory under high-fidelity dynamical systems.

4.1 Spiral Orbit-raising Phase

In the spiral orbit-raising phase, we need to consider systematic constraints such as radiation environment and Earth/Moon eclipses [11]. To do so, we adopt multi-objective trajectory optimization via genetic algorithm [2].

We divide the spiral orbit-raising phase into three sub-phases. The first sub-phase is for the initial checkout operation of DESTINY$^+$and is expected to be 30 days. In the second sub-phase, we continuously operate the ion engine so that DESTINY$^+$can escape from the radiation belt as quickly as possible. In the third sub-phase, we optimize multi-revolution low-thrust trajectory optimization via multi-objective optimization using genetic algorithms. We split the trajectory into ten segments and apply the control policy defined by the design parameters shown in Fig. 7 for each segment. Table 4 summarizes the objective function, design parameters, terminal boundary condition, and constraints of multi-objective optimization. We use the averaging method [12] to propagate the low-thrust multi-revolution trajectory. Figure 8 shows one example trajectory where the time of flight is 528.2 days and fuel consumption is 46.17 kg.

To improve the robustness against uncertainties, we solve trajectory optimization problems with various thrust magnitude 30∼40mN and keep enough timing margin until the first lunar flyby.

4.2 Moon Flyby Phase

At the end of the spiral phase, DESTINY$^+$ will rely on a number of lunar flybys to escape from the gravitational influence of the Earth and proceed to the interplanetary phase. The maximum time allocated for this phase is 6 months.

The design of this phase is performed backwards in time. The interface with the interplanetary phase consists of the state vector and epoch at the outward crossing of the Earth's sphere of influence. We analytically computed the set of hyperbolic escape trajectories from different Moon positions that patch with the state vector at the SOI at the right epoch; these steps are explained in detail in Appendix 6. The computed trajectories provide the velocity vector right after leaving the Moon's sphere of influence as well as the perilune distance. There are two groups of trajectories: those that reach the escape state directly (shown in Figure 9) and those that reach the escape state after a final Earth flyby (shown in Figure 10); these two scenarios are called short and long arc transfer, respectively. Since the required initial velocity is too high to connect the states at the outward crossing of the Moon's sphere of influence with the final state of the spiral phase, we designed a Moon-to-Moon sequence to bridge the gap. The multi-lunar-flyby approach has been successfully implemented in past missions [3, 4], and has been shown to provide the necessary energy boost to patch the spiral and interplanetary phases [13–15]. In the present work, we designed the Moon-to-Moon sequence through a grid search under the high-fidelity dynamical system: for each state at the final lunar flyby, we grid the direction of $\mathbf{v}_\infty^{\mathbf{in}}$ and we propagate each case backward in time until they cross the Moon's sphere of influence again. The final states of this propagation become the set of states that may be patched with the spiral phase. That is, the spiral phase is followed by a number of lunar flybys which then lead to a escape from the Earth directly or through a final Earth flyby.

The backward propagation is performed using an n-body integrator. Figure 12 illustrates a number of successful Moon-to-Moon transfers for up to 8 months of duration. Figure 11 analyses the range of short arc solutions obtained via this method. There exist multiple instances of v_∞ lower than 0.5 km/s for different times of flight, with a number of instances reaching as low as 0.3 km/s. This is the speed that the spacecraft must achieve at the end of the spiral phase.

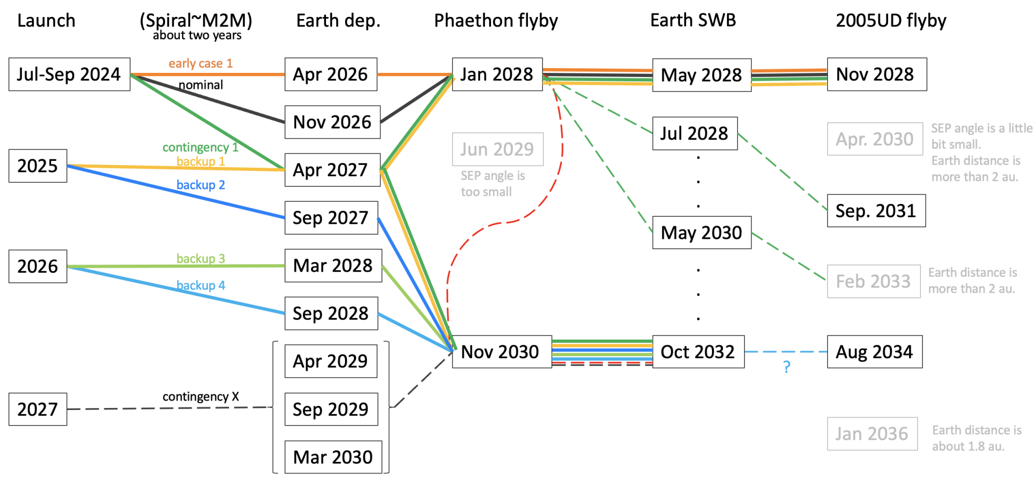

Fig. 4: Mission scenario tree of DESTINY$^+$.

Table 2: Sequence of events in baseline trajectory

Date time, UTC	Event	Spacecraft mass m, kg	V_∞ (or V_{rel}), km/s
2024 NOV 29 01:58:52	Launch	480.0	-
2026 JUN 18 20:30:24	Moon flyby #1	430.0	0.6890
2026 JUL 03 08:33:34	Moon flyby #2	430.0	0.6507
2026 NOV 24 18:36:51	Moon flyby #3 (Earth escape)	430.0	2.0850
2028 JAN 05 01:54:30	Phaethon flyby	426.1	33.056
2028 MAY 06 12:39:37	Earth flyby	426.1	3.1912
2028 OCT 17 01:09:32	2005 UD flyby	426.1	35.00

Table 3: Mission phase interface condition

Launch to Spiral orbit-raising	
Perigee altitude	230 km
Apogee altitude	37,000 km
Inclination	31 deg
Initial mass	480 kg
Spiral orbit-raising to Moon flyby	
Moon flyby epoch	Arbitrary
Initial Moon flyby V_∞ w.r.t. Moon	$\sim$1 km/s
Moon flyby to Interplanetary transfer	
Earth departure V_∞ w.r.t. Earth	$\sim$1.5 km/s
Spacecraft mass	$\sim$450 kg

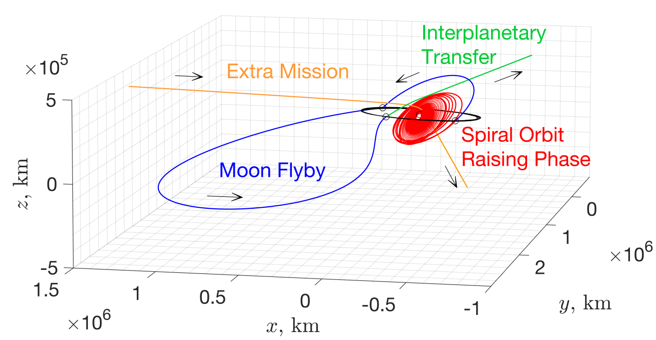

Fig. 5: Baseline near Earth trajectory of DESTINY$^+$ in the Earth-centered ECLIPJ2000 inertial frame.

Among the feasible solutions, lower v_∞ at the first lunar swingby and shorter times of flight are preferred.

4.3 Interplanetary Transfer Phase

In the baseline solution, we assume that the initial target asteroid Phaethon flyby occurs on January 2028. With

4.3 Interplanetary Transfer Phase

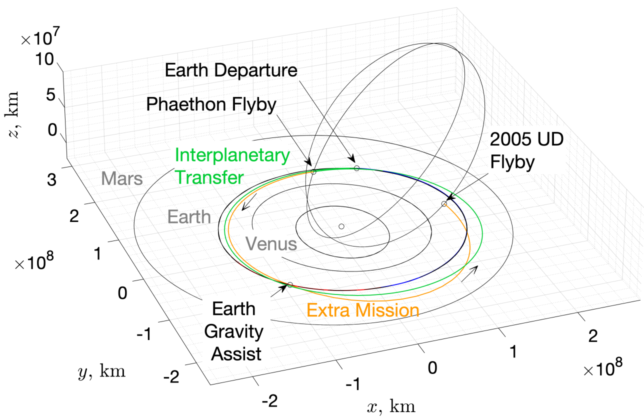

Fig. 6: Baseline interplanetary trajectory of DESTINY$^+$ in the Sun-centered ECLIPJ2000 inertial frame.

Table 4: Multi objective optimization settings.

Objective function
1. Minimize the time of flight
2. Minimize the fuel consumption
3. Minimize the maximum solar eclipse duration
Design parameters
1. Perigee thrust arc ΔL_p
2. Apogee thrust arc ΔL_a
3. Asymmetric angle η
Terminal boundary condition
The ascending or descending node radius w.r.t. Moon orbital plane is more than 385,000km altitude.
Constraint
1. Thrust direction is along velocity direction
2. Ion engine is suspended during eclipse

a V_∞ of 1.5 m/s and 450 kg of remaining mass, the spacecraft from the Moon flyby phase will enter the interplanetary transfer phase. Initial analysis of the launch window using Lambert's solution suggests that candidate Earth departure dates of April 2026, November 2026, and April 2027 exist for a January 2028 flyby of Phaethon [6]. Using the initial guess trajectory, we solve the low-thrust trajectory optimization problem via direct multiple shooting methods [16]. To improve the robustness against missed-thrust, we set 80 % duty cycle throughout the interplanetary trajectory optimization.

As shown in Figure 13, this present work aims at the nominal departure date of November 2026. After the Phaethon flyby, DESTINY$^+$ targets the asteroid 2005 UD.

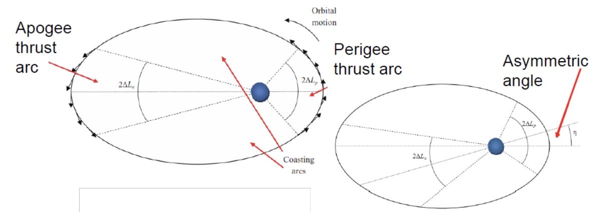

Fig. 7: Design parameters of spiral trajectory.

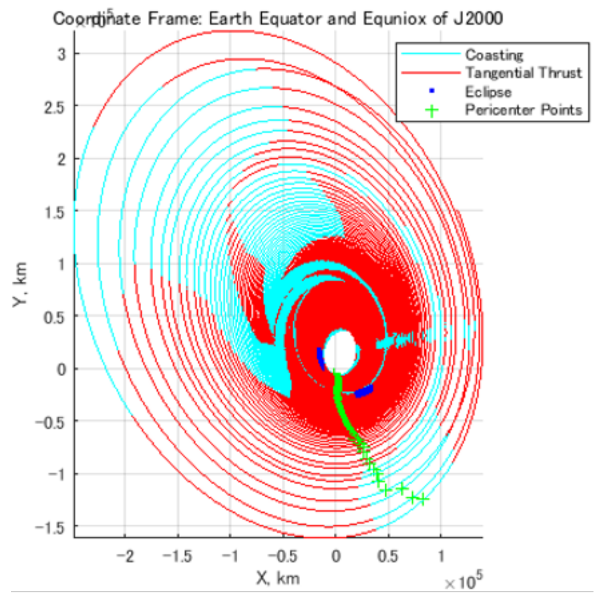

Fig. 8: Example of spiral trajectory.

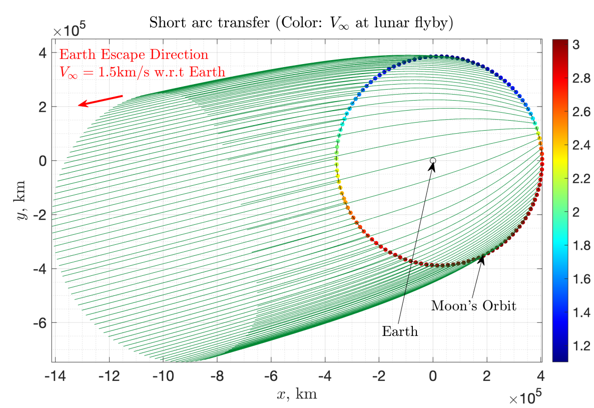

Fig. 9: Earth escape trajectory with lunar flyby (Short arc, Earth-centered, ECLIPJ2000).

The transfer from Phaethon to 2005 UD is enabled via the Earth gravity assist maneuver. Several Earth-Phaethon-Earth-2005-UD mission sequences with low Earth escape

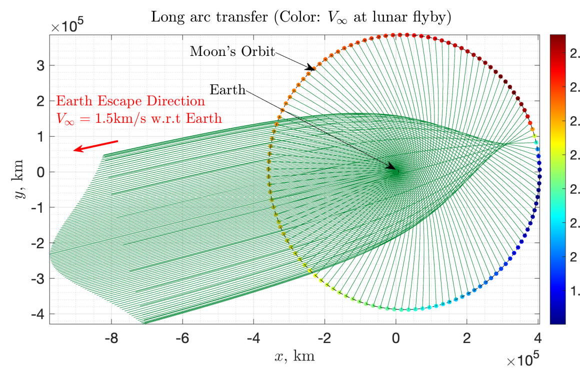

Fig. 10: Earth escape trajectory with lunar flyby (Long arc, Earth-centered, ECLIPJ2000).

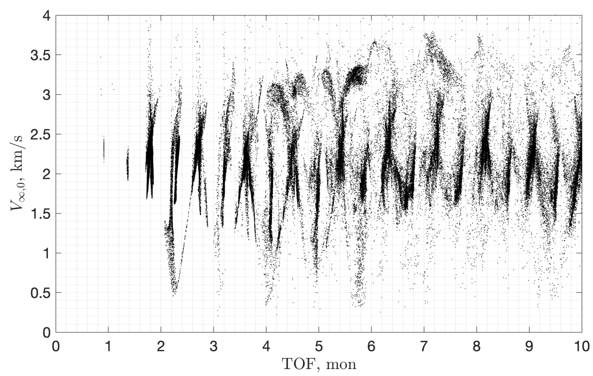

Fig. 11: Initial $V_{\infty,0}$ required for lunar flyby trajectories.

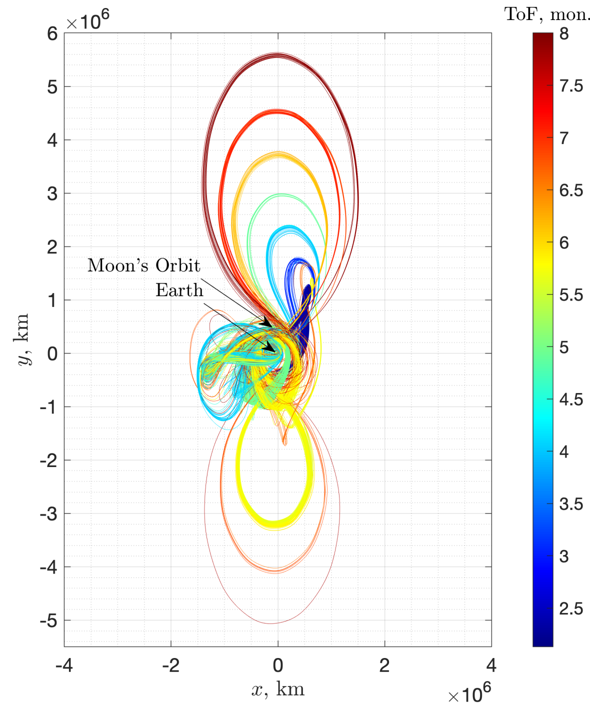

Fig. 12: Lunar flyby trajectories for $V_{\infty,0} < 1$ km/s (Earth-centered, Sun-Earth line fixed rotational frame)

energy were observed between the end of 2025 and the middle of 2027, with possible 2005 UD flybys in 2028, 2031, and 2034. We analyzed mass-optimal transfer trajectories and found that they are feasible in terms of final mass and spacecraft thermal and power requirements. Utilizing the Earth gravity assists multiple times, we can also design some trajectories that allow for visiting multiple targets with a relatively small amount of ΔV.

5. Flight Operation Plan

This section describes the flight operation plan in two critical operations including the spiral orbit-raising phase and Phaethon flyby phase.

5.1 Spiral Orbit-raising Operation

The spiral orbit-raising phase requires ion engine operation for about 1.5 years, and the spacecraft consume 80% of the onboard fuel in this operation phase. DESTINY$^+$ can control its orbit in two different ion engine operation modes: onboard automatic orbit control mode and manual orbit control mode. In the onboard automatic orbit control mode, the spacecraft can accelerate in the tangential direction of the orbit. This mode is mainly used in the first half of the spiral orbit-raising phase. Especially in the first half of the spiral orbit-raising phase, the spacecraft shall escape from the radiation belt as soon as possible, and we found that the continuous tangential acceleration is optimal.

On the other hand, in the latter half of the spiral orbit-raising phase, we specify the time series of thrust directions using the manual orbit control mode because more efficient orbit control and phase adjustment for the lunar flyby is required. Regardless of the ion engine operation mode, the spacecraft can accelerate in any direction, and maximum power generation can always be obtained by rotating the single-axis gimbal of solar array panels. By determining thrust direction and sun direction, we can uniquely define the attitude of the spacecraft. We assume a maximum of 90 minutes of Earth and Moon eclipses and plan to suspend the ion engine acceleration during the eclipse period.

We need to consider the counterplan against uncertainties such as navigation errors and contingency operations in the spiral orbit-raising operation. In particular, we plan a contingency operation so that the ground station antenna can acquire the spacecraft again even if the ion engine unexpectedly stops during no communication. These contin-

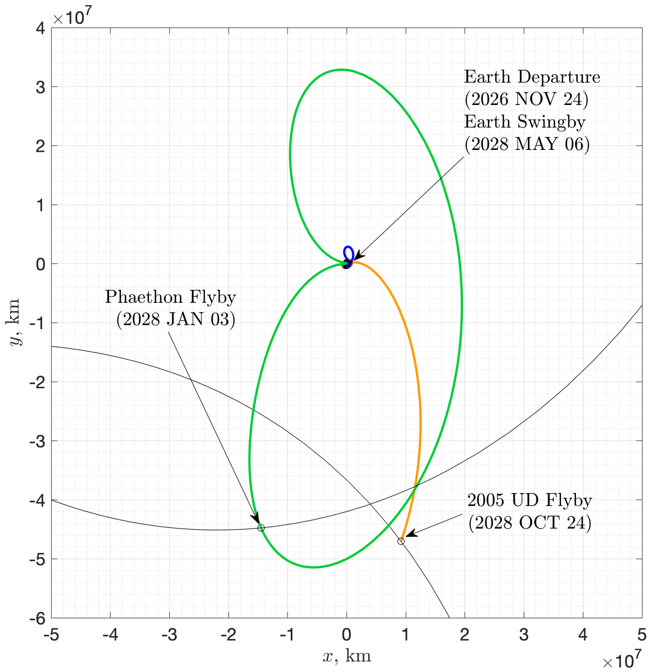

Fig. 13: Interplanetary trajectory (Earth-centered, Sun-Earth line fixed rotational frame)

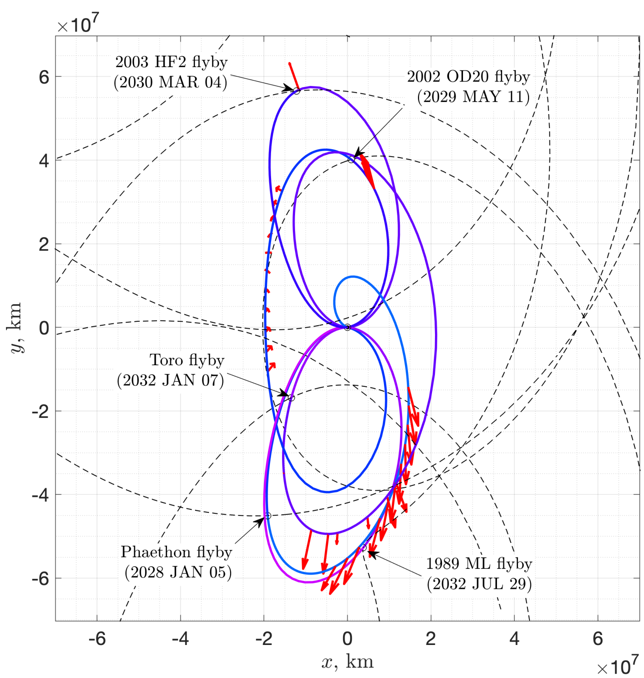

Fig. 14: Example of multiple asteroid flyby trajectory (Earth-centered, Sun-Earth line fixed rotational frame)

gency operations will lead to the delay of the first lunar flyby. Therefore, we plan to keep enough timing margin, about several orbital periods of the moon, until the first lunar flyby. Because the spiral orbit is inclined to the lunar orbital plane, we must wait for one lunar orbital period if we miss the lunar flyby at the nominal epoch. Therefore, we plan to design a robust trajectory connected to the interplanetary trajectory even if we fail the nominal first lunar flyby.

5.2 Phaethon Flyby Operation

We divide the Phaethon flyby phase into three types of operations: Phaethon detection and identification operations, relative orbit control operations, and Phaethon tracking observation operations. In the Phaethon detection and identification operation, TCAP detects and identifies the Phaethon in the background star. After the Phaethon identification is completed, we perform optical navigation and trajectory correction maneuvers (TCMs). As a result of TCMs, we achieve 50 km (3σ) closest approach position accuracy on the B-plane. In the Phaethon tracking observation operations, DESTINY controls the single-axis telescope and its attitude using autonomous onboard optical navigation so that TCAP can track Phaethon with a pointing accuracy of 1.2e-3 deg/0.3 ms (3σ) and pointing stability of 0.15-0.2 deg (3σ) at the closest approach. Table 5 summarizes the sequence of events in the Phaethon flyby operation.

6. Conclusions

DESTINY$^+$ is an upcoming medium-class mission by JAXA to be launched in 2024 using Epsilon S launch vehicle. Its main scientific goal is to perform a flyby of (3200) Phaethon. DESTINY$^+$ will demonstrate advanced technologies that include efficient solar electric propulsion and low-energy astrodynamics; these technologies play an important role in enabling small-scale spacecraft to carry out deep space exploration. This paper presented an overview of the mission profile, the spacecraft systems, the trajectory design approach for each phase of the mission, and the flight operation plan for the relevant phases.

Different methods of trajectory design are used for different parts of the mission. In the first of its three phases, the spacecraft will depart from a near-GTO and gradually raise its apogee in a spiral trajectory. The spacecraft will be propelled by four ion engines, and will rely on novel, thin solar array panels for the required power. The spiral trajectory is optimized by means of a genetic algorithm. In the second phase, the final conditions from the spiral phase and the initial conditions of the interplanetary phase are bridged through several lunar flybys that provides the required energy boost and address phasing problems. The

Table 5: Sequence of events in Phaethon flyby operation

Time	Operation	Events
T-30d to T-5d	Phaethon detection and identification	Precise orbit determination by radio navigation Misalignment estimation between TCAP and star tracker Phaethon detection completed (T-10d at the latest) Phaethon identification completed (T-5d at the latest)
T-5d to T-2.5d	Relative orbit control	Downlink Phaethon images for optical navigation
T-2.5d to T-2d		Relative orbit determination using optical images TCM1 planning and execution
T-2d to T-1d		Dust trail observation by DDA started Downlink Phaethon images for optical navigation
T-1d to T-7.5h		Relative orbit determination using optical images TCM2 planning and execution if needed
T-7.5h to T-5m	Phaethon tracking observation	Maneuver to closest approach attitude Tracking mirror control started Science observation by TCAP started
T-5m to T+15m		3D attitude fixed
T+15m to T+1d		Attitude maneuver for high speed communication Phaethon flyby operation completed

initial guess for between subsequent lunar encounters is designed directly in real ephemeris through a grid search. The interplanetary portion of the mission is designed using two-body dynamics initially and optimized through a high-fidelity multiple shooting method.

In the nominal scenario, DESTINY$^+$ will perform a flyby of Phaethon in January 2028. The instrument suite for the scientific exploration of Phaethon and subsequent asteroids consists of a telescope, a multi-band camera, and a dust analyzer. Operational considerations for the critical parts of the mission profile are discussed. The flight operation plan for the spiral phase accounts for propulsion incidents, space environment effects, eclipses, communication windows, and navigation errors. A timeline of planned events for the Phaethon flyby sequence is provided; it groups the operations into asteroid detection, relative orbit control, and asteroid tracking.

Acknowledgment

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Appendix

A. Final Lunar Flyby Condition

Given the departure v-infinity with respect to the Earth $\boldsymbol{v}_{\infty\oplus}^{\text{out}}$ in the Moon reference frame and the final lunar flyby position $\boldsymbol{r}_M$, let us calculate the spacecraft velocity at $\boldsymbol{r}_M$ after the final lunar flyby.

The velocity magnitude of the spacecraft at $\boldsymbol{r}_M$ after final lunar flyby is

$$v_M = \sqrt{v_{\infty\oplus}^{\text{out}2} + \frac{2\text{GM}_\oplus}{r_M}}, \tag{A.1}$$

and the semi-major axis is

$$a = -\frac{\text{GM}_\oplus}{v_{\infty\oplus}^{\text{out}2}}. \tag{A.2}$$

The velocity direction can be calculated by the following procedure.

The inclination of the hyperbolic orbit is given by applying the spherical trigonometry to $\triangle ABC$ as shown in Fig. 15.

$$i = \sin^{-1}\left(\frac{\sin\delta_\infty}{\sin\theta}\right) \tag{A.3}$$

where δ_∞ is the longitude of $\boldsymbol{v}_{\infty\oplus}^{\text{out}}$ in the moon reference plane, and θ is defined by

$$\theta = \begin{cases} \cos^{-1}\left(\frac{\boldsymbol{r}_M \cdot \boldsymbol{v}_{\infty\oplus}^{\text{out}}}{\|\boldsymbol{r}_M\|\|\boldsymbol{v}_{\infty\oplus}^{\text{out}}\|}\right) & \text{if short arc transfer} \\ 2\pi - \cos^{-1}\left(\frac{\boldsymbol{r}_M \cdot \boldsymbol{v}_{\infty\oplus}^{\text{out}}}{\|\boldsymbol{r}_M\|\|\boldsymbol{v}_{\infty\oplus}^{\text{out}}\|}\right) & \text{if long arc transfer} \end{cases} \tag{A.4}$$

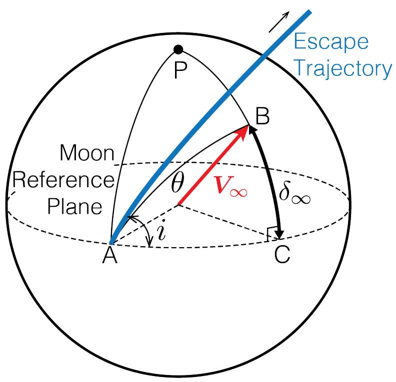

Fig. 15: Final lunar flyby geometry (out-of-plane)

The eccentricity of the hyperbolic orbit is calculated by the following equations:

$$e = \sqrt{\chi^2 + 1} \tag{A.5}$$

where $\chi (\geq 0)$ is given by solving the following quadratic equation

$$a\chi^2 + r_M \sin\theta\chi + (1 - \cos\theta) r_M = 0 \tag{A.6}$$

This quadratic equation is obtained from

$$\begin{cases} 1 + e\cos\nu_\infty & = 0 \\ 1 + e\cos(\nu_\infty - \theta) & = \frac{a(1-e^2)}{r_M} \end{cases} \tag{A.7}$$

where $\theta = \nu_\infty - \nu_M$ as shown in Fig. 16.

Finally, we can calculate the radial and tangential components of the velocity.

$$v_r = \sqrt{\frac{\text{GM}_\oplus}{a(1-e^2)}} e\sin(\nu_\infty - \theta) \tag{A.8}$$

$$v_\theta = \sqrt{\frac{\text{GM}_\oplus}{a(1-e^2)}} \{1 + e\cos(\nu_\infty - \theta)\} \tag{A.9}$$

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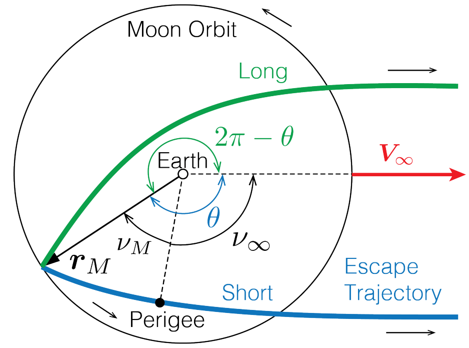

Fig. 16: Final lunar flyby geometry (in-plane)

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