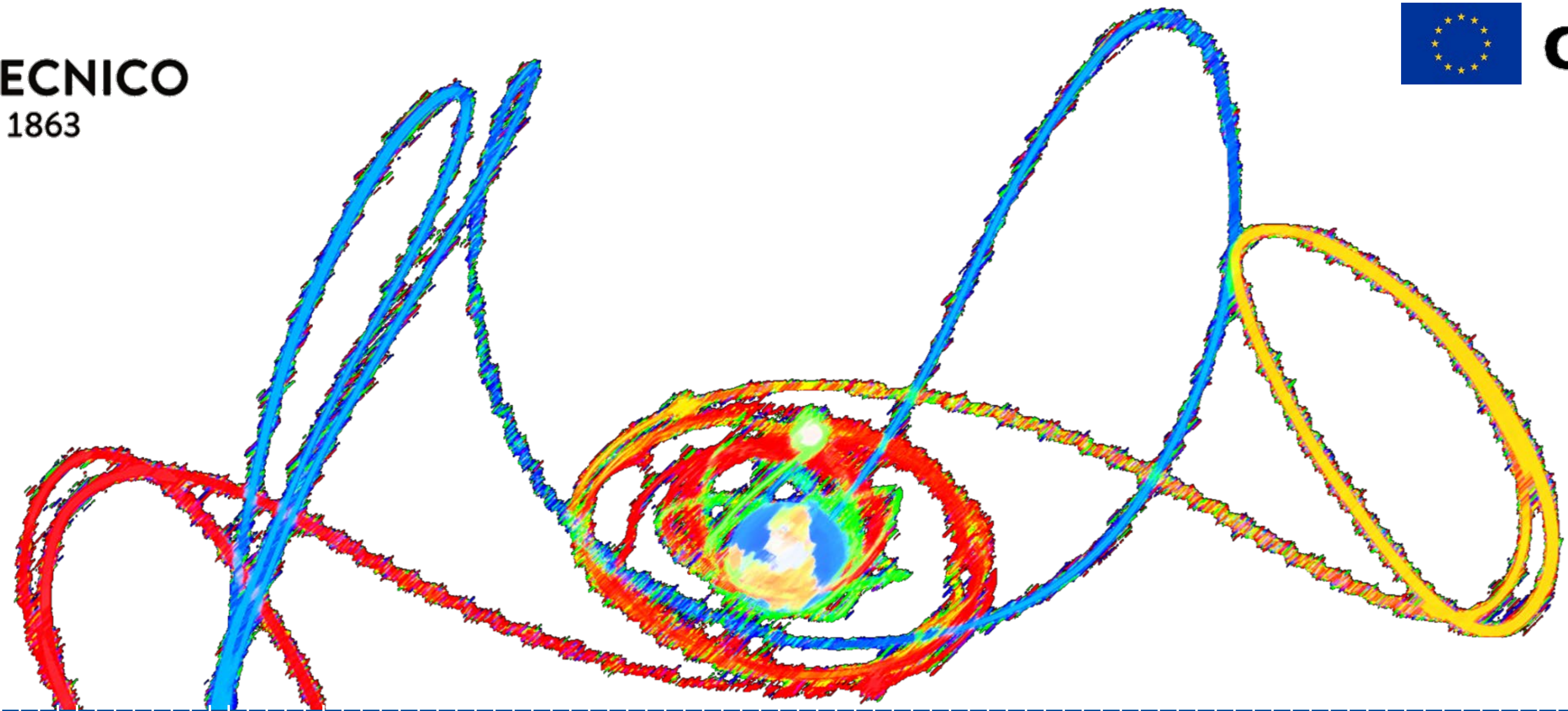

Trajectory Optimization for The Proximity Rendezvous Operation Considering The Relative Navigation Error

Yu Nakajima*(PoliMi/JAXA),
Giacomo Borelli, Gaias Gabriella, Camilla Colombo (PoliMi),
Taisei Nishishita, Hiroyuki Okamoto (JAXA)

Clean Space Industiral Days, Oct. 18 2023@ ESTEC

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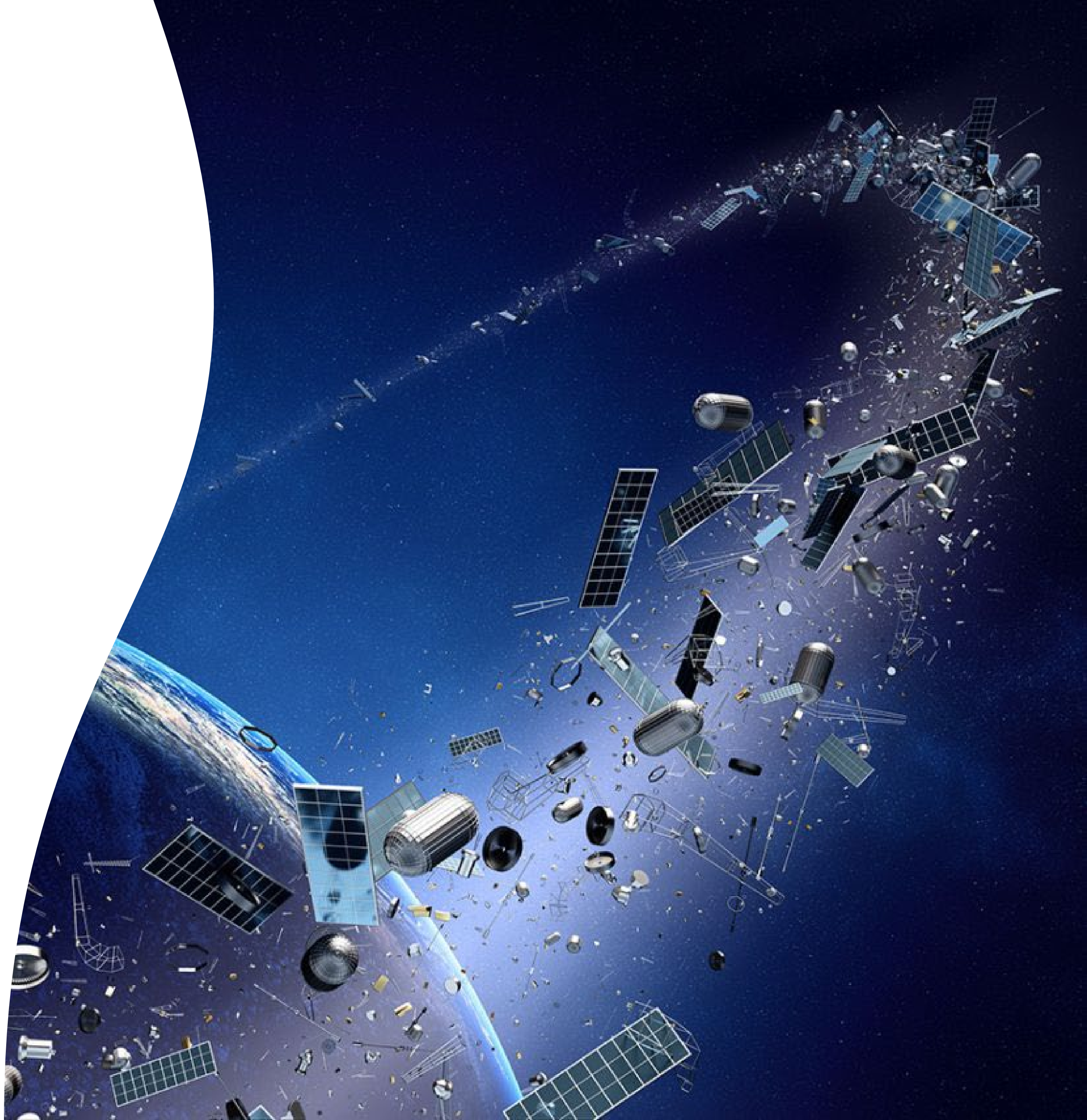
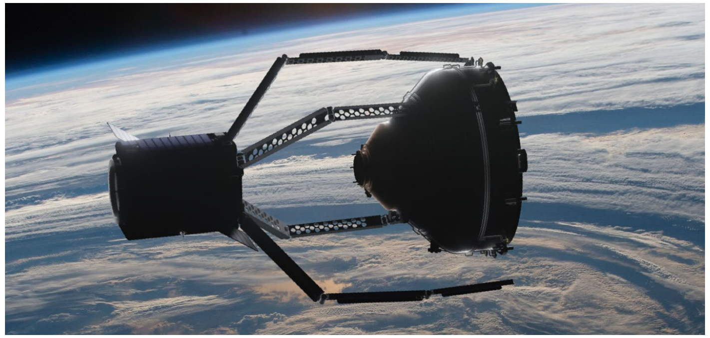
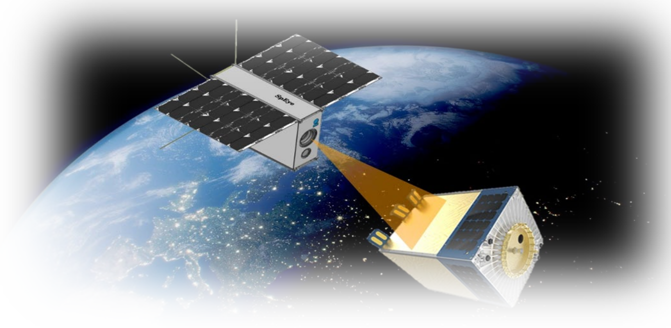


Background

- Paradigm shift from one-time use platform to reusable and recycling of systems (satellite and orbits)
- **In-orbit Servicing (Mission extension, repair, refueling)** is demanded to improve mission effectiveness
- **Active Debris Removal (ADR)** for collision risk mitigation of crowded orbit will ensure a future sustainable exploitation of space environment
- Technical demonstration of above technologies with small satellites are increasing
  - **SpEye Mission** (Italy) to demonstrate inspection & proximity operation by cubesat
  - **CRD2 Program** (Japan) to demonstrate the technological feasibility of removing rocket upper stage from the orbit


OSAM-1 mission, image taken from [1].


ClearSpace-1 mission, image taken from [2].

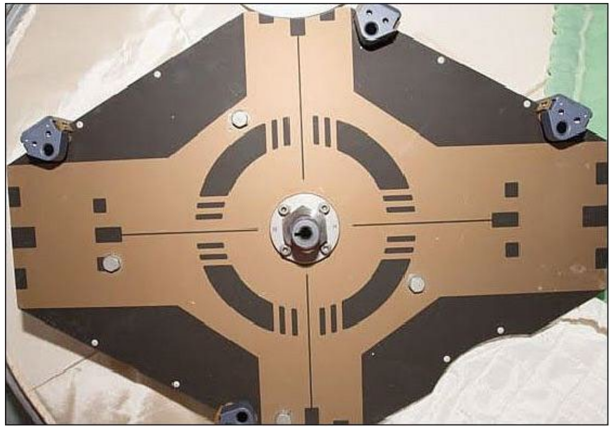

SpEye mission


CRD2 phase I (ADRAS-J), image taken from [3]

[1] https://nexis.gsfc.nasa.gov/osam-1.html Accessed: 1-7-2023
[2] https://www.esa.int/ESA_Multimedia/Images/2020/11/ClearSpace-1_captures_Vespa Accessed: 1-7-2023
[3] https://astroscale.com/ja/missions/adras-j/ Accessed: 10-1-2023

The Key Technologies for Non-cooperative Rendezvous

- The safe and robust rendezvous is required for achieving in-orbit servicing or ADR
- The most challenging technologies is **NAVIGATION**
  - The rendezvous itself has a long history of development by ISS operation
  - The navigation performance is relatively high due to the **reflector installed on ISS**
  - Navigation accuracy is degraded against a **non-cooperative target** since there is no clue for navigation
  - The navigation accuracy has strong dependency on the **relative attitude, position, or direction of earth/sun**
  - It is difficult to set a unified **navigation performance interface**



Retro-reflector installed on ISS[4]

HTV-8 captured by ISS [5]

[4] https://www.eoportal.org/other-space-activities/iss-storrm#iss-utilization-storrm-sensor-test-for-orion-relnav-risk-mitigation Accessed: 29-9-2023
[5] https://iss.jaxa.jp/htv/mission/htv-8/news/capture.html Accessed: 29-9-2023

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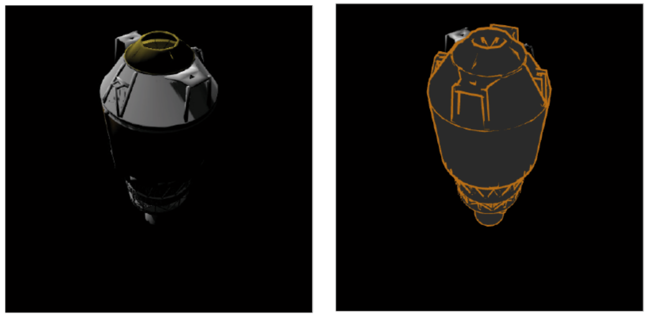
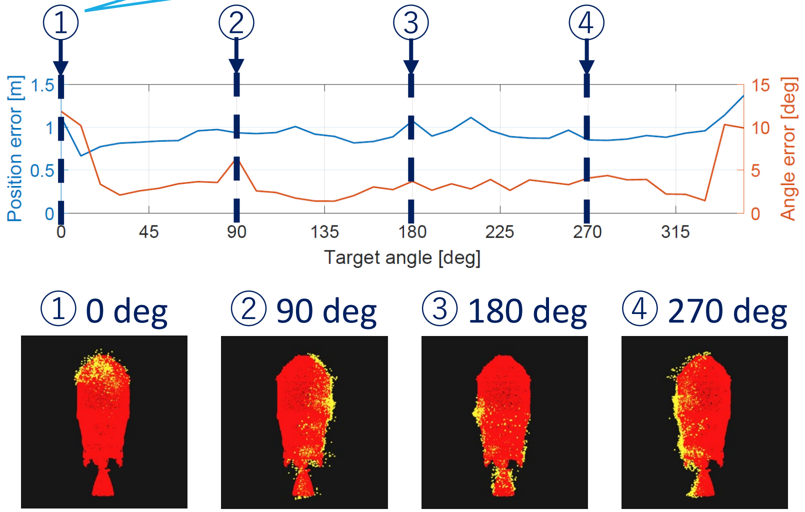

a) Input image (grand truth) b) Overlay estimation on grand truth

Optical camera-based pose estimation failure case [6]

If you see the target from position facing PAF, navigation error increases



LiDAR based matching accuracy with reference to attitude [7]

It is ideal if we could pass the trajectory with **high confidence navigation**
High confidence: the relative conditions where the sensor can handle easily

[6] Hashimoto et al. "6-DoF Pose Estimation for Axisymmetric Objects Using Deep Learning with Uncertainty," IEEE Aerospace Conference, 2020.
[7] Nishishita et al. "LiDAR-Based Navigation Strategies for a Non-Cooperative Target Considering Rendezvous Trajectory," 74th IAC, 2023.

Goals of this research

- We develop a new trajectory design approach to achieve **safe** and **robust** rendezvous, although only affordable COTS sensors are used
  - The trajectory also satisfies:
    - Safety constraints (KOZ, corridors)
    - Approach speed limit to the target
  - The optimized trajectory minimizes:
    - Total Δv
    - **Relative navigation error during the approach**

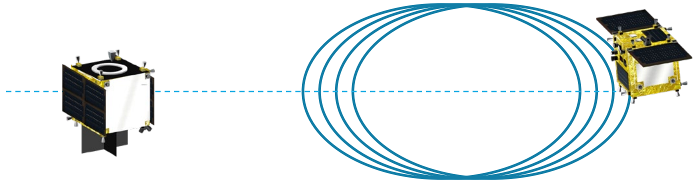
The previous works [9]

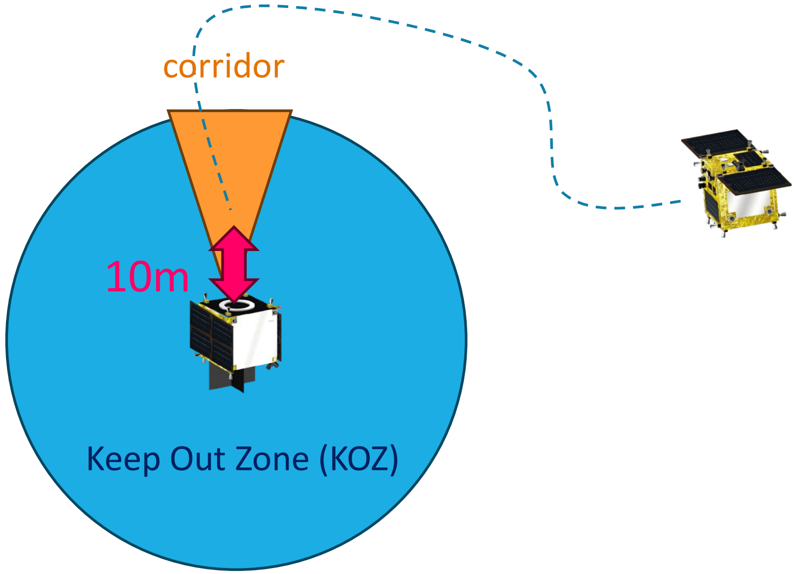
An originality of this work

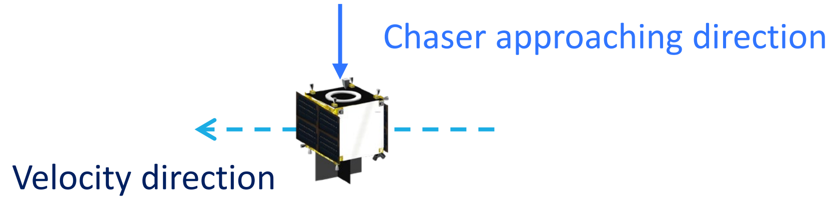
[9] Giacomo Borelli et al. "SAFETY IN FORCED MOTION GUIDANCE FOR PROXIMITY OPERATIONS BASED ON RELATIVE ORBITAL ELEMENTS," AAS/AIAA 33rd Space Flight Mechanics Meeting, Jan 2023.

The simulated conditions

- Relative motion
  - Initial state
    - Spiral E/I separated trajectory that satisfies the passive abort safety
  - Final state
    - Coupled with the attitude motion of ION
      - Trying to face a specific point on the target (Let's say try to point PAF of the ION)
      - Keeping relative COG distance 10 m (TBD)
- Chaser attitude
  - Pointing to the target
- Target attitude
  - LVLH fixed
  - PAF is facing zenith (chaser approaching direction)


Relative parking orbit
(initial condition)





Types of Navigation Sensors

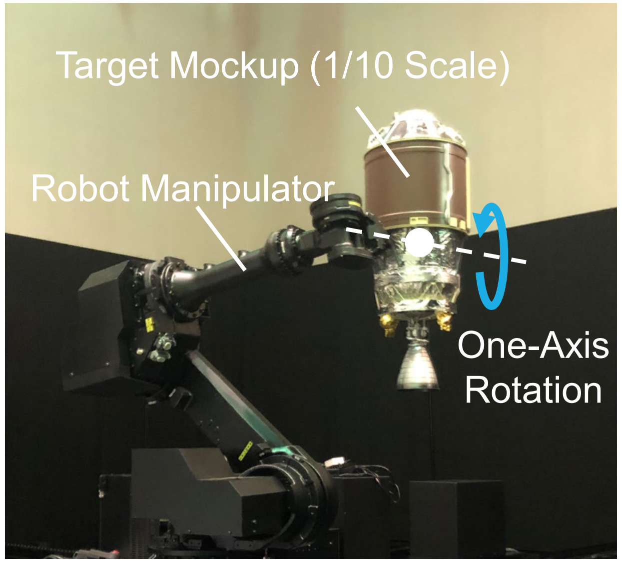
- Various navigation sensors are investigated for rendezvous to a non-cooperative target
  - LiDAR
  - Optical camera (visual light, IR)
  - Radar
  - Laser sensor
- Each sensor has good/bad conditions for navigation
- It is difficult to evaluate actual performance on ground and set a unified interface, as we cannot fully emulate the in-orbit situation.
- Model interface: Possibility of in-orbit update of sensor models exist, because it may be different from a ground evaluation. Therefore, a simple datatable and function format is adopted.

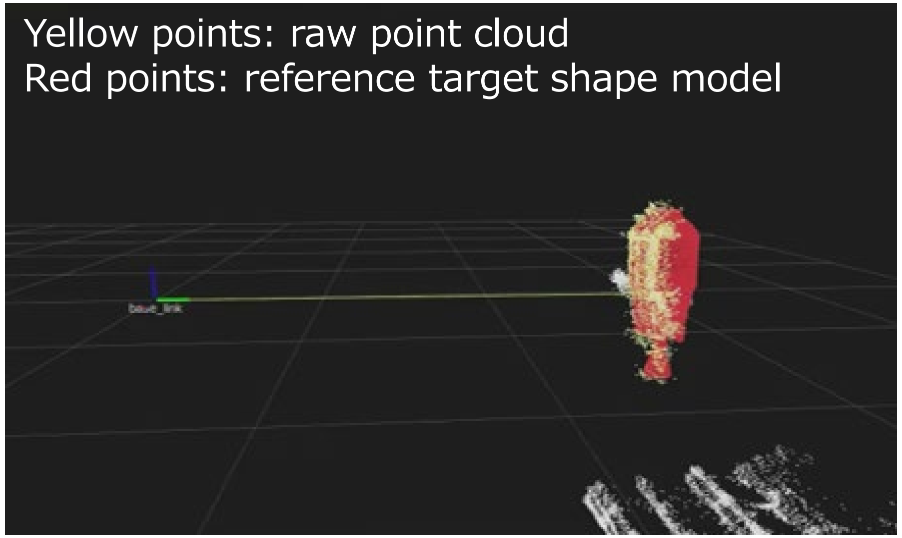
Sensor	Pros	Cons
LiDAR	Accuracy is robust to relative distance	Accuracy is dependent on relative attitude
IR cam	Accuracy is robust to sun direction	Estimation is difficult if Earth is in FOV
Visual cam	Accuracy is robust to relative attitude	Accuracy is dependent on relative sun direction and relative distance. Estimation is difficult if Earth is in FOV
Radar	Accuracy is robust to relative distance	Relative attitude estimation is difficult
Laser sensor	Accuracy is robust to relative distance	Relative attitude estimation is difficult

Characteristics of Navigation Sensors

- Characteristics of relative navigation accuracy
  - Relative navigation, such as image processing generally have uneven accuracy depending on the relative position or attitude
  - The unevenness is basically coming from the shape and materials of the target (target dependent)
  - The navigation error distribution can be verified through ground evaluation & in-orbit inspection
  - The navigation errors can be modelled as either a data table or a function:
- We modelled two types of relative navigation error model
  - LiDAR based ICP matching
  - Optical Camera based visual matching
- The LiDAR navigation has dependency on the relative attitude
  - A data-table from ground experimental results is interpolated to obtain an expected navigation accuracy
- The optical camera has dependency on relative distance
  - Approximated function is derived from the experimental results on a literature

$$E(r_{rel}, q_{rel}) = \begin{cases} interpolating\ datatable & \text{LiDAR} \\ 0.0036e^{0.07|r_{rel}|} & \text{Optical camera} \end{cases}$$




Yellow points: raw point cloud
Red points: reference target shape model

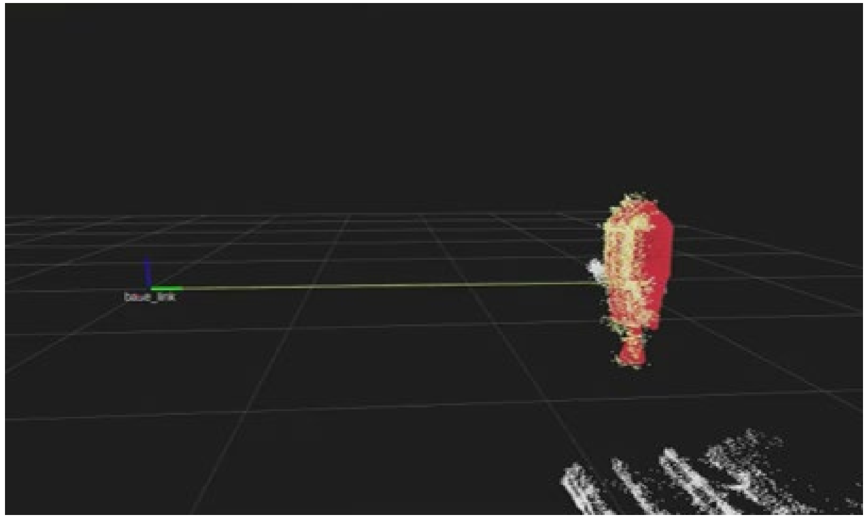
[7] Nishishita et al. "LiDAR-Based Navigation Strategies for a Non-Cooperative Target Considering Rendezvous Trajectory," 74th IAC, Baku, Oct. 2023.

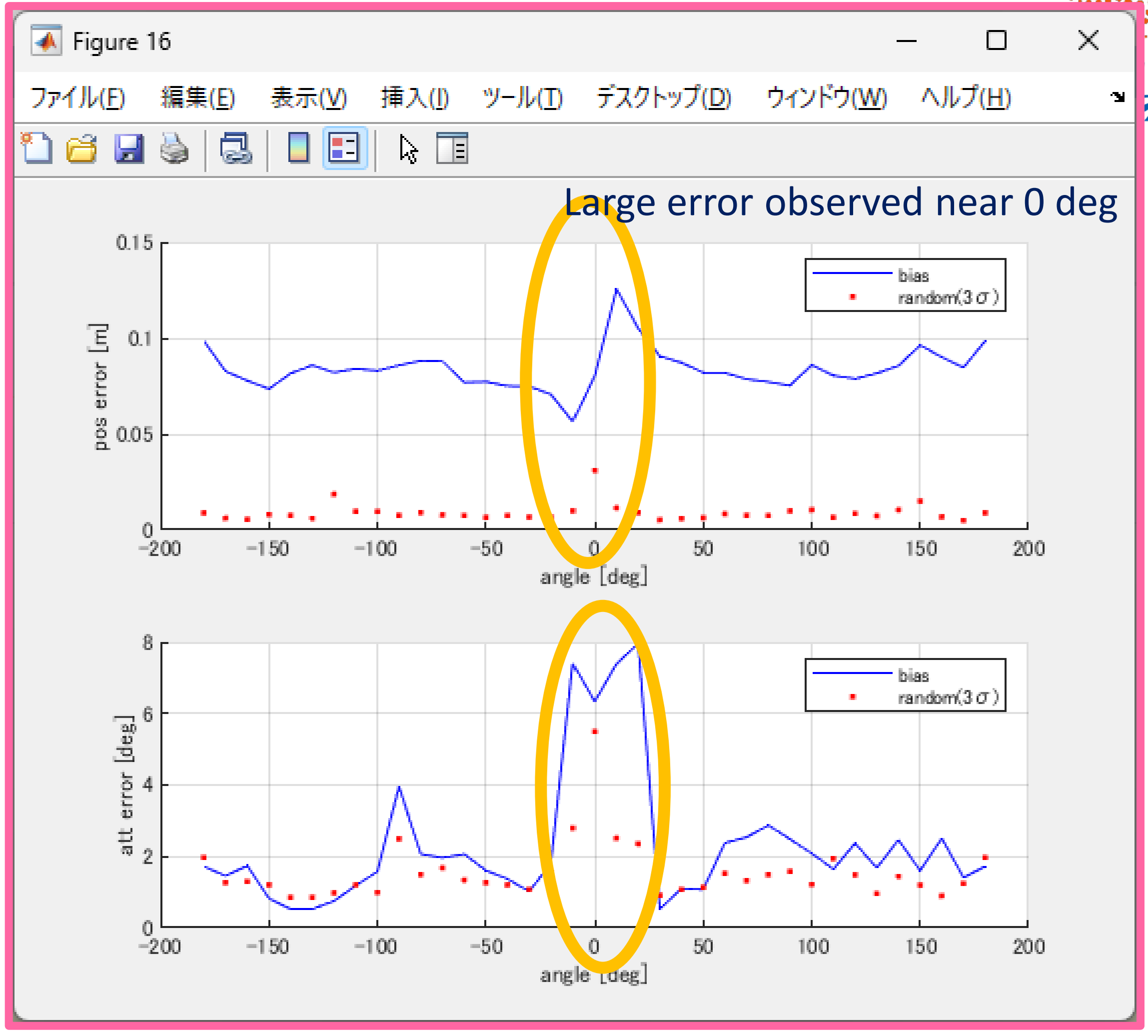
LiDAR Navigation Error Model

- Target:

  H-2A rocket upper stage body

- Datatable:
  - Experimentally obtained performance with reference to the rotation on Z axis
  - The performance validation with reference to rotation on X axis is modelled with cosine function
  - The nav error with arbitral relative angle is derived by interpolating the datatable





Large error observed near 0 deg

Random error can be minimized by filter, so from **bias error** the expected model was constructed

LiDAR Navigation Error Model

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  H-2A rocket upper stage body

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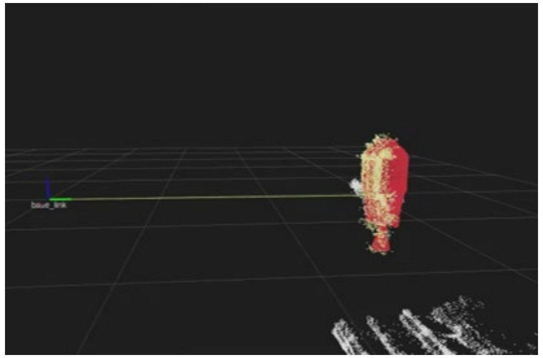
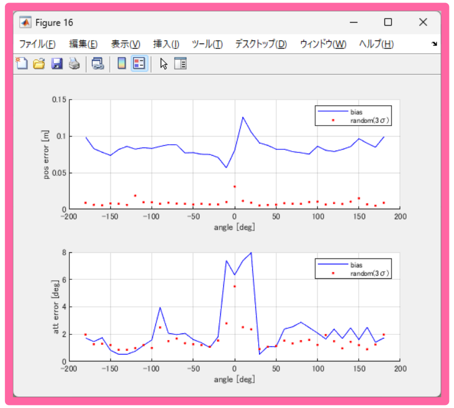




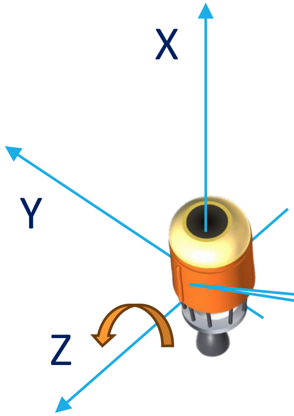
θ_{ele} [deg]	Nav error expect.
0	Xxx
10	Yyy
20	Zzz
30	Aaa
350	bbb

Interpolation

$$\epsilon(\theta_{azi},\theta_{ele}) = \underline{(\cos(\theta_{azi})+2)}\,\underline{\epsilon(\theta_{ele})}$$

Coefficient with reference to azimuth angle

Experimentally obtained datatable for error function of elevation angle

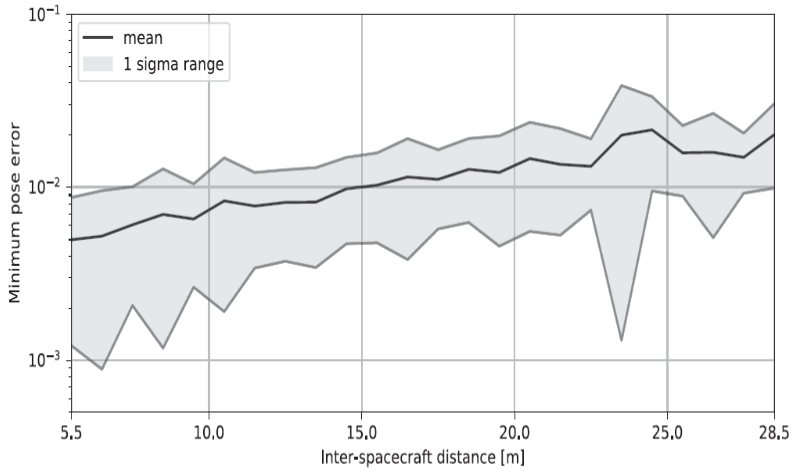


Assuming that if the external pipe-line (feature point) are observable, the accuracy is triple compared to that of the case where pipe-line is not observable

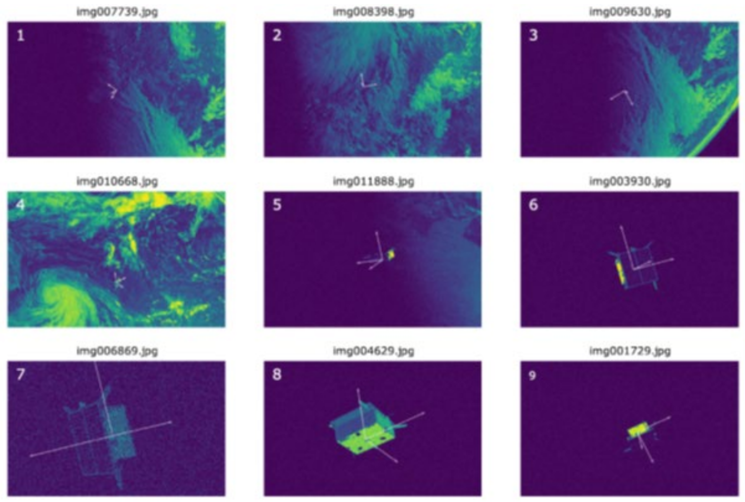
Visual Camera Matching Error Model

Relative navigation accuracy using optical camera (Visual light) is modelled from literatures.

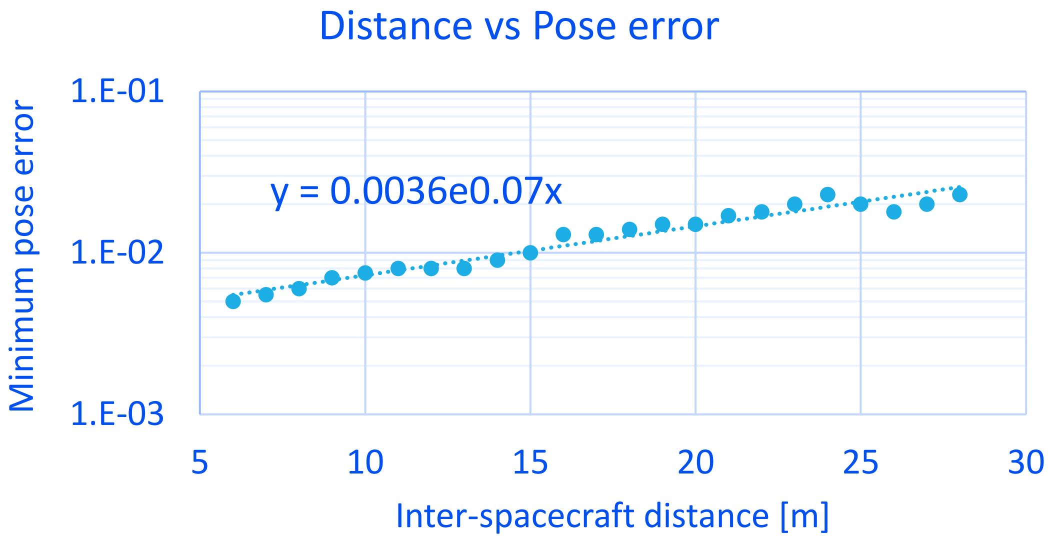
- Most literatures explained they get better quality as it get close to the target
- Error was modelled using experimental data from a literature[8], which indicate clear exponential relationship to the inter-spacecraft distance
- No model was constructed with reference to relative attitude



Experimental results of performance with reference to the relative distance [8]



Experimental input generated by simulator [8]



The navigation performance model I made from the literature

[8] M. Kisantal, S. Sharma, T. H. Park, D. Izzo, M. Martens, S. D'amico, "Satellite Pose Estimation Challenge: Dataset, Competition Design, and Results," IEEE Transactions on Aerospace and Electronics Systems, Vol. 56, No.5, Oct. 2020.

Trajectory Optimization

- Cost function ***J*** terms includes:
  - Acceleration at each node (Δv)
  - Expected navigation error at each node
- Constraints:
  - First and Last epoch relative position/velocity
  - Maximum acceleration
  - PA safe trajectory
  - Approach corridor / max speed for final approach

Minimizing acceleration (Δv)

$$\min_{U^k} \boldsymbol{J} = \boxed{\boldsymbol{U}^{\boldsymbol{T}}\boldsymbol{U}} + \boxed{w^k \boldsymbol{E}_{\boldsymbol{nav}}^{\boldsymbol{T}}(\boldsymbol{x}(\boldsymbol{u}))\boldsymbol{E}_{\boldsymbol{nav}}(\boldsymbol{x}(\boldsymbol{u}))}$$

Minimizing navigation error expectation at each node

s.t.

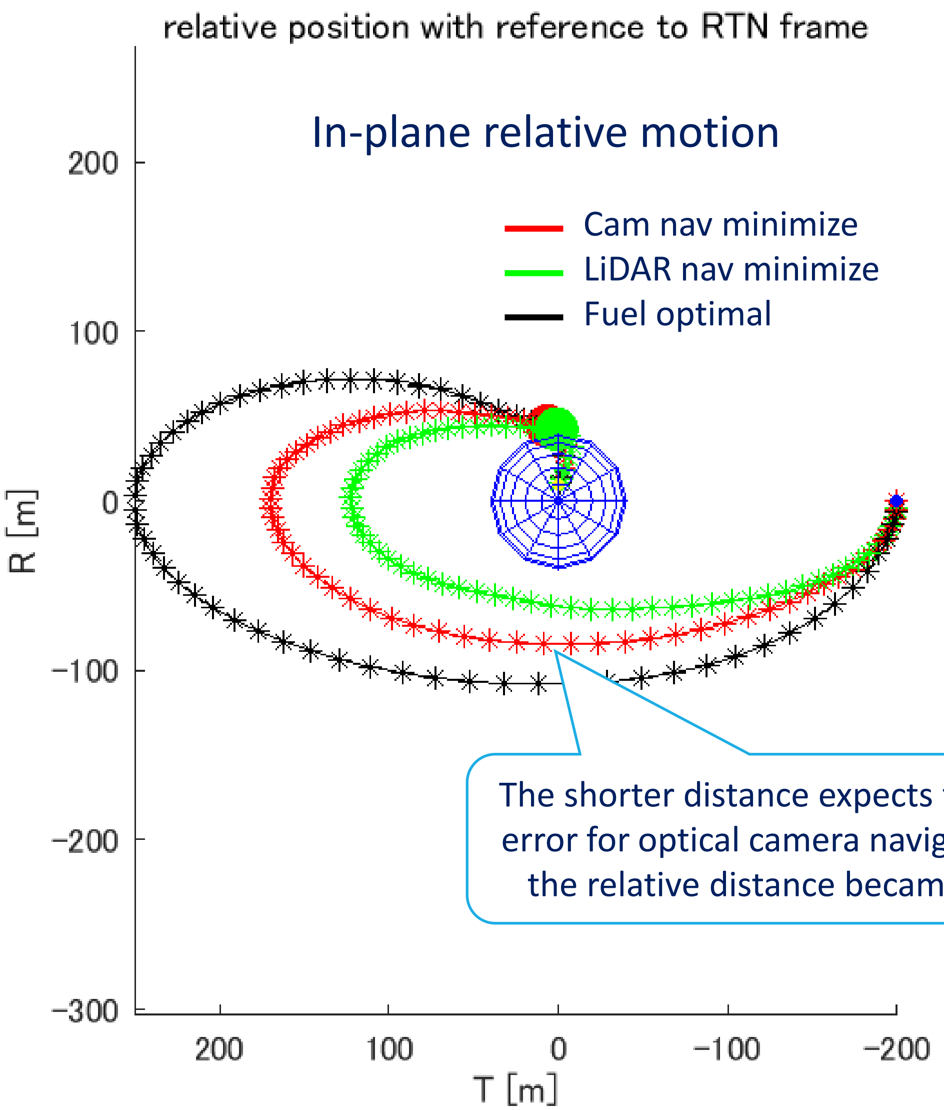
$$\delta\boldsymbol{\alpha}_{\boldsymbol{f}} = \Phi(t_0, t_i)\delta\boldsymbol{\alpha}_{\boldsymbol{0}} + \boldsymbol{H}_{\boldsymbol{f}}\boldsymbol{U}^{\boldsymbol{k}}$$
$$\delta\boldsymbol{\alpha}(t_0) = \delta\boldsymbol{\alpha}_{\boldsymbol{0}}$$
$$\boldsymbol{U}^{\boldsymbol{k}} \leq U_{max}$$

w^k: weighting coefficient

Thanks to the minimization of the navigation error expectation, the navigation sensor will experience the trajectory which can easily handle the navigation

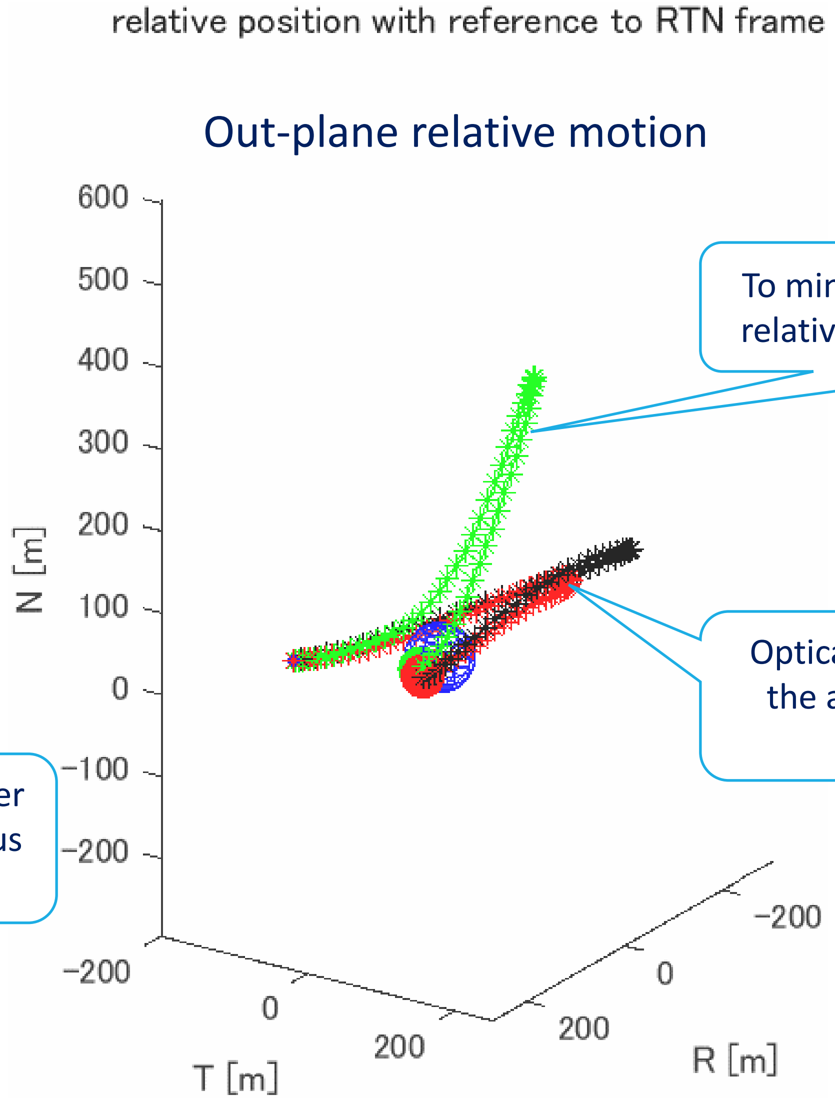
Results

- Optimized trajectories



In-plane relative motion

The shorter distance expects the smaller error for optical camera navigation, thus the relative distance became smaller



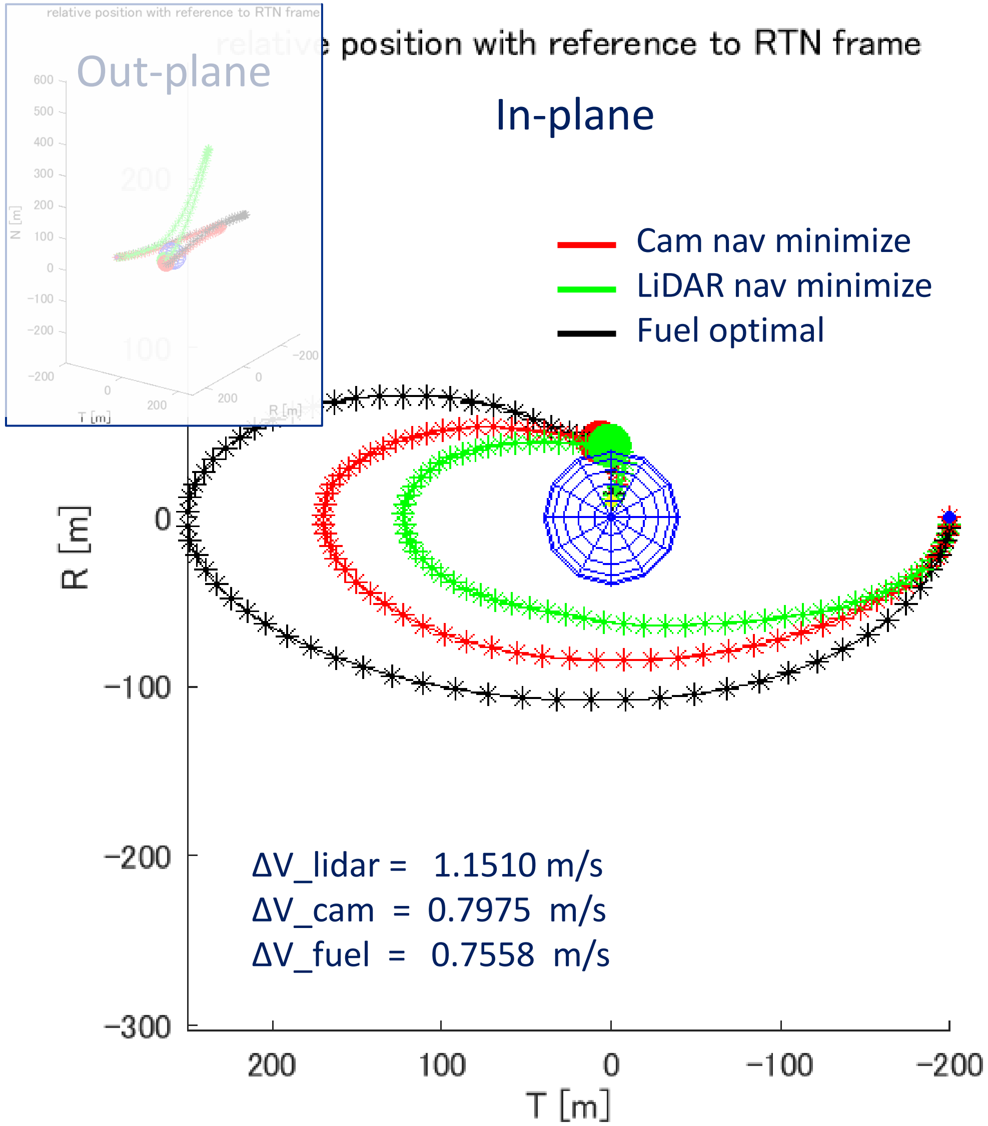
Out-plane relative motion

To minimize the LiDAR navigation error, relative orbital plane has been changed

Optical camera has no dependency on the attitude, thus the plane was not changed from the orginal

Results

- Optimized trajectories

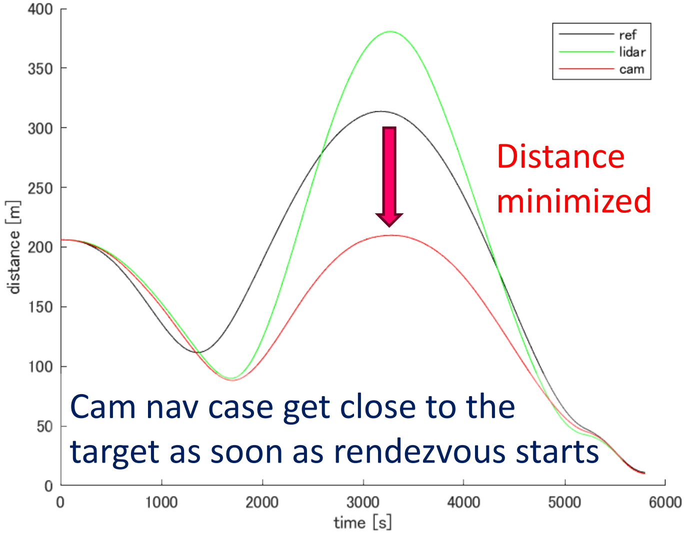


Cam nav minimize

LiDAR nav minimize

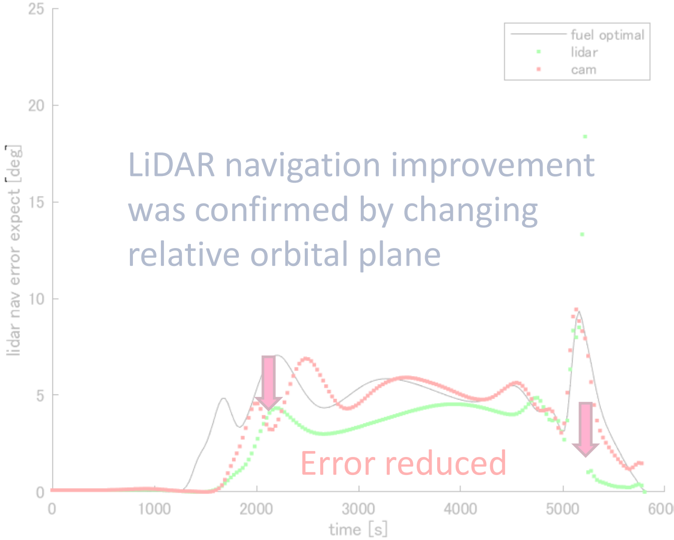
Fuel optimal

ΔV_lidar = 1.1510 m/s
ΔV_cam = 0.7975 m/s
ΔV_fuel = 0.7558 m/s



Distance minimized

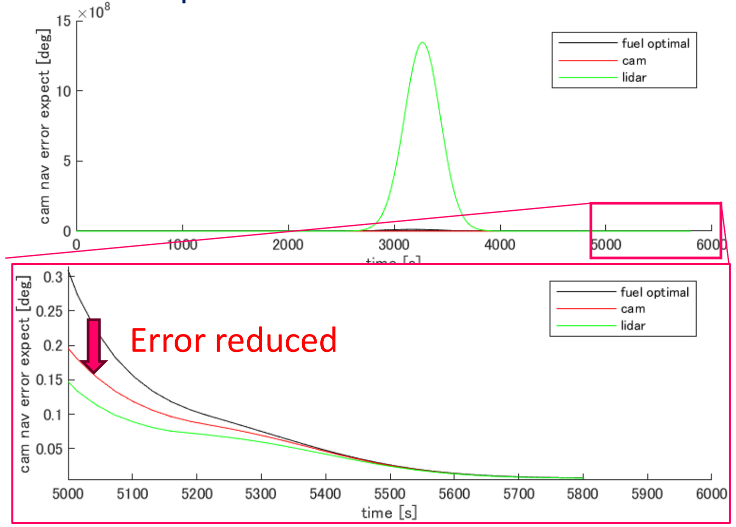
Cam nav case get close to the target as soon as rendezvous starts



LiDAR navigation improvement was confirmed by changing relative orbital plane

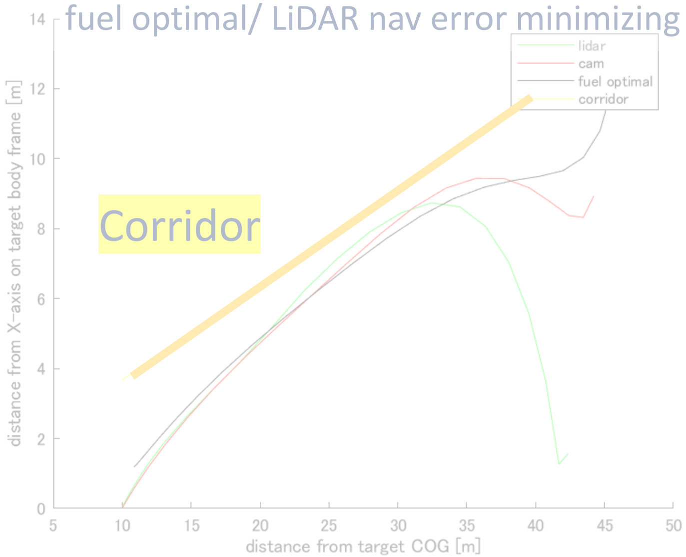
Error reduced

Cam nav minimizing case tries to get close as soon as possible to minimize the nav error



Error reduced

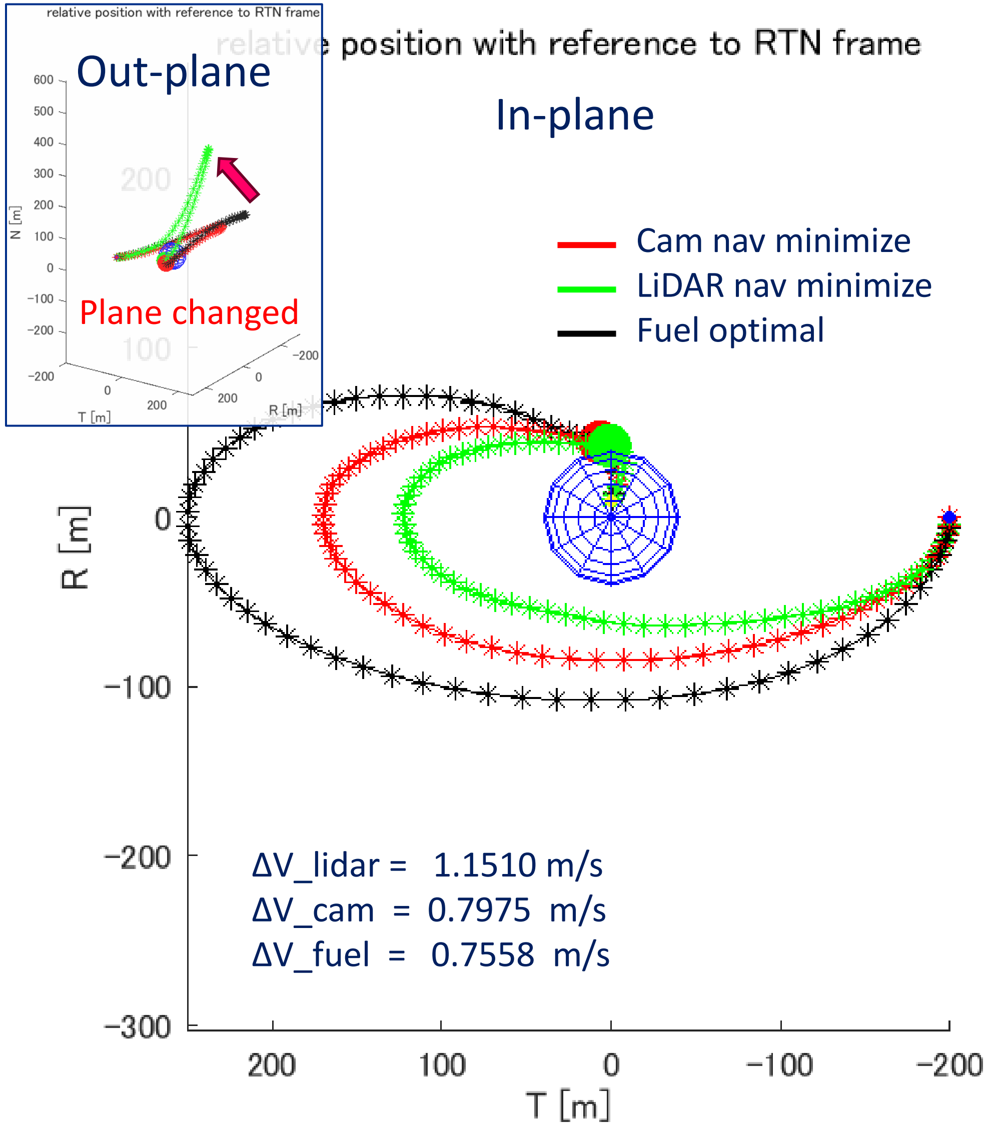
All the trajectories pass through the corridor. It passes the edge of corridor for fuel optimal/ LiDAR nav error minimizing



Corridor

Results

- Optimized trajectories



Out-plane

Plane changed

In-plane

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LiDAR nav minimize

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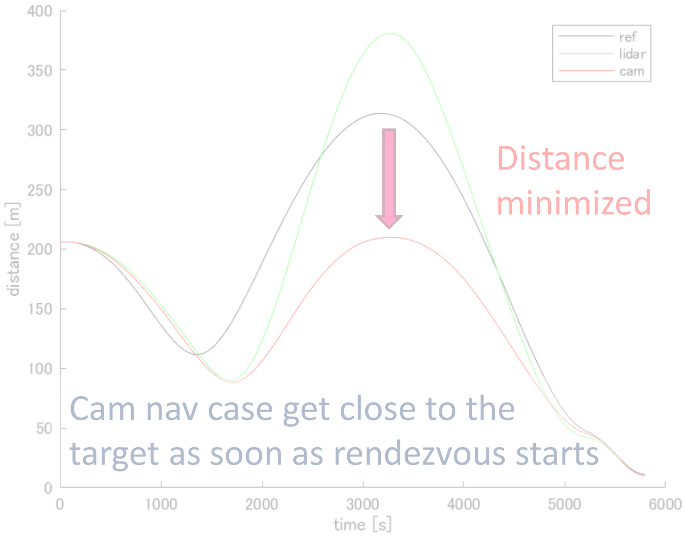

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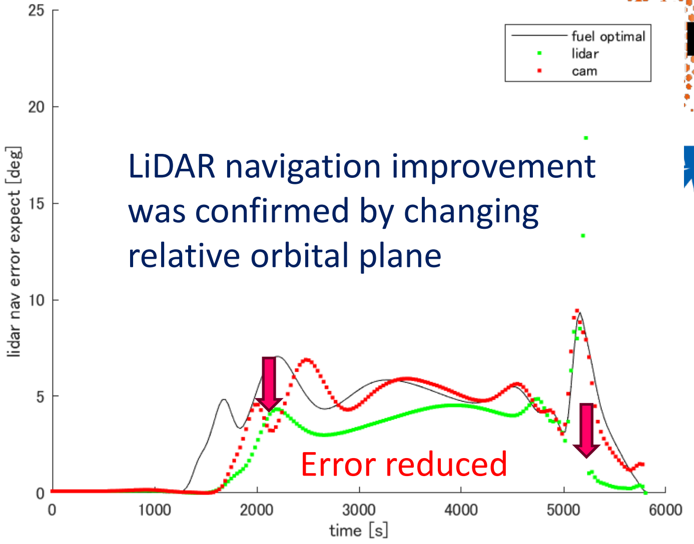

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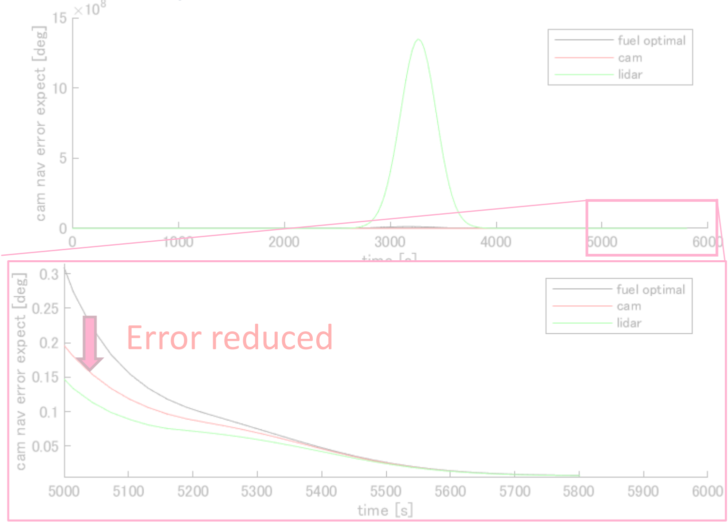

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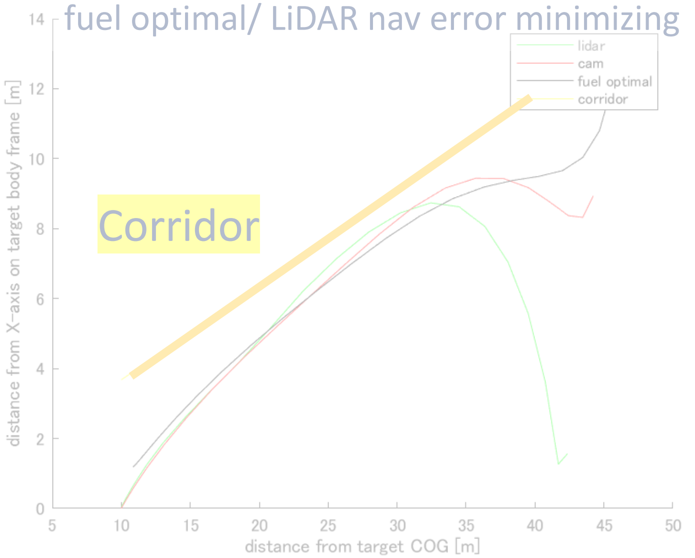

Corridor

Results

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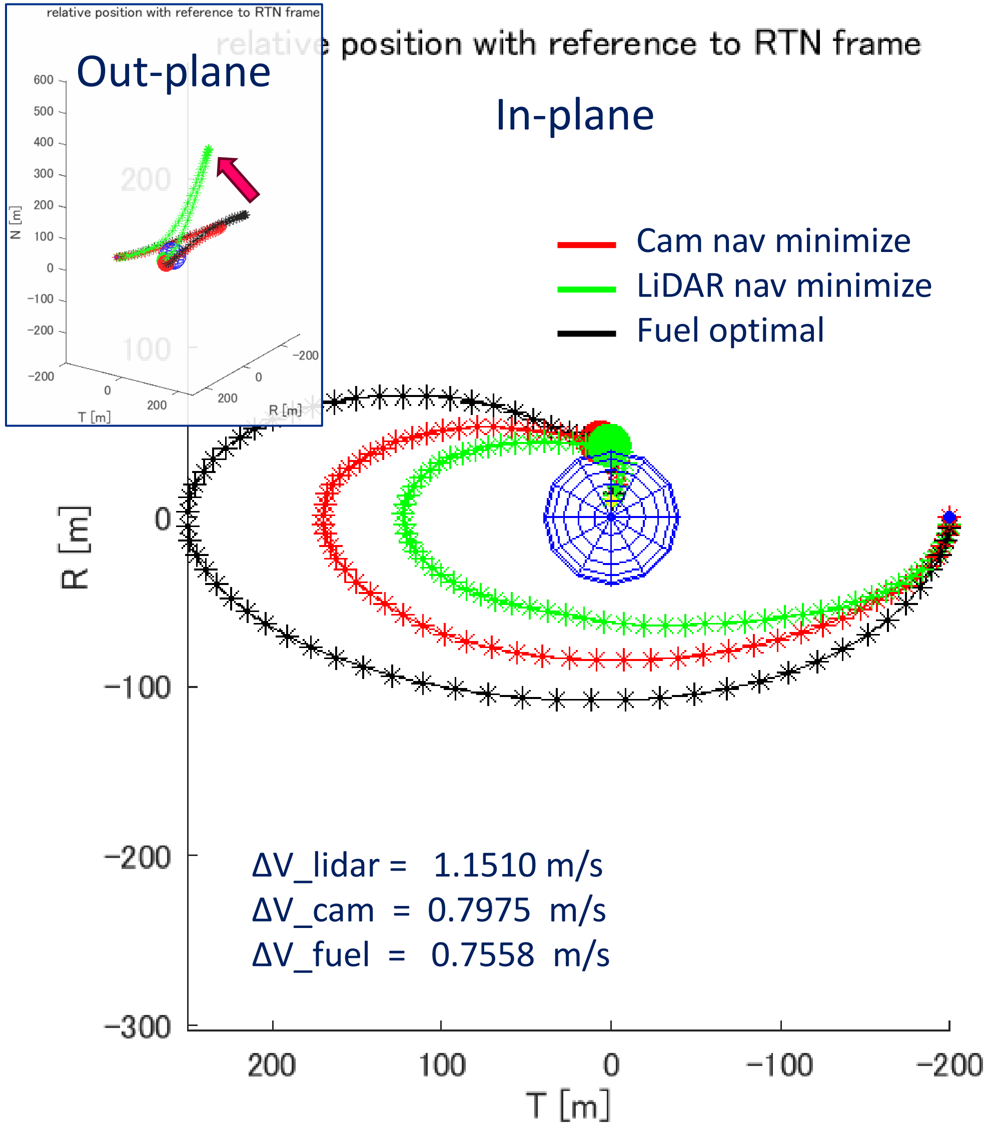

Out-plane

In-plane

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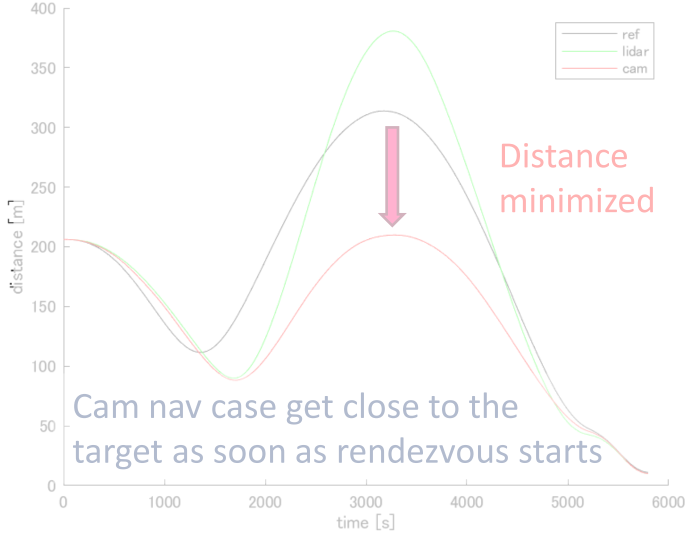

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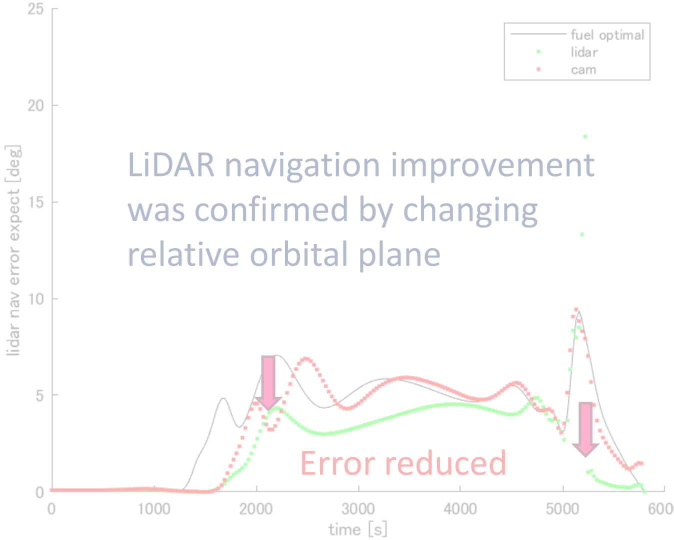

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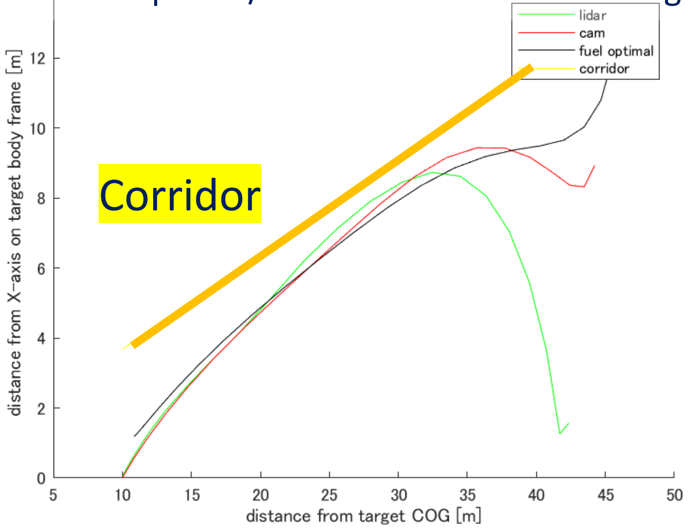

Corridor

Discussions

- Overall characteristic was natural considering the navigation error model
- LiDAR matching optimization case
  - Tried to stay the best relative position and change the relative orbital plane for the rendezvous
  - The navigation error expectation was reduced by approximately 40% on average
  - The Δv was increased but necessary to get robust navigation during the rendezvous
  - The safety constrains are satisfied: PA safe was guaranteed before KOZ and it followed the corridor in the KOZ
- Optical camera
  - Tried to get close as soon as the rendezvous start to reduce the navigation error
  - The navigation error expectation was reduced by approximately 30%
  - The Δv was slightly increased
  - The safety constrains are satisfied: PA safe was guaranteed before KOZ and it followed the corridor in the KOZ

Conclusions

- We proposed a new approach to find out a rendezvous trajectory which expect less navigation error during the approach
  - Two types of sensors are modelled:
    - LiDAR
    - Optical camera
  - The trajectories are optimized with each sensor models and difference were discussed
  - The navigation error expectation during the rendezvous phase was reduced compared to the original trajectory (Δv minimum trajectory)
- The increased of Δv was limited while it minimizes the relative navigation errors during the rendezvous

Way Forwards

- The approach was comprehensive approach to minimize a sensor error expectations with reference to the relative motion to the target
- The interface of the navigation error model can be provided by datatable or function
- The approach has possibility to be expanded to maximize:
  - Communication link
  - Other sensors / actuators performance

- Works to be done:
  - The optimized trajectory to the rotational target
  - Considering the sun direction

Thank you

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nakajima.yu@jaxa.jp

BACK UPS

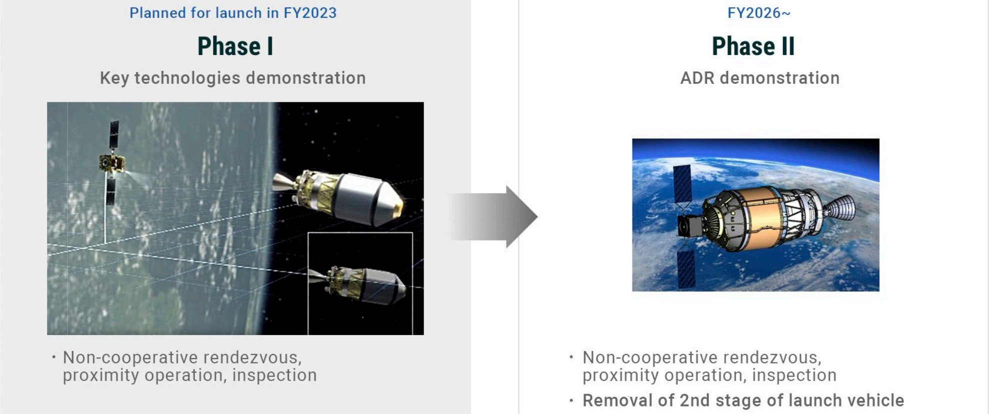
SpEye Mission

- **Space Eye (SpEye) mission**: **6U Cubesat experiment** for inspection and proximity operations
- CubeSat released by D-Orbit's ION satellite carrier will investigate the ION satellite carrier itself from the proximity, demonstrating the safe rendezvous capability
- CubeSat mission funded by the **Alcor Programme** of **Agenzia Spaziale Italiana (ASI)**

Credits: D-Orbit

CRD2 Program

- **Commercial Removal of Debris Demonstration (CRD2) program:** acquire debris removal technologies to address the problem of space debris, and to support commercial activities of Japanese companies
- The program consists of two phases:
  1. demonstrating non-cooprative rendezvous
  2. demonstrating an object removal from the orbit
- **Astroscale Japan Inc.** develops ADRAS-J for the phase I to demonstrate these technologies



Planned for launch in FY2023

Phase I

Key technologies demonstration

- Non-cooperative rendezvous, proximity operation, inspection

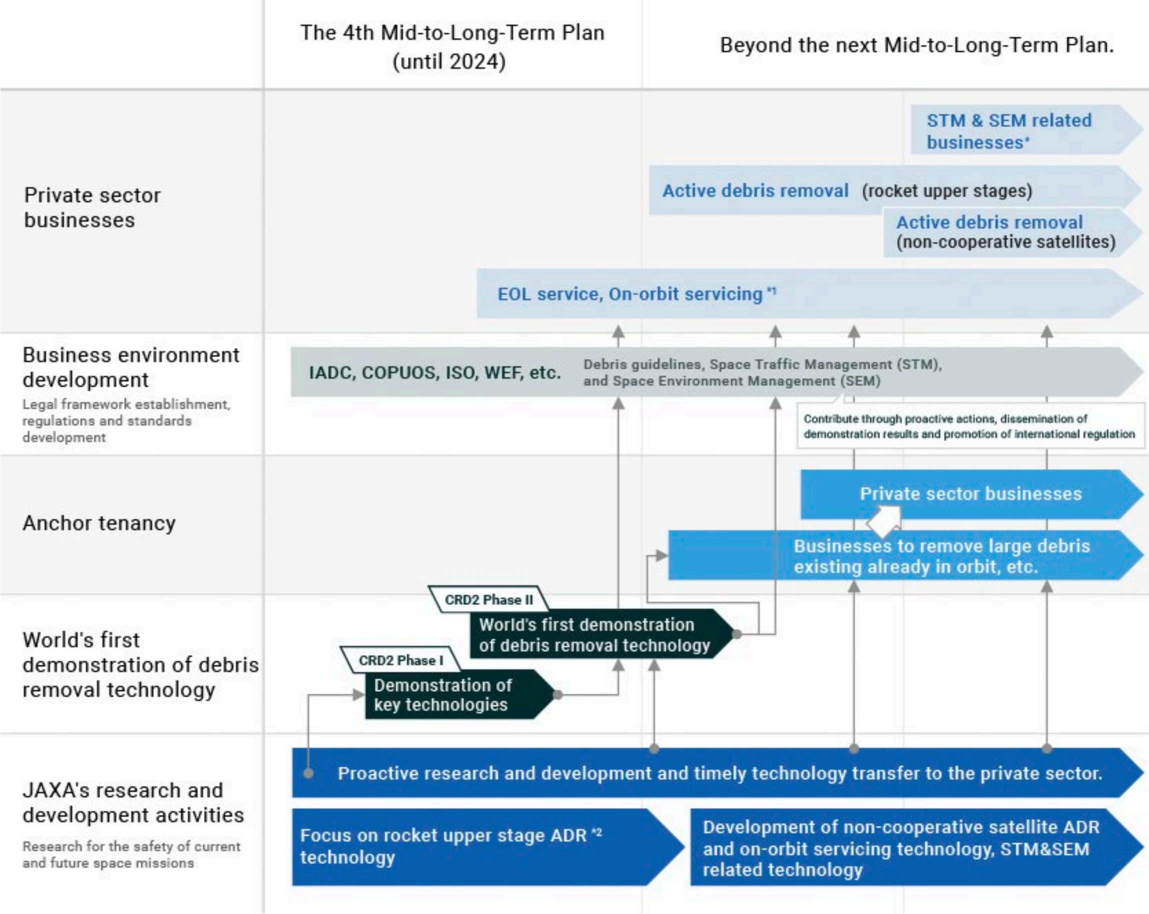
FY2026~

Phase II

ADR demonstration

- Non-cooperative rendezvous, proximity operation, inspection
- Removal of 2nd stage of launch vehicle

[3] https://astroscale.com/ja/missions/adras-j/ Accessed: 10-1-2023



The 4th Mid-to-Long-Term Plan (until 2024)

Beyond the next Mid-to-Long-Term Plan.

Private sector businesses

STM & SEM related businesses*

Active debris removal (rocket upper stages)

Active debris removal (non-cooperative satellites)

EOL service, On-orbit servicing *1

Business environment development

Legal framework establishment, regulations and standards development

IADC, COPUOS, ISO, WEF, etc.

Debris guidelines, Space Traffic Management (STM), and Space Environment Management (SEM)

Contribute through proactive actions, dissemination of demonstration results and promotion of international regulation

Anchor tenancy

Private sector businesses

Businesses to remove large debris existing already in orbit, etc.

World's first demonstration of debris removal technology

CRD2 Phase II

World's first demonstration of debris removal technology

CRD2 Phase I

Demonstration of key technologies

JAXA's research and development activities

Research for the safety of current and future space missions

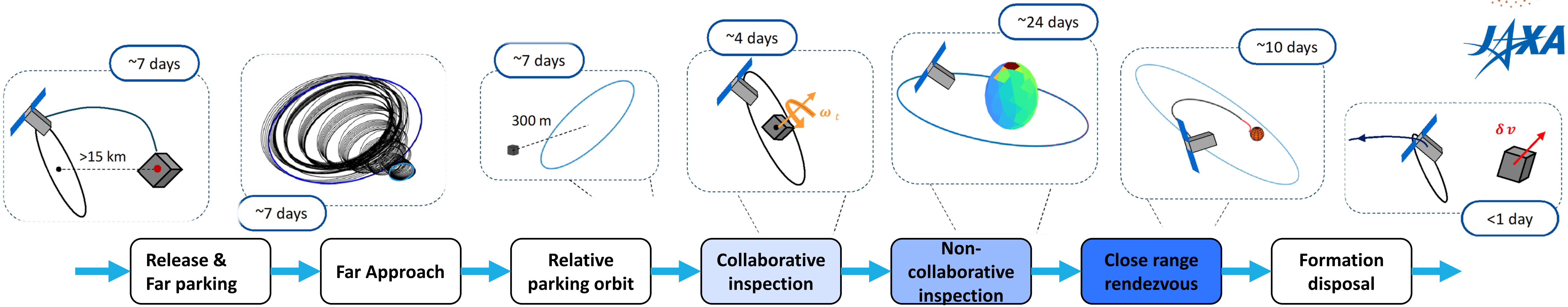
Proactive research and development and timely technology transfer to the private sector.

Focus on rocket upper stage ADR *2 technology

Development of non-cooperative satellite ADR and on-orbit servicing technology, STM&SEM related technology

Concept of Operations

- **SpEye Mission**

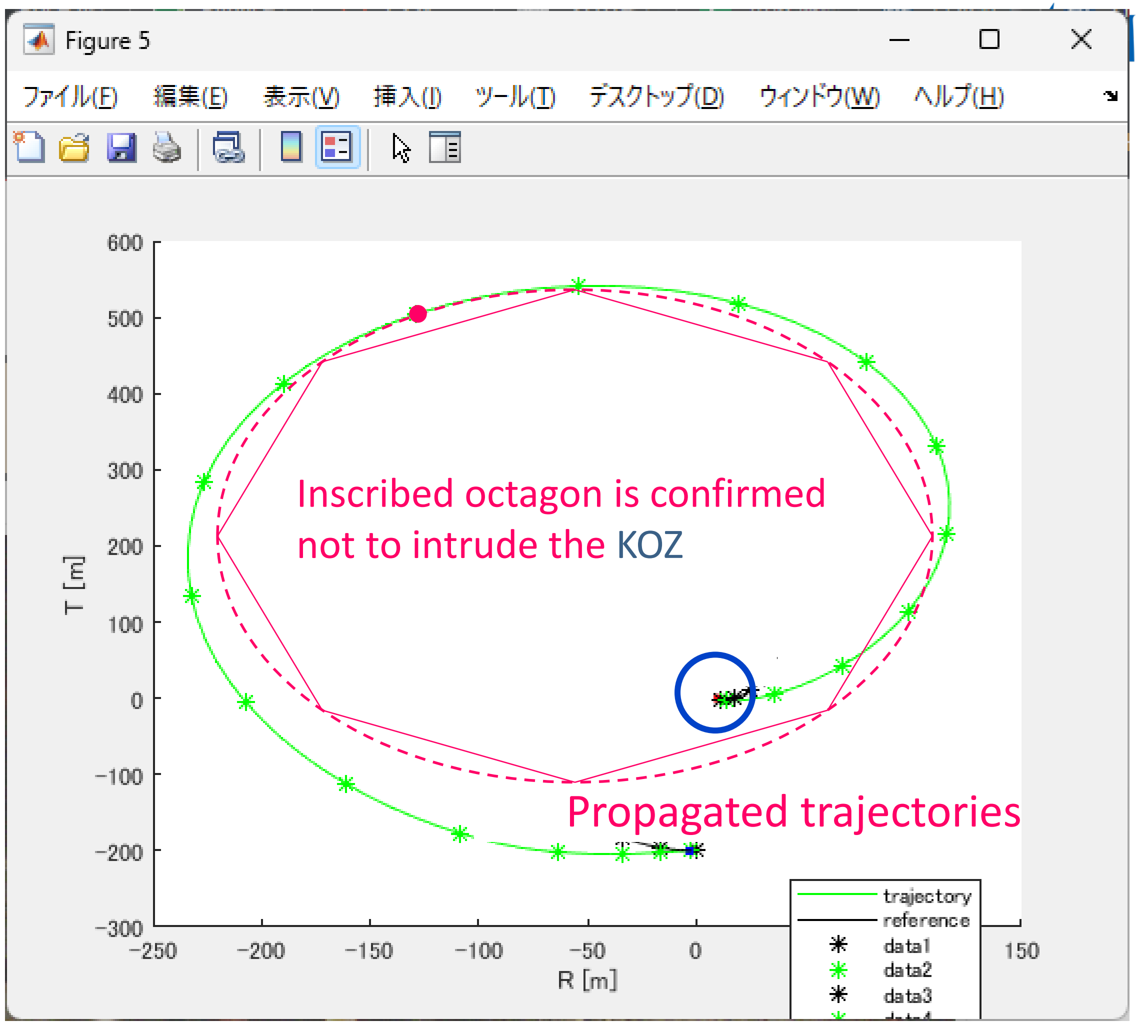


Release & Far parking → Far Approach → Relative parking orbit → Collaborative inspection → Non-collaborative inspection → Close range rendezvous → Formation disposal

- **CRD2** has a similar ConOps.
- Inspect, get close, inspect, get close …
- In the final stage of missions, both projects try to bring a chaser satellite within a proximity range of approximately 10~30 m to the target
- Both project tries to achieve the above goal **with limited resources**, thus the high-end relative navigation tailored for each project cannot be expected

Passive Abort Safety Constraint Modelling

- First part of the rendezvous (0~180 steps)
  - PA safety approach [9] to guarantee the PA trajectory at each node do not intersect with the KOZ
- Latter part of the rendezvous (180~200 steps)
  - Final approach is constrained to the corridor
  - Approach velocity is slower than 0.1 m/s

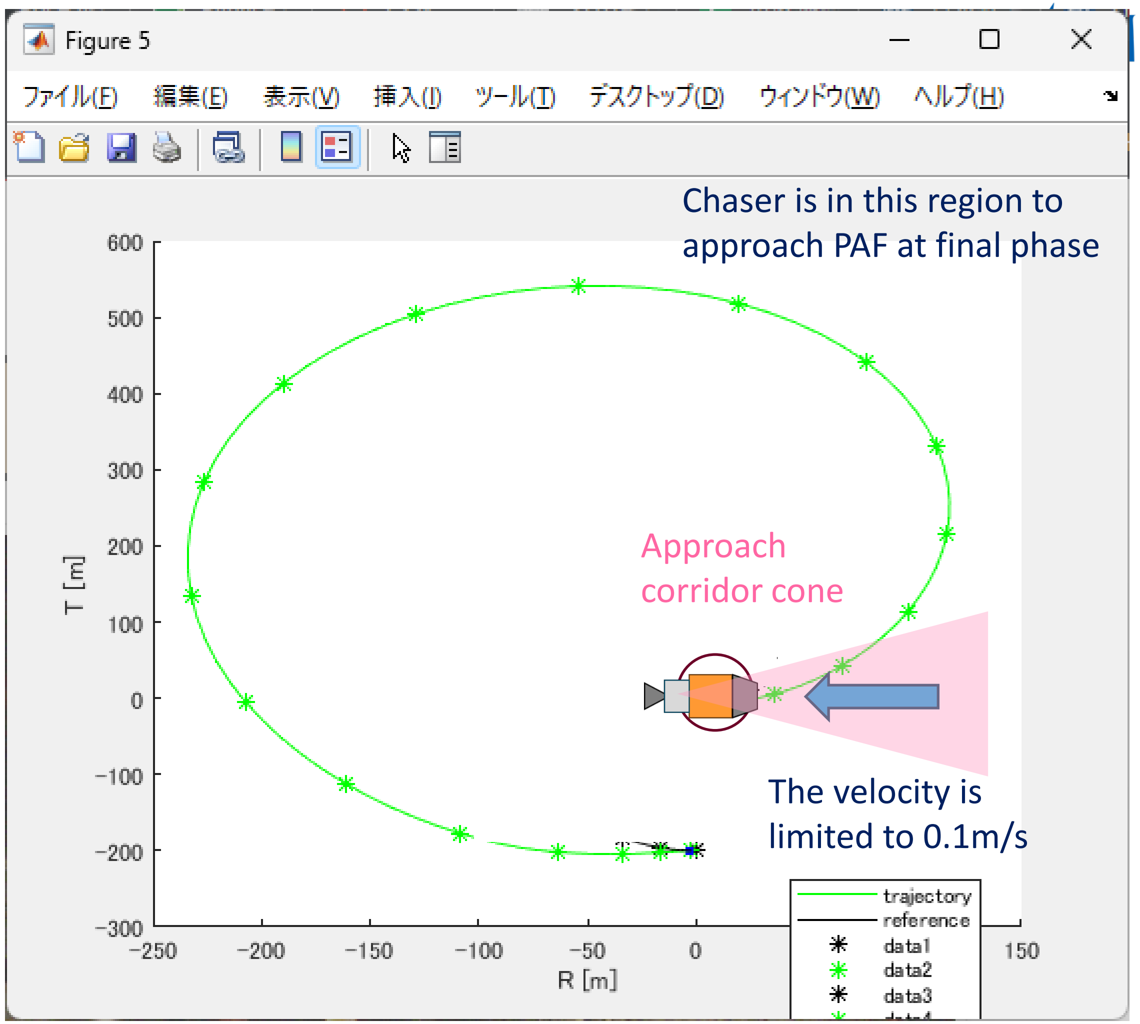


Inscribed octagon is confirmed not to intrude the KOZ

Propagated trajectories

Passive Abort Safety Constraint Modelling

- First part of the rendezvous (0~180 steps)
  - Giacomo’s PA safety approach [9] to guarantee the PA trajectory at each node do not intersect with the KOZ
- Latter part of the rendezvous (180~200 steps)
  - Final approach is constrained to the corridor
  - Approach velocity is slower than 0.1 m/s



Chaser is in this region to approach PAF at final phase

Approach corridor cone

The velocity is limited to 0.1m/s