Initial development of asteroid tracking mirror for telescopic camera onboard DESTINY+ spacecraft

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Abstract: Demonstration and Experiment of Space Technology for Interplanetary voYage with Phaethon fLyby and dUst Science (DESTINY+) mission will conduct a flyby-observation at asteroid Phaethon. This observation requires a tracking mirror for the camera because its higher relative angular velocity than previous small body flyby missions provides difficulty to track the target only by spacecraft's attitude control. The tracking mirror should keep Phaethon's sunlit area in the field of view during the closest approach to the asteroid and obtain images without motion-blur during the exposure. We determined the pointing accuracy and pointing stability requirements for the tracking mirror based on the error distribution with the spacecraft system and camera optics. As a result of the conceptual study of the tracking mirror, we obtained the specification of the actuator composed of a step motor with a microstepping driver, a reducer (harmonic drive), and a parabolic mirror. We manufactured a prototype of the actuator and evaluated its rotational performances to establish an environment and method for correctly evaluating the tracking mirror and also to measure the pointing accuracy and stability on the actual device. Although we found that the pointing accuracy, stability, and angular reproducibility of the actuator prototype meet the required specifications, we plan to improve the prototype using the mechanics and mechanical parts more similar to those used in the flight model to solve the identified problems.

DESTINY+搭載小惑星追尾望遠カメラの駆動鏡検討

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摘要：深宇宙探査技術実証機 DESTINY+（Demonstration and Experiment of Space Technology for INterplanetary voYage with Phaethon fLyby and dUst Science）はふたご座流星群の母天体と考えられている小惑星（3200）フェートンを近接フライバイし、地表面の高解像度撮像を行う予定である。高解像度地形撮像を行う望遠カメラ TCAP（Telescopic Camera for Phaethon）にはフライバイ中に自律的に小惑星を視野内に収め続け、かつぶれのない高解像度画像を取得するような小惑星追尾機構（駆動鏡）が要求される。私たちは理学要求に基づいて、探査機の姿勢制御や追尾アルゴリズムおよび光学系の擾乱を考慮して、駆動鏡の指向精度・指向安定度の要求仕様を決定した。要求仕様を満たすアクチュエータの概念検討を行い、測定環境・解析手法の確立および実機の回転性能評価のため、駆動鏡アクチュエータの試作機を製作した。試作機の性能評価によって追尾の成立性の目途がついたが、課題も抽出されたため、エンジニアリングモデル・フライトモデル開発の前に、再度試作を行い、課題解決を図る予定である。

1. Introduction

DESTINY+ mission plans to conduct a close flyby of asteroid (3200) Phaethon [1], which is considered as a parent body of Geminid meteor shower [2]. The science instruments onboard DESTINY+ are Telescopic CAmera for Phaethon (TCAP), Multiband CAmera for Phaethon (MCAP) [3] and DESTINY+ Dust Analyzer (DDA) [4]. During the closest approach, TCAP is planned to perform high-resolution imaging of the surface of Phaethon with an imaging rate of more than one frame per second and with a spatial resolution up to 3.5 m/px at closest approach (CA) [3]. Since the relative flyby speed and closest distance to Phaethon are ~36 km/s and 500±50 km, which results in a maximum angular velocity of 4.6 deg/s, it is difficult to track the asteroid only by the rotation of the spacecraft itself. Therefore, an asteroid tracking system is required for TCAP to obtain unblurred high-resolution images, which would enhance the scientific achievements. The tracking system is also required to obtain images at a wide range of

Table 1. Flyby parameters of previous small-body missions using cameras with tracking system. Figures in parentheses are planned values.

Mission / Camera [ref.]	Closest distance to object (km)	Relative velocity to object (km/s)	Achieved Max angular velocity (deg/s)	Achieved Max spatial resolution (m/px)	Status
Giotto / HMC [5, 6, 7]	605	68.4	0.8	39	Successful flyby of 1P/Halley
Stardust-NExT / NavCam [8, 9]	178	10.9	3.5	11	Successful flyby of 9P/Tempel
CONTOUR / CRISP [10, 11, 12]	NA (130)	NA (28.3)	NA (12.4)	NA (< 10)	Lost contact before flyby of 2P/Encke
PROCYON / asteroid observation camera [13]	NA (<30)	NA (~10)	NA (19)	NA (< 10)	Lost contact before flyby of 2000 DP107
DESTINY$^+$ / TCAP [1, 3]	500±50	36	4.6	3.5	Planned flyby of 3200 Phaethon

solar phase angles during the high-speed flyby.

Table 1 summarizes previous flyby missions to small bodies using cameras equipped with tracking system. There are only two small-body missions, Giotto and Stardust, successfully performing flyby observations with tracking system. Both CONTOUR and PROCYON would have performed flyby observations at angular velocities larger than 10 deg/s and at spatial resolutions smaller than 10m. However, they have lost contact before the flyby observations. If successful, TCAP would observe the surface of Phaethon at higher angular velocities and spatial resolutions compared to previous flyby missions. Demonstration of such tracking system for a high-speed flyby mission would result in more frequent and low-cost deep-space explorations.

2. Concept study of TCAP tracking mirror

TCAP will be equipped with a one-axis tracking system consisting of a motor, reducer, and a parabolic mirror, which will be called "tracking mirror" hereafter. Observations of Phaethon by DESTINY$^+$ mission is divided into three phases: Phaethon identification phase (30 to 5 days before CA), relative orbital maneuver phase (5 to 2.5 days before CA), and Phaethon tracking observation phase (from 7.5 hours before CA). During the first two phases TCAP tracking mirror is fixed relative to the spacecraft body. During the last phase, tracking mirror is rotated to keep Phaethon within the TCAP field of view (FOV) and the spacecraft attitude will be controlled by automatic optical navigation using TCAP images. Scientific observations by TCAP are conducted during Phaethon tracking observation phase with an imaging interval of 1 frame per second and a nominal exposure time of 0.3 ms.

There are two main requirements for TCAP tracking mirror: pointing accuracy and pointing stability. Pointing accuracy is the error between the command angle and the angle after rotation, while pointing stability is the motion-blur caused by the movement of boresight with the rotation of the tracking mirror during the exposure. The total error

Table 2. Major required performances for TCAP tracking mirror

Motor	2-phase stepping motor step angle: 1.8°
Driving System	64 microstepping drive
Reducer	Harmonic Drive® reduction ratio 100
Maximum torque	0.18 Nm
Minimum angular resolution	1.025"
Maximum angular velocity	27.05°/s
Mass	4.5 kg
Zero-point detection (ZPD)	LED, photosensor, shielding plate, slit
Onboard Angle detection	ZPD + number of motor steps, resolver (optional)
Stopper	mechanical stopper

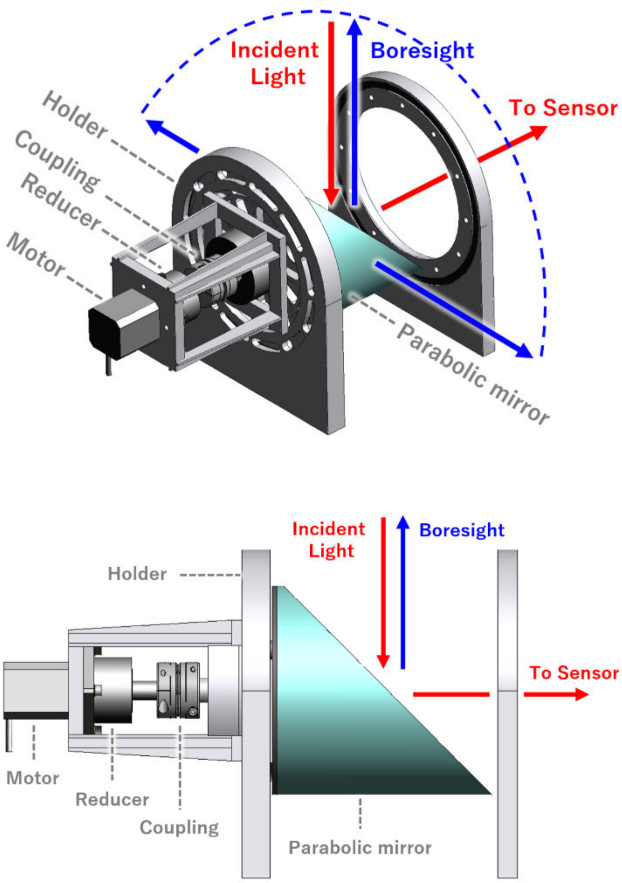

Figure 1. 3D CAD images of TCAP tracking mirror without covers

budget was determined based on the scientific observation requirements, and those errors were distributed among TCAP and the spacecraft system through an error allocation study. In addition, the errors are divided into the error caused by the tracking mirror actuator and those by the internal alignment within TCAP optics. The pointing accuracy and pointing stability requirements are divided into horizontal direction (rotating direction of tracking mirror) and vertical direction (parallel to the rotating axis of tracking mirror), and the pointing accuracy requirement is further divided into bias and random components. Since the major vibration components of step motors are caused by horizontal torque ripple, we assumed that the tracking mirror actuator has only horizontal components and its vertical components are negligible. This assumption is partially verified through tests of tracking mirror actuator prototype described later.

Table 2 summarizes major required performances for TCAP tracking mirror. Pointing accuracy requirement is calculated based on that Phaethon's sunlit area must be always kept within the FOV of TCAP during the flyby. Bias component of the pointing accuracy is defined as the bias errors which cannot be corrected by onboard calibration. The pointing accuracy requirement shown in Table 1 includes zero-point position error and its angular repeatability. Reproducible angular errors can be corrected by onboard calibration. On the other hand, random components having short time scales cannot be corrected, thus they must be considered in the error budget. The pointing stability requirement for tracking mirror is calculated based on that the boresight of TCAP does not blur by more than 2.5 pixels (0.6 pixels as a target value) on the image sensor during one exposure.

Figure 1 show 3D CAD images of TCAP tracking mirror. The tracking mirror is fixed to the spacecraft housing and can change its line of sight 180 degrees using a parabolic mirror tilted at 45 degrees to the boresight of telescope. The direction perpendicular to the mirror rotation is controlled by the spacecraft's attitude based on the result from the onboard optical navigation [14].

Table 3 shows the specifications of actuator obtained by our conceptual study. A stepping motor with micro-step driver is adopted because of its rich experience in space, easy control, and the smooth rotation. For reducer, a hormonic drive is adopted because of its non-backlash characteristics as well as rich space-experience. In orbit, current angle of the mirror is estimated by the number of motor steps from the zero-point determined by zero-point detection (ZPD) mechanism using a LED, photosensor, shielding plate and slit. Since this method cannot detect actual angle, in order to further improve the feasibility of asteroid tracking, we are considering a resolver for optional instrument to detect angle in orbit. A mechanical stopper is planned to be attached to prevent incorrect movement of tracking mirror.

Table 3. Actuator of TCAP tracking mirror

Tracking Range*	0° - 180° * (rotation range: -120° - +180°)
Maximum Angular Velocity	4.6°/s
Pointing Accuracy (horizontal)	Bias ≤ 0.04° (Target ≤ 0.01°) Random ≤ 0.01°
Pointing Stability (horizontal)	≤ 1.0×10^{-3} °/0.3 msec (Target ≤ 4.0×10^{-4} °/0.3 msec)

The pointing stability for the tracking mirror is defined as the motion blur within the exposure time of TCAP (0.3 ms for nominal). Since stabilities of motors and reducers are generally defined by fluctuations of angular velocities during more than one rotation, there are few stability data for such a very short time scale. In addition, pointing accuracy of the actuator is difficult to evaluate based only on theoretical models. For these reasons we built and evaluated a prototype of actuator of TCAP tracking mirror.

3. Breadboard model of tracking mirror actuator

Figure 2 shows the breadboard model (BBM) of actuator which consists of a motor, reducer, encoder, FPGA board, mass dummy. Due to lead time and cost, we utilized non-space grade components for all mechanical parts. A PC sends control commands to the motor and four kinds of operation modes are performed through the microstep driver implemented in the FPGA board: velocity mode for constant rotation at a specified angular velocity, position mode for rotation to specified angle, flyby model simulating angular profile based on feedforward control during Phaethon flyby, and zero-point search mode. Optical limit switches for preventing incorrect rotation are installed at angles of 0° and 300° to automatically stop the rotation. An absolute rotary encoder with a sampling rate up to 20 kHz detects the current angle of actuator with an angle resolution of 23 bits per revolution (0.15").

Due to the eccentric error between encoder and actuator's rotor shaft, a system-derived bias error was observed, thus data analysis was limited to a short angle range (<10°). To reduce the effect of encoder's bias error, the first data of observed angle and command angle were regarded as offset error, and they were subtracted from each subsequent dataset. Although this method corresponds to the evaluation of pointing accuracy for a very localized range of angles, it can confirm that the magnitude of pointing error does not clearly deviate from the requirement. We plan to evaluate tracking mirror's

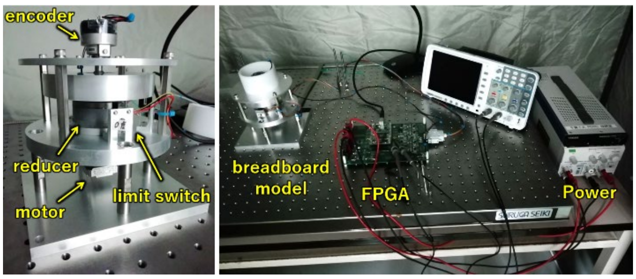

Figure 2. Breadboard model (BBM) of TCAP actuator (left) and configuration for evaluation test (right).

pointing accuracy over a wide range of angles with a calibrated high-precision angle encoder and to check encoder's alignment using a polygon mirror and autocollimator for the next prototype of tracking mirror, the engineering model (EM), and the flight model (FM).

For pointing stability measurement, a laser-doppler velocimeter (LDV), which can detect velocity without contact, is used to independently measure linear velocity of the wall of mass dummy at a sampling rate of 10 kHz. The linear velocities obtained by the LDV were converted to angular velocity and then integrated to angle data to calculate pointing stabilities. During the evaluation, the BBM was placed on an optical bench in a dark room because the encoder and LDV are highly influenced by the environmental noises.

For evaluation of actuator BBM, the pointing accuracy and stability are defined as follows: Let $\theta_{\mathrm{obs},I}$ be the ith angle data measured by the encoder, $\theta_{\mathrm{com},\,I}$ be ith command angle, then pointing accuracy $\Delta\theta_i$ for ith data is calculated as,

$$\Delta\theta_i = \theta_{\mathrm{obs},i} - \theta_{\mathrm{com},i} \quad .$$

Pointing stability γ_i for ith data for a sampling rate of 20 kHz is defined as,

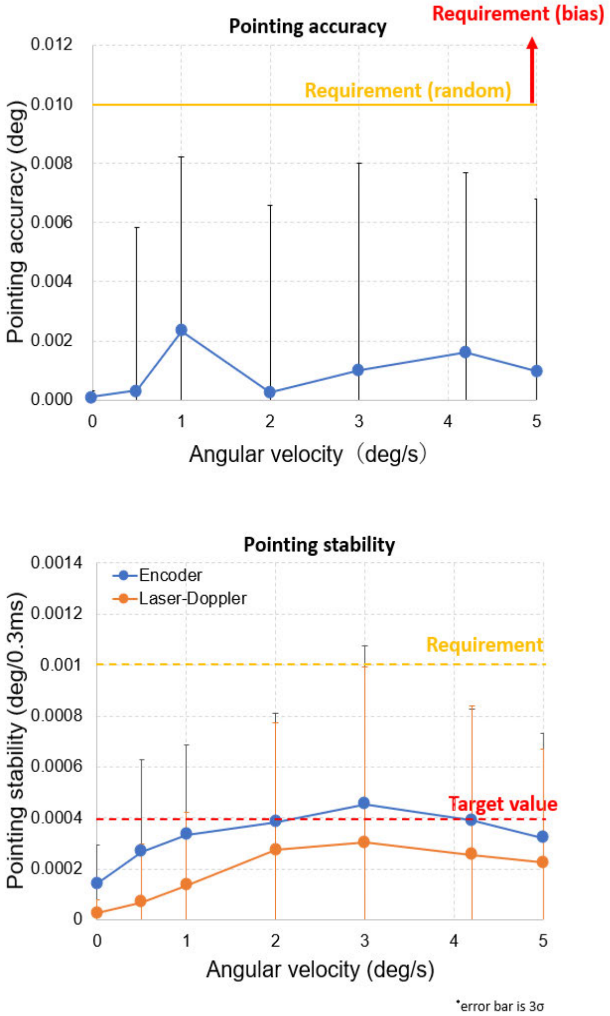

Figure 3. Pointing accuracies and stabilities of TCAP actuator BBM.

$$\gamma_i = \max(\Delta\theta_j) - \min(\Delta\theta_j) \quad (i-2 \le j \le i+3),$$

that means difference between the maximum and minimum values of pointing accuracies is calculated to obtain motion blur within the exposure time. In general, pointing stabilities of ground-based telescopes are evaluated by the root mean square of angular velocity or pointing accuracy within the telescope's exposure time. In our performance tests, however, pointing stability is defined differently because the exposure time of TCAP is much shorter than typical exposure time of a ground-based telescope. If we apply the same method as the ground-based telescope, the number of data points will be limited due to the extremely short exposure time (i.e., six data points for 20 kHz sampling), being difficult to obtain statistically significant results. For evaluation tests, no data smoothing or bandpass filtering was used in order to obtain the worst value.

Figure 3 summarizes typical pointing accuracies and pointing stabilities of actuator BBM at various angular velocities with their mean values and 3σ errors. As mentioned earlier, although bias error of the encoder could be too large for evaluation of pointing accuracy at a wide range of angles, our analyses show that the pointing accuracies for narrow angle ranges are sufficiently small to meet the requirement even considering the random components represented by 3σ errors. Random components are mainly composed of vibrations of motor and other mechanical parts as well as electrical noise from the encoder, thus it is noted that EM/FM actuators, which are composed of different mechanical parts, are not guaranteed to show similar pointing stabilities. It is also noted that this evaluation does not consider the zero-point error, thus evaluations for EM/FM should be performed over a wide range of angles after measuring the zero-point error. Despite these issues, our BBM tests were important for establishing the measurement environment and analysis methods. Vertical components of pointing accuracies are measured with a mirror and an autocollimator and we found that the vertical components are negligible for actuator BBM.

The pointing stabilities measured by the encoder and

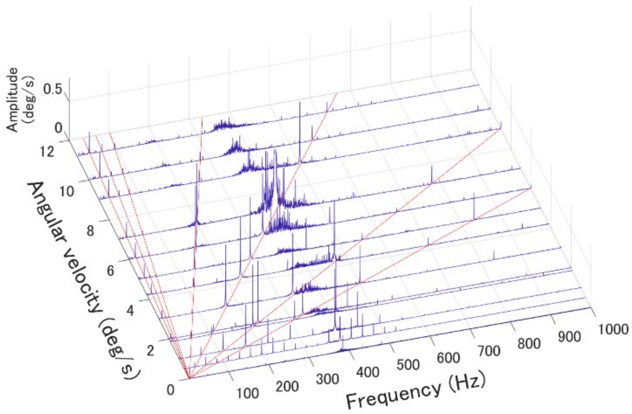

Figure 4. Waterfall plot of frequency analyses of the angular velocities measured by the encoder. Red lines show the frequencies related to motor pulses.

LDV are generally consistent with each other. However, the pointing stabilities measured by the encoder tend to be slightly larger than those measured by LDV (Figure 3). This is because the vibration of actuator highly affects the measurement of encoder. In fact, the pointing stabilities measured by the encoder deteriorate significantly in the range of 5 °/s to 7 °/s caused by the structural resonance suggested by the frequency analyses, while the LDV show less vibration than the encoder. Figure 4 shows the waterfall plot of frequency analyses of the angular velocities measured by the encoder. Large vibrations occur at the same frequencies as the motor pulses. There is a natural vibration of actuator occurring around 350 – 400 Hz. When the frequency of actuator's natural vibration and pulse vibration of the motor coincide, vibration of the actuator is significantly amplified. When 3.0 °/s rotation, the pointing stability converted to motion blur is 2.6 pixels slightly exceeding the requirements (2.5 px), while that measured by the LDV is 2.5 px. When the exposure time is increased, the pointing stability increases linearly up to about 2 ms exposure time. This is because the pulse vibration of motor is the main component to worsen the stability, which is suggested by our frequency analyses. This pulse vibration has a timescale of about 2 ms, thus if the exposure time is shorter than that, the pointing stability deteriorates linearly with the exposure time. In order to achieve motion blur less than 1 pixel, we need further improvement of actuator's stability, especially for the micro-step control of motor. We also compared the pointing stabilities for between 32 and 64 micro-steps and we found that there is no significant difference. This indicates that even if the angular resolution of actuator is decreased, the vibration level caused by the step-motor does not change significantly. Since the estimates of Phaethon's surface albedo have uncertainties, and there is a possibility of extending the exposure time of TCAP from nominal of 0.3 ms to obtain sufficient S/N ratio, improvement of actuator's stability is our future work.

We also test the angular reproducibility of the actuator BBM by rotating the actuator between specific angles more than 50 times and found to be 0.001° - 0.002°, which is much smaller than the requirement for pointing accuracy. Since the measured angular reproducibility is same level to the background noise of the encoder (~0.002°), it can be concluded that the angular reproducibility of actuator BBM sufficiently meet the requirement.

Detailed observation of the behavior of actuator BBM revealed that there is a rapid angle jump by several tens of micro-steps immediately after the start and stop of rotation. This phenomenon was observed regardless of the stopped position or angular velocity, which is a characteristic nature of the step-motor. With micro-step driving, actuator can hold at a halfway position between motor's full step angle, but electromagnetically it is less stable position compared to stop at full step angles. The BBM tests show that it is vital for the successful flyby observation to fully understand the characteristics of the actuator of TCAP tracking mirror.

4. Discussions and future works

Evaluation of BBM of actuator highlights several issues of the development of TCAP tracking mirror.

First, a calibrated encoder should be used for the evaluation of pointing accuracies over a wide range of angles. The encoder used for the BBM tests has a relatively large interpolation error (±40”), which hinders the evaluation of pointing accuracies during rotation. We plan to adopt a calibrated high-precision encoder with ±5” of interpolation error for EM/FM evaluations. In addition to encoder's interpolation error, imperfect alignment between the encoder and motor shaft causes most of the bias error in pointing accuracy. For future evaluations of actuators, we plan to attach a calibrated polygon mirror to check the misalignment with an autocollimator. The polygon mirror can also be used to evaluate pointing accuracies of actuators discretely.

Second, angle measurement methods without using encoder should be employed, because encoder cannot be equipped to the actuator after the attachment of parabolic mirror. We consider four methods to measure actuator's angle without using encoder: (1) using a calibrated polygon mirror with an autocollimator to measure the static pointing accuracies, angular reproducibility, and zero-point accuracy, (2) using an alignment calibration jig for TCAP optics to measure angles discretely, which is composed of multiple collimators, (3) measuring pointing stabilities using a LDV without contact, and (4) using a resolver to detect actuator's angle in orbit. The resolver is considered as an optional instrument in orbit and mainly used for angle measurement in ground tests. The detection accuracy of the resolver greatly depends on the alignment accuracy when the installation, thus we plan to conduct absolute angle calibration of the resolver using the polygon mirror and a calibrated high-precision encoder.

Third, a prototype of the zero-point detection mechanism should be developed and evaluated. If the resolver cannot be used in orbit, current angle of TCAP tracking mirror must be estimated by the number of steps of motor from the zero-point. To detect the zero-point, the change of light intensity of diffracted LED light through the slit is measured by a photosensor. In addition to the zero-point, slits are installed at least every 45° between 0° and 180° so that the reference angles can be detected at each position. This ZPD mechanism is not designed to detect angle in real time, rather it is designed to detect reference angles after the actuator has passed those angles. If TCAP tracking mirror went to off-nominal in orbit, the ZPD mechanism would be useful for investigating the cause by obtaining approximate angle at which the actuator is presumed to have stopped.

To solve these issues, we plan to develop another prototype of TCAP tracking mirror before the development of EM/FM. The BBM reported in this paper uses different reducer and mechanical parts with EM/FM. However, as the design study of EM/FM has progressed, next prototype of the actuator (BBM3) is planned to be developed with mechanical parts closer to EM/FM. A mass dummy equivalent to the mass of parabolic mirror will be installed to BBM3 and vibration tests will be conducted to evaluate the mechanical vibration characteristics. Although we have so far conducted evaluation tests only for the actuator, the feasibility of tracking should be confirmed including TCAP optics and the tracking algorithm. After the performance tests of EM/FM actuator of the tracking mirror, we plan to conduct end-to-end tracking tests including TCAP optics by feeding back the target positions and angular velocities calculated by the captured images. Tracking Phaethon by TCAP tracking mirror is not closed within the TCAP system but is also closely related to the attitude control of the spacecraft. Our preliminary studies suggest that the disturbance of tracking mirror, rather than the stability of spacecraft attitude, is the dominant error component of pointing stability because the timescale of disturbance of spacecraft attitude is much longer than the exposure time of TCAP. On the other hand, disturbance of the accuracy of spacecraft orbit estimation significantly affects the pointing accuracy. Therefore, it is important to perform tracking simulation using a mechanistic model including disturbances of spacecraft orbit estimation, TCAP optics and tracking mirror.

5. Summary

We reported the initial development status of the TCAP tracking mirror onboard the DESTINY$^+$ mission. Requirements for the tracking mirror were obtained based on the science requirements and the error distribution among the spacecraft system, tracking algorithm, and TCAP optics. As a result of the conceptual study of the tracking mirror, we obtained the specification of the actuator composed of a step motor with a microstepping driver, reducer, parabolic mirror, zero-point detection system, and mechanical stopper. We developed a breadboard model of the actuator using non-space grade components to test the basic rotational performances. Results of evaluation tests of the BBM show that the pointing accuracies and pointing stabilities are within the requirements. However, several issues are highlighted. We attempt to resolve those issues through the evaluation test of another breadboard model using similar mechanical parts to EM/FM actuators.

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