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非協力的ターゲットに対する航法誘導制御技術の研究

A research toward guidance, navigation, and control for a Non-Cooperative Target

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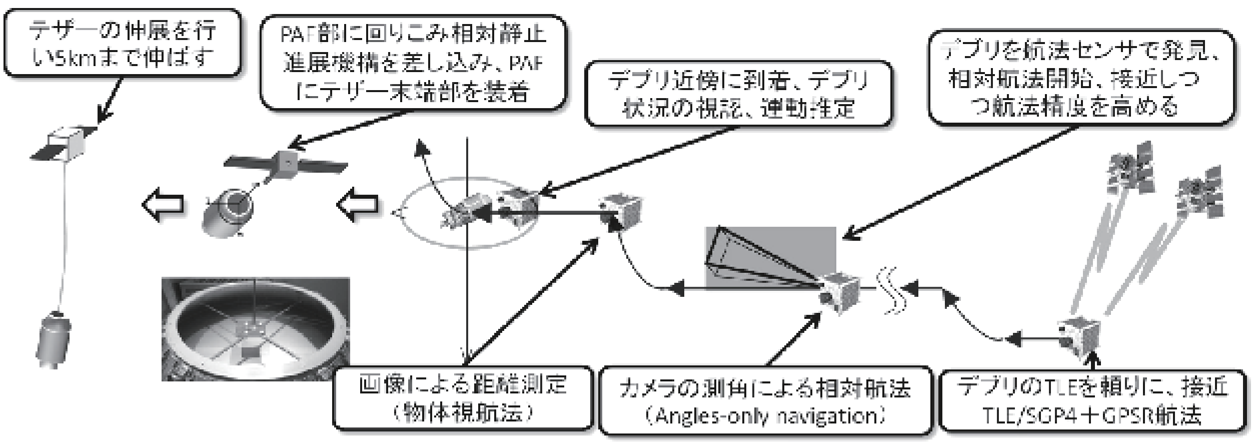
デブリの積極的除去にあたり、チェイサ衛星はデブリに接近し推進系を取り付ける必要がある。ISS のような協力的ターゲットと異なり、デブリのような非協力的ターゲットへの接近は、入手できる軌道情報の精度が低い、相対航法の継続性・安定性の確保が困難、といった課題がある。これらの課題を考慮した接近シナリオの検討状況について紹介する。遠方域では TLE/SGP4+GPSR を利用して接近し、搭載カメラでターゲットを認識できる距離まで近づくと Angles-only Navigation による相対航法を開始する。ターゲットの大きさを認識できる距離へ接近後は物体視航法によって接近する。航法センサ候補として可視光・赤外カメラ、LIDAR 等があり、これらの性能を評価するために実物大ロケット PAF モデルを用いた試験を実施した。また、近傍域での接近軌道と接近シミュレーションの結果も示す。デブリ除去の推進系の一例として導電性テザーの進展ダイナミクスの検討も紹介する。最後に、今後の課題と技術開発プランについて述べる。

For the sake of Active Debris Removal (ADR), a chaser satellite is required to attach a propulsion system on the space debris. Unlike cooperative targets such as ISS, Non-cooperative targets like debris are difficult to approach and rendezvous since its trajectory information (TLE) has low precision and relative navigation has less reliability and stability. In order to overcome those technical difficulties, our groups has examined a possible approach scenario. For a far approaching phase, the chaser approaches toward the debris based on TLE/SGP4 and GPSR information. As they get close such that the debris is observed as a tiny dot through navigation camera, the chaser started approach by Angles-Only Navigation (AON) to start relative navigation and get more closer. Lastly, for the near phase such that the size and posture of debris is observable, the chaser starts for precise control and approach. Visible cameras, Infra-Red (IR) cameras, and LIDARs are candidates of the navigation sensor for rendezvous, thus those cameras are evaluated through the experiment using a full-scale H-IIA PAF model. In addition, near phase approaching trajectory plan and its simulation study are introduced. Moreover, ElectroDynamic Tether Tether (EDT), one of the candidate propulsion system to de-orbit the debris, is described and its extending dynamics study is also introduced. Lastly, future works toward the ADR are explained.



JAXA

A research toward guidance, navigation, and control for a Non-Cooperative Target

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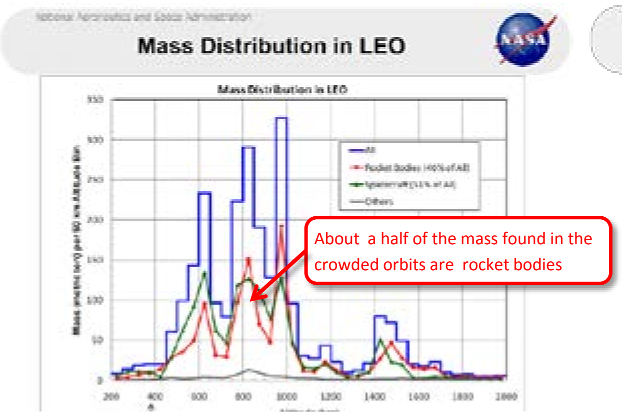
JAXA

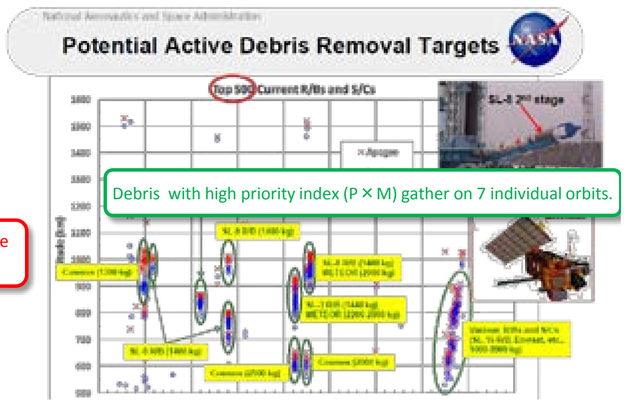
1. Background and Motivations

JAXA

- Target debris to be removed
  - Priority index of target debris is defined as Collision possibility (P) × Mass (M)
  - About half of the mass found on crowded orbits are rocket bodies
  - Most rocket bodies have similar structure, which reduces requirements for navigation and caputre



J.-C. Liou, Orbital Debris and Future Environment Remediation, OCT Technical Seminar NASA HQ, Washington, DC, 2011

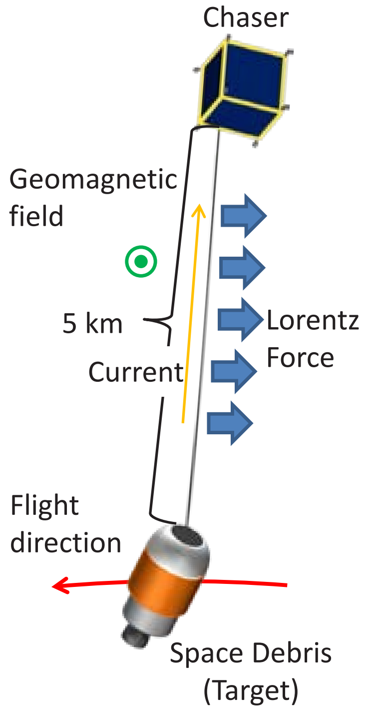


J.-C. Liou, The Near-Earth Orbital Debris Problem and the Challenges for Environment Remediation, The 3rd International Space World Conference, Frankfurt, Germany, 2012

Rocket bodies on the crowded orbits are good options for ADR

1. Background and Motivations

- JAXA studies the Electro-Dynamic Tether (EDT) system as one of the candidate devices for Active Debris Removal (ADR)
- The ADR mission to apply the EDT system for deorbiting a rocket upper stage is investigated as one of the reference design missions
- Non-cooperative rendezvous is a key technology for the ADR mission
  - Navigation system
  - Safe trajectory
- Extending EDT without entanglement is a major difficulty in case of ADR using EDT



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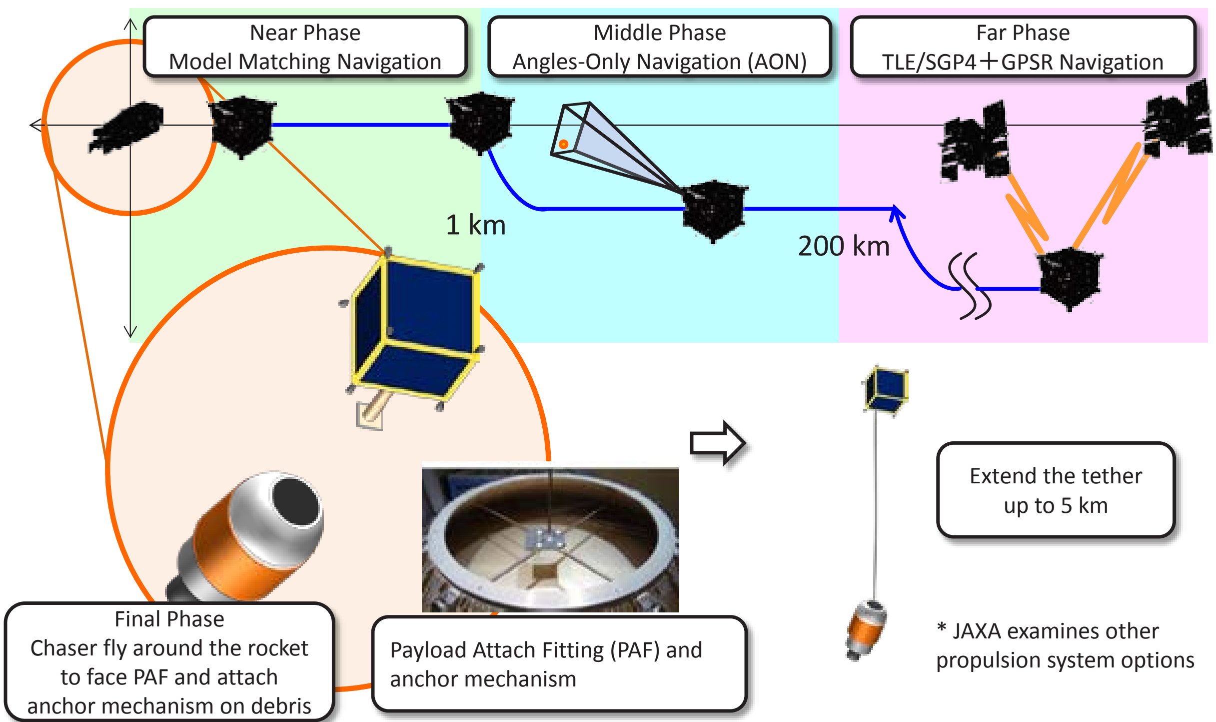
1. Background and Motivations

- ADR plan overview



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1. Background and Motivations

Objectives

- Prototyping the rendesvous system and operation scenario for the ADR mission
  - Overall navigation concept
  - Navigation sensor system
  - Navigation filter
  - Rendezvous trajectory
- Demonstration of the proposed system and operation scenario by numerical simulations
- Funadamental experiment to characterize the navigation sensor candidates using real scale rocket model
- Simulation studies for EDT extension to clarify its difficulties

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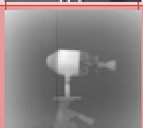
2.1. Navigation Sensors Concept

Candidates comparison

			Attitude	Range		LOS Angles	Night	Pros	Cons
				Far	Near				
Visible Camera (VISCAM)			✓	NG	✓	✓	NG	Low cost Avaliable at long distance High resolution	Not available during eclipse Sensitive to lighting conditions Poor range accuracy
Infrared Camera (IRCAM)			✓	NG	✓	✓	✓	Low cost Available during eclipse Robust to lighting conditions	Low resolution Poor range accuracy
Laser Sensor (LIDAR)	LIDAR (Range only)		NG	✓	✓	NG	✓	Available during eclipse Available at long distance High range accuracy	Expensive LOS angles not measured Expensive
	Scanning LIDAR		✓	✓	✓	✓	✓	Available during eclipse Avalialbe at long distance High range accuracy Pose estimation capability	Very Expensive
	Flash LIDAR		✓	NG	✓	✓	✓	Available during eclipse Pose estimation capability	Expensive

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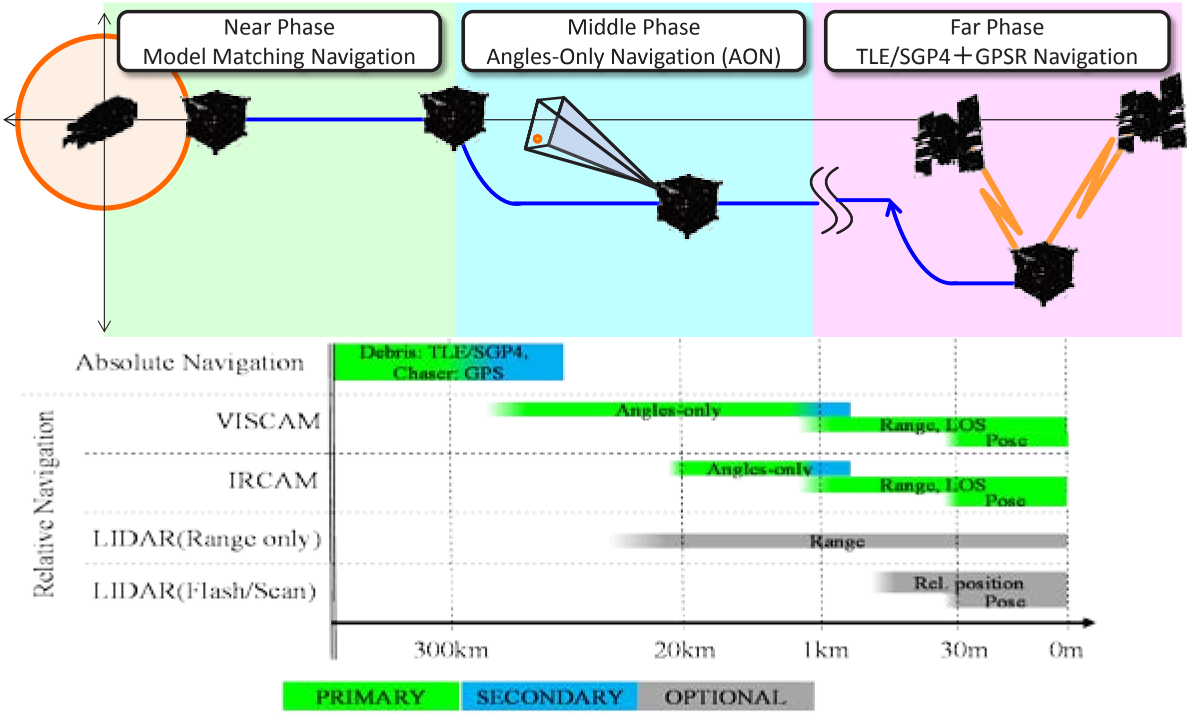
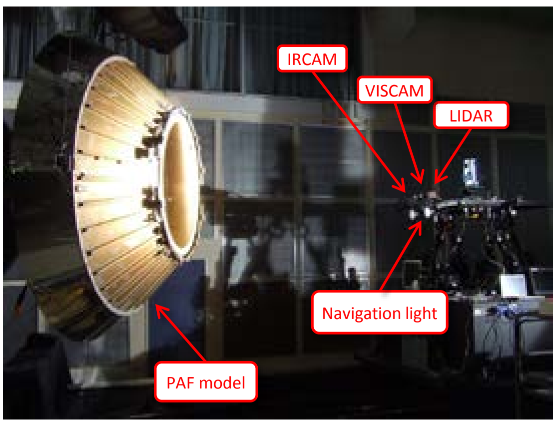
2.2. Overall Navigation Concept

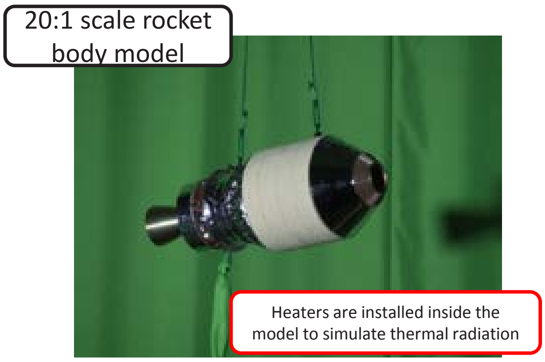
- Navigation Sensor Usage

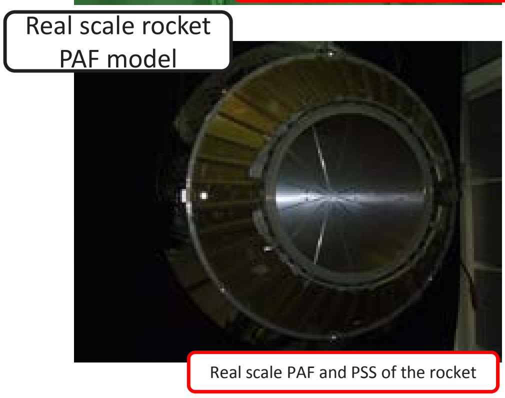


2.3. Navigation Sensors Evaluation

- Experimental verification



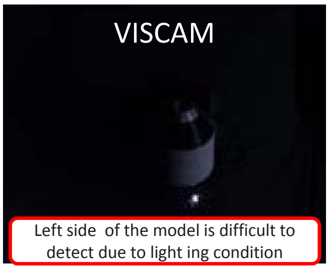


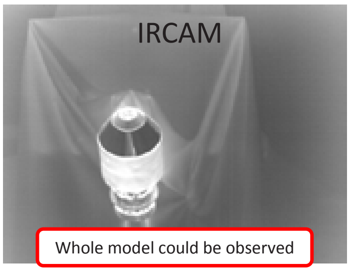


- Conditions
  - 3 sensors (IRCAM/VISCAM/LIDAR)
  - 2 models
    - 20:1 rocket body scale model
    - Real scale rocket PAF model
  - Solar light / navigation light
  - Distance (20m〜2m)

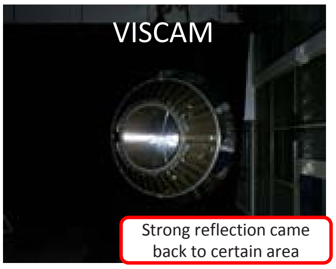
2.3. Navigation Sensors Evaluation

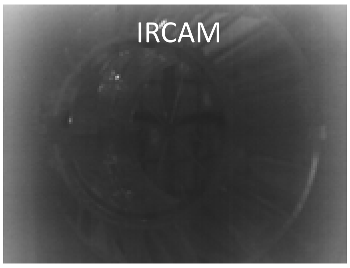
- Scale model images @ 2.5m (corresponding to 50m in real scale)

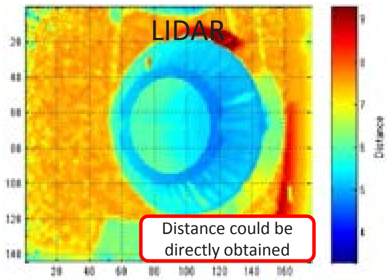




- Real Scale PAF images @ 5m



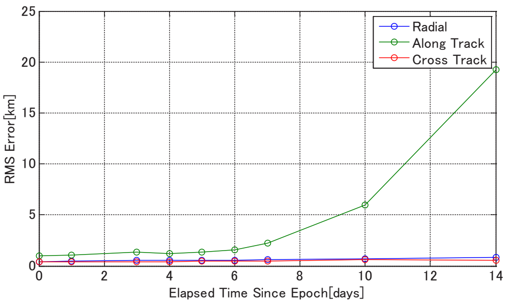




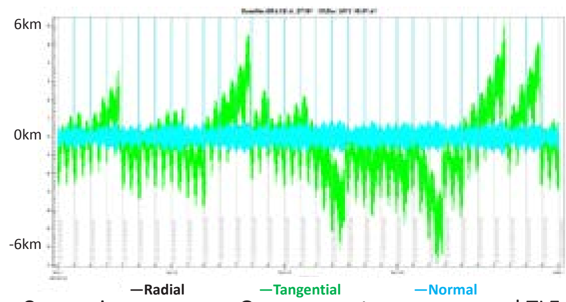
- **Various images are obtained through the experiment**
- **Now we use them to evaluate navigation sensors and design the navigation system**

3.1. Far Phase Navigation (TLE/SGP4)

- Orbit determination accuracy by TLE/SGP4
  - JSpOC (TLE)
    - Various researchers have evaluated orbit prediction error by TLE/SGP4
    - ADEOS-II (800km) data suggested the along-track error after 2 days of propagation is 2 km
    - GRACE-A (500km) data implied the along-track error after 2 days of propagation is 2~7 km
  - Domestic / Oversea Radar site
    - Domestic site: Kamisaibara Spaceguard Center Oversea Site：TIRA(FHR; Germany)
    - The timing of orbit determination can be intentionally chosen, thus suitable for critical operation phase
    - TIRA has the accuracy of 400 m (along-track) after 1 day of propagation [1]



Comparison between GPS orbit determination and TLE/SGP4(ADEOS-II)



Comparison between GPS orbit determination and TLE/SGP4 (GRACE-A) TLE updated every 2 days

[1] Kahle R., Weigel M., Kirschner M., Spiridonova S., Kahr E., Letsch K.: Relative Navigation to Non-Cooperative Targets in LEO: Achievable Accuracy from Radar Tracking Measurements, 5th International Conference on Spacecraft Formation Flying Missions and Technologies, 2011

Holding chaser 20km apart from the target can be achieved by TLE/SGP4

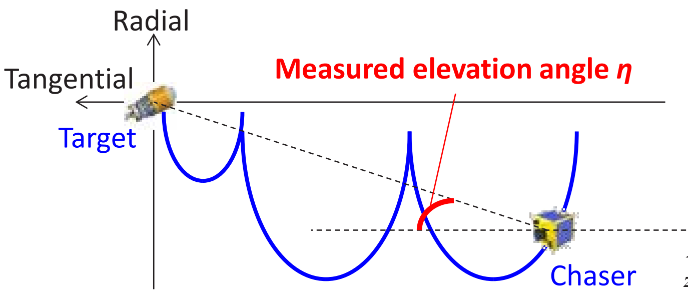
3.2. Middle Phase Navigation (AON)

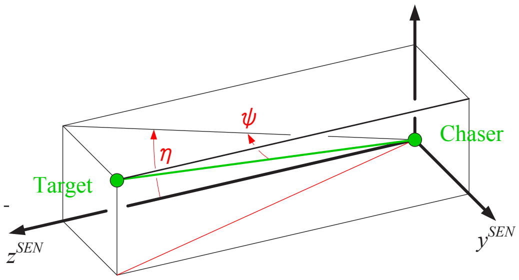
- What is Angles-only navigation (AON)?

  Navigation method to estimate relative position and velocity by only target direction (Azimuth/Elevation) from cameras

- Why angles-only navigation is necessary ?
  - A target is seen as a tiny point from long distance
  - If laser sensors are not available, a chaser must approach to a target using only direction information until target shape can be seen on a camera image

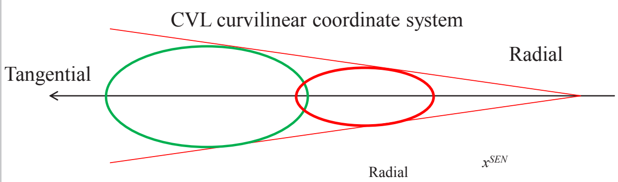
- Features of angles-only navigation
  - No direct 3D position information
  - Trajectory should ensure visibility and observability
  - Proper maneuver execution stimulates observability

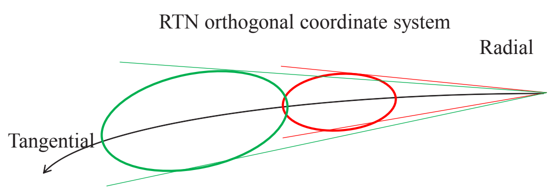


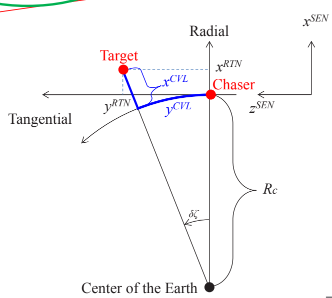


3.2. Middle Phase Navigation (AON)

- Observability of AON
  - Processing LOS angle measurements of natural relative orbit can make the system observable
  - There are infinite similar solutions comprising relative orbits to reproduce the same LOS angle measurement profiles
  - However, the CW equations are actually linearized with respect to the curvilinear CVL coordinate frame, whereas the LOS angles are measured in the orthogonal RTN frame
  - Similar solutions of relative orbits obtained by CW equations in the CVL frame are not similar when mapped into the RTN frame
  - Unique relative orbit can be determined by the LOS angle measurements



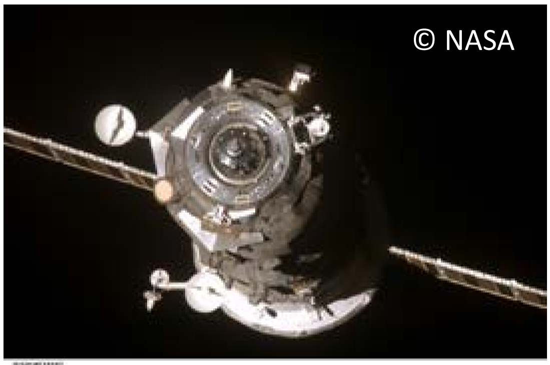




$$
\boldsymbol{c}_{CVL}^{RTN}\left(\delta\hat{\boldsymbol{r}}^{CVL}\right) = \begin{pmatrix} \delta\hat{r}_x^{CVL}\cos(\delta\hat{\xi}) - R_c\left(1-\cos(\delta\hat{\xi})\right) \\ \left(R_c + \delta\hat{r}_x^{CVL}\right)\sin(\delta\hat{\xi}) \\ \delta\hat{r}_z^{CVL} \end{pmatrix}
$$

3.3. Near Phase Navigation (MMN)

- Model Matching Navigation
  - The target shape can be recognized from the distance of 1 to 2 km
  - Distance to the target is estimated by comparing the structure model and obtained image
  - Whole target may not be obtained by visible cameras due to its shadow
  - Image obtained by IR cameras will not be interfered by lightning conditions

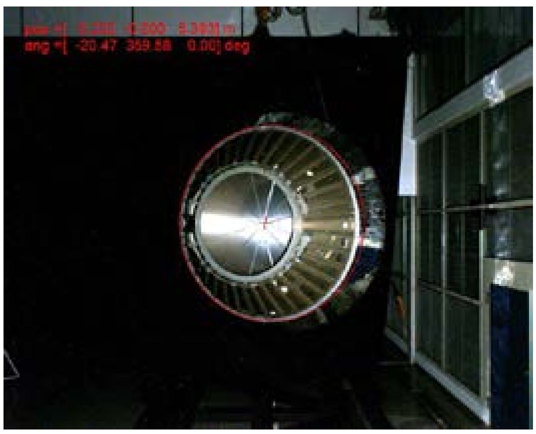


Progress observed from ISS
Shaded part of the Progress is difficult to distinguish from the background

MMN is used from the distance of 1 to 2 km to the target

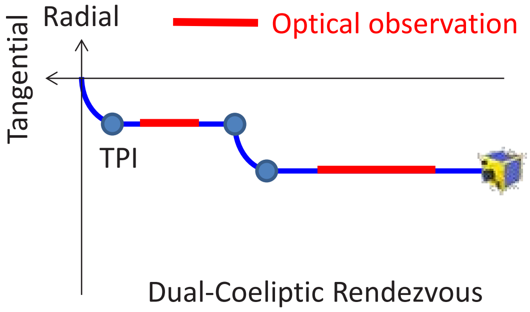
3.4. Final Phase Navigation (MMN)

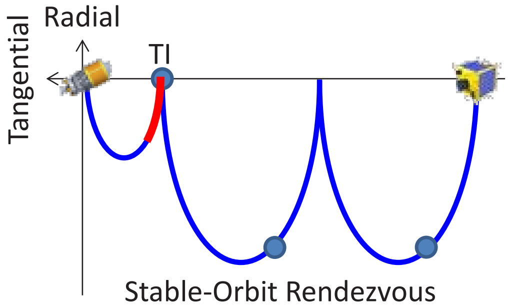
- Model Matching Navigation
  - Control requirements are ±10 cm for distance and ±5 deg for attitude
  - A simple model matching algorithm is tested as a preliminary study
    - Circular joint plane of the PAF is detected from the image
    - Distance and orientation of the circular joint plane are estimated from the detected result
  - Further improvement might be achieved by enriching the algorithm, however it would increases the calculation time
  - The trade-off study will be conducted to find out the optimal design



4.1. Far/Middle Phase Trajectory Design

- Candidate Trajectories



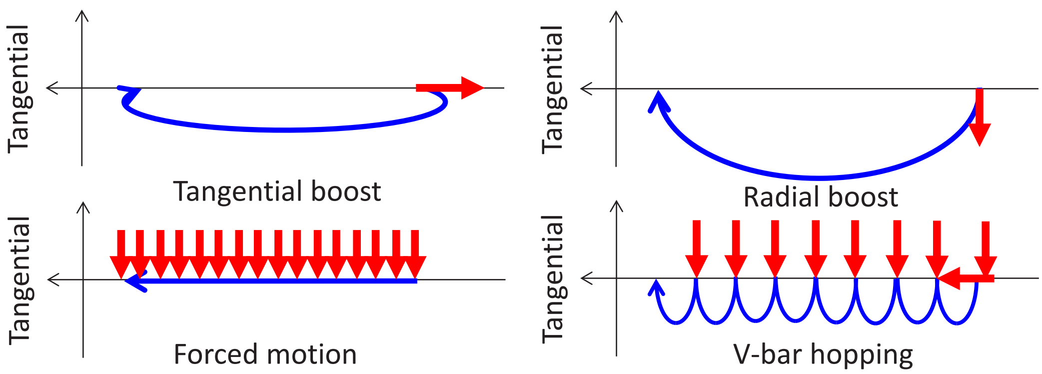


Dual Co-elliptic Rendezvous (DCR)	Stable Orbit Rendezvous (SOR)
Pros: PA is safe	Pros: Chaser can stay at the V-bar hold point and adjust the arrival time arbitrarily
Cons: Restriction to the arrival time adjustment	Cons: Difficulty in ensuring passive abort (PA) safety

DCR is adopted for far phase rendezvous

4.2. Near Phase Trajectory Design

- 4 kinds of possible V-bar approach trajectories are compared

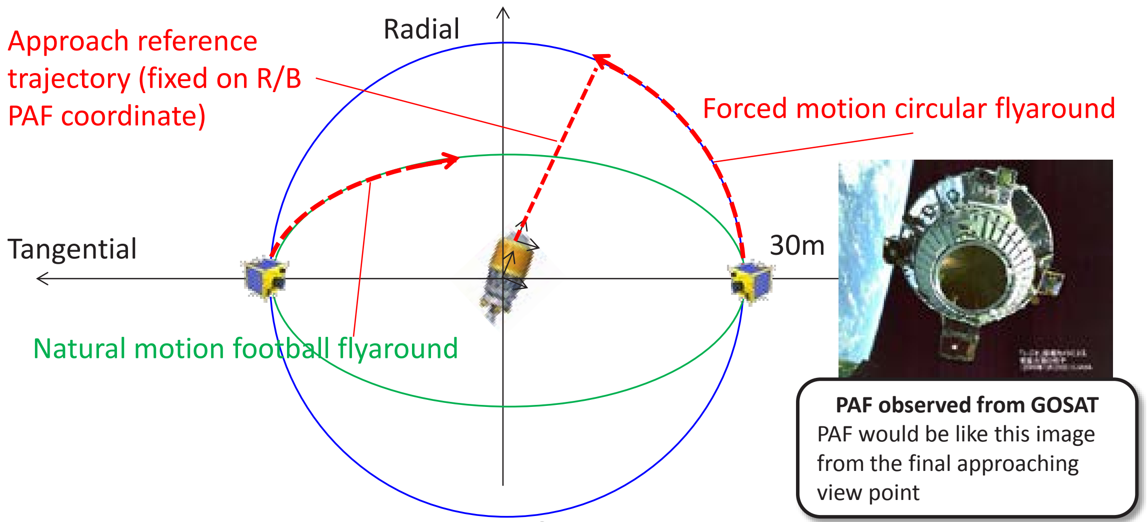


	PA Safety	Guidance Error	ΔV
Tangential boost	×	△	○
Radial boost	△	△	○
Forced motion	○	○	×
V-bar hopping	○	○	△

V-bar hopping trajectory is adopted for near phase approach

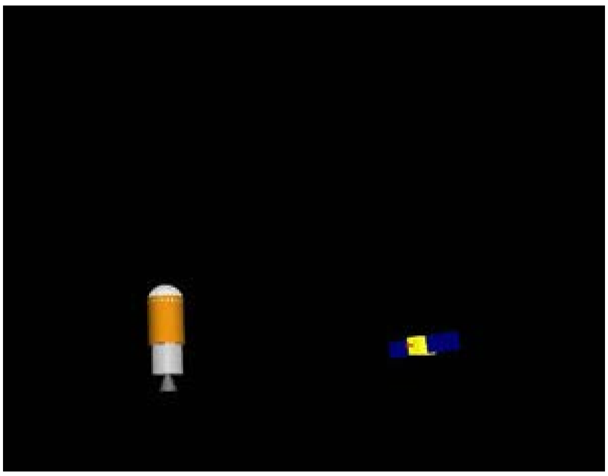
4.3. Final Approach Trajectory

- Since energy has been dissipated by Eddy current effect, the rocket bodies are expected to stand still and slightly swinging by gravity gradient torque
- Gravity center, motion, and rotation of the debris are observed from the 30m point
- Chaser flies tracing the circular trajectory to face PAF and relative navigation start as chaser get in front of PAF
- The anchor mechanism is attached to the PAF after approaching by relative navigation



4. 3. Final Approach Trajectory

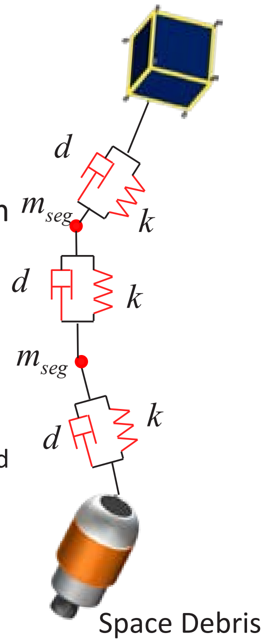
- Several initial conditions of the debris rotation were tested
- Estimation error of the image processing was modeled tentatively
- As long as the navigation is successful, the chaser could approach to the debris by relative navigation to attach the anchor mechanism



- **Chaser could attach the anchor mechanism on the debris with slow rotation**
- **Navigation error model must be refreshed reflecting the experimental data**

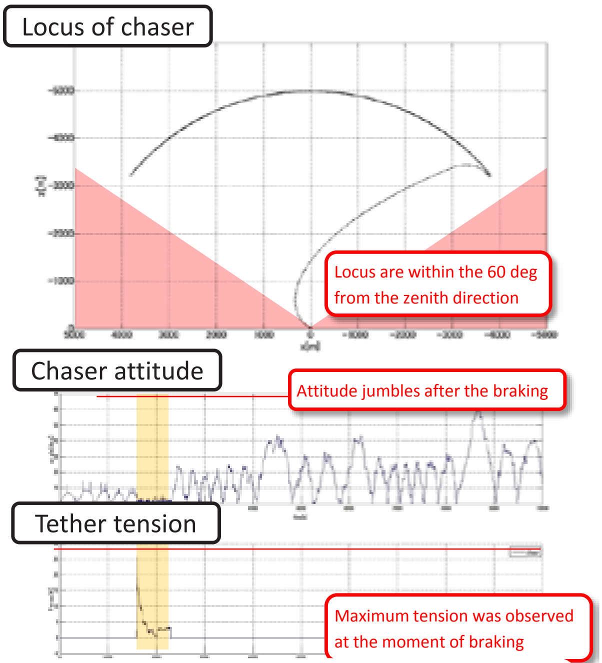
5. EDT Extension

- **Objectives**
  - It is desirable if EDT could be extended passively
  - De-orbitting efficiency would be the best if EDT is extended to the vertical to the flight direction
  - Tension of the EDT must be kept under 100 N
  - It is desirable if the attitude of chaser and debris are calm
- **Simulations**
  - Multi-mass model
    - soft tissue of the EDT is modeled as:
      - divided into the segments with mass connected by spring and damper
      - tension will not be generated if the segment length is less than natural length
  - Brakes are implemented to reduce the speed before 5km



5. EDT Extension

- **Simulation Results**



- **EDT extension can be achieved with only the early phase acceleration**
- **However, EDT swings back and forth with quite a large angle**

6. Conclusions and Way Forward

- This work addressed the design of the relative navigation and the rendezvous trajectory toward debris.
  - Overall navigation concept for the reference mission is designed
  - Preliminary experimental study of the candidate navigation sensors are introduced
  - The approach trajectory is elected from the viewpoint of passive abort safety considering unreliable relative navigation
  - Numerical simulations are conducted to verify the designed reference trajectory and EDT extension up to 5 km
- Navigation system should be refined, reflecting the results of experimental verifications.
- Simulations with updated parameters based on the experiments should be done to verify the reference scenario more precisely.
- Further discussions are needed to select the propulsion sytem to de-orbit the debris.