C05

安全・推薬消費・運用を考慮したデブリ接近軌道のトレードオフ

Tradeoff Study for Approach Trajectory of Active Debris Removal Satellites Considering Safety, Fuel Consumption, and Operation

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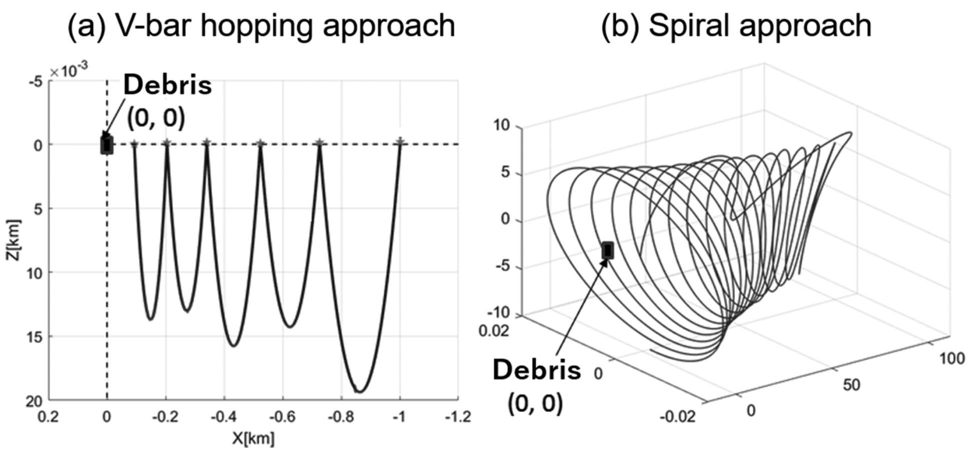
近年，デブリの自然増加が懸念されることから，積極的デブリ除去ミッションが注目を集めている．宇宙航空研究開発機構 (JAXA)でも大型デブリの除去に関する検討がなされており、デブリ除去衛星がデブリへ安全に接近するための軌道の検討が行われている．そこで本発表では，1km から 100m までのデブリ近傍における衛星の接近軌道について，V-bar 上をホップしながら接近する V-bar Hopping と V-bar を中心に螺旋状に接近する Spiral Approach といった 2 つの接近手法について相対軌道運動表現を用いた理論および数値シミュレーションの結果を示す．そして，これら 2 つの手法について，燃料消費量，センサ要求，姿勢制御のしやすさ，センサやアクチュエータが故障した際のミッションアボートなどといった観点からトレードオフ評価を行い，比較および考察する．

The problems of orbital debris tend to be more and more serious in accordance with increase of the amount of space debris. It has become a global challenge for all space-related nations. To solve such crucial problems, much attention is paid to the active debris removal (ADR) missions. In such a mission, satellites should approach to debris which are non-cooperative targets. However, it is hard for them to approach while considering trajectory safety that ensures passive abort (PA) safety even if a part of navigation sensors or control actuators is failed. This paper introduces two types of trajectories (V-bar hopping approach and spiral approach) and compares the robustness to the navigation error and the off-nominal thruster burn, the amount of fuel consumption, and trajectory safety.



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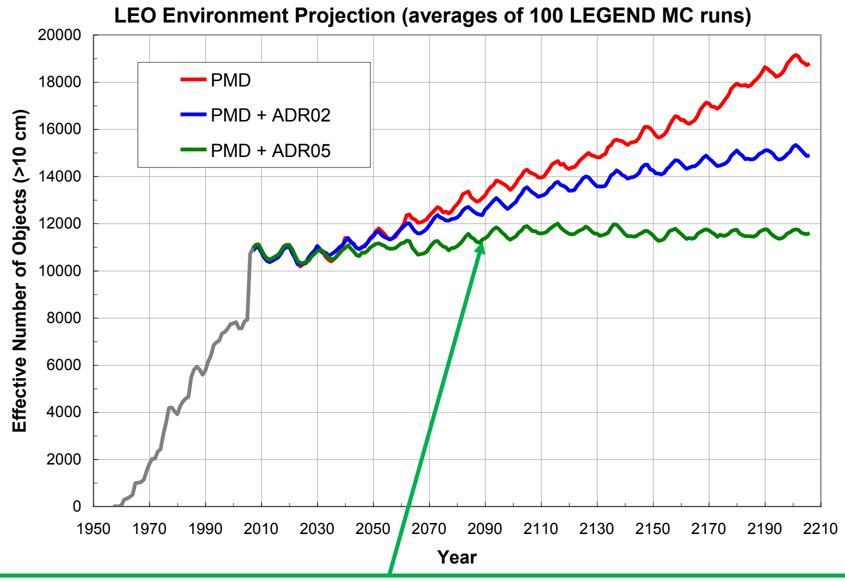
Background (1/3)

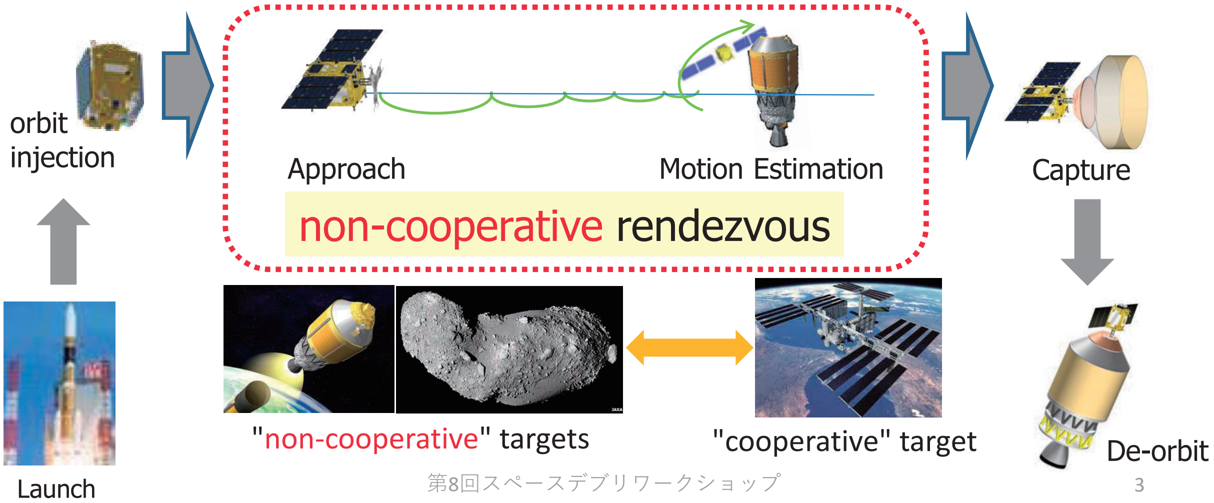


A good implementation of the commonly-adopted mitigation measures and an ADR of **5 objects per year** can control debris growth.

J.-C. Liou, The Near-Earth Orbital Debris Problem and the Challenges for Environment Remediation, The 3rd International Space World Conference, Frankfurt, Germany, 2012

Background (2/3)

- Orbital debris is a serious environmental problem.
- JAXA is now studying cost-effective Active debris removal (ADR)
  - Target debris: Large rocket bodies in crowded orbits in LEO
  - Removal satellite: 500 kg-class small satellite, which could be launched as part of a dual launch, or as clusters.

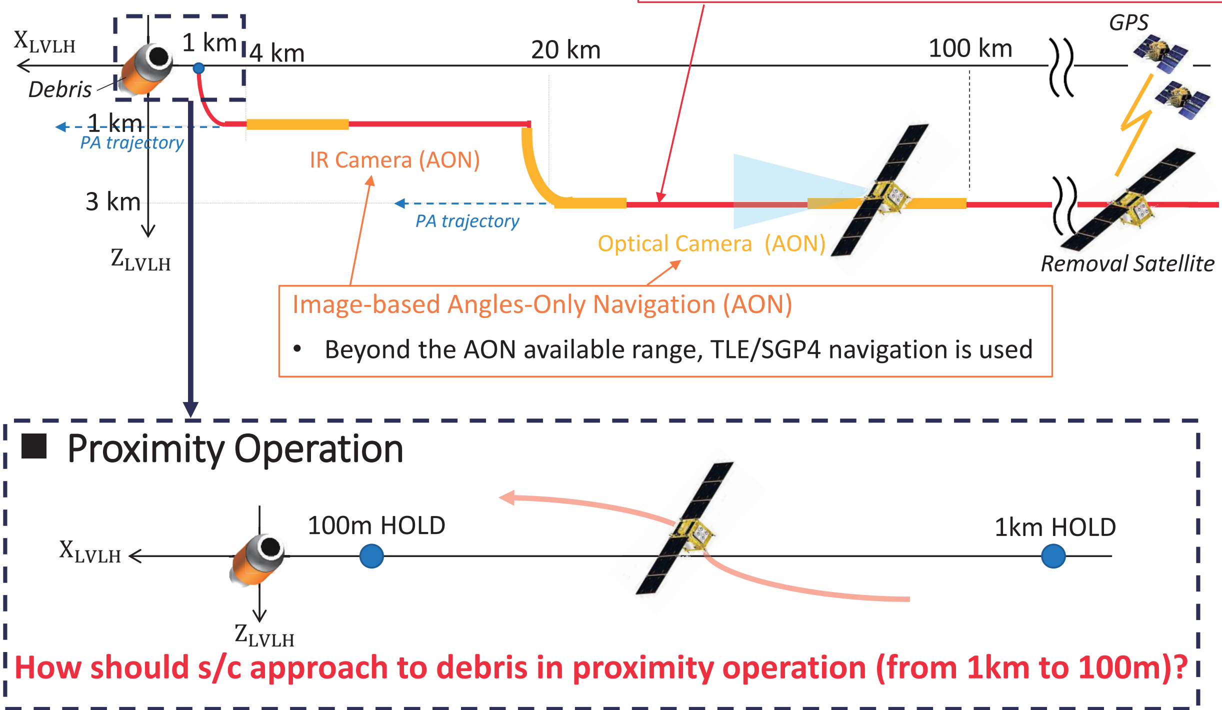


Background (3/3)

Dual co-elliptic orbit

- Passive Abort (PA) safety would be prioritized considering the navigation uncertainty

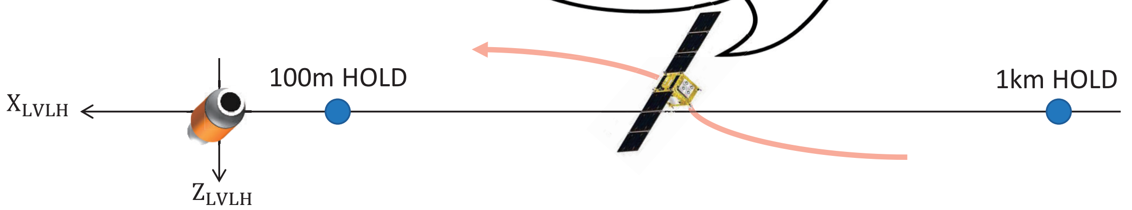
■ Rendezvous Scenario



Motivation (1/2)

- Proximity Operation

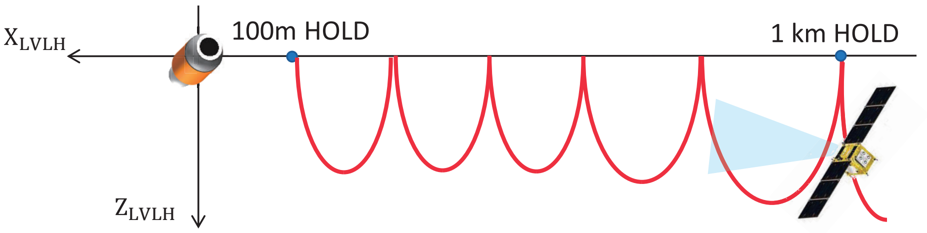
What is “safe trajectory*” to non-cooperative target??



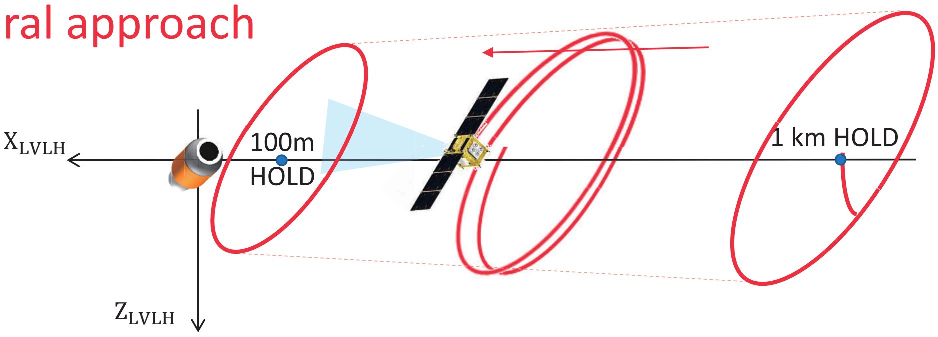
Two safe trajectories are compared in this presentation!!
*Safe trajectory:
guarantee the passive abort safety and the robustness to off-nominal thruster burn

Motivation (2/2)

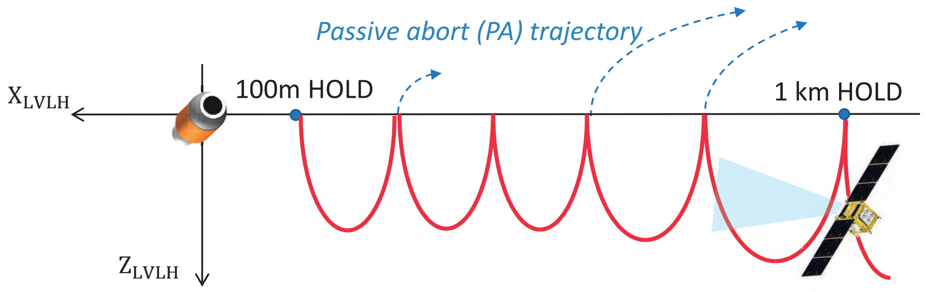
- V-bar hopping approach



- Spiral approach



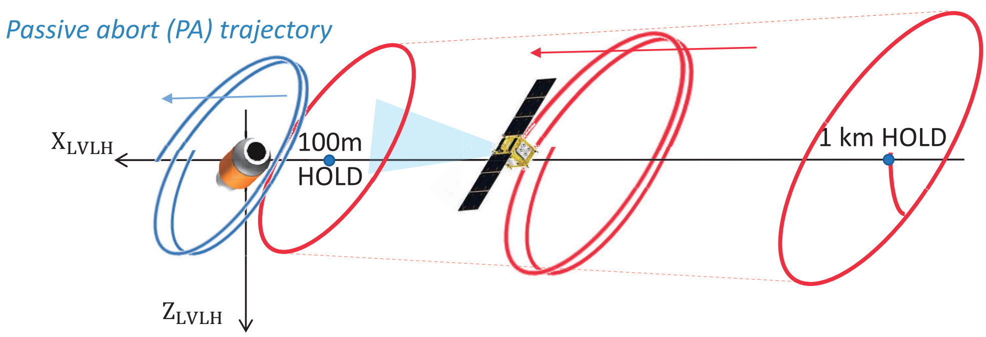
V-bar hopping approach



- V-bar hopping requires lower ΔV compared to straight-line forced motion approach on the V-bar
- Keep Passive Abort (PA) safety
  - insufficient maneuver might be problematic for safety.
  - excessive maneuver might be problematic for safety

ex) Space Shuttle

Spiral approach (1/4)



- Spiral approach also requires lower ΔV compared to straight-line forced motion approach on the V-bar
- Keep Passive Abort (PA) safety
  - insufficient maneuver is safe (still (e/i) Vector Separation can be kept)
  - excessive maneuver might be problematic for safety

ex) AVANTI, PRISMA

Spiral approach (2/4)

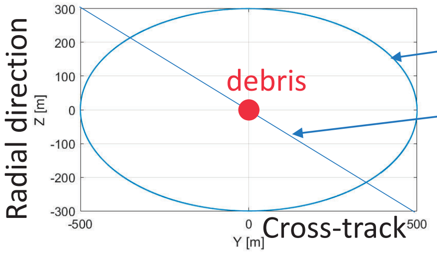
Eccentricity/Inclination (e/i) Vector Separation

Relative orbital elements (ROEs) are defined by

$$a\delta\boldsymbol{\alpha} = a \begin{bmatrix} \delta a/a \\ \delta e_x \\ \delta e_y \\ \delta i_x \\ \delta i_y \\ \delta u \end{bmatrix}$$

- $\delta a/a$: Relative semi-major axis
- δe_x, δe_y : Eccentricity vector *Δe*
- δi_x, δi_y : Inclination vector *Δi*
- δu : Relative argument of latitude

Parallel or unti-parallel vectors *Δe* and *Δi* imply safe trajectory while keeping distance between s/c and debris.



$\Delta e \parallel \Delta i$ This relationship is used in spiral approach!

$\Delta e \perp \Delta i$

Spiral approach (3/4)

Relative orbit control

Gauss equation:

$$\begin{bmatrix} Da \\ De_x \\ De_y \\ Di_x \\ Di_y \\ Du \end{bmatrix} = \frac{1}{v} \begin{bmatrix} 0 & 2a & 0 \\ \sin u & 2\cos u & 0 \\ -\cos u & 2\sin u & 0 \\ 0 & 0 & \cos u \\ 0 & 0 & \sin u \\ 0 & -3v/a \cdot \Delta t & 0 \end{bmatrix} \begin{bmatrix} \Delta v_R \\ \Delta v_T \\ \Delta v_N \end{bmatrix}$$

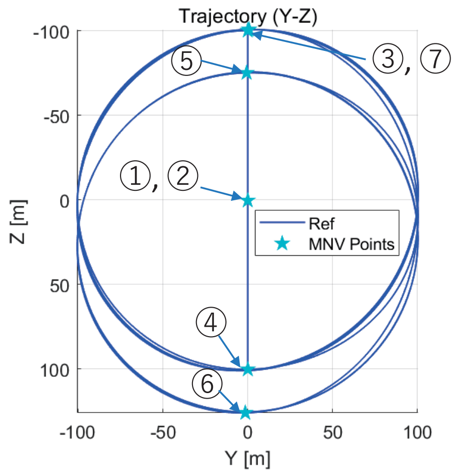
It provides the relationship between the velocity changes ΔV and the desired orbital corrections and can be used to solve the maneuver planning problem.

Spiral approach (4/4)

Step1: Elliptic motion

①, ②: ΔV (Radial direction) for tracking by desired Δe

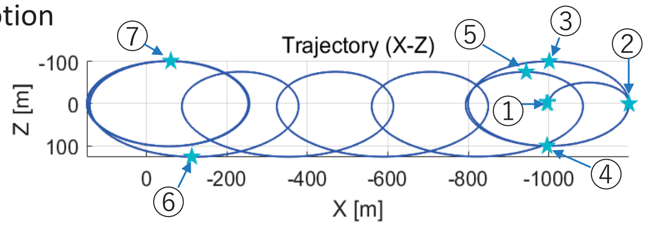
③: ΔV (Cross-track) for tracking by desired Δi



Step2: Spiral motion

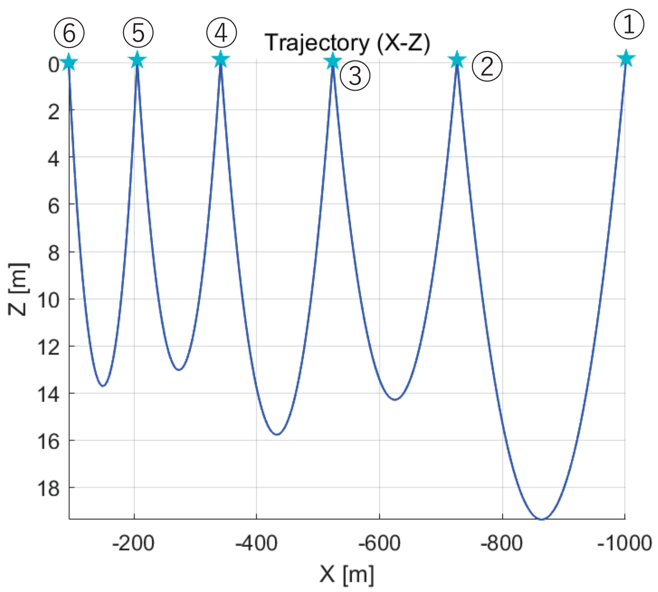
④, ⑤: ΔV (tangential direction) for spiral motion

⑥, ⑦: ΔV (tangential direction) for stopping



Comparison of ΔV consumption (1/2)

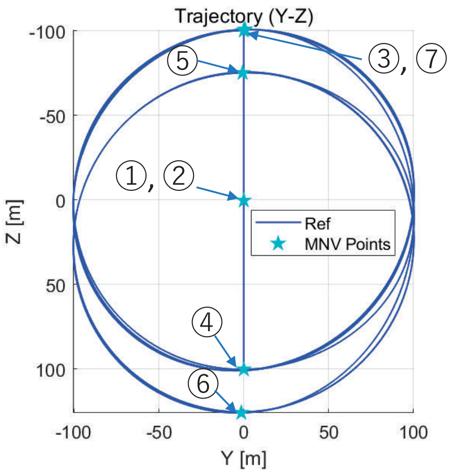
V-bar hopping



①	1.273 m/s
②	0.773 m/s
③	0.608 m/s
④	0.513 m/s
⑤	0.391 m/s
⑥	0.323 m/s
Total ΔV:	3.881 m/s

Comparison of ΔV consumption (2/2)

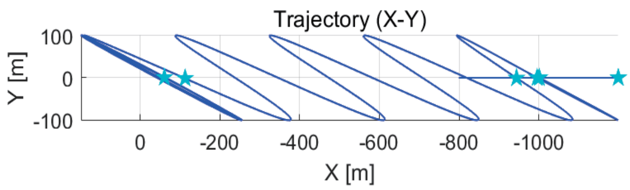
Spiral approach

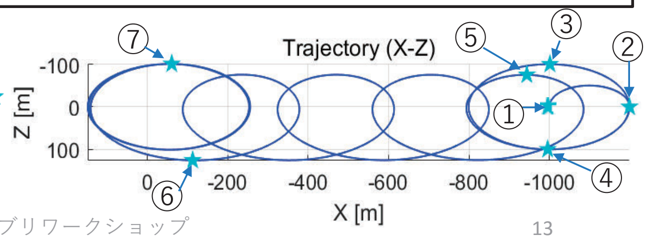


① 0.0539 m/s ($u = 0$)
② 0.0539 m/s ($u = 2\pi$)
③ 0.1079 m/s ($u = \pi/2$)
④ 0.0067 m/s ($u = -\pi/2$)
⑤ 0.0067 m/s ($u = \pi/2$)
⑥ 0.0067 m/s ($u = -\pi/2$)
⑦ 0.0067 m/s ($u = \pi/2$)

ΔV consumption of V-bar hopping

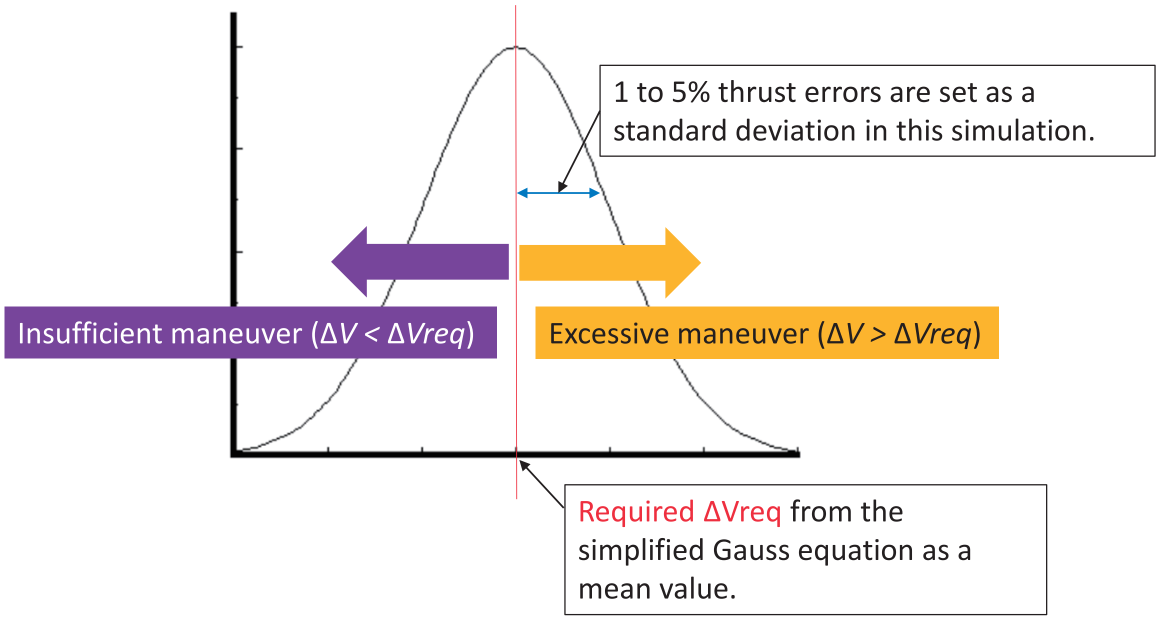
Total ΔV: 0.243 m/s (< 3.881 m/s)





10 run MC* simulation results (1/5)

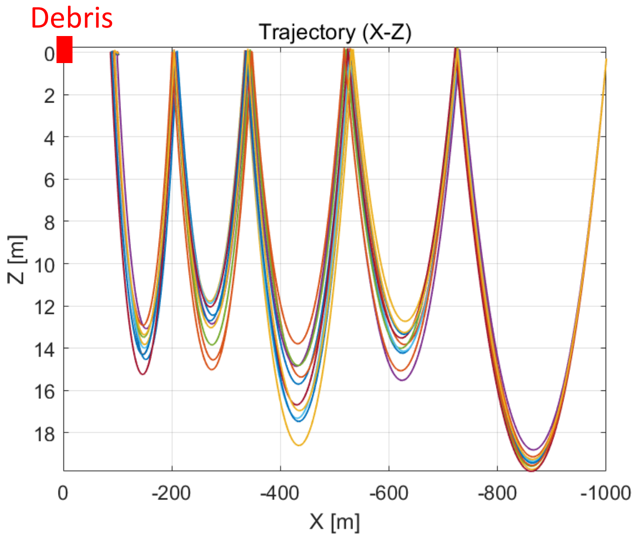
Thrust error is considered using the following probability density function (PDF) of the normal distribution.



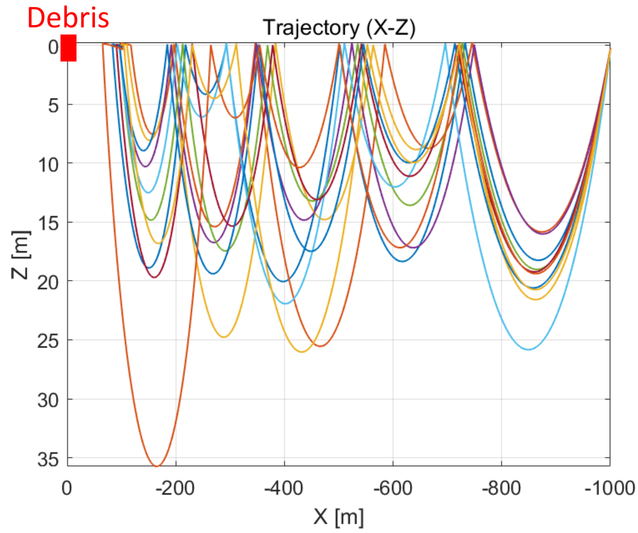
10 run MC* simulation results (2/5)

V-bar hopping (X-Z plane)

* MC: Monte Carlo



X-Z plane trajectory with 1% thrust error

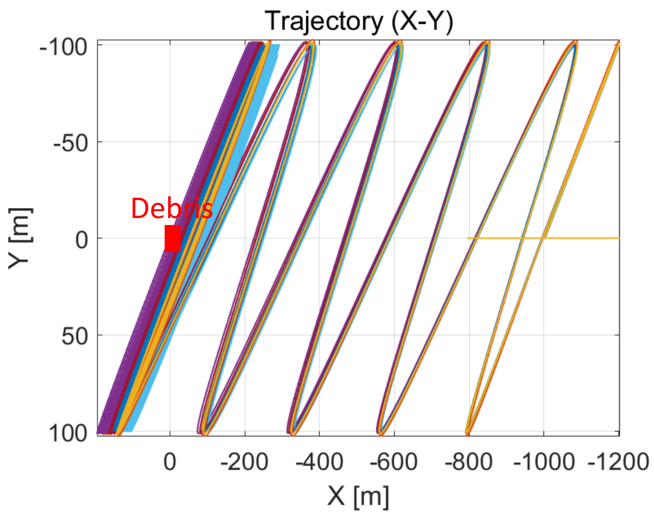


X-Z plane trajectory with 5% thrust error

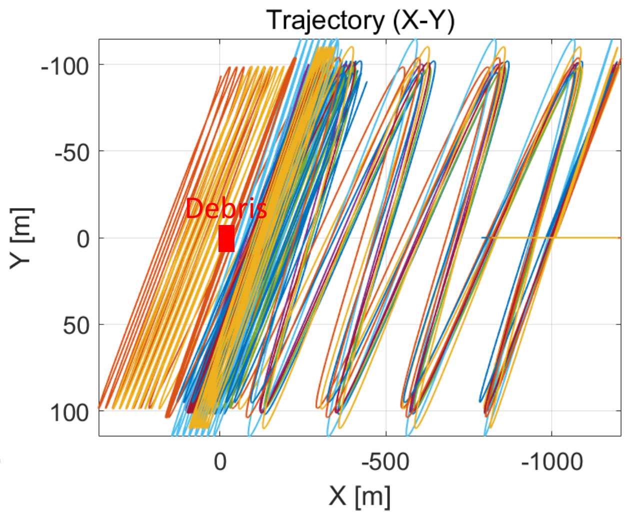
10 run MC* simulation results (3/5)

Spiral approach (X-Y plane)

* MC: Monte Carlo



X-Y plane trajectory with 1% thrust error

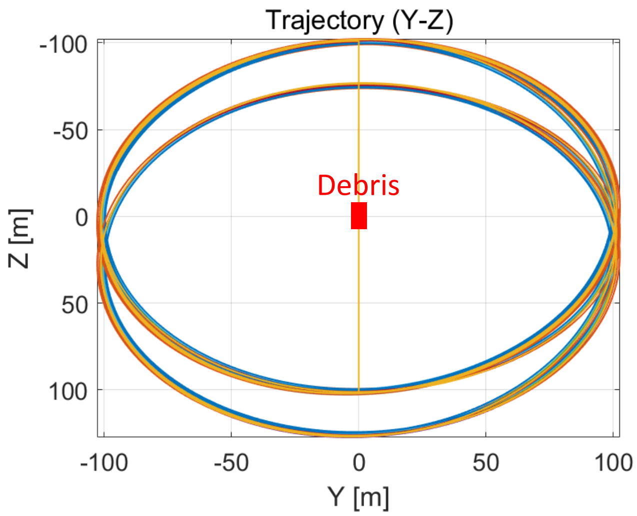


X-Y plane trajectory with 5% thrust error

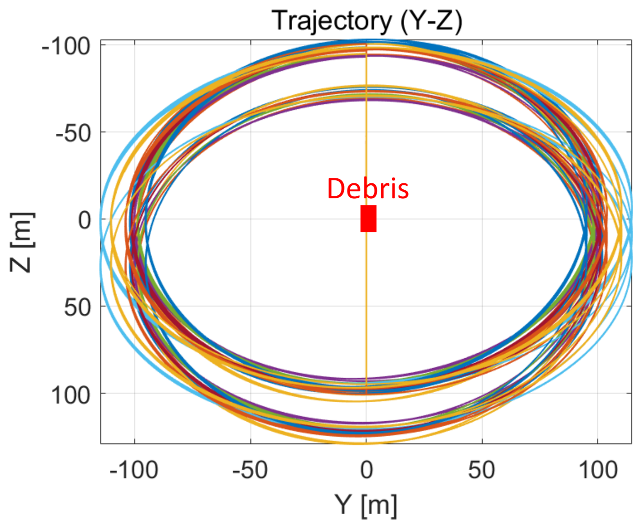
10 run MC* simulation results (4/5)

Spiral approach (Y-Z plane)

* MC: Monte Carlo



Y-Z plane trajectory with 1% thrust error

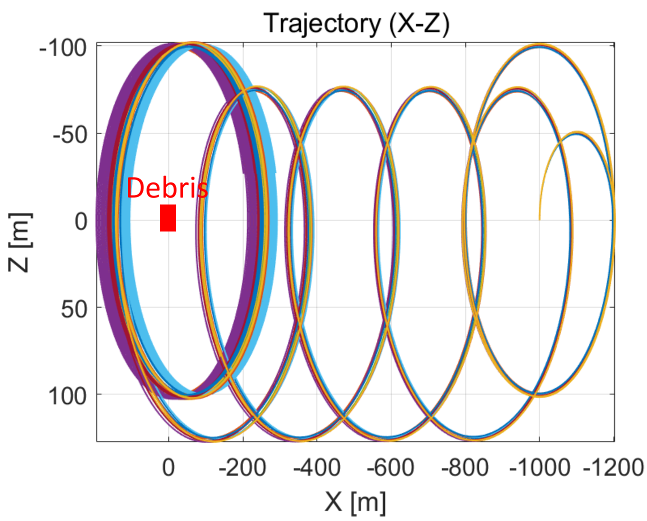


Y-Z plane trajectory with 5% thrust error

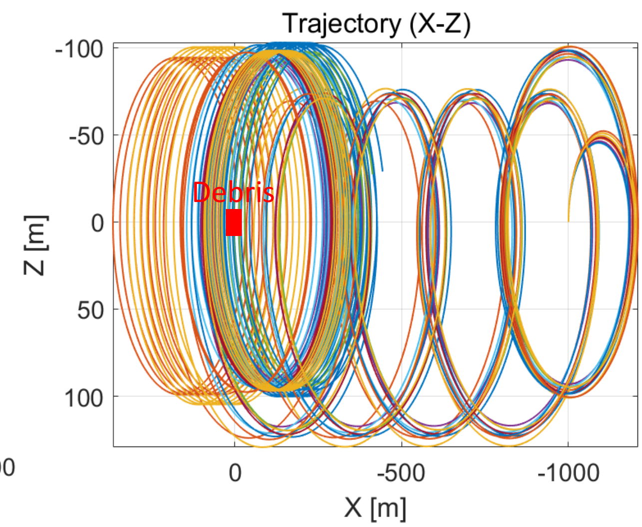
10 run MC* simulation results (5/5)

Spiral approach (X-Z plane)

* MC: Monte Carlo



X-Z plane trajectory with 1% thrust error



X-Z plane trajectory with 5% thrust error

Summary

- Two safe trajectories (V-bar hopping trajectory and spiral one) are presented.
- The amounts of fuel consumption (ΔV) are calculated and compared.
- Trajectory safety (in the case of excessive/insufficient maneuver) are demonstrated through Monte Carlo simulations.

Open questions remain

- How to determine the parameters. (e.g. hopping rate, desired relative orbital elements…)
- Considering sensor modeling and navigation error