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デブリ近傍領域における除去衛星の姿勢軌道制御について

Attitude and orbit control of the active debris removal satellite

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本論文はデブリ近傍領域における除去衛星の姿勢軌道制御について議論する。除去衛星はデブリからの距離約 100km の地点から相対航法を開始し、DCR 接近、Vbar 接近、最終接近を経てデブリに到達する。この最終接近フェーズにおいて、はやぶさで用いられたスラスタ ON/OFF 制御を適用し、誘導が可能であることを数値的に示した。また同じ制御則を用いて、デブリに対して相対停止、デブリから離脱できることを確認した。

This paper discusses the attitude and orbit control of the active debris removal satellite in the vicinity of the target. The satellites begins the relative navigation w.r.t. the debris at 100 km from it and approaches it through the DCR and V-bar trajectories. We proposes that the same thruster-control law as the asteroid explorer HAYABUSA can be applied in the very final approaching phase of this mission and confirms its validity through a numerical calculation. The results shows that the proposed navigation successfully guides the satellite in the direction of the debris.

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Attitude and Orbit Control of the Active Debris Removal Satellite

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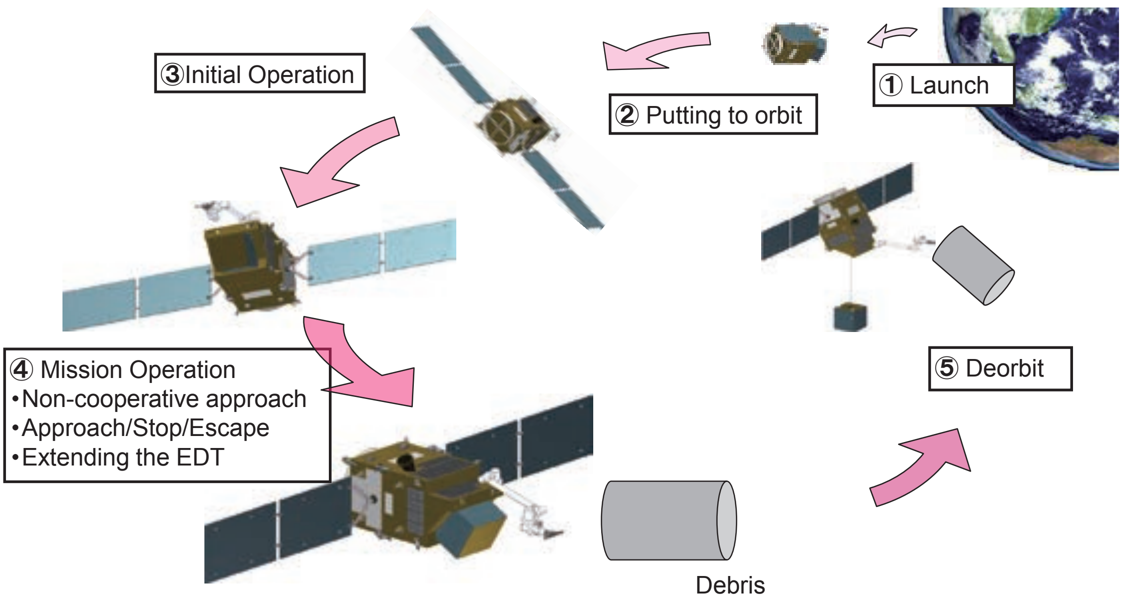
Debris Removal Satellite

- A satellite which makes a debris deorbit by attaching a removal device on it.



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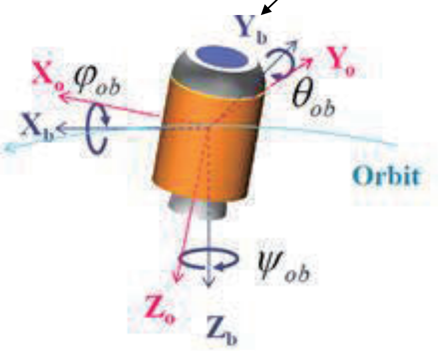
Target

Target

- ●Upper part of a H2A rocket.
- ●Attach a debris-removal devices on the PAF.



Debris removal device

- ●Electrodynamic Tether(EDT）

EDT system
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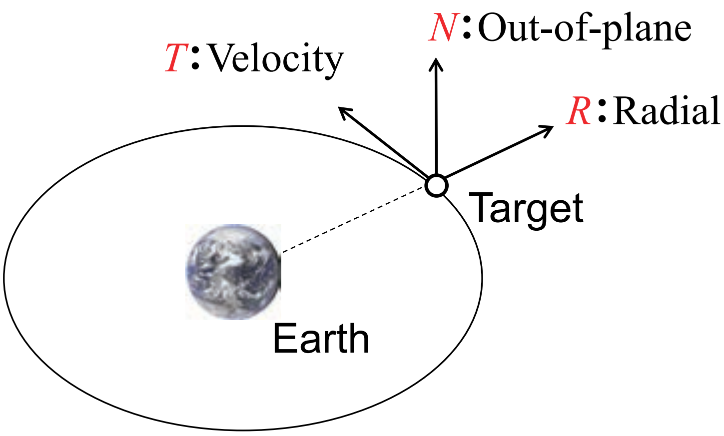
Objective

Show a feasible operating plan
of the debris-removal mission
from the viewpoint of the attitude/orbital control.

Coordinate

Target-centered RTN coordinate system

- Target-fixed orthogonal coordinate system.



Analysis

Motion of the satellite in the distant realm from the debris.

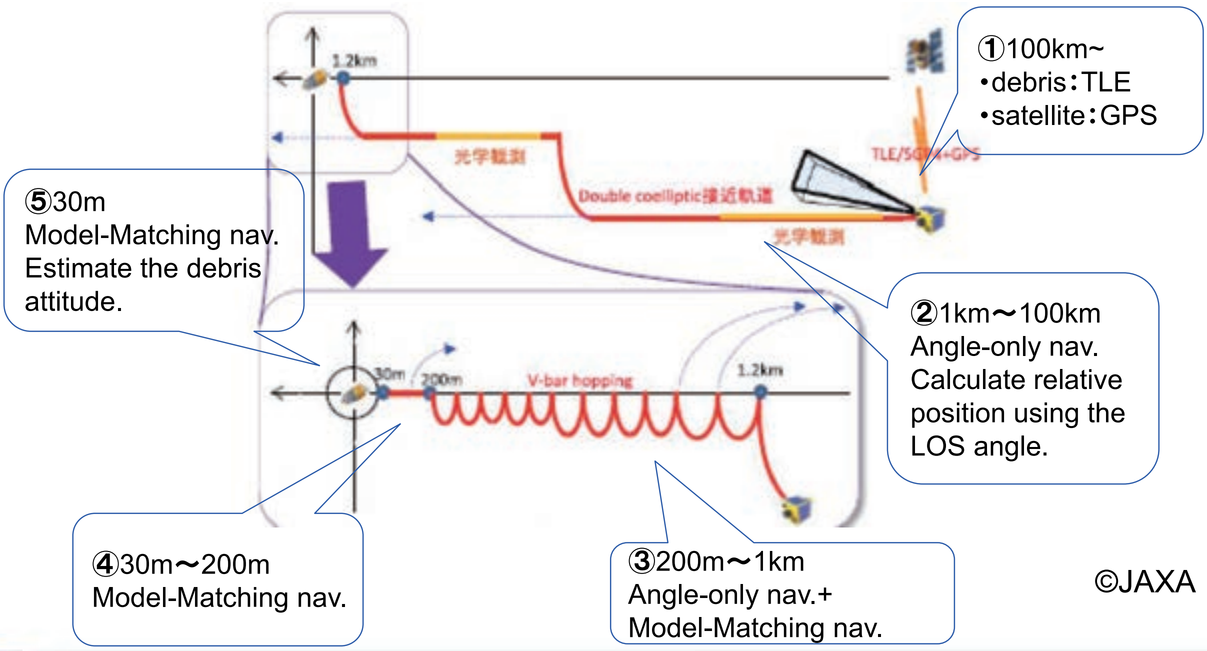
- Orbital motion of the satellite
- Orbital motion of the debris

Motion of the satellite in the vicinity of the debris.

- Orbital / Attitude motion of the satellite
- Orbital / Attitude motion of the debris

Motion of the satellite in the distant realm from the debris

- Analyze the motion of the satellite in the realm of 30m ~ 100km from the debris.



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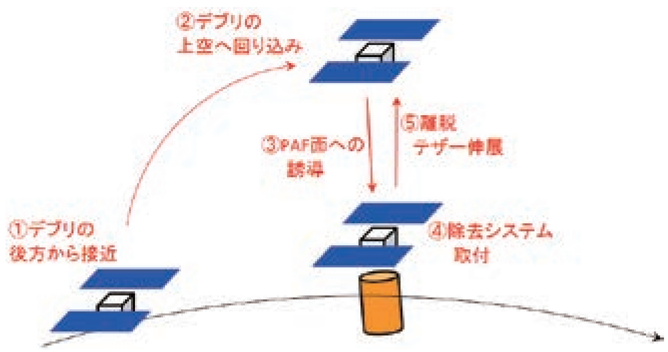
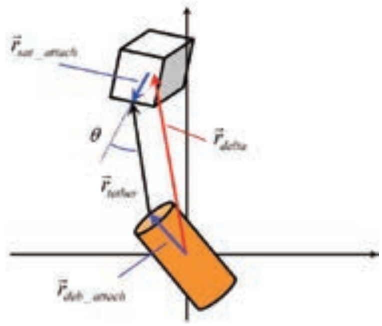
Motion of the satellite in the vicinity of the debris

- Analyze the motion of the satellite in the realm of 1m ~ 30m from the debris.
  - ●Estimate the attitude of the debris at 30m from it.
  - ●Plan the approaching trajectory.
  - ●Fly around above the PAF.
  - ●Approach.
  - ●Stop and keep an appropriate distance from the debris.
  - ●Attach the removal device.
  - ●Escape.



Equation of Motion

- Calculate the motion of the satellite and the debris using the following the equations. of motion.



$$
\begin{cases}
\dfrac{d\vec{x}_{deb}}{dt} = \vec{v}_{deb} \\
\dfrac{d\vec{v}_{deb}}{dt} = -\mu \dfrac{\vec{x}_{deb}}{|\vec{x}_{deb}|^3} + \dfrac{\vec{F}_{deb\_tether}}{m_{deb}} + (\text{摂動による加速度}) \\
\dfrac{d\vec{\omega}_{deb}}{dt} = \vec{I}_{deb}^{-1}\left(\vec{Trq}_{deb\_tether} + \vec{Trq}_{deb\_gravity} - \vec{\omega}_{deb} \times \vec{I}_{deb}\vec{\omega}_{deb}\right) \\
\dfrac{d\vec{q}_{deb}}{dt} = \dfrac{1}{2} E([q_{deb}])\vec{\omega}_{deb} \\
\dfrac{d\vec{x}_{sat}}{dt} = \vec{v}_{sat} \\
\dfrac{d\vec{v}_{sat}}{dt} = -\mu \dfrac{\vec{x}_{sat}}{|\vec{x}_{sat}|^3} + \dfrac{\vec{F}_{sat\_thruster} + \vec{F}_{sat\_tether}}{m_{sat}} + (\text{摂動による加速度}) \\
\dfrac{d\vec{\omega}_{sat}}{dt} = \vec{I}_{sat}^{-1}\left(\vec{Trq}_{sat\_thruster} + \vec{Trq}_{sat\_tether} - \vec{\omega}_{sat} \times \vec{I}_{sat}\vec{\omega}_{sat}\right) \\
\dfrac{d\vec{q}_{sat}}{dt} = \dfrac{1}{2} E([q_{sat}])\vec{\omega}_{sat}
\end{cases}
$$

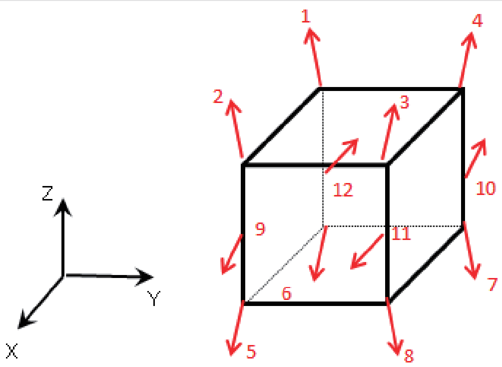
$$
E([q_{sat}]) = \begin{bmatrix} q_4 & -q_3 & q_2 \\ q_3 & q_4 & -q_1 \\ -q_2 & q_1 & q_4 \\ -q_1 & -q_2 & -q_3 \end{bmatrix}
$$

$F_{thruster}$: Force due to the thruster
F_{tether} : Force due to the tether.
$Trq_{thruster}$: Torque due to the thruster
Trq_{tether} : Torque due to the tether.
$Trq_{gravity}$: gravity gradient torque

Modeling of the satellite

- Model the satellite as a cube.
  - Size = 1m*1m*1m
  - Mass = 500kg

- Set 12 thrusters.
  - Force = 4N
  - Isp = 220s
  - Error = 5%

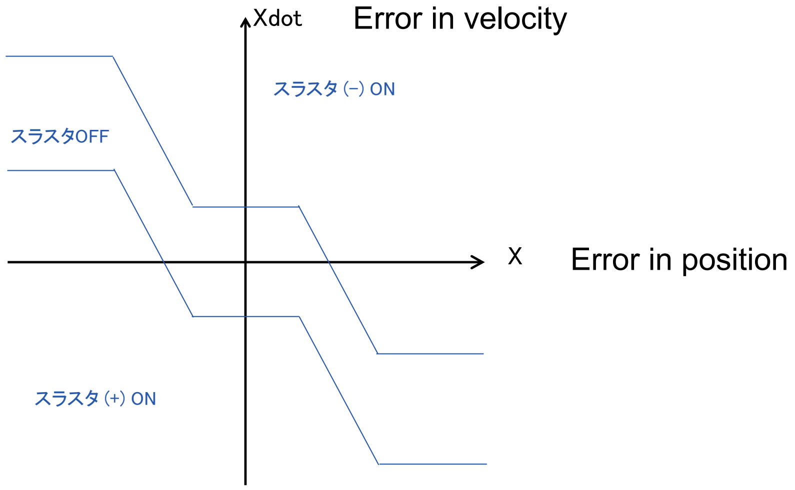


		使用スラス	並進力 [N]			トルク [Nm]		
			X	Y	Z	X	Y	Z
並進	+X	10,12	7.52	0	0	0	0	0
	−X	9,11	−7.52	0	0	0	0	0
	+Y	10,11	0	2.74	0	0	0	0
	−Y	9,12	0	−2.74	0	0	0	0
	+Z	5,6,7,8	0	0	15.76	0	0	0
	−Z	1,2,3,4	0	0	−15.76	0	0	0
回転	+X	1,2,7,8	0	0	0	6.09	0	0
	−X	3,4,5,6	0	0	0	−6.09	0	0
	+Y	2,3,6,7	0	0	0	0	5.75	0
	−Y	1,4,5,8	0	0	0	0	−5.75	0
	+Z	11,12	0	0	0	0	0	5.13
	−Z	9,10	0	0	0	0	0	−5.13

Thruster control in the vicinity of the debris

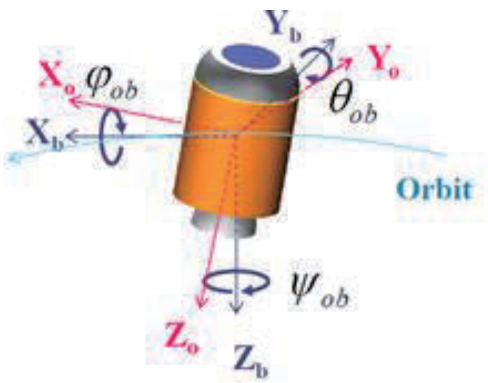
- Plan a reference trajectory and navigate the satellite to follow it.
- Switch on and off of the thrusters depending on the difference between the actual and planned states.

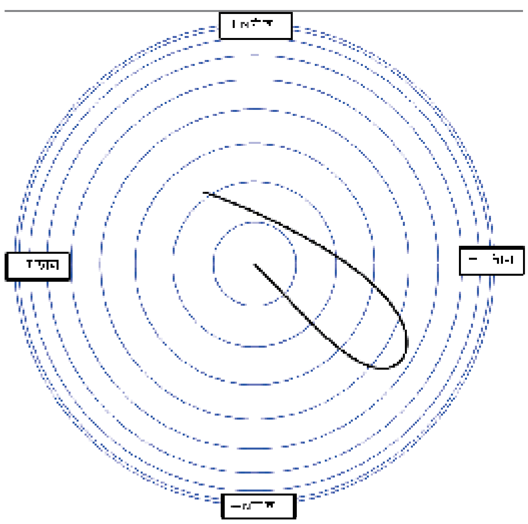
  ⇒ Control law of HAYABUSA.



Modeling the debris

- Model the debris as a cylinder stabilized due to the gravity gradient.
  - Nutation





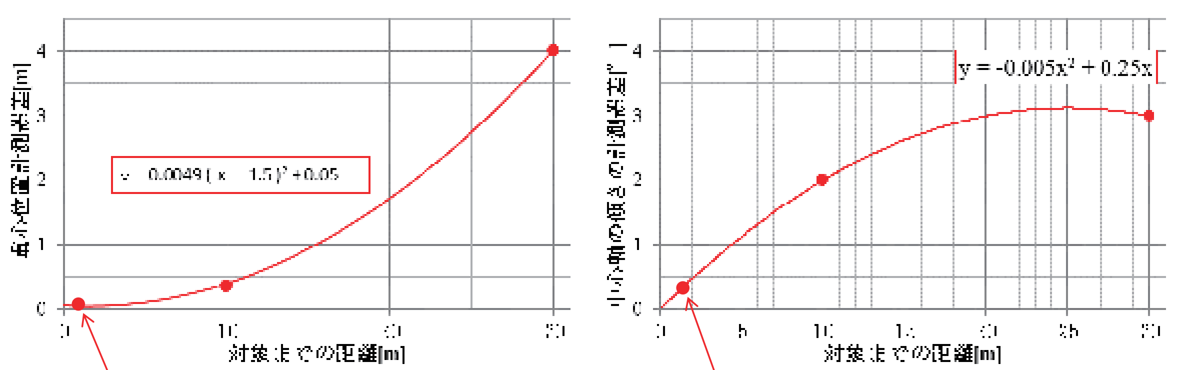
Movement of the central axis

Observation error

- Define observation errors as a function of the distance between the satellite and the debris.

  Error in position [m] = $0.0049\,(x-1.5)^2 + 0.05$

  Error in attitude [°] = $-0.0048x^2 + 0.2433x$

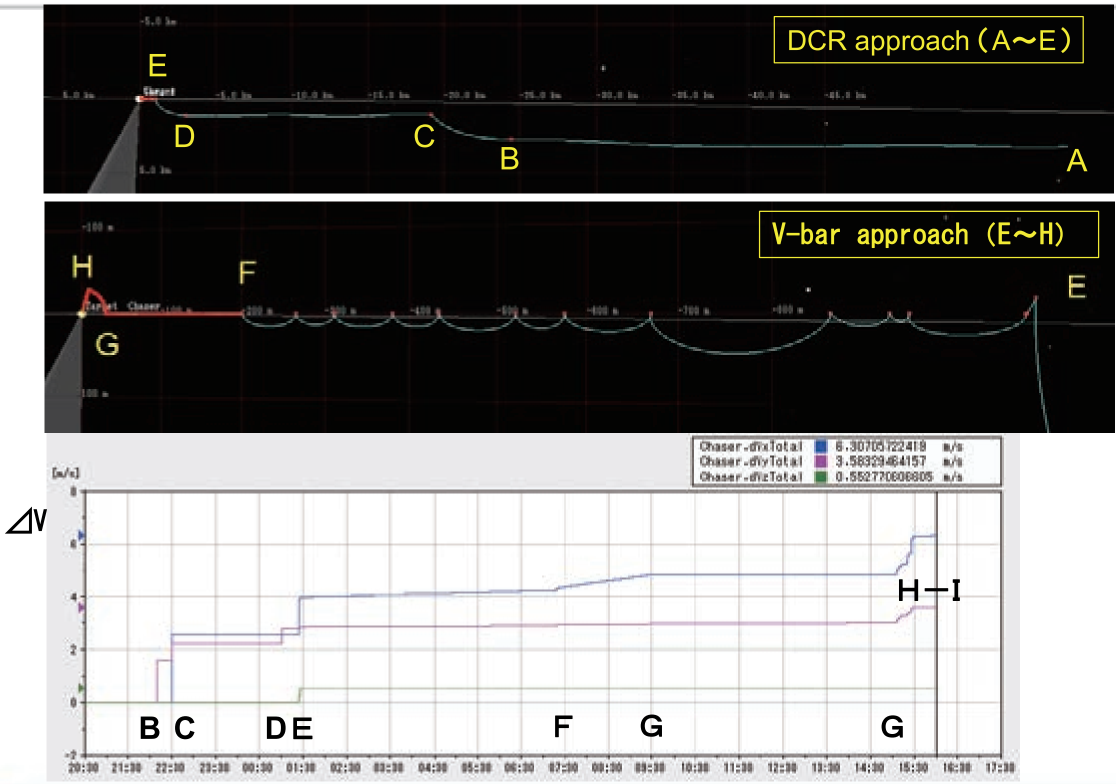


5cm error @1.5m

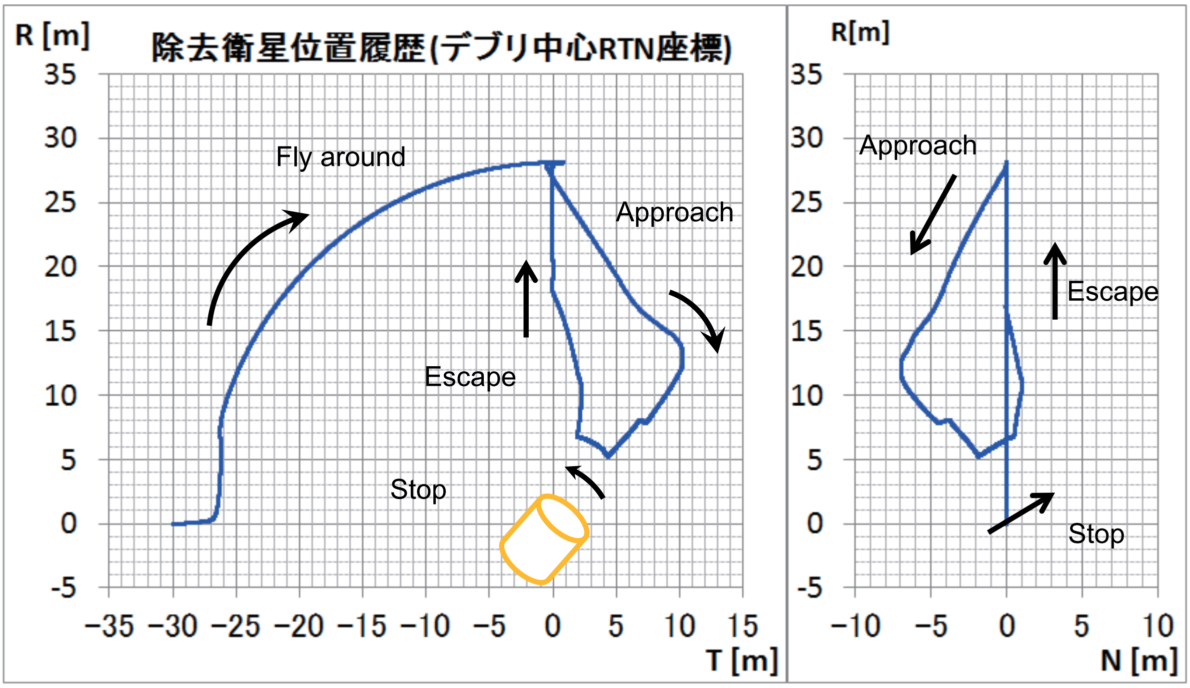
0.36° error @1.5m

Simulation results

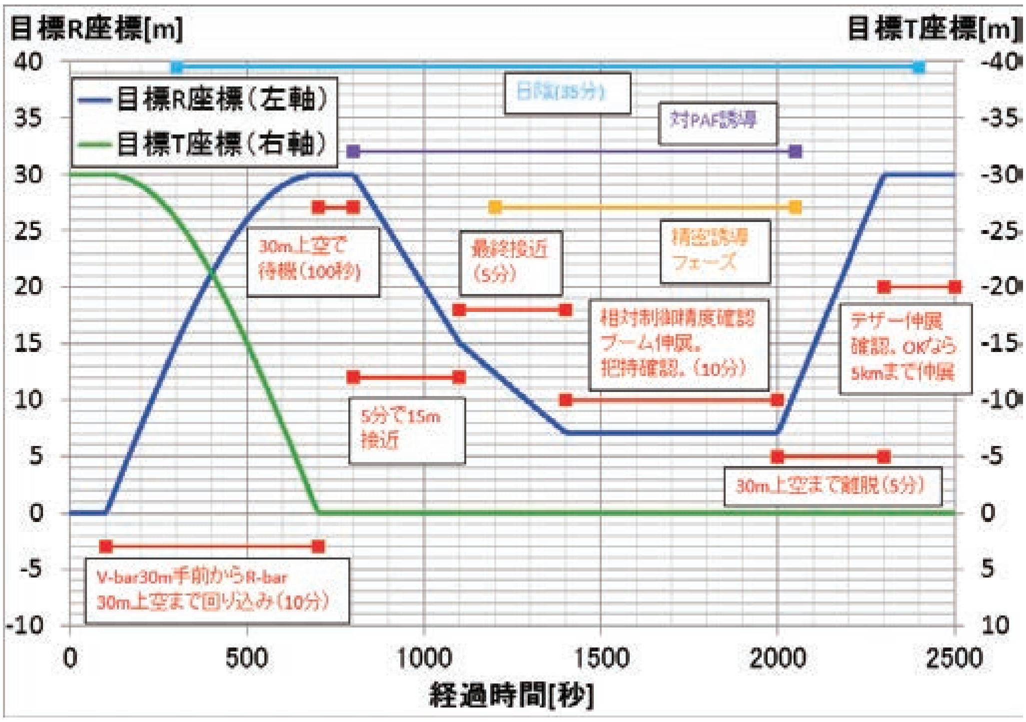
Motion of the satellite in the distant realm from the debris



Motion of the satellite in the vicinity of the debris

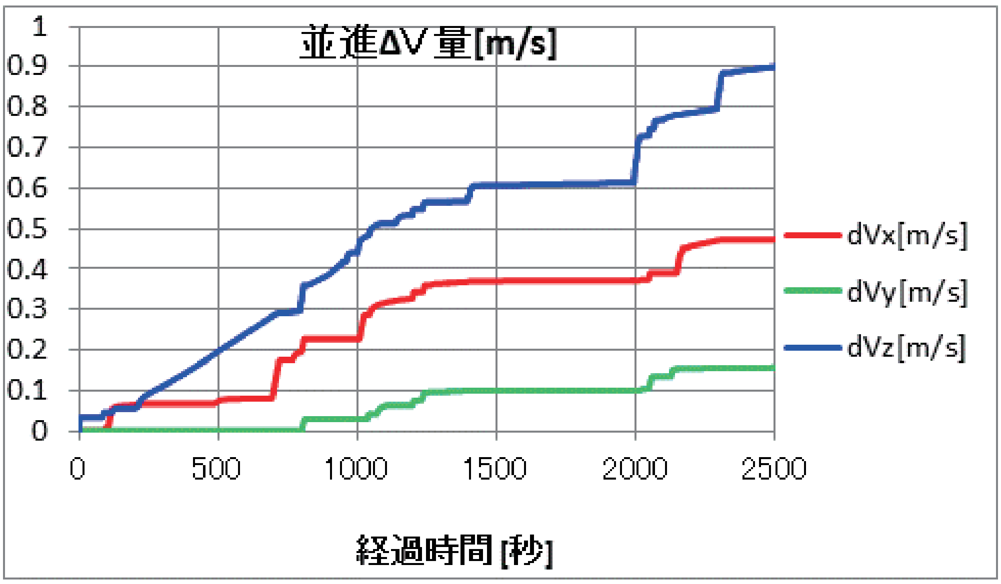


Navigation



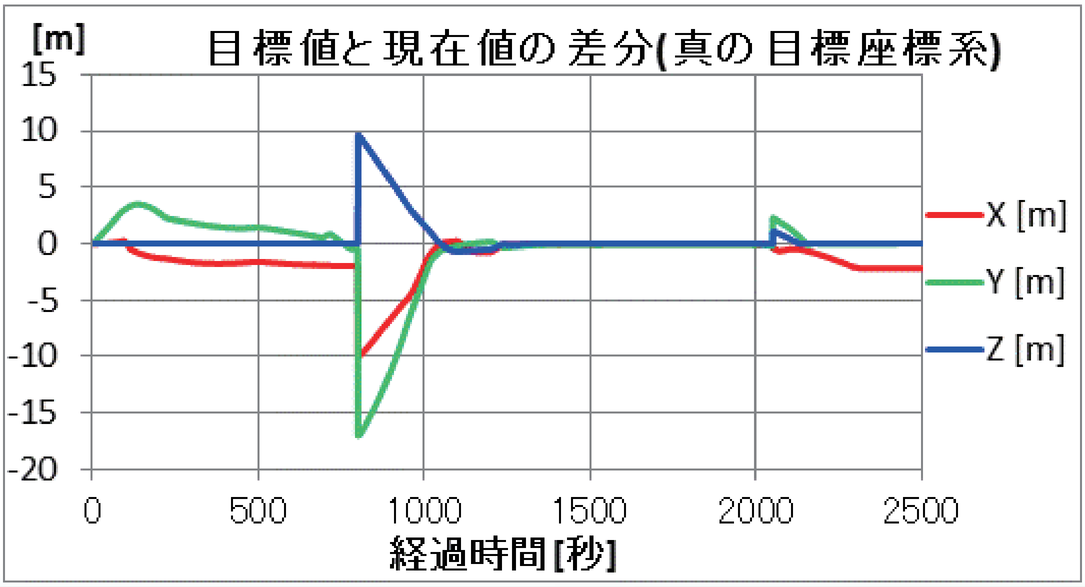
ΔV

- ΔV of each axis is less than 1m/s (x=0.45m/s, y=0.15m/s, z=0.9m/s) at the end of the sequence.



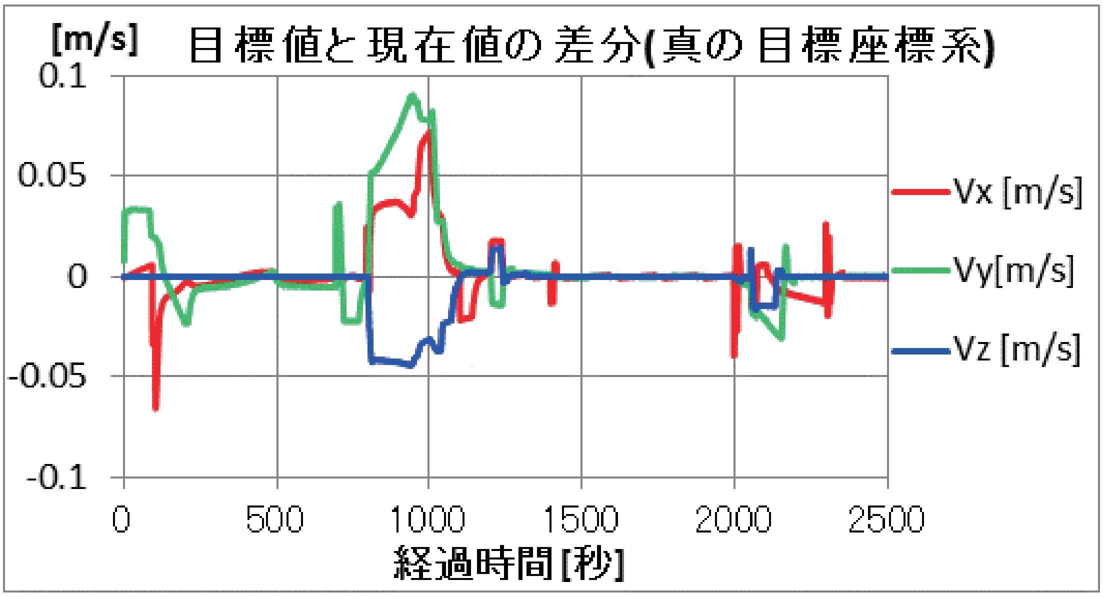
Error in position

- Converge gradually and become nearly-zero at the relative-stop phase.
  - less than ±10cm



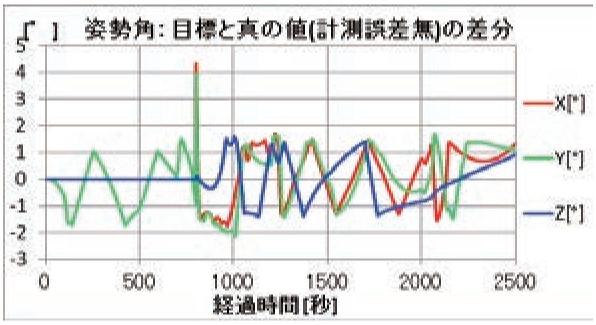
Error in velocity

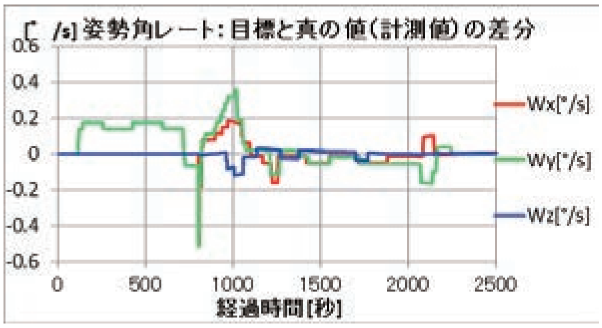
- Less than ±5cm/s



Error in attitude angle / attitude angle rate

- Less than ±5deg in the attitude angle.
- Less than ±1deg/s in the attitude angle rate.





Summary

- Simulate the orbital / attitude motion of the satellite in the distant and close realms from the debris.

- The result shows that the satellite gets closer the debris through DCR and Vbar approach.
  - 19 hours, ΔV=10.4m/s, stating from 80km point

- It also shows that the satellite successfully approaches, stops and escapes from the debris using the thruster control law of HAYABUSA.
  - ΔV of each axis is less than 1.0m/s
  - Errors in position/velocity are nearly-zero.

- Estimation of the position and attitude of the debris using image processing is now under study.

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