HIGH-SPEED FLYBY OBSERVATION OF SMALL ASTEROID BY DESTINY+

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DESTINY+ flies by asteroid named Phaethon at a speed of 33 km/s. At flyby phase, it is planned to image Phaethon by 2 kinds of camera. To take good quality images in terms of science, it is necessary that the view of cameras continue to catch Phaethon. In this paper, to achieve this mission, how to track Phaethon and how to control the view of camera during flyby are showed. And it is indicated by numerical analysis that DESTINY+ can take the image which is satisfied scientific request.

DESTINY+による小惑星高速フライバイ観測

DESTINY+は相対速度 33km/s という速さで小惑星 Phaethon にフライバイするが，その時望遠モノクロカメラ（TCAP）とマルチバンドカメラ（MCAP）の 2 種類のカメラを用いて光学観測することを計画している．この際，理学的に有意な画像を撮像するためにはカメラを小惑星方向に安定して指向させる事が要求される．本論文では，DESTINY+が Phaethon フライバイにおいて科学観測を行う際に，ミッション要求を満たす方法として一軸駆動望遠鏡を用いた 2 種類の追尾方法についてその検討状況をまとめる．

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INTRODUCTION

DESTINY$^+$ (Demonstration and Experiment of Space Technology for INterplanetary voYage, Phaethon fLyby and dUst Science) The mission of DESTINY$^+$ is to validate key technologies for our future deep space exploration.[1, 2] DESTINY$^+$ will demonstrate the high performance electric propelled vehicle technology and execute the flyby exploration of asteroid 3200 Phaethon. DESTINY$^+$ starts its voyage from a low elliptic orbit, spirals up the orbits, fly-by the Moon, escapes from the Earth, and depart for the asteroid 3200 Phaethon. It will detect and analyze interplanetary and interstellar dust particles during deep space cruise.

At the time of flyby, optical observation of Phaethon using 2 kinds of camera. One of them is a telephoto monochrome camera(TCAP), and the other is a multiband camera(MCAP). In order to acquire a physically high-quality image for science, it is required to steadily point the camera towards the asteroid. In this paper, two types of tracking methods to satisfy mission requirements by using a uniaxial tracking mirror during flyby are shown.

REQUIREMENTS FOR OBSERVATION

Requirements for observation is summarized in this chapter. There are 3 phases during flyby for TCAP in terms of spatial resolution and the requirements for each phase are organized as follows.

1. Observation of Phaethon light curve

After Phaethon can be spatially decomposed (≧5km/pixel）, images are taken at S/N≧10 and at the rate of 1frame/10min in the range that can be regarded as the same solar phase angle(the range where the angle formed by the line connecting the DESTINY$^+$ and Phaethon and the velocity vector of the DESTINY$^+$ is less than 0.5 °).

2. Observation of Phaethon outline

After Phaethon can be spatially resolved to more than 5 pixels (≧1km/pixel）, images are taken more than once at S/N≧10 in the range that can be regarded as the same solar phase angle.

3. Observation of Phaethon 3D shape

After Phaethon can be spatially resolved to more than 10 pixels (≧100m/pixel）, images are taken at S/N≧10 at each 5degrees of solar phase angle.(called requirement 1)

4. Observation of Phaethon surface geography

Surface of Phaethon are taken at S/N≧20 after Phaethon can be spatially resolved to more than 5m/pixel and at the rate of over 1Hz. (called requirement 2)

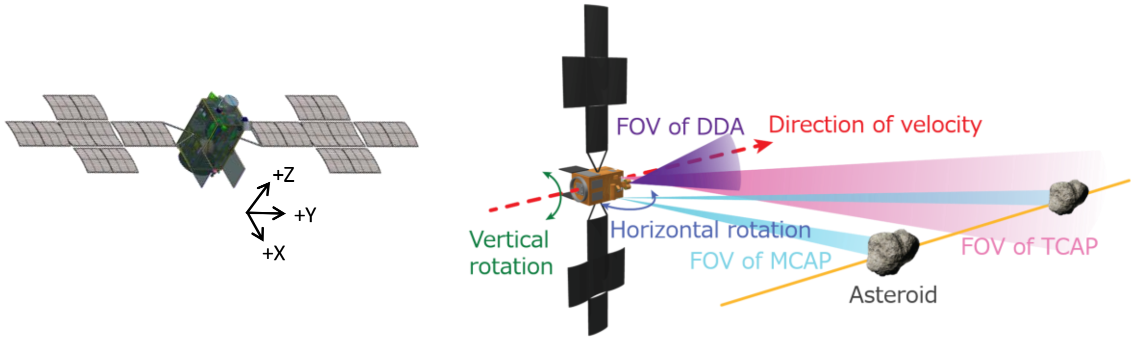
Requirements for MCAP is listed as follows

After Phaethon can be spatially resolved to more than 10 pixels (≧100m/pixel）, images are taken at S/N≧30 at the wavelength of 390, 480, 700, 860 nm, at S/N≧50 at the wavelength of 550, and at S/N ≧20 at the wavelength of 950 with a wavelength width of 50 nm. (called requirement 3)

HOW TO TRACK ASTEROID DURING FLYBY

In order to find optimal attitude and how tracking during flyby, 2-staged trade-off is performed. The closest approach distance between asteroid and spacecraft is assumed 500 km and the distance to image is assumed 1000 km or less. The field of view(FOV) of the telephoto monochrome camera is 0.94 × 0.71 deg., that is, FOV is 16 × 12 km at the distance of 1000 km. On the other hand, since the orbit determination error of asteroid is about 100 km and that error of the spacecraft by the radio navigation is about 300 km, a biaxial tracking mechanism is required to keep asteroid within the FOV and take multiple images.

First trade-off is performed in terms of what to use for tracking, and the second is performed in terms of the basic attitude of spacecraft during flyby. Furthermore, some assumptions are set to avoid increasing the number of trade-off case. First, tracking mirror is mounted only on TCAP and MCAP is fixed to the spacecraft body. Second, the rotation of tracking mirror doesn't stop during exposure. The last, the candidates of first trade-off are how to rotate in a horizontal direction and vertical direction. Evaluation points of the



(a) Definition of spacecraft body coordinate axes

(b) Definition of rotation axes

Figure 1. Definition of axes

trade-off are the quality of image and the feasibility of operation. The definition of the rotation axes is indicated in Fig. 1

From the results of two trade-offs, the baseline of how to flyby is as follows.

- The horizontal rotation is realized by the tracking mirror and the vertical rotation by the attitude control of the spacecraft
- The basic attitude of the spacecraft is that +Z plane is directed to the velocity direction, and the + X or -X plane is directed to the direction of the target at the closest approach

The plan is based on the baseline.

THE SEQUENCE OF ASTEROID TRACKING OBSERVATION

In nominal plan, DESTINY$^+$ performs a flyby observation with a closest approach distance of 500 [km] and a relative velocity of 33 [km/s]. In this study, it is assumed that the asteroid's gravity is very small and the spacecraft performs a uniform linear motion with respect to the asteroid. In this case, the angular velocity rises up to about 3.7 deg/s when approaching the asteroid.

In order to track the asteroid and achieve observation under the flyby condition as described above, imaging by TCAP starts before asteroid can be identified in the images and tracks asteroid by using image information. Two kinds of methods are studied according to the method of using image information. The one is the simple PD feedback control that makes tracking commands from the deviation between the center of FOV and Phaethon position in the image. The other is the method which estimates relative trajectory from image information.[3] This method can realize more accurate tracking by giving commands predicting the movement of the asteroid even at the time of closest approach when fast relative angular velocity is necessary.

- Tracking by using PD control

This method calculates the angular difference between the camera orientation direction and the Phaethon direction from the Phaethon image obtained from TCAP and tracks and observes the asteroid by driving the driving mirror by PD control in order to fill up the angle difference. This method consists of some phases as follows.

0. Radio navigation + Phaethon detection

First of all, according to the result of orbit determination by radio navigation, the attitude of the spacecraft is changed to put the asteroid in the FOV of TCAP. The asteroid is detected when the number of occupied pixel becomes sufficiently larger than other stars. Furthermore, the asteroid is moved to the center of the FOV by attitude control of the spacecraft so as not to lose the asteroid from the FOV.

1. Attitude correction amount calculation

Next, the attitude of the spacecraft is controlled to be fixed in the inertial space, and the inclination of the horizontal axis and the movement direction is calculated from the movement of the asteroid in the image. At this time the asteroid moves about 100 pixels in 10 minutes.

2. Attitude correction

By rotating the attitude of the spacecraft in the direction of the Roll axis by the calculated angle, the attitude is corrected so that the asteroid moves horizontally in the FOV at the time of flyby.

3. Tracking asteroid by the tracking mirror

As a result, tracking during flyby is possible with only uniaxial rotation of the tracking mirror, so the tracking mirror tracks the asteroid by PD control using image information.

- Tracking by using trajectory estimation

This method estimates the relative trajectories between the spacecraft and the asteroid from image information by TCAP and tracks asteroids and observes the asteroid using the tracking mirror based on the estimation result.

0. Radio navigation + Phaethon detection
1. Attitude correction amount calculation
2. Relative trajectory estimation

After attitude maneuver, the relative trajectory of the spacecraft and the asteroid is estimated. The closer to the asteroid, the more accurate information can be obtained, so the relative trajectory can be estimated with high accuracy.

3. Tracking asteroid by the tracking mirror

When approaching the asteroid, it becomes difficult to accurately detect the direction of the center of gravity of the asteroid due to phases or patterns of the asteroid. For this reason, feedforward control is adopted to direct TCAP to the predicted direction of the asteroid from the estimated relative trajectory information. When the tracking mirror drives by feed-forward control, it isn't necessary to estimate the position of the asteroid from the image.

FEASIBILITY STUDY OF TRACKING ASTEROID

Numerical simulation is conducted to confirm feasibility of tracking method above. In this study, PD control method is adopted to confirm basic feasibility. First, feasibility at nominal condition is analyzed. Inertial coordinate system in this study is shown in Fig. 2. The center of this coordinate is the asteroid, and X-axis is relative velocity direction. Nominal condition is shown in Table 2. Next, sensitivity analysis, that is, what extent the change of each initial condition affects the feasibility is investigated. In this study, three parameters change independently, relative velocity, attitude, and imaging time interval.

- Nominal case analysis

Time histories of each parameters are shown in Fig.3~Fig.8. Fig. 3 shows that the spacecraft and asteroid are closest at about 3650 [s]. At that time, Fig.4 shows that the angle of tracking mirror is following the angle of asteroid. Fig.5 and Fig.6 shows whether the images acquired by TCAP or MCAP are satisfied with mission requirement in terms of blurring and spatial resolution. The dashed line indicates the required value, and if the value is smaller than this, the requirement is satisfied. According to these figures, at nominal condition, TCAP is capable of imaging that meets the requirements for about 40 seconds. And MCAP is also capable of imaging that meets the requirements for about 35 seconds. Fig.7 shows that TCAP can keep capturing asteroid within the FOV. And Fig.8 is extended figure of Fig.7. It is indicated that overshoot is occurring after the tracking mirror follows the delay with the influence of PD control at the time of closest approach.

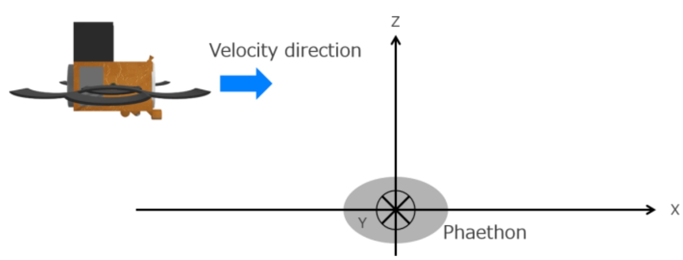


Figure 2. Definition of inertial coordinate system

Table 1. Analysis condition

	Item	Unit	Value
calculation	time step	ms	10
	end time	s	6000
spacecraft	mass	kg	450
	inertia moment[I_{xx},I_{yy},I_{zz}]	kgm^2	[450, 127, 387]
	max output torque	Nm	0.12
camera	FOV(TCAP)[horizontal, vertical]	deg	[1.1,0.82]
	FOV(MCAP)[horizontal, vertical]	deg	[18.9,14.2]
	exposure time(TCAP)	ms	0.3
	exposure time(MCAP)	ms	2
	angular resolution capability(TCAP)	deg/pix	3.3×10^{-4}
	angular resolution capability(MCAP)	deg/pix	5.7×10^{-3}
tracking mirror	inertia moment	kgm^2	0.1
	max output torque	Nm	0.18
asteroid	diameter	km	5.1
control	time interval	s	0.5
	proportional gain(spacecraft)	–	3
	differential gain(spacecraft)	–	60
	proportional gain (tracking mirror)	–	0.27
	differential gain (tracking mirror)	–	0.27
initial condition	position[X,Y,Z]	km	[−120000,0,500]
	velocity[X,Y,Z]	km/s	[33,0,0]
	acceleration[X,Y,Z]	km/s^2	[0,0,0]
	attitude[Roll,Pitch,Yaw]	deg	[0,0,0]
	angular verocity[Roll,Pitch,Yaw]	deg/s	[0,0,0]
	angular acceleration[Roll,Pitch,Yaw]	deg/s^2	[0,0,0]

- Sensitivity analysis

Sensitivity analysis about velocity, attitude, imaging time interval was conducted. The effect of adding each error to nominal condition independently was confirmed.

1. Relative velocity

The results of sensitivity analysis about velocity is shown in Fig. 9. As the relative velocity becomes faster, MCAP fixed to the spacecraft body can't satisfy the requirement because the moving distance during the exposure time increases. Although the result that tracking mirror can track the asteroid at the present condition has been obtained, there are restrictions on angular velocity due to hardware limitations.

2. Initial attitude

Relationship between pitch angle error and time to satisfy requirement is shown in Fig.10.In this figure, when the pitch angle is inclined by half of the FOV, the observation is not established, and if it is less than half of the FOV, the observation is established. It is indicated that it is necessary to control the attitude with accuracy of less than half of FOV. On the other hand, the figure about yaw angle is shown in Fig.11. In this figure, observation has been established even if the attitude is inclined by large angle. This is because when the attitude is inclined toward +yaw direction, the asteroid will across the FOV at some point in time. So, tracking command of the mirror can be calculated by PD control.

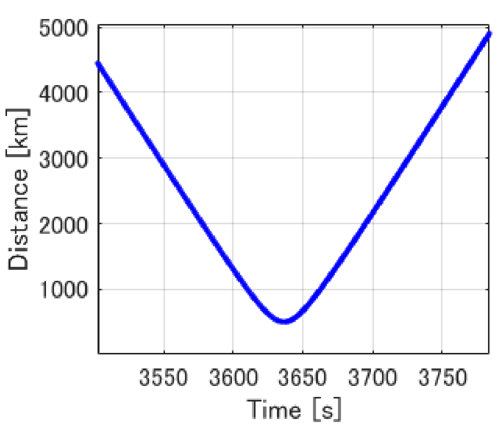


Figure 3. Time history of distance between spacecraft and asteroid

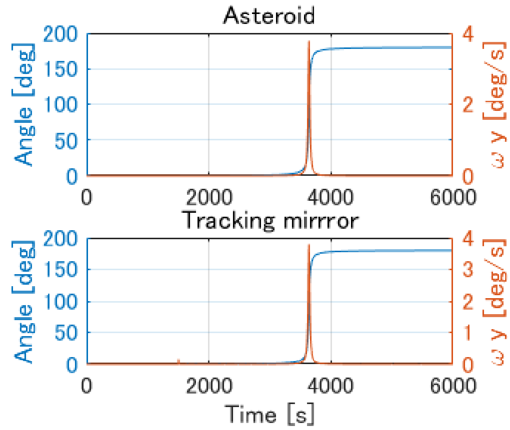


Figure 4. Time history of angle and angular velocity

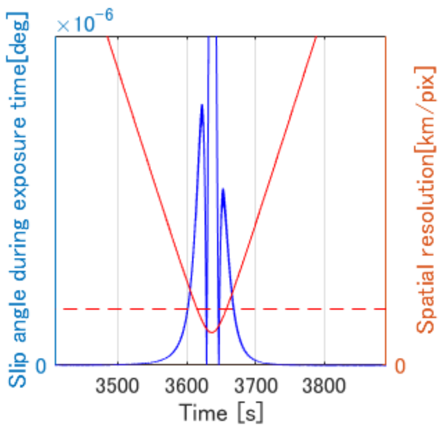


Figure 5. Time history of image blurring and spatial resolution (TCAP)

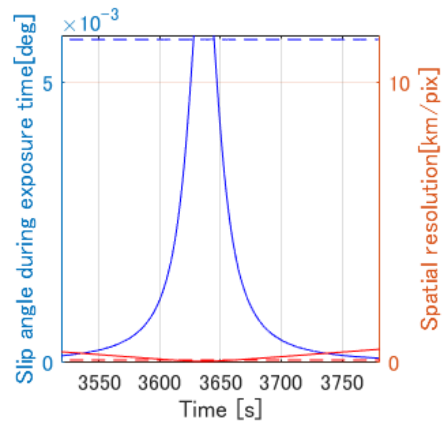


Figure 6. Time history of image blurring and spatial resolution(MCAP)

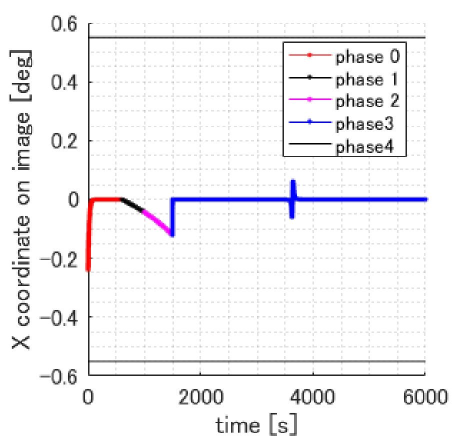


Figure 7. Time history of asteroid position in image (TCAP)

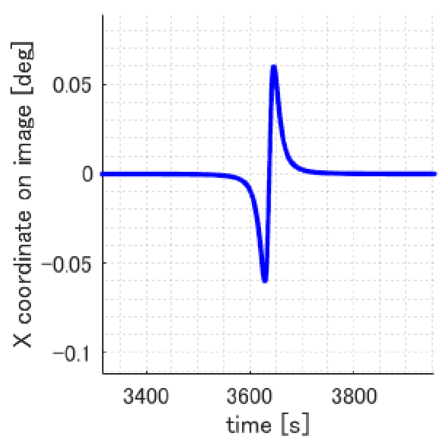


Figure 8. Extended figure of Fig.7

3. Imaging time interval

Relationship between imaging time interval error and time to satisfy requirement is shown in Fig. 12. When the imaging time interval becomes long, the time interval of control command also become long. Therefore, it is considered that tracking performance gradually deteriorates. Fig.12 shows max feasible time interval is 0.78 s. Time history of angle and angular velocity when the time interval is 0.8 s is shown in Fig.13. As the interval increases, the deviation at the time of calculation becomes large, so the torque command increases and the movement of tracking mirror diverges. It is necessary to optimize the gain setting at each time interval.

Table 2. Results of sensitivity analysis

	Relative Velocity [km/s]	Initial attitude (Pitch) [deg]	Initial attitude (Yaw) [deg]	Imaging time interval[s]
Nominal	33	0	0	0.5
Limit value	100	0.4	40	0.78

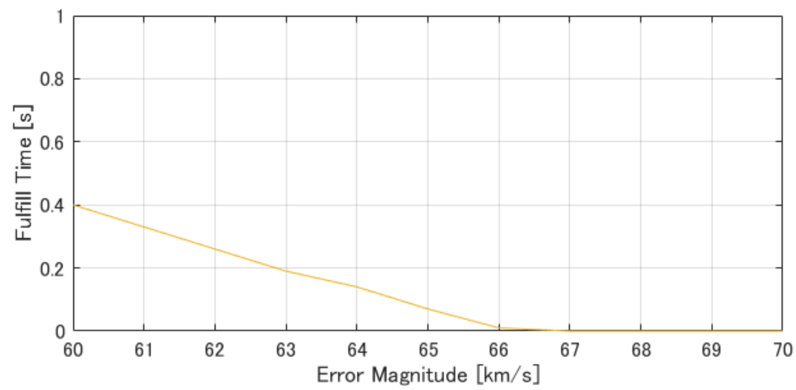


Figure 9. Relationship between velocity error and time to satisfy requirement 3.

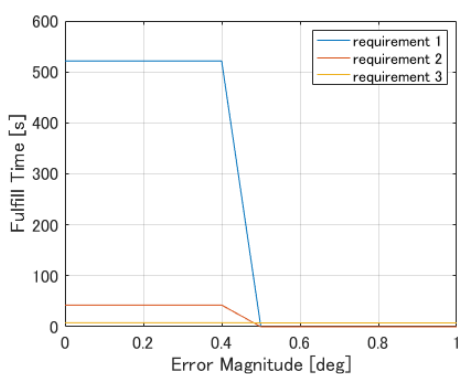


Figure 10. Relationship between pitch angle error and time to satisfy requirement

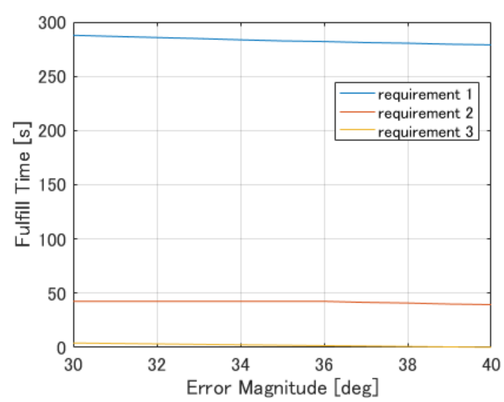


Figure 11. Relationship between yaw angle error and time to satisfy requirement

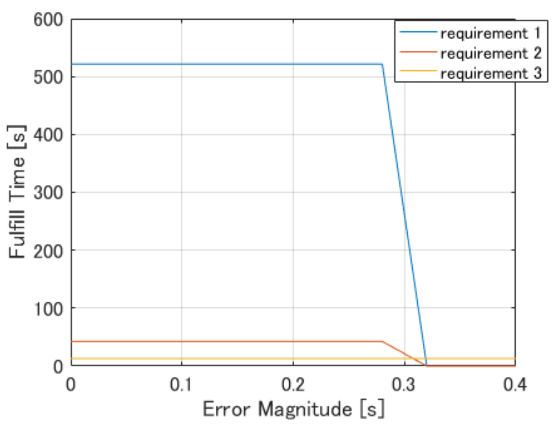


Figure 12. Relationship between imaging time interval error and time to satisfy requirement

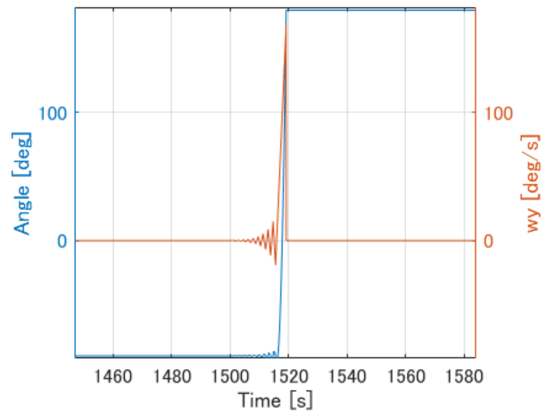


Figure 13. Time history of angle and angular velocity

CONCLUSION

How to track and image Phaethon when DESTINY$^+$ conducts high-speed flyby was studied. Two steps trade-off found out optimal method to change the line of sight of camera and attitude of spacecraft to track asteroid. Two kinds of flyby sequence were introduced. One was the way using PD control and the other was the way using trajectory estimation. In addition, the feasibility of the way using PD control was analyzed by numerical simulation. In nominal case, it was shown that the observation satisfying the scientific requirements was established for about 35 seconds. And the sensitivities for the feasibility of some parameters were investigated.

For the future, the feasibility of the way using trajectory estimation should be analyzed. And It is necessary to perform feasibility analysis considering various constraints and errors.

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