はやぶさ２小惑星フライバイ観測のための画像フィードバック姿勢マヌーバ制御系設計

Attitude Maneuver Controller Design for Hayabusa2 Asteroid Flyby Observation

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Background

☐ About Hayabusa2

The asteroid explorer Hayabusa2, developed and operated by JAXA, arrived at the asteroid Ryugu in June 2018 and performed pinpoint touchdown and other proximity operations. After returning to the earth in December 2020 and completing the asteroid sample return, it left the earth's gravity sphere and is now flying toward the next asteroid.

☐ Hayabusa2's extended mission overview

2021/1~2026/7：Long-term Deep Space Cruise
2026/7　：Flyby to 2001 CC21
2027/12：Earth Swing-by
2028/6　：Earth Swing-by
2031/7　：Rendezvous to 1998 KY26

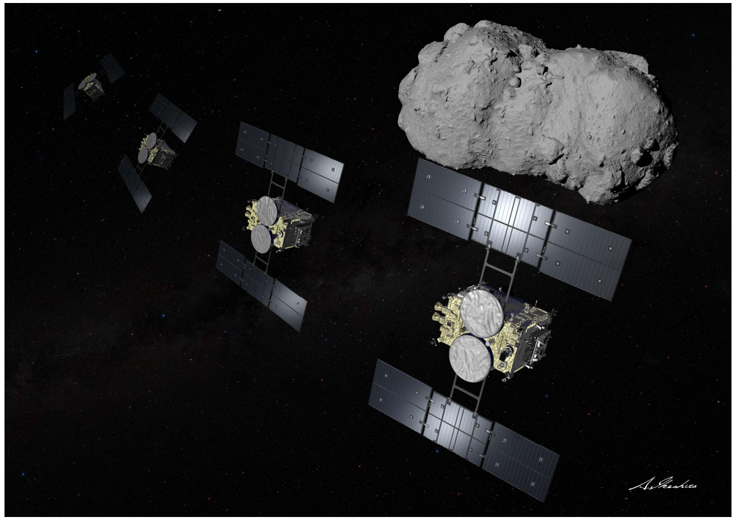


Fig.1 Artist's illustration of 2001 CC21 flyby
(©Akihiro Ikeshita)

Asteroid flyby observation

The Misson

- During an asteroid flyby, ONC-T camera mounted in the direction to $-Z_{sc}$ axis of the spacecraft's fixed coordinate system will try to capture images of the asteroid.

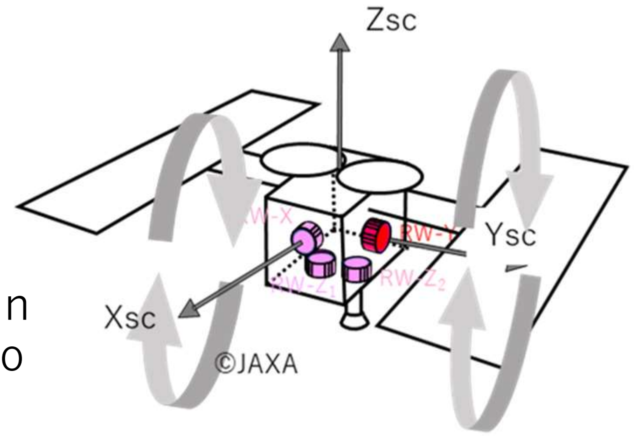


Fig.2 RW placement

Preconditions

- Relative velocity along flyby trajectory: $5\ {}^{km}/_{s}$
- Nominal closest approach distance to the asteroid: $20\ km$
- Speculated diameter of asteroid 2001 CC21: $700\ m$
- Maximum torque for attitude maneuver generated by reaction wheels: $0.045\ Nm$
- Moment of inertia of the spacecraft around $\mathrm{X_{sc}}$ and $\mathrm{Y_{sc}}$ axes: $300\ \mathrm{kgm^2}$

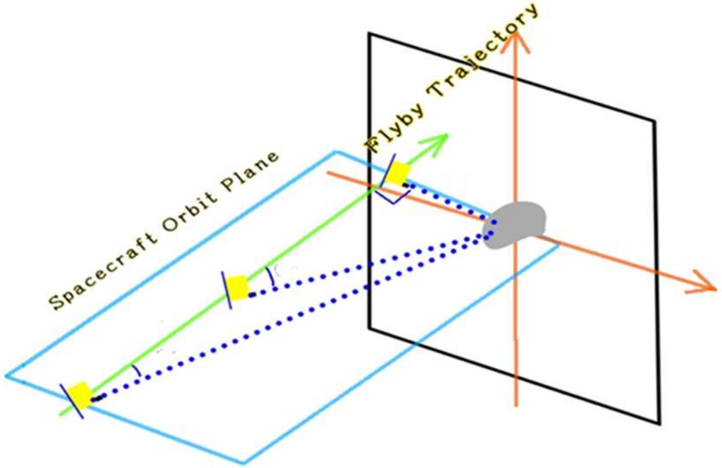
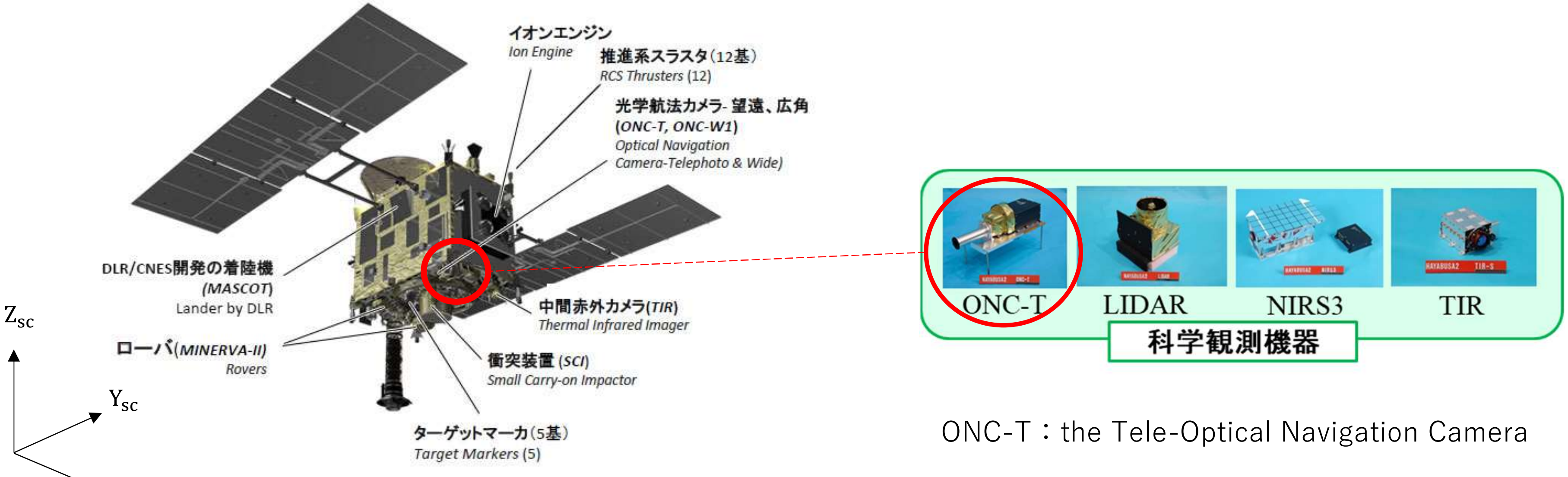


Fig.3 Flyby trajectory planning

Camera used for asteroid flyby observation



ONC-T：the Tele-Optical Navigation Camera

Fig.4 Hayabusa2 onboard equipment © JAXA

☐ Optical Navigation Camera ONC-T Specifications
- CCD size: 1024 pixel ×1024 pixel
- FOV: 6.32 deg
- Exposure time: 0.3 s

Attitude maneuver strategies for the asteroid flyby observation

Attitude Control Method	Details	Advantage	Disadvantage
Fixed Attitude	The attitude is fixed to an imaging-ready one during the flyby.	If the image capture timing is correct, reliable imaging could be possible.	● Possibility for image blurring ● The possible asteroid image size would be small
Feed-Forward (FF) Control	From a specific time before the flyby, the attitude angle of the spacecraft is accelerated using the maximum torque of the reaction wheel and the instant when the velocity of the asteroid in the ONC-T image becomes zero is set as the image capture time.	● The attitude maneuver itself can be carried out reliably since the maneuver does not depend on any FB information. ● The asteroid image could be obtained at the fixed image capture time even in the worst case.	● Since there are only two instants when the velocity of the asteroid in the ONC-T image becomes zero (when the asteroid velocity ″catches up″ and “overtake” the attitude angular velocity), the appropriate image capture time (″shutter chance″) is limited to these two instants. ● Continuous shooting should be considered because the shutter chance fluctuates due to orbital errors.
Inertial Attitude Feedback (FB)	● Time series of nominal target attitude in the inertial space is stored in the spacecraft’s memory. ● During the flyby, the attitude maneuver is performed by FB control using the angle and angular velocity estimates from the attitude determination system instead of using the information from the ONC-T images.	● Since images are not used for FB, the attitude control system is reliable and image blurring is expected to be small in the case of small orbital errors.	● The best shutter chance could fluctuate due to the orbital errors so continuous shooting should be considered.
Visual Feedback (FB)	The position of the asteroid in the ONC-T image is obtained by image recognition and the attitude angle error and the attitude angular velocity error are calculated from this information. Then, FB attitude control maneuver is carried out using these errors.	● Capable of dealing with asteroid position and velocity fluctuations in the image caused by orbital errors. ● The best “shutter chance” varies. It can be handled by continuous shooting.	● It is necessary to recognize the position of the asteroids in the image autonomously and to calculate their position and velocity in real time onboard. ● The reliability of image recognition depends on the prediction of luminance of the asteroid image.

Relative position between the asteroid & the spacecraft during flyby

d_{c_act}: Closest distance
d_z: Orbital error in the z-axis direction

θ_{nom}: Target attitude angle
θ_x: Attitude error around $-X_{sc}$ axis
θ_y: Attitude error around $+Y_{sc}$ axis

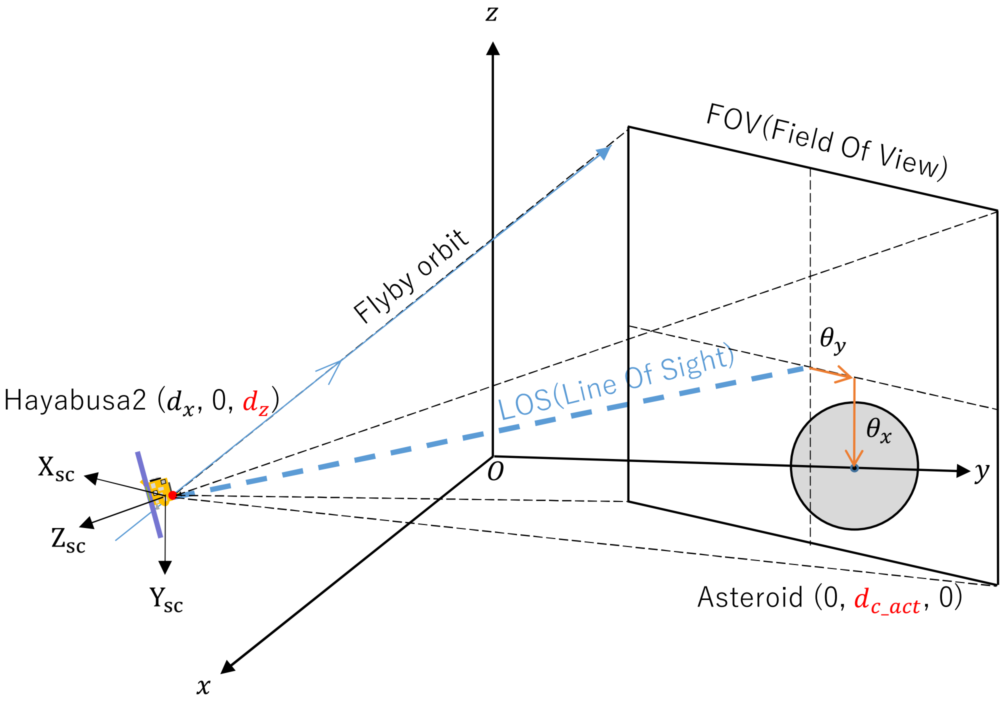


Fig.5-1 Relative position between asteroid and spacecraft

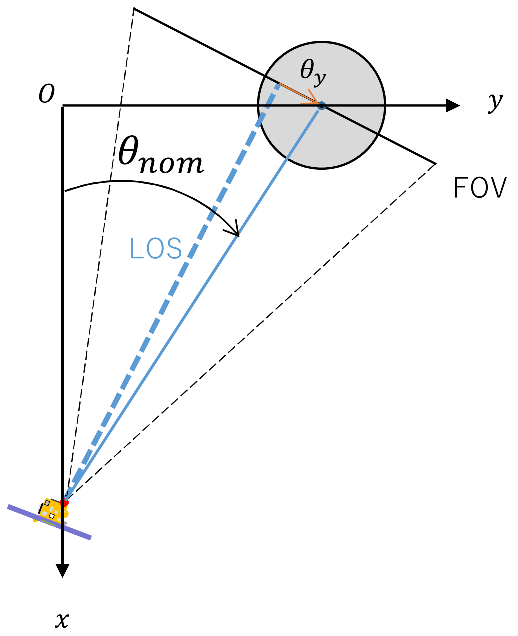


Fig.5-2 Relative position between asteroid and spacecraft （$xy-$plane）

Target attitude angle $\boldsymbol{\theta_{nom}}$ $(\boldsymbol{\theta_y = 0})$
Target attitude angular velocity $\boldsymbol{\dot{\theta}_{nom}}$ $(\boldsymbol{\dot{\theta}_y = 0})$

d_{c_nom} ：20 km
d_{z_nom} ：0 km

$t = 0$s, Location of the spacecraft: (1000, 0, 0) km

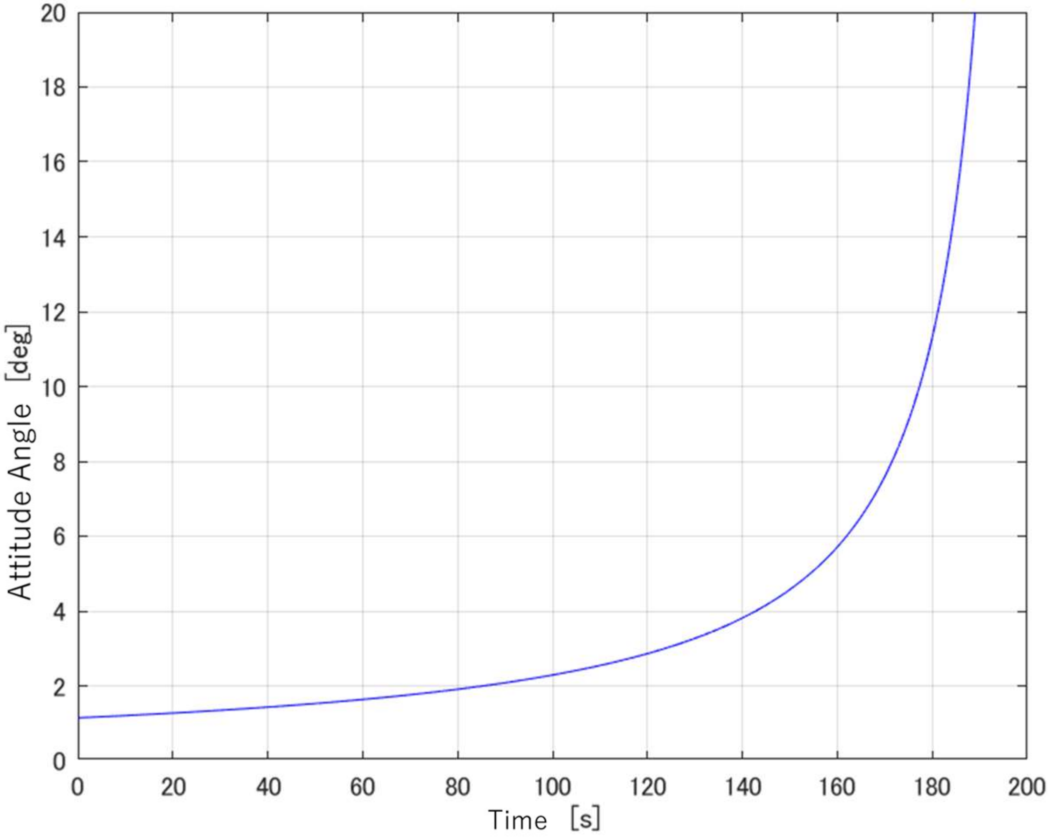


Fig.6-1　Target attitude angle θ_{nom} $(\theta_y = 0)$

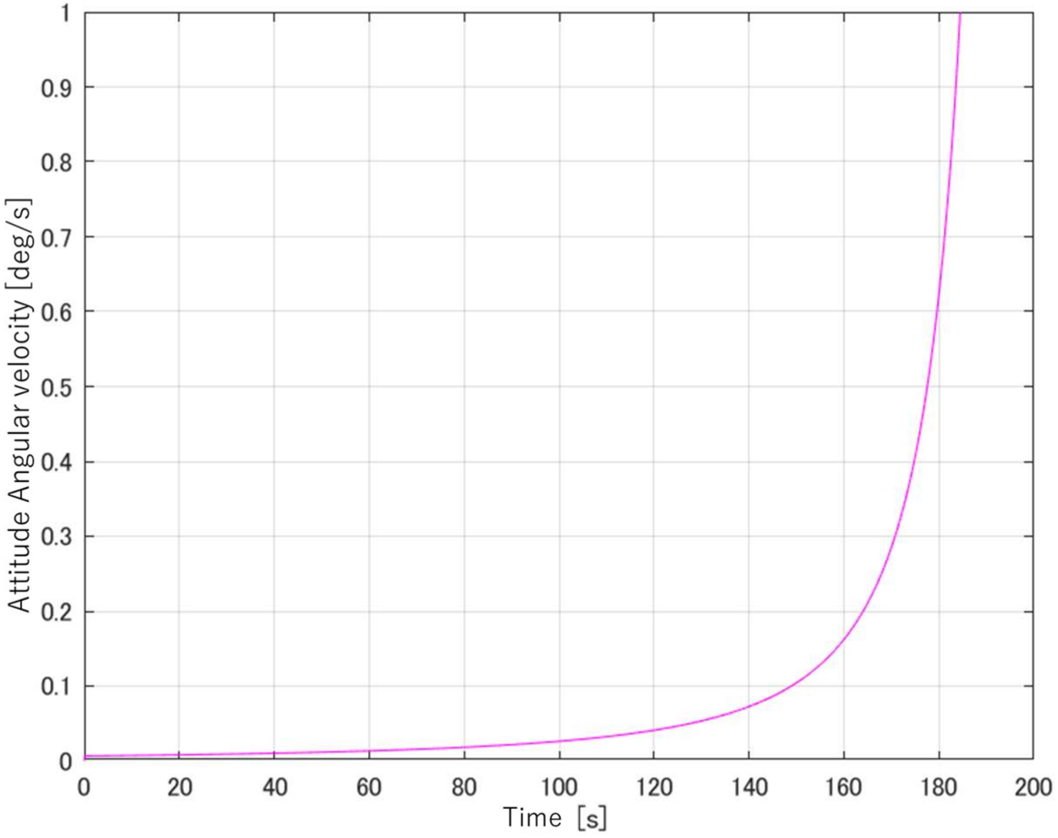


Fig.6-2　Target attitude angular velocity $\dot{\theta}_{nom}$ $(\dot{\theta}_y = 0)$

Visual feedback attitude control
(around $\boldsymbol{Y_{sc}}$ axis, nominal case: $\boldsymbol{\theta_y = 0}$)

d_{c_nom} ：20 km
d_{z_nom} ：0 km

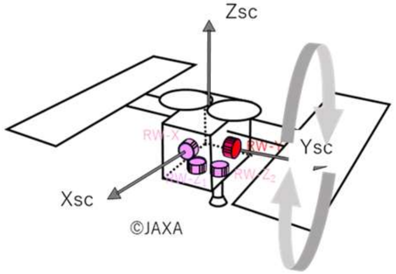


Fig.7 RW location

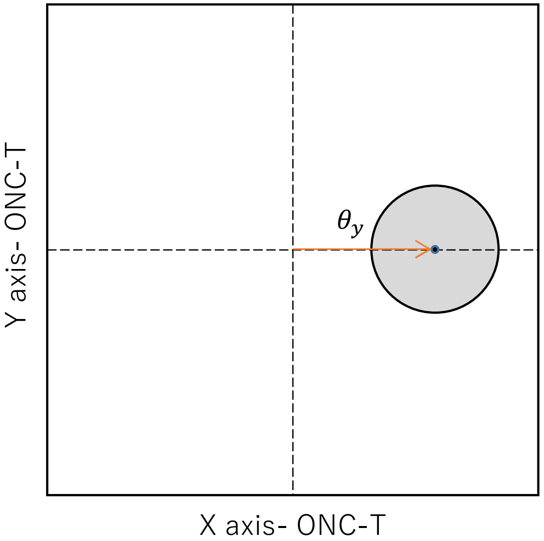


Fig.8 Attitude error around Y_{sc} axis and asteroid position in image

t = 0s, spacecraft position: (1000, 0, 0) km

Visual feedback attitude control is performed by PD control around the Y_{sc} axis of the spacecraft fixed coordinate system.

The control torque T_y can be expressed as

$$T_y = -k_d \frac{d\theta_y}{dt} - k_P \theta_y \qquad (1)$$

T_y : Control torque around Y_{sc} axis
θ_y : Attitude error around Y_{sc} axis
k_P ：Proportional feedback gain
k_d ：Derivative feedback gain

＊ $k_P = 12$, $k_d = 9$

Visual feedback attitude control

(around $\boldsymbol{Y_{sc}}$ axis, nominal case: $\boldsymbol{\theta_y = 0}$)

d_{c_nom} ：20 km
d_{z_nom} ：0 km

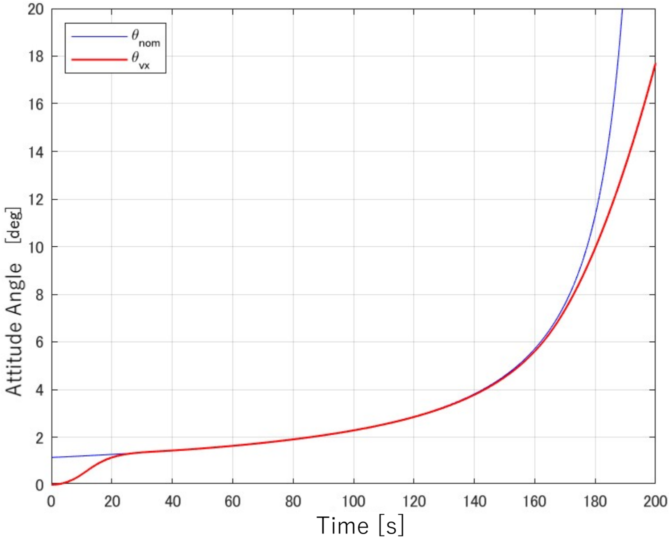


Fig.9-1 Target attitude angle $\boldsymbol{\theta_{nom}}$ $(\theta_y = 0)$ and attitude of the S/C θ_{vx}

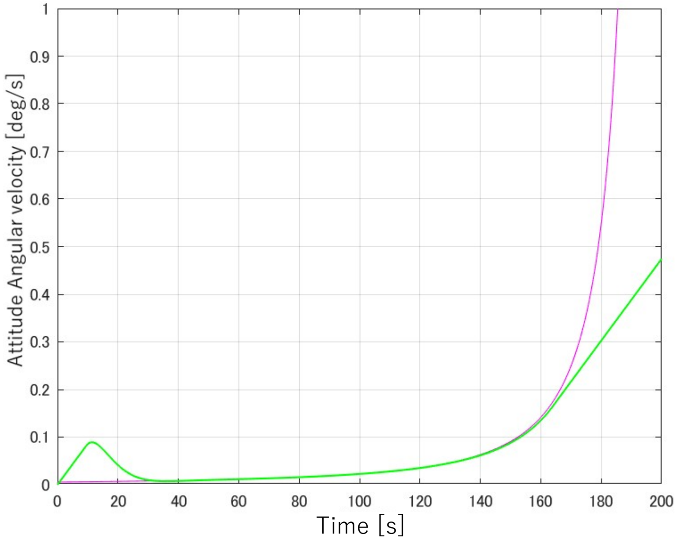


Fig.9-2 Target angular velocity $\boldsymbol{\dot{\theta}_{nom}}$ $\boldsymbol{(\dot{\theta}_y = 0)}$ and angular velocity of the S/C $\boldsymbol{\dot{\theta}_{vx}}$

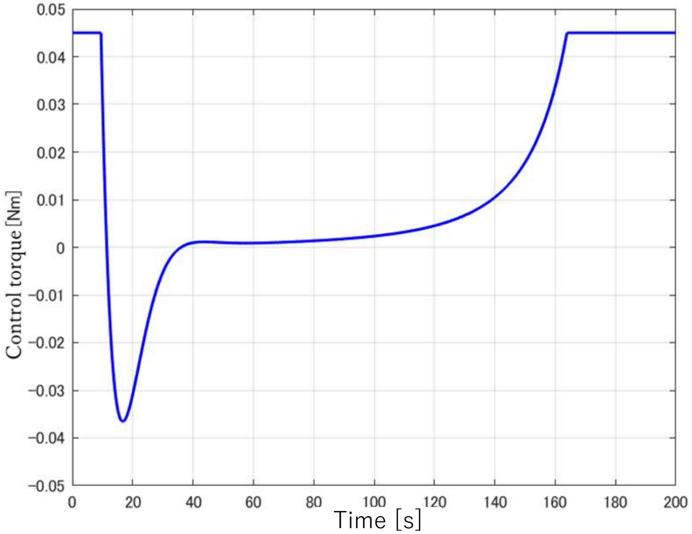


Fig.10 Control torque for visual FB control

Visual feedback attitude control

(around $\boldsymbol{Y_{sc}}$ axis, nominal case: $\boldsymbol{\theta_y = 0}$)

d_{c_nom} : 20 km
d_{z_nom} : 0 km

LSC (Latest Shutter Chance) : the latest time when attitude angular velocity error goes to 3.0 pixel/s.

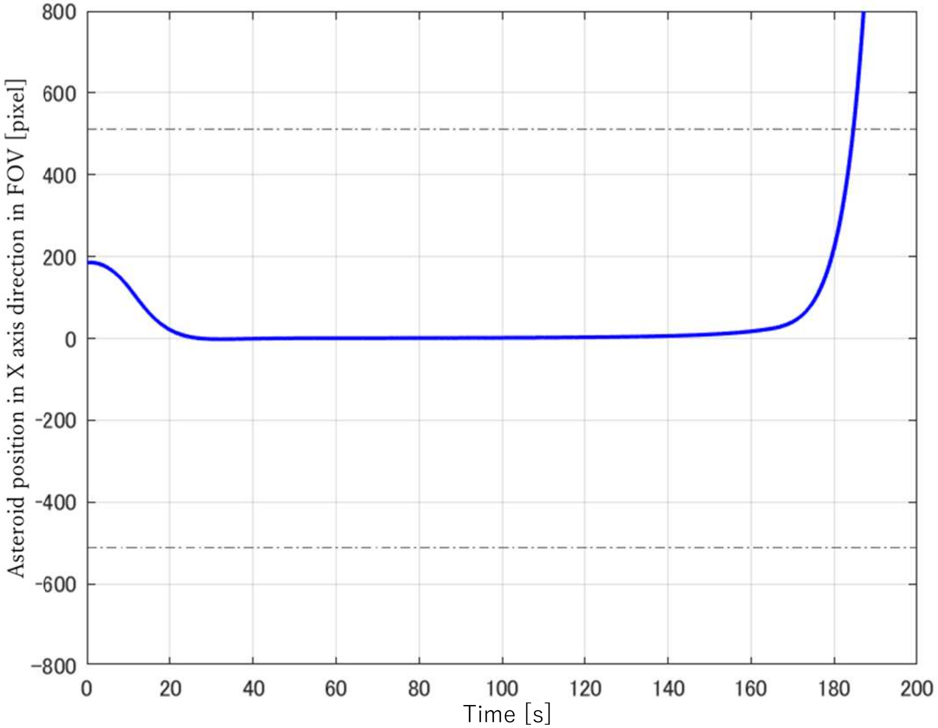


Fig. 11　Asteroid position in X axis direction in FOV

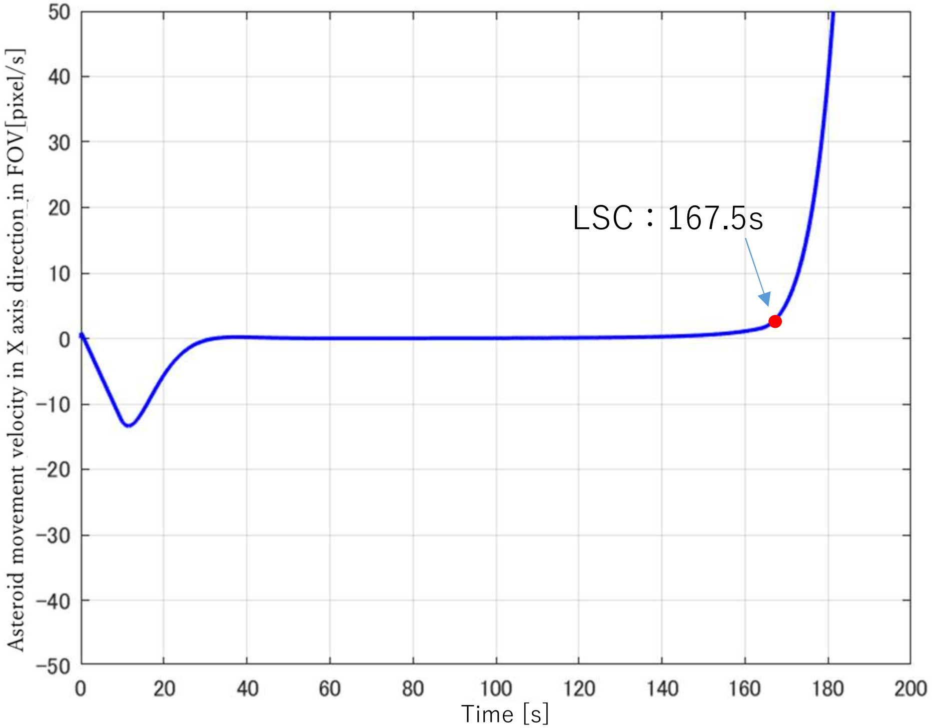


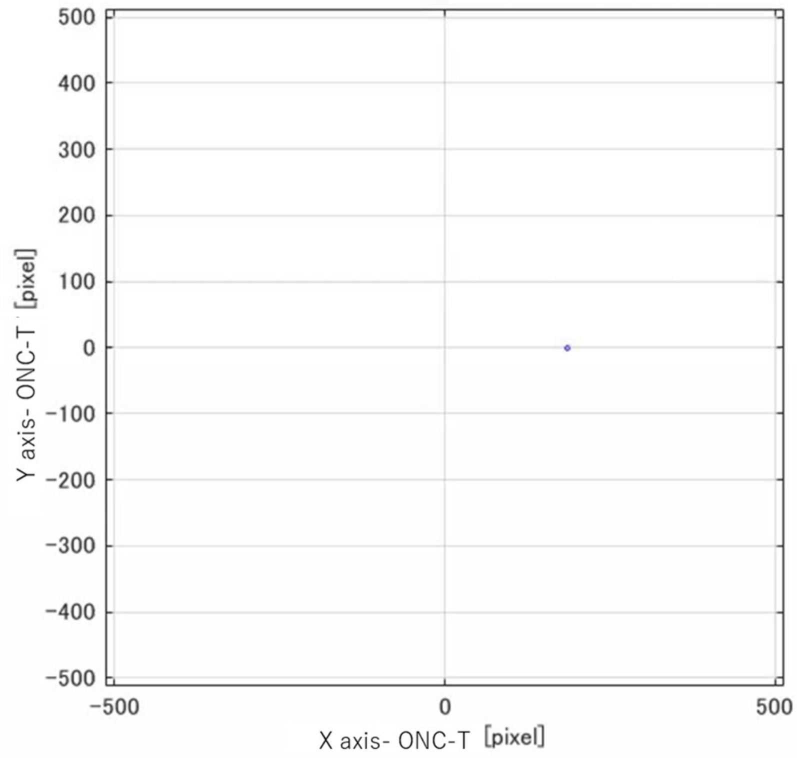
Fig. 12　Asteroid velocity in X axis direction in FOV

Visual feedback attitude control

(around $\boldsymbol{Y_{sc}}$ axis, nominal case: $\boldsymbol{\theta_y = 0}$)

d_{c_nom} ：20 km
d_{z_nom} ：0 km

LSC：167.5s , Size of asteroid ：39.7 pixel



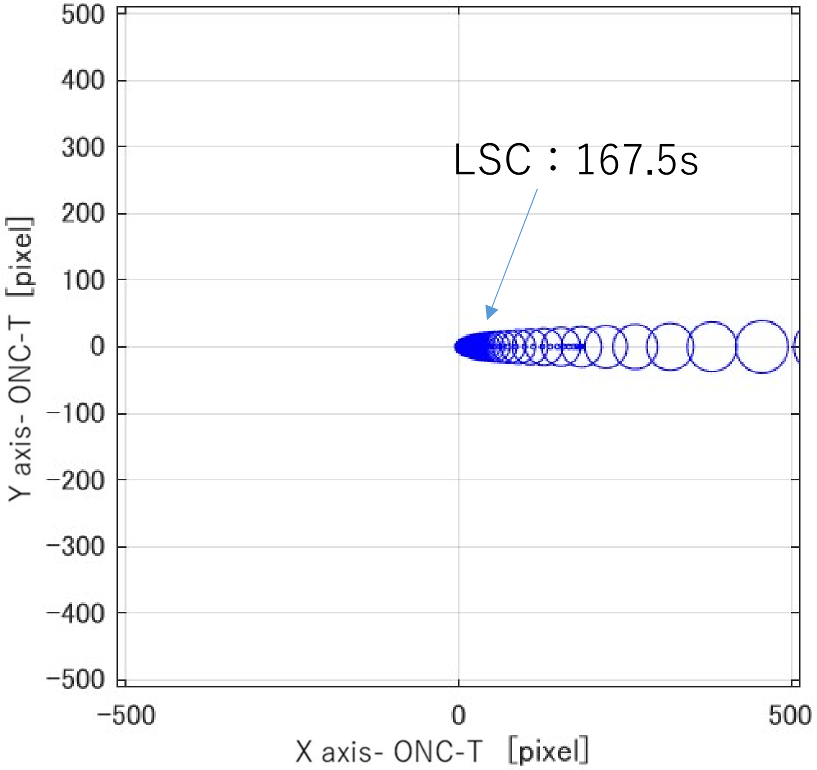


Fig.13　Visibility of asteroids in FOV

Evaluation of attitude controller performance degradation due to orbital error

(around X_{sc} and Y_{sc} axes)

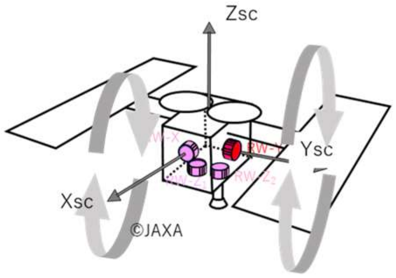


Fig.14 RW location

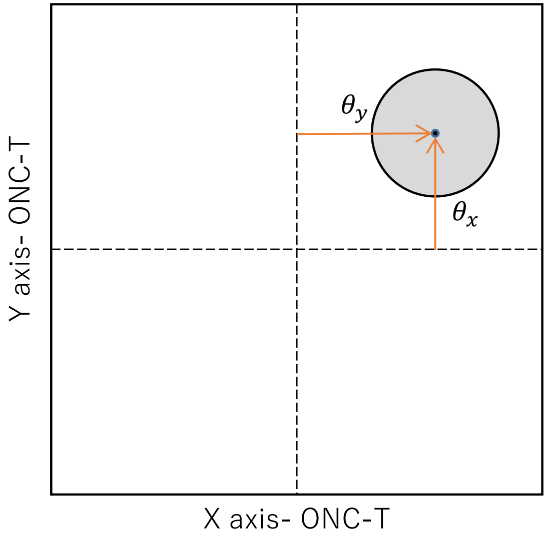


Fig.15 Attitude error around the axes

Visual feedback control around X_{sc} and Y_{sc} axes with PD control.
The control torque $\boldsymbol{T}$ is given as follows.

$$\boldsymbol{T} = -k_d \frac{d\boldsymbol{\theta}}{dt} - k_P \boldsymbol{\theta} \qquad (1')$$

$\boldsymbol{T} = \begin{bmatrix} T_x \\ T_y \end{bmatrix}$: Control torque around X_{sc} and Y_{sc} axes

$\boldsymbol{\theta} = \begin{bmatrix} \theta_x \\ \theta_y \end{bmatrix}$: Attitude error around X_{sc} and Y_{sc} axes

k_P : Proportional gain
k_d : Derivative gain

Evaluation of attitude controller performance degradation due to orbital error

(around $\mathbf{X}_{sc}$ and $\mathbf{Y}_{sc}$ axes)

The performance of the attitude controller was evaluated considering the following 49 different orbit errors.

- Closest distance d_{c_act} ：20 ± 3 [km]
- Orbital error in the z-axis direction d_z ：0 ± 3 [km]

$$d_{c\_act} = [17\ 18\ 19\ 20\ 21\ 22\ 23]$$
$$d_z = [-3\ -2\ -1\ 0\ 1\ 2\ 3]$$

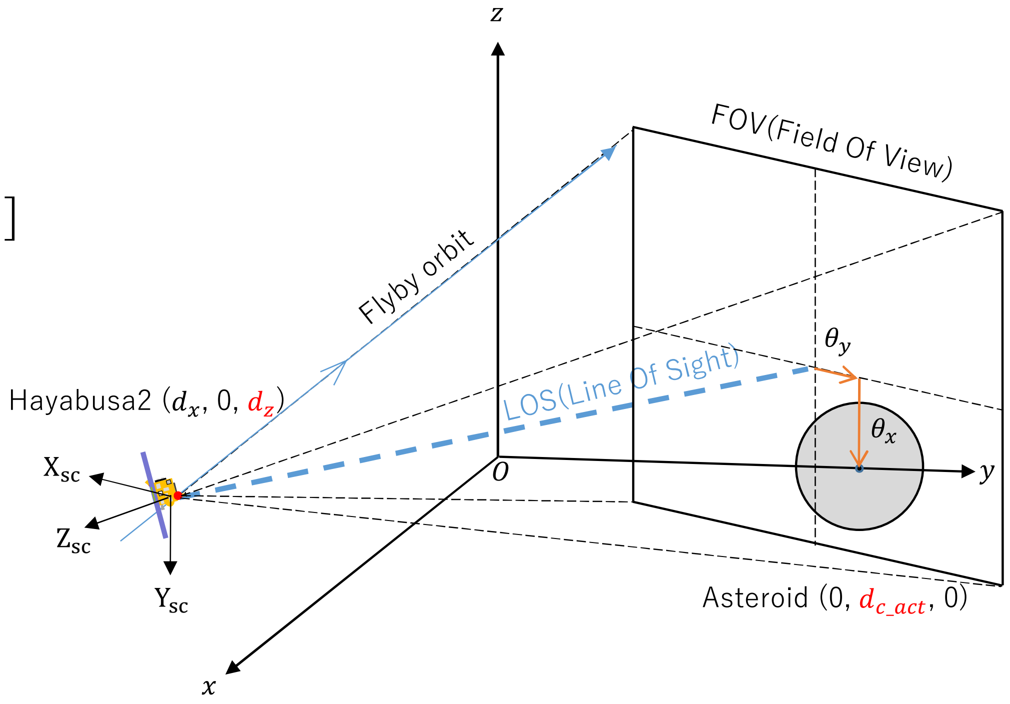
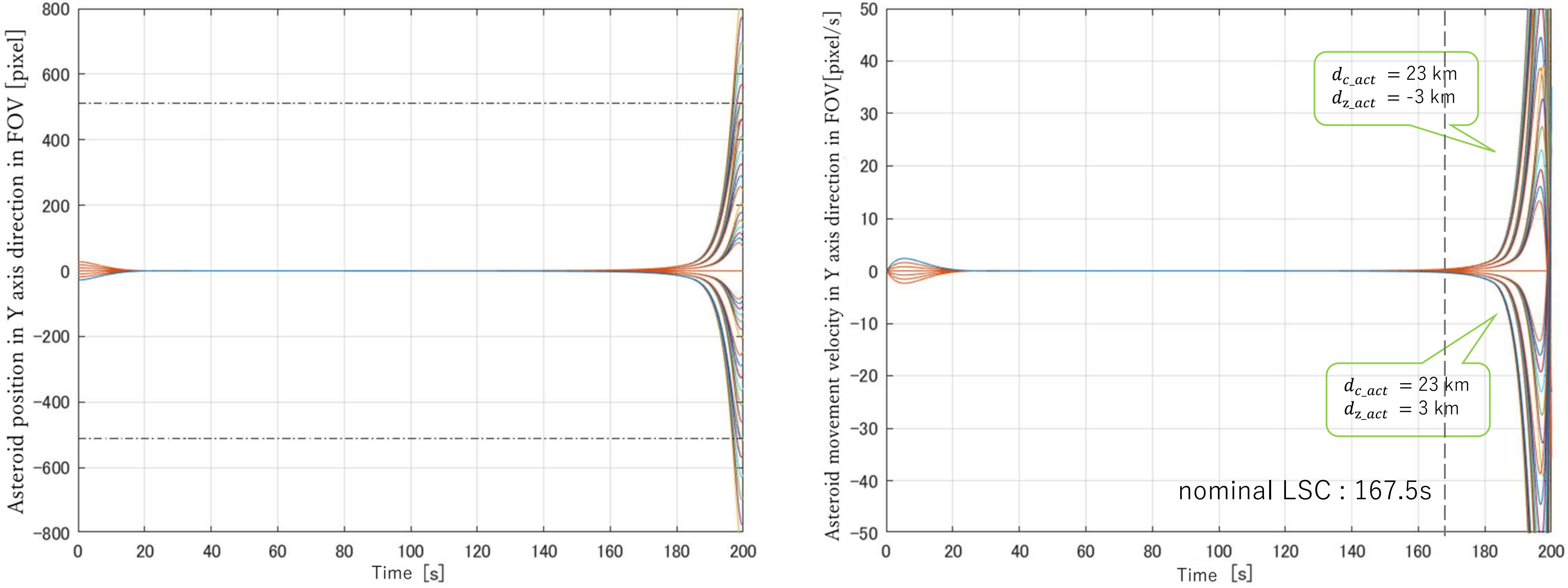


Fig.5-1 Relative position between asteroid and spacecraft

Evaluation of attitude controller performance degradation due to orbital error

(around $\mathbf{X}_{sc}$ axis = Y axis direction in FOV)

d_{c_act} : 20 ±3km
d_{z_act} : 0 ±3 km



d_{c_act} = 23 km
d_{z_act} = -3 km

d_{c_act} = 23 km
d_{z_act} = 3 km

nominal LSC : 167.5s

Fig.16 Asteroid position and Asteroid velocity in Y axis direction in FOV considering orbital error

Evaluation of attitude controller performance degradation due to orbital error

(around $\boldsymbol{Y_{sc}}$ axis = X axis direction in FOV)

d_{c_act} : 20 ±3km
d_{z_act} : 0 ±3 km

LSC : 166.0s ← nominal LSC : 167.5s

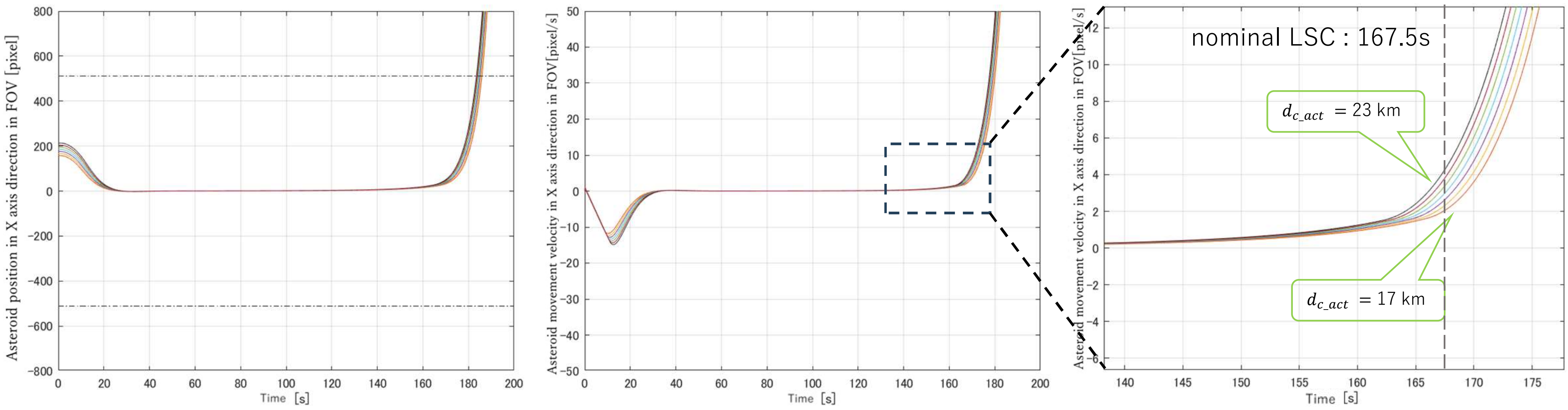


Fig.17 Asteroid position and Asteroid velocity in X axis direction in FOV considering orbital error

Evaluation of attitude controller performance degradation due to orbital error

(around $\mathbf{X}_{sc}$ and $\mathbf{Y}_{sc}$ axes)

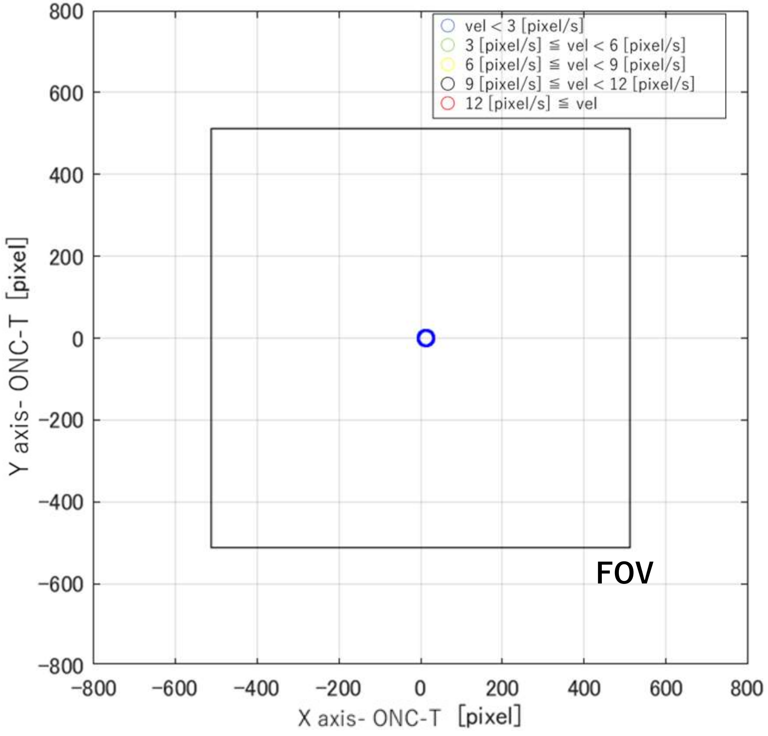


Fig.19 Asteroid image at shutter chance (165.9s)

LSC: 165.9s which is slightly earlier than 166.0s is determined to avoid blurring asteroid images considering all orbital errors.

The asteroid velocity in the image (**vel** in the figure) is given from x and y axis velocity V_x, V_y as shown,

$$\mathbf{vel} = \sqrt{{V_x}^2 + {V_z}^2}$$

Since the camera exposure time is 0.3s,
it is considered that the velocity in the image becomes less than 1 [pixel/0.3s]
when " vel < ○ 3 [pixel/s] " in the left figure.
resulting in no blurring of the asteroid image.

Size of asteroid image(LSC: 165.9s) : 37.8pixel

Evaluation of attitude controller performance degradation caused by the constraints from the image processing process (around $\mathbf{X}_{sc}$ and $\mathbf{Y}_s$ axes)

A) Image transfer time delay from ONC-T to the image recognition computer is 2s
  → Attitude angle error is input to the attitude control computer with delay of 2s

B) ONC-T image acquisition interval is 2s
  → Attitude angle error is updated at intervals of 2s

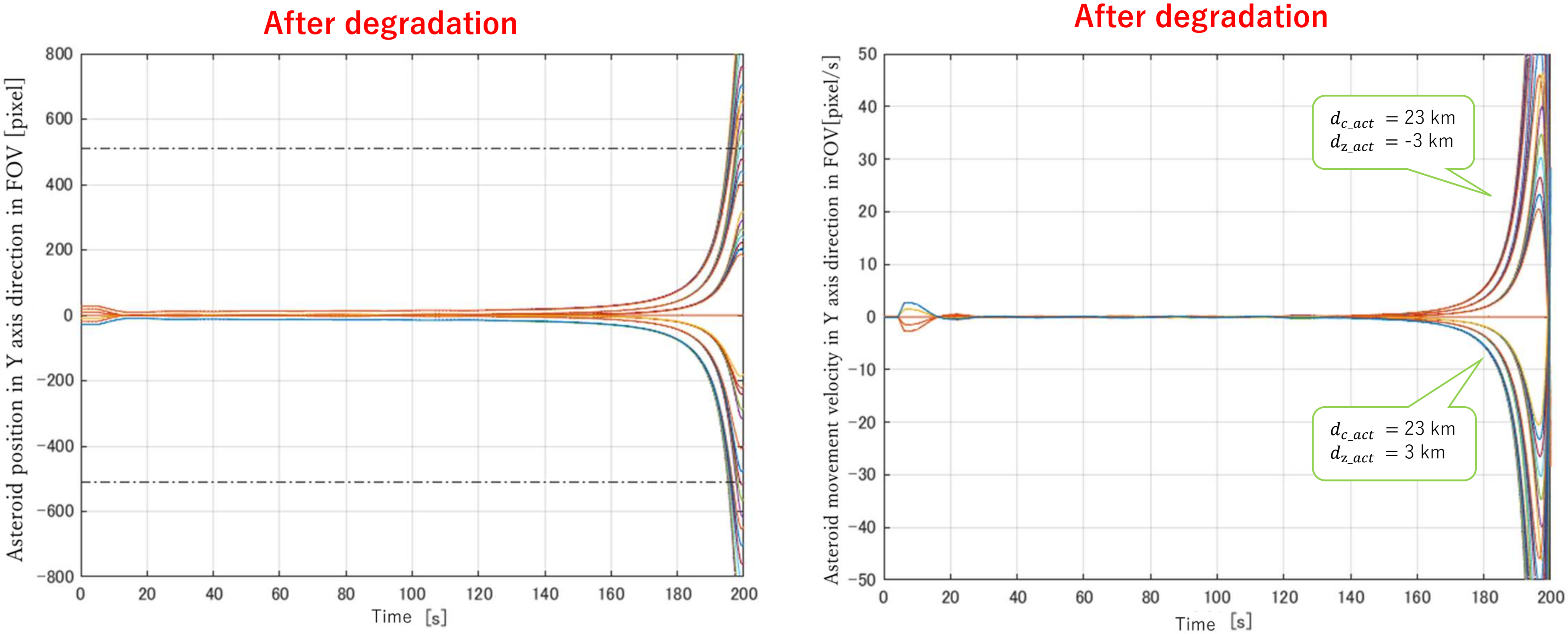
C) Differential calculation of attitude angular velocity
  → Sampling of attitude angle errors under the above conditions A) and B) at intervals of 0.1s
  → Calculate the attitude angular velocity by backward differential calculation
  → Since the angular velocity obtained from the angle error updated every 2s is in the form of pulses, these pulses are transformed to staircase type angular velocity by zero-order holding

✓ Attitude angle error and attitude angular velocity error given under the above conditions are used for the attitude controller

✓ Attitude controller instability → Parameter tuning for PD controller
  → Resulting in attitude control performance degradation

Evaluation of attitude controller performance degradation caused by the constraints from the image processing process (around $\mathbf{X}_{sc}$ axis = Y axis direction in FOV)

d_{c_act} : 20 ±3km
d_{z_act} : 0 ±3 km


After degradation

After degradation

d_{c_act} = 23 km
d_{z_act} = -3 km

d_{c_act} = 23 km
d_{z_act} = 3 km

Fig.20 Asteroid position and Asteroid velocity in Y axis direction in FOV considering orbital error

Evaluation of attitude controller performance degradation caused by the constraints from the image processing process (around $\mathbf{Y}_{sc}$ axis, X axis direction in FOV)

d_{c_act} : 20 ±3km
d_{z_act} : 0 ±3 km

LSC : 145.1s ← LSC : 166.0s ← nominal LSC : 167.5s

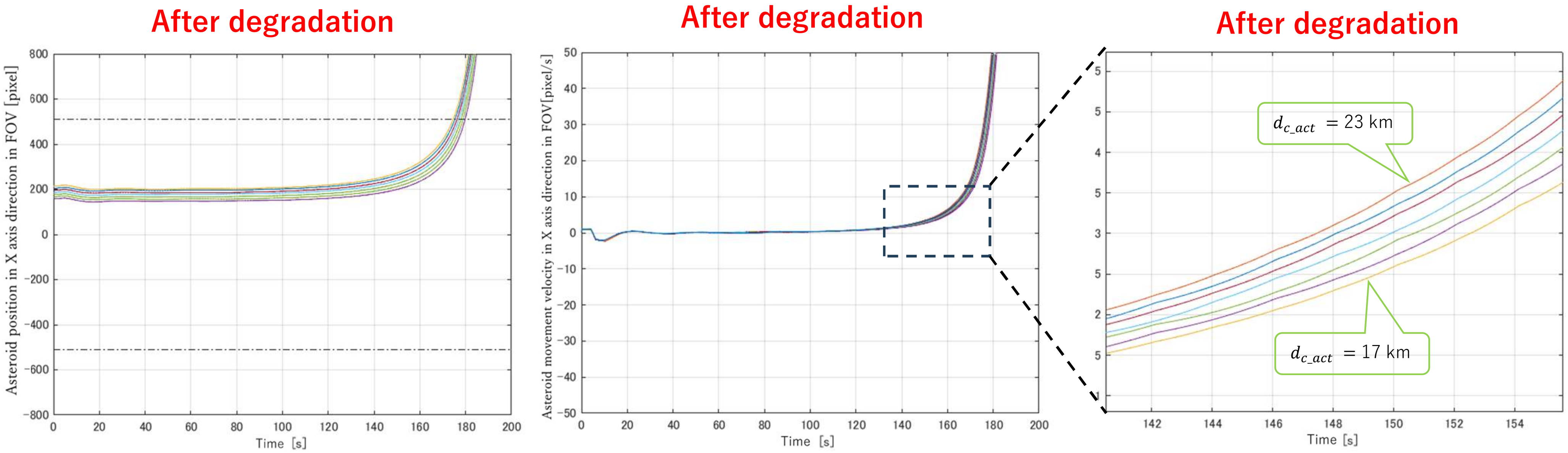


図21 Asteroid position and Asteroid velocity in X axis direction in FOV considering orbital error

Evaluation of attitude controller performance degradation caused by the constraints from the image processing process (around $\mathbf{X}_{sc}$ and $\mathbf{Y}_{sc}$ axes)

d_{c_act} : 20 ±3km
d_{z_act} : 0 ±3 km

After degradation

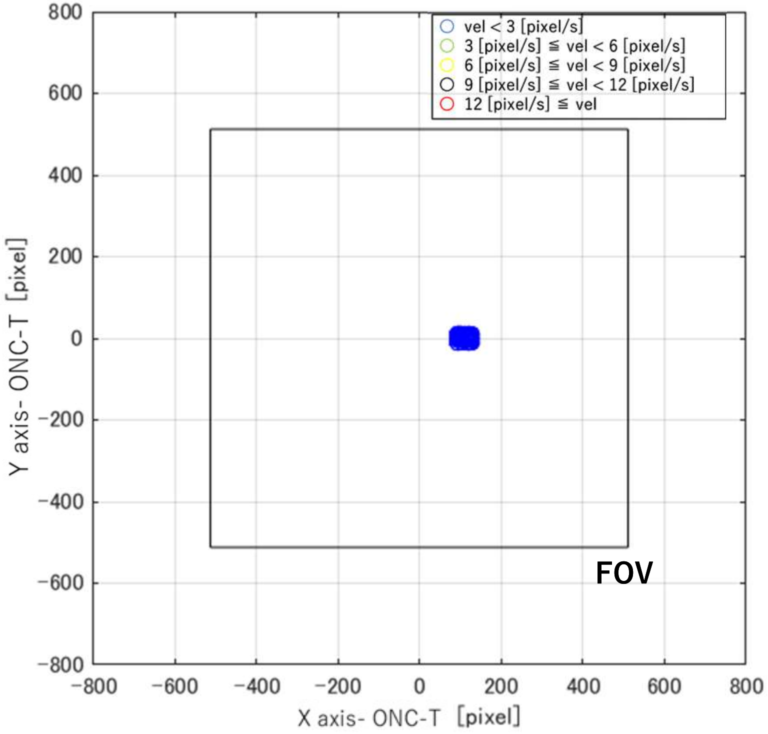


Fig.22 Asteroid image at shutter chance (**145.1s**)

LSC: 145.1s
is determined to avoid blurring asteroid images considering all orbital errors.

The asteroid velocity in the image (vel in the figure) is given from x and y axis velocity V_x, V_y as shown,

$$\mathrm{vel} = \sqrt{{V_x}^2 + {V_z}^2}$$

Since the camera exposure time is 0.3s,
it is considered that the velocity in the image becomes less than 1 [pixel/0.3s]
when " vel < ○ 3 [pixel/s] " in the left figure.
resulting in no blurring of the asteroid image.

Size of asteroid image ：23.5pixel ← 39.7pixel (nominal)

Conclusions and future studies

- It was shown that the visual feedback attitude controller using the position and the velocity of the asteroid in the Hayabusa2 onboard camera image enables asteroid flyby imaging by performing an attitude maneuver for cases where the target attitude changes rapidly.

- Although the proposed image feedback controller generates attitude angle and attitude angle rate error under the assumed orbital error in the transverse direction (orthogonal to the flyby velocity) and the constraints from the image processing process, it is shown that blur-free imaging is possible by setting the image capture time earlier and allowing the asteroid image to become smaller.

- Although, not included in this report, the position error in the direction of the flyby velocity simply affects the proper time of imaging which results in image blurring, it is expected that a series of shots will solve this problem.

- In accordance with the mission requirements for asteroid flyby observations, possibility and implementation for attitude maneuver is under consideration at this moment.