V&V of Safe Close-Proximity Operations for Non-cooperative Targets

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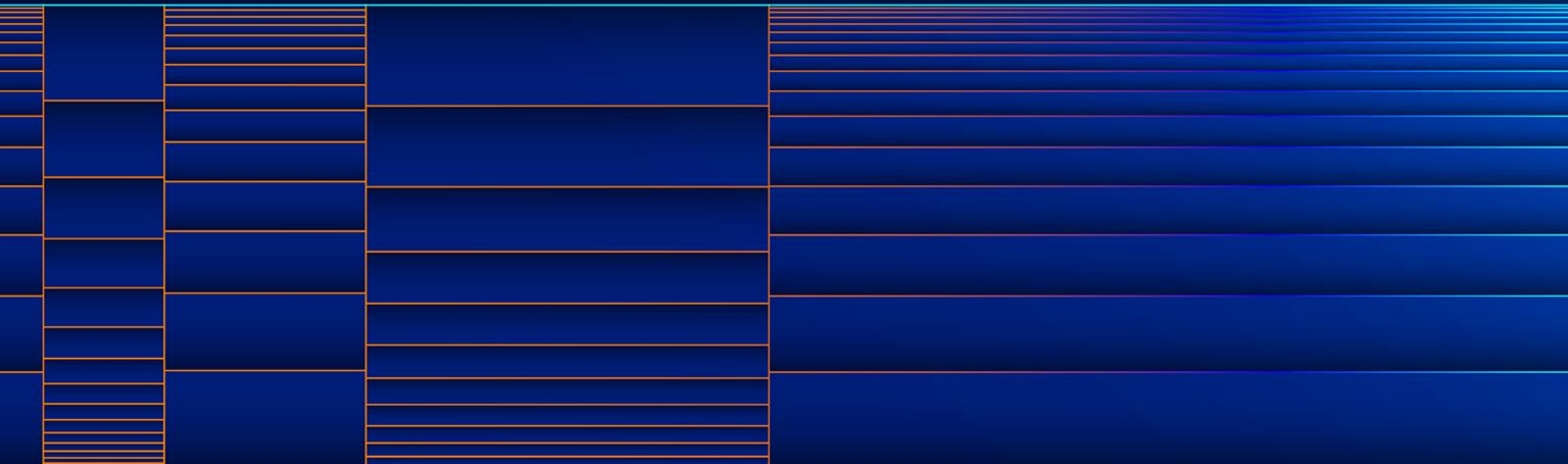


Presentation scope

Goal: identify requirements Verification and Validation methods for safe close-proximity operations around uncooperative targets.

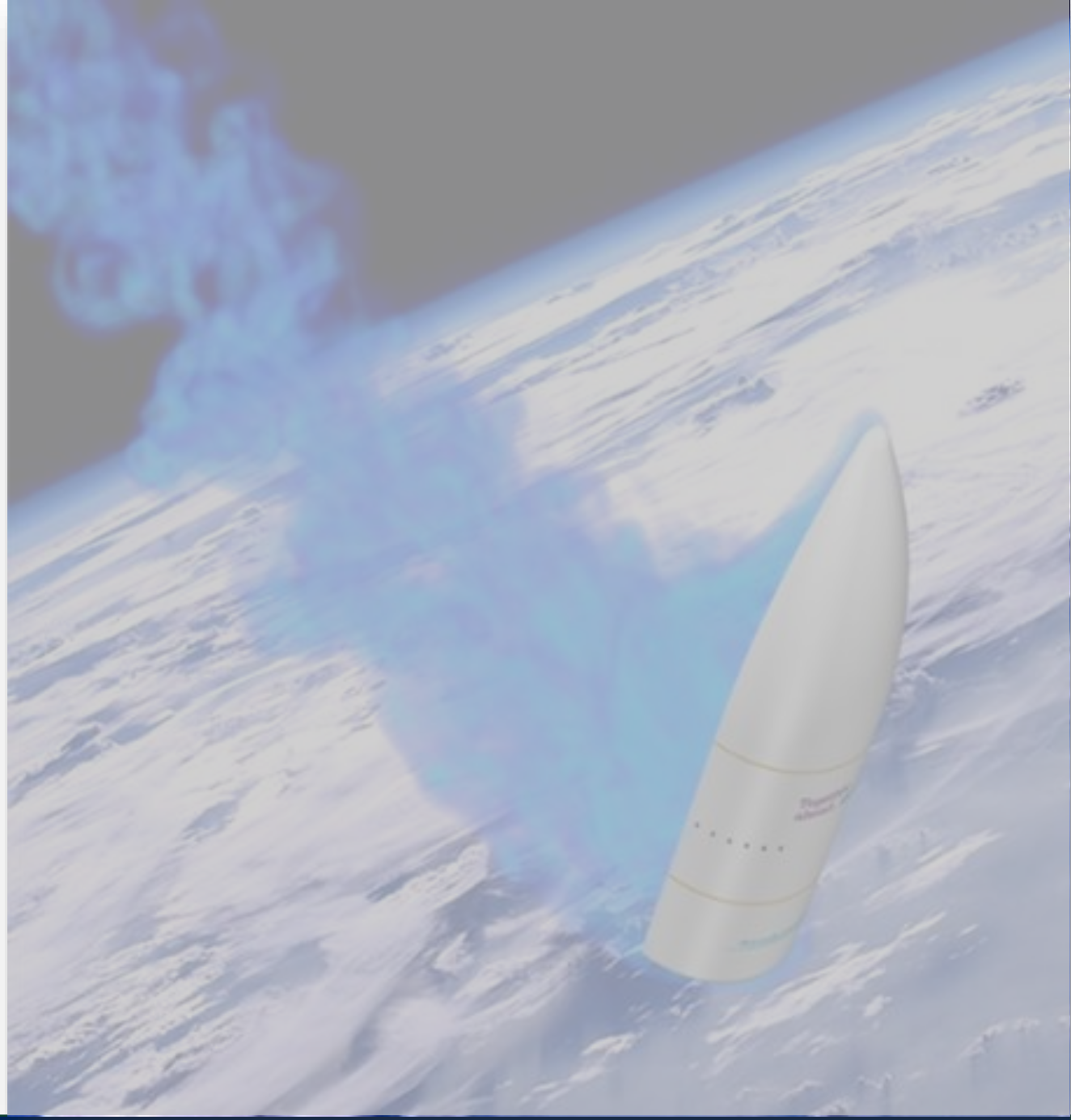
Methods:

- V&V by design
- V&V by analysis
- V&V by test

Outcomes:

- Elaborated for GNC and Mission Analysis
- Demonstrated for Clearspace-1 (CS-1) case

* The Authors want to acknowledge the **European Space Agency ESA** and the industrial partners **Thales Alenia Space** and **GMV** for their fruitful support and collaboration on the study “Verification and Validation of Rendezvous and Proximity Operations Safety”, which was financed under an ESA contract issued with the invitation to tender AO11351.



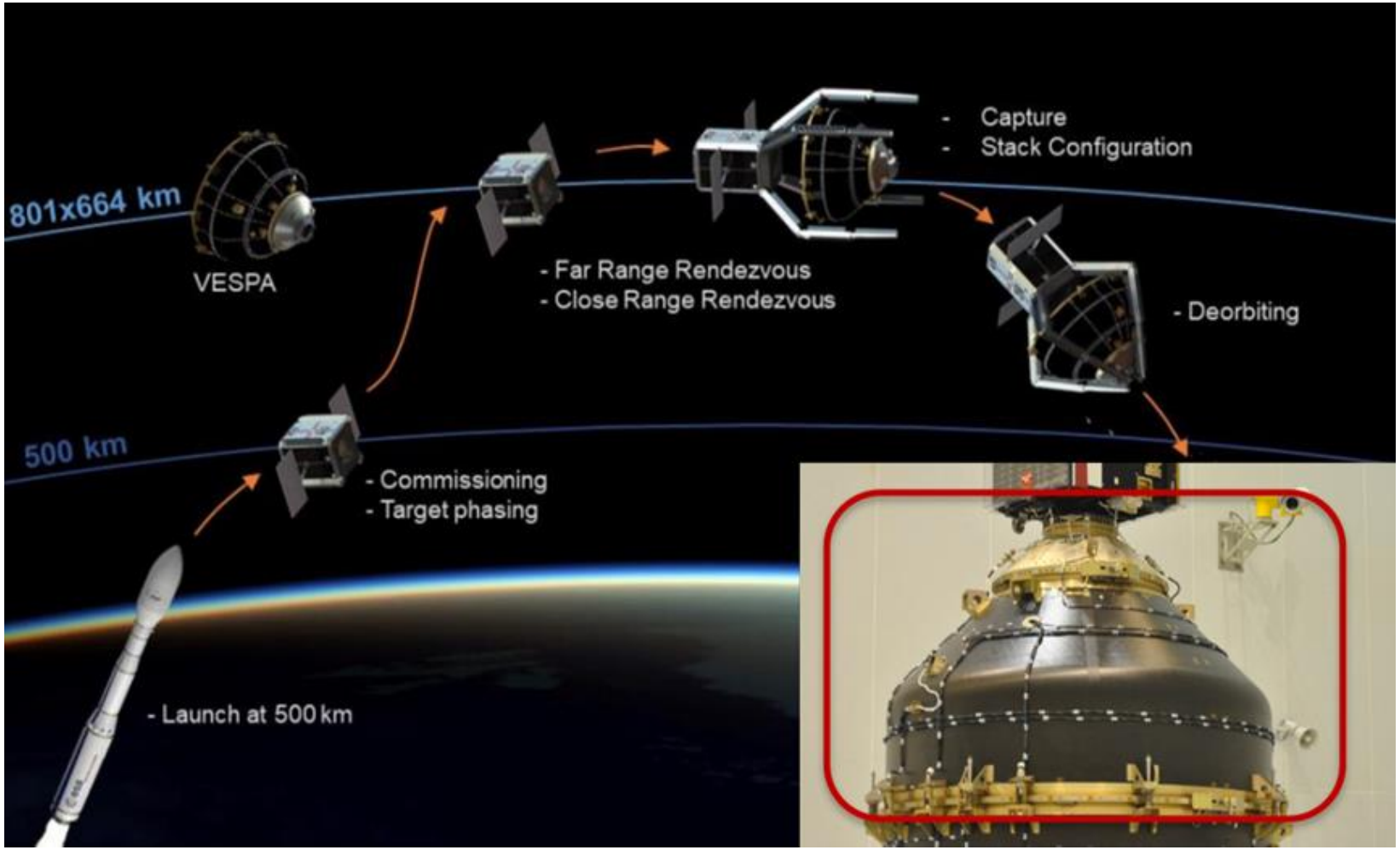
Overview of the case-study – Clearspace-1

Context

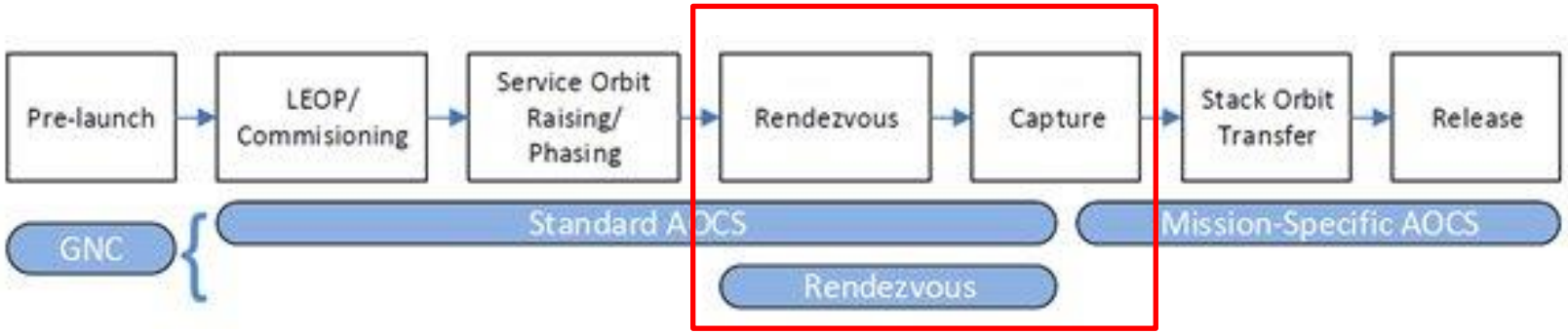
- Part of ESA ADRIOS program;
- Rendezvous, capture and de-orbit a VESPA upper stage.

Objective

- Demonstrate removal of VESPA from LEO with tentacles capture system
- Develop building blocks for active debris removal (ADR) commercial missions.



Concept of operations



Rendezvous phases

Client phasing: the servicer is brough closer to the client using the ROEs approach of walking safety ellipses.

Far rendezvous: the servicer is brought even closer to the client through fly-around trajectories with impulsive ΔVs and naturally inspects the client.

Close rendezvous: forced motion towards capture.

Capture and stack configuration: capture of the client with the robotic arm and stabilization.

GNC subsystems

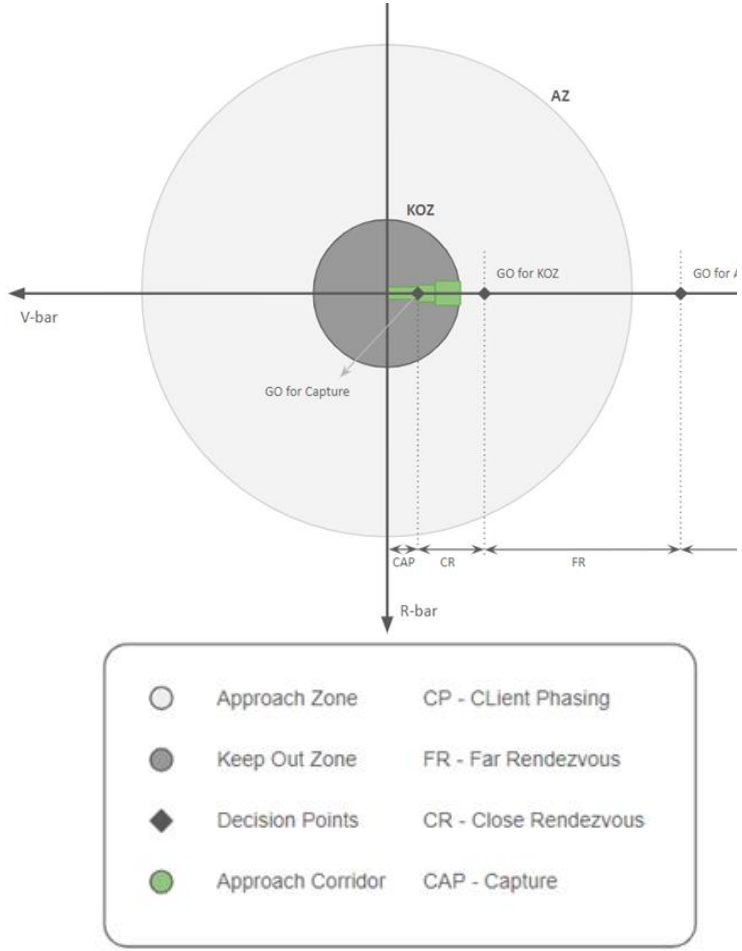
Attitude and Orbit Control System: dedicated to the absolute 6DoF motion;

Rendezvous GNC: dedicated the 6DoF motion relative to the target.

V&Ved requirements

Requirements that will be V&Ved address the following topics:

- Definition and sizing of zones and corridors, e.g.:
  - Trajectories will be constrained to zones;
  - Zones shall be transitioned only intentionally;
- Definition of decision points and the associated criteria for GO/NO-GO, e.g.
  - GO/NO-GO for approach zone, keep out zone, and capture.

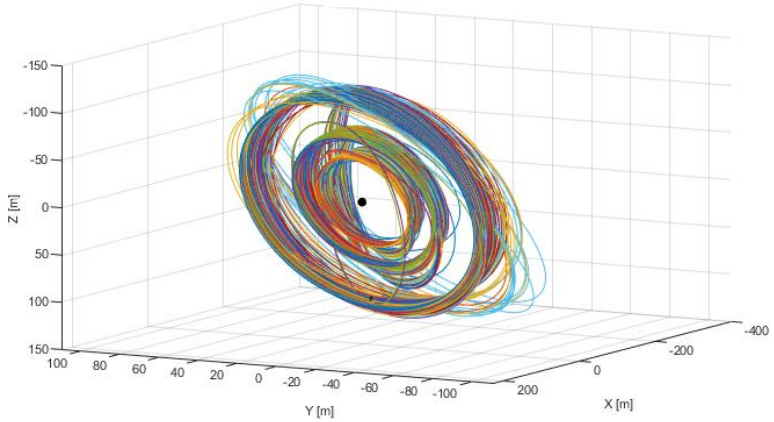


V&Ved requirements

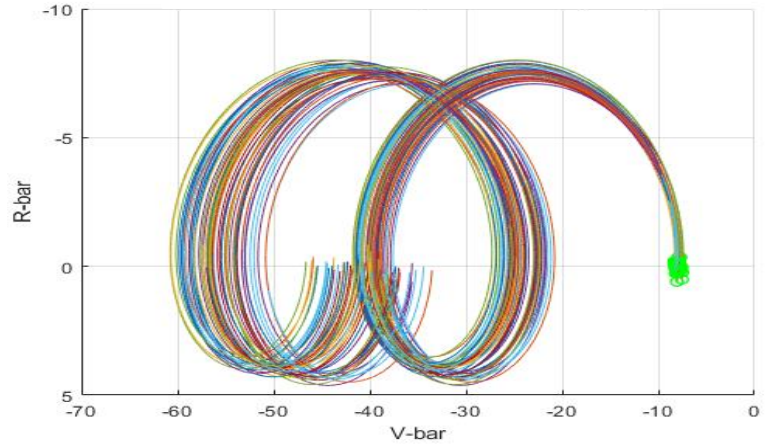
Requirements that will be V&Ved (cont'd)

- Client inspection, namely before the close range operations;
- General servicer controllability, including 6DoF relative control close to the target
- Accurate, continuous and reliable estimate of servicer state
- Redundancy and safety of abort and cancel procedures, which shall be executed autonomously

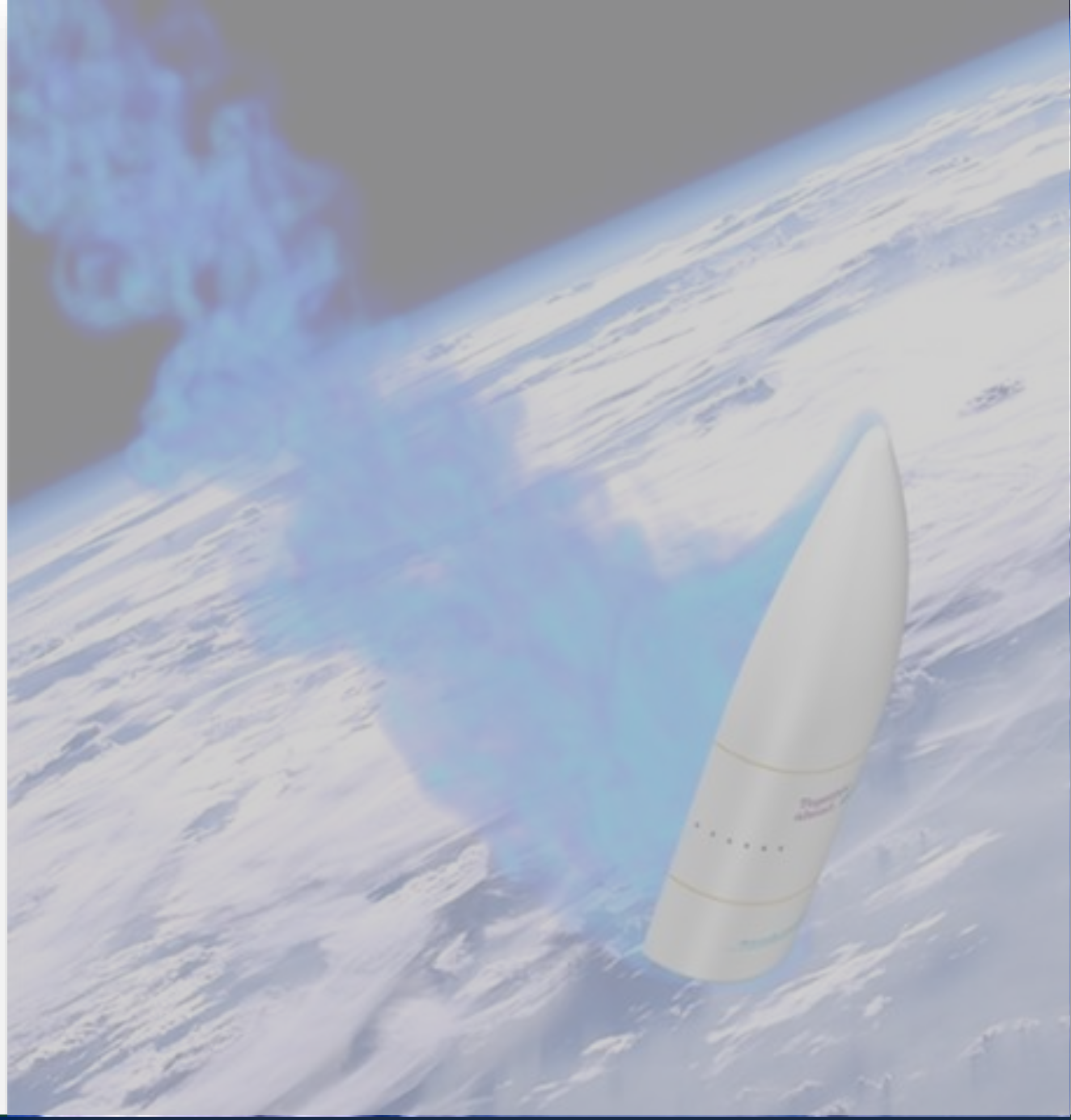
Inspection



Safety of Cancel Procedure

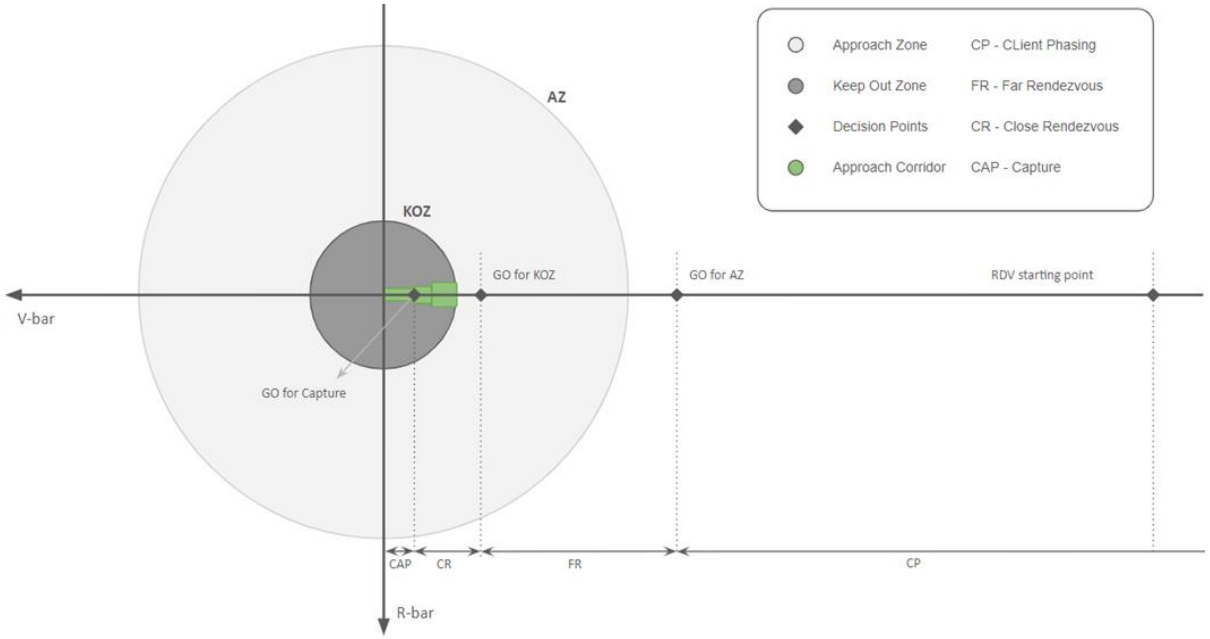


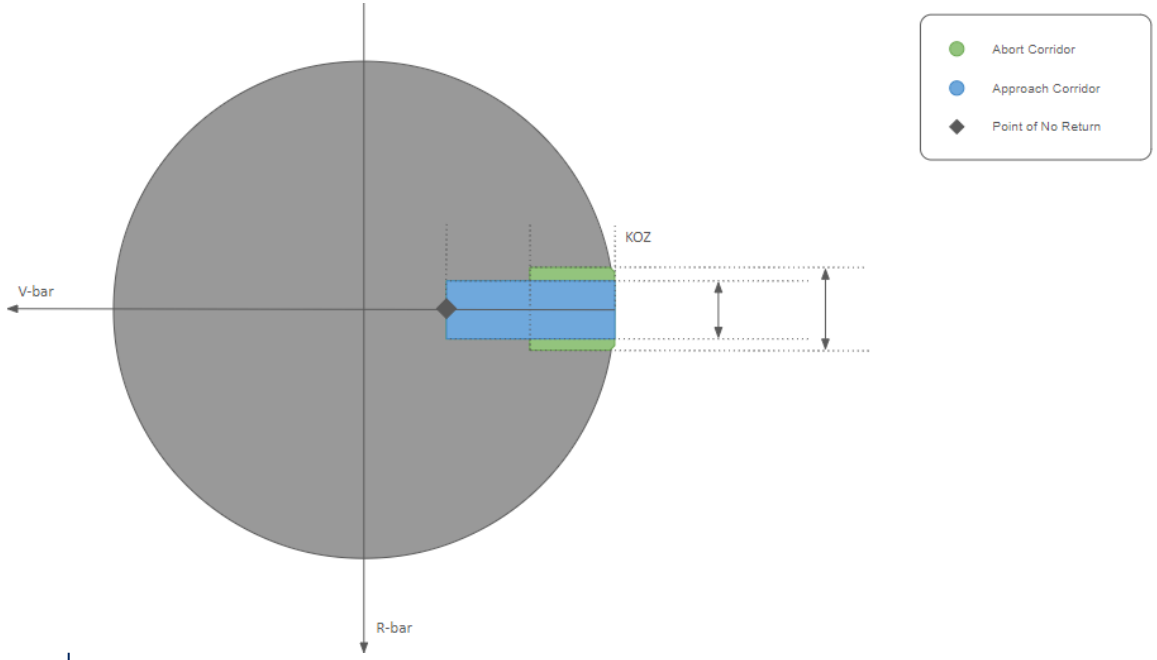
V&V by design



Zones, corridors, decision points

Features are designed to be compliant with the requirements, then V&V is performed by review of design





Zones:

- Approach Zone (AZ) – separates closing from fly-around
- Keep Out Zone (KOZ) – zone where collision may occur

Corridors:

- Abort corridor – triggers the ABORT (CAM)
- Approach corridor – triggers the CANCEL to a recovery point

Decision points:

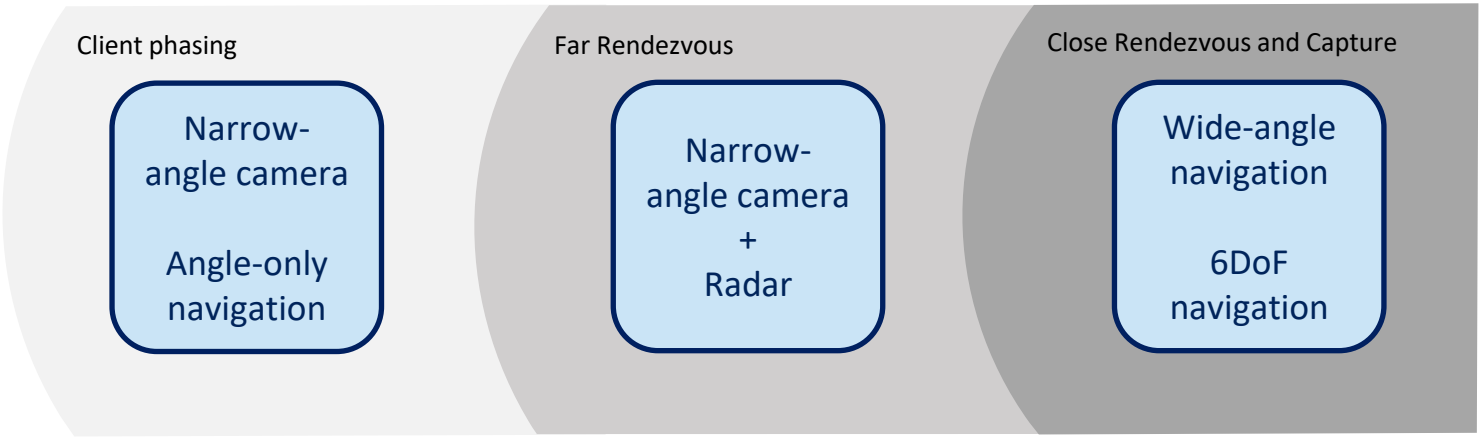
- AZ entrance, KOZ entrance, Capture

Decision criteria

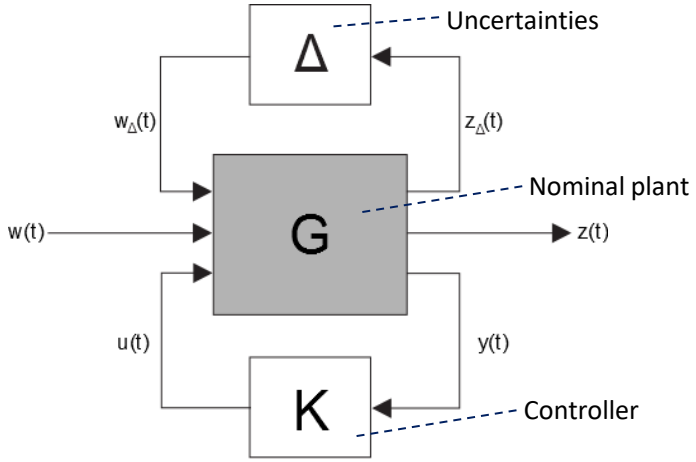
- Critical systems operationality
- Commissioning of associated navigation system
- Commissioning of associated actuation system

GNC design and safety strategy

Navigation: Accurate, continuous and reliable



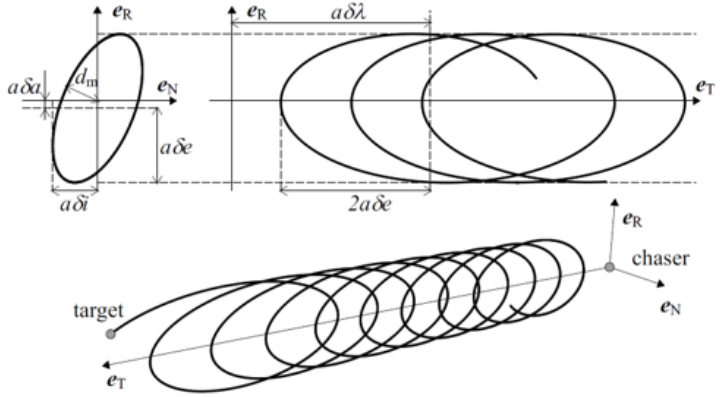
Control: H-infinity ensures robustness by design

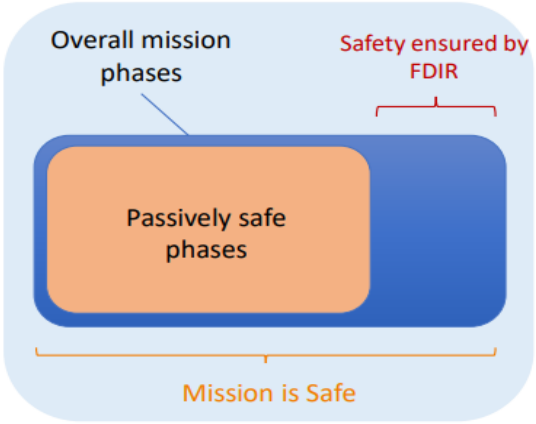


Control Synthesis Problem

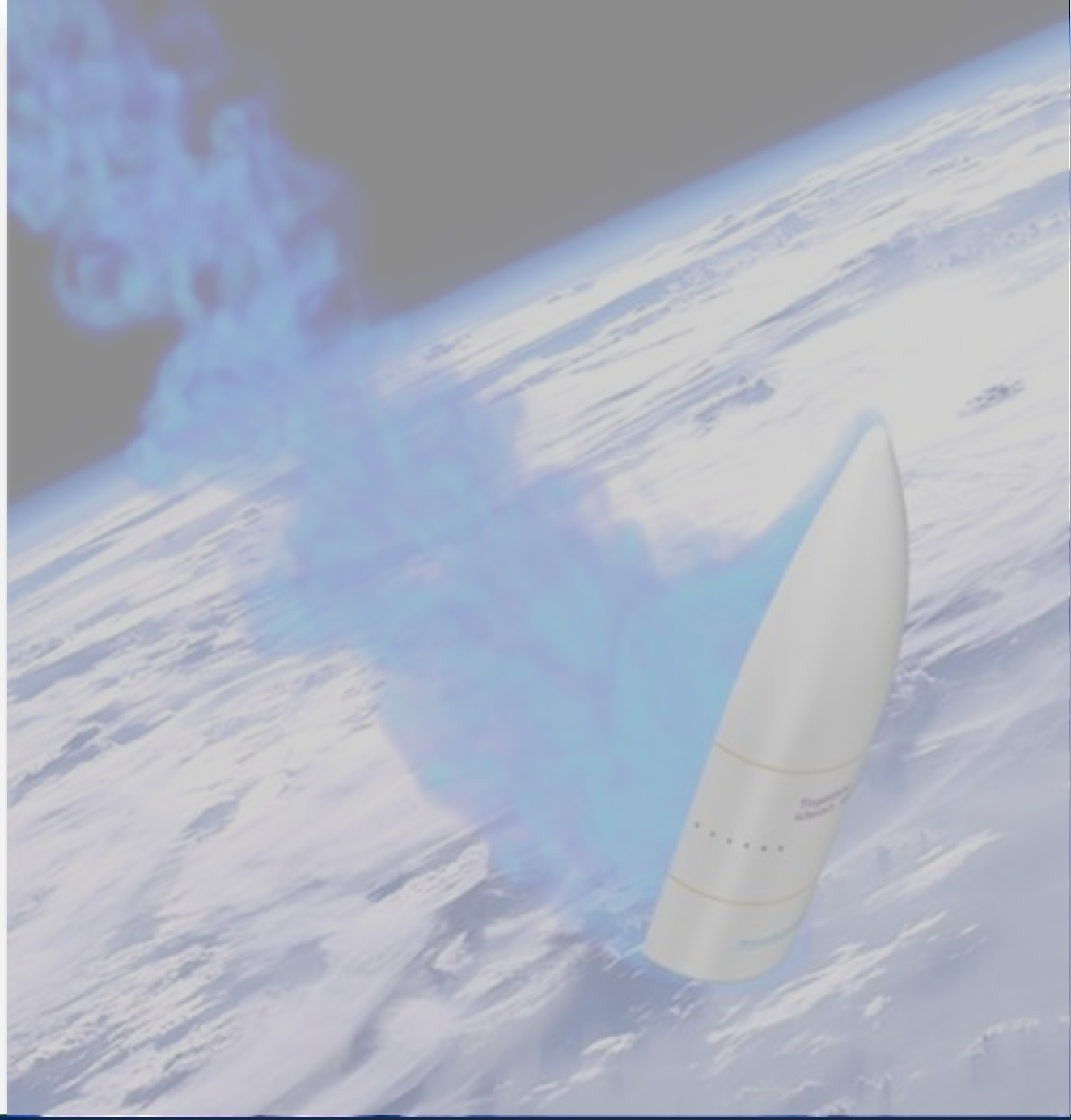
Safety:

- passively safe trajectories by design (ROE)
- active safety for collision avoidance (CAM)





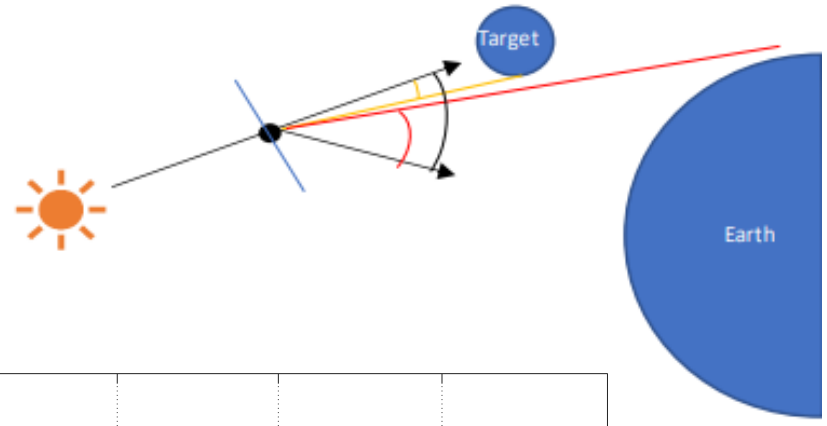
V&V by analysis

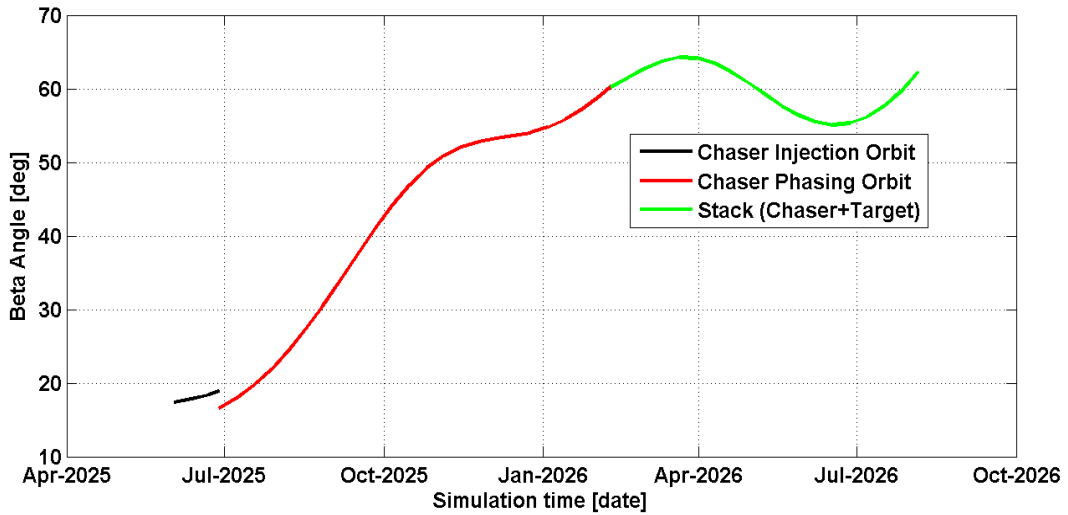


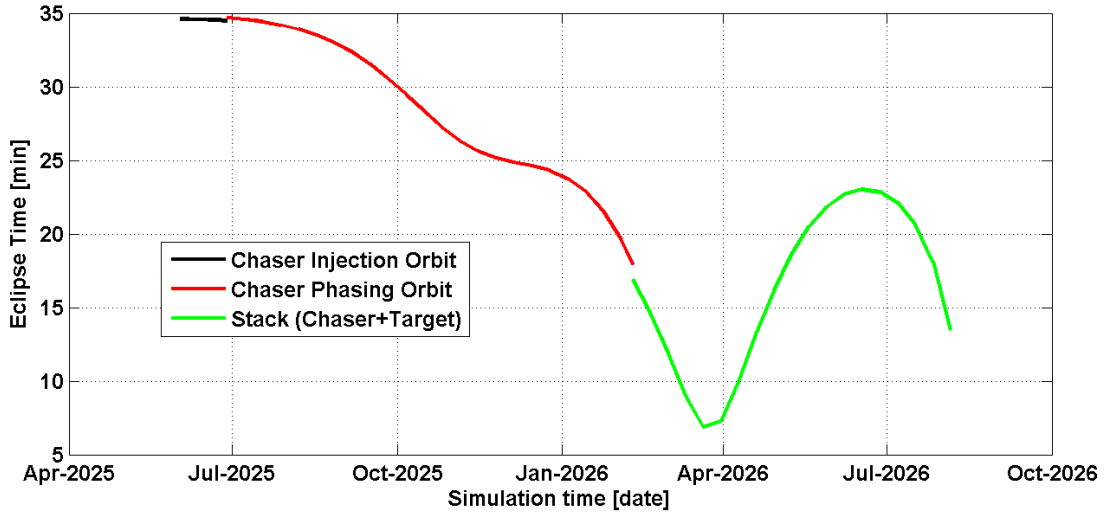
Navigation

Illumination analysis: fundamental to have good light conditions

- Beta-angle analysis: elevation of the sun wrt orbital plan
- Eclipse analysis: should be as short as possible







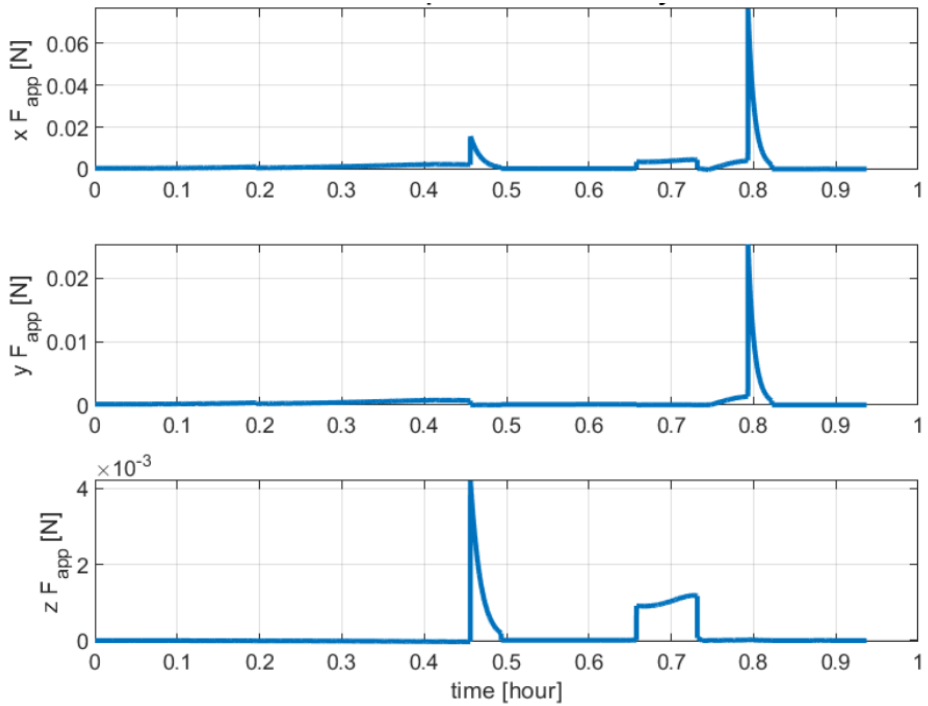
Complemented by a test campaign

1) Synthetic image generation with scattering of relevant optical parameters

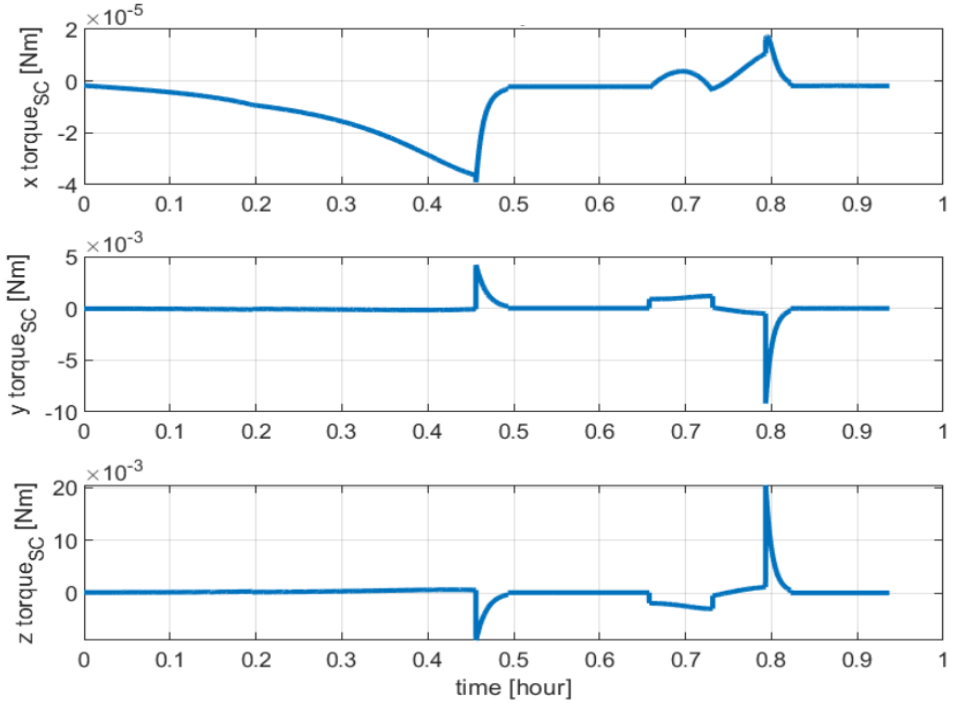
2) Optical test bench campaign at GRAALS with target mockup and camera model

Controllability analysis

- Analysis of relative position and velocity profiles → **required forces**

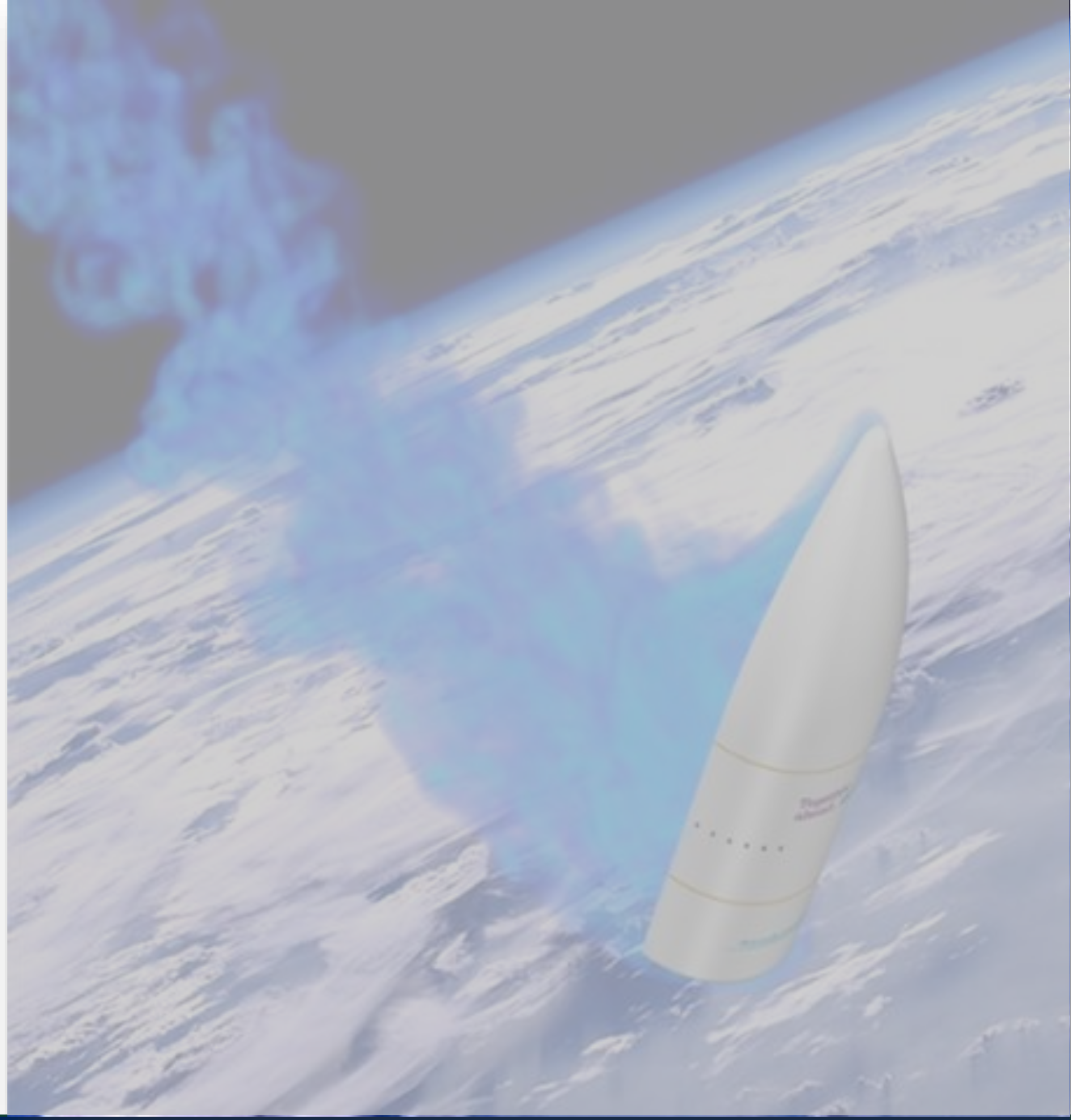


- Analysis of angular velocities and accelerations → **required torques**



+ authority margin

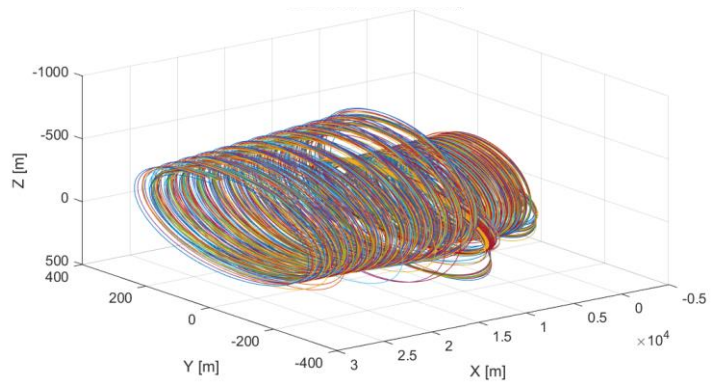
V&V by test

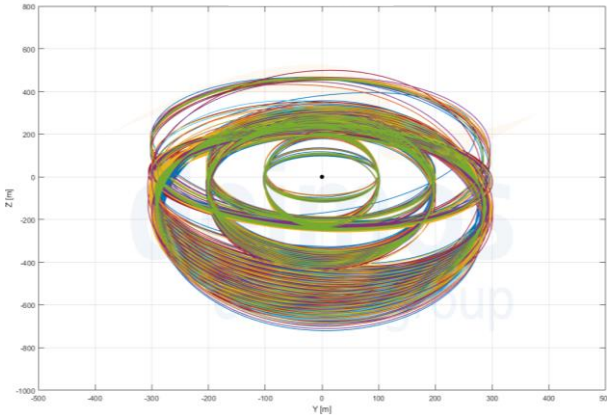


MIL MC campaigns

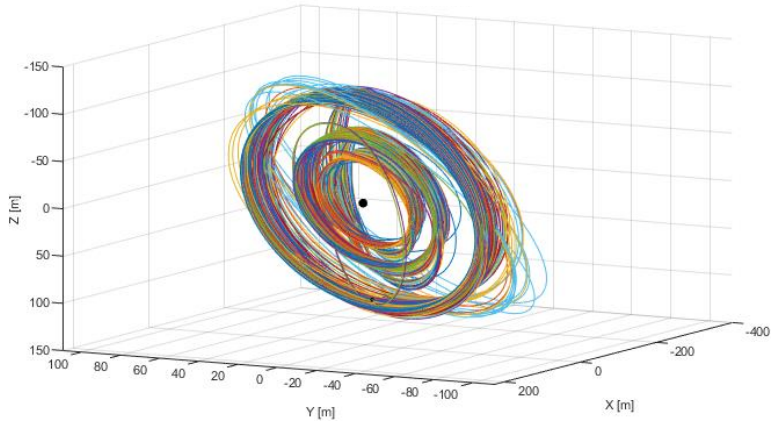
- **MIL MC simulations for**
  - Client phasing
  - Far rendezvous
  - Close rendezvous
  - Capture
- **Effects considered**
  - MCI dispersions
  - Dispersion of sensors and actuators non-idealities
  - Flexible modes and fuel sloshing
  - Orbital perturbations
  - Illumination conditions

Client Phasing

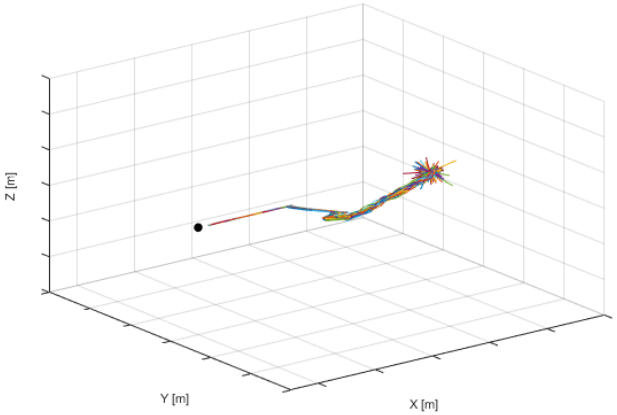




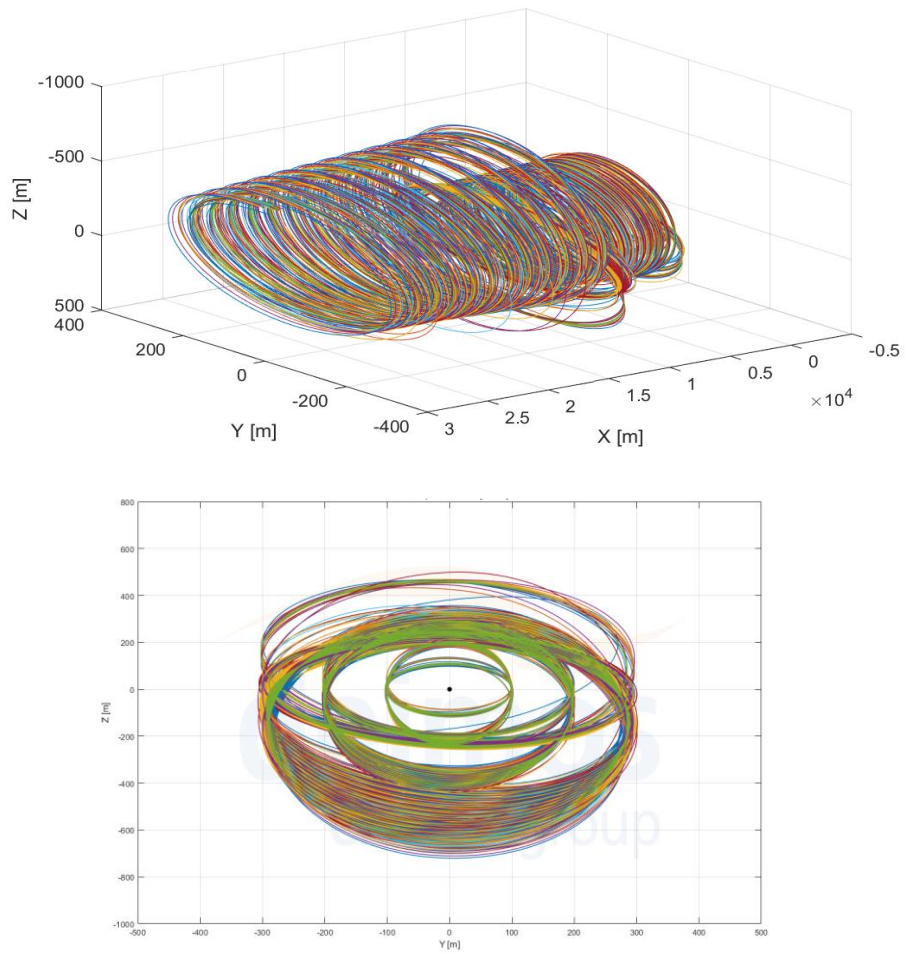
Far Rendezvous



Close Rendezvous and Capture

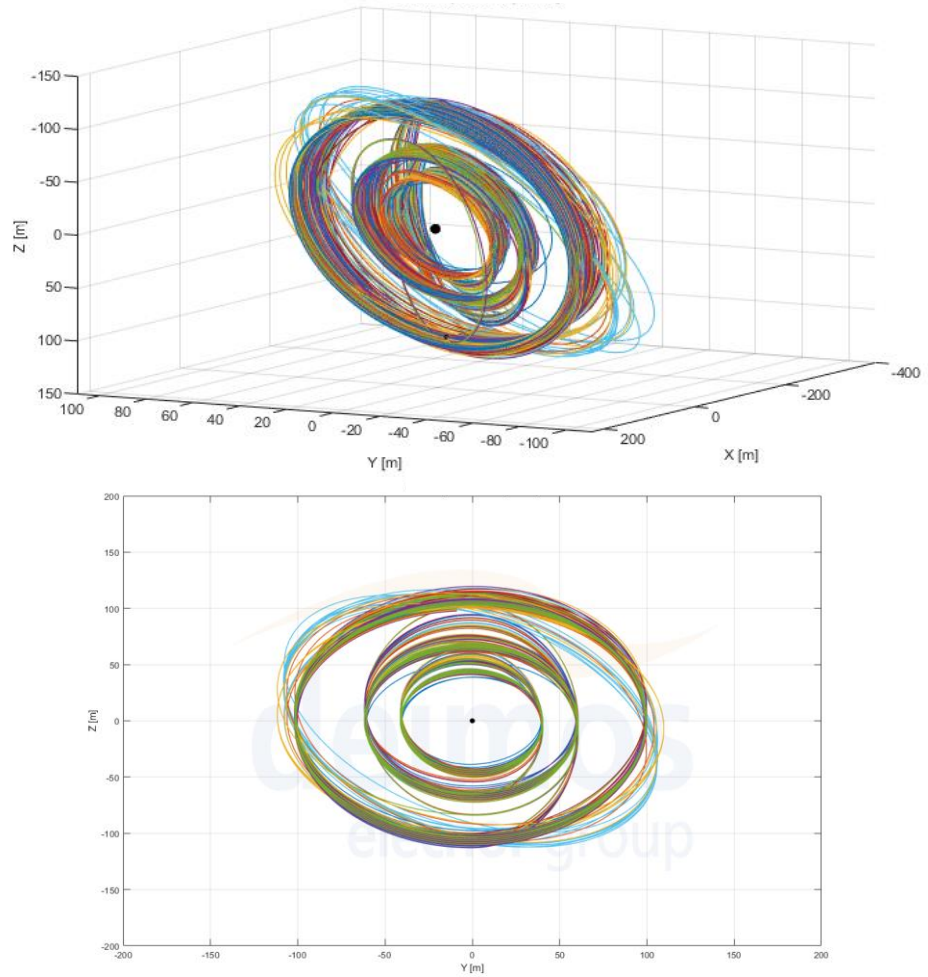


Client phasing



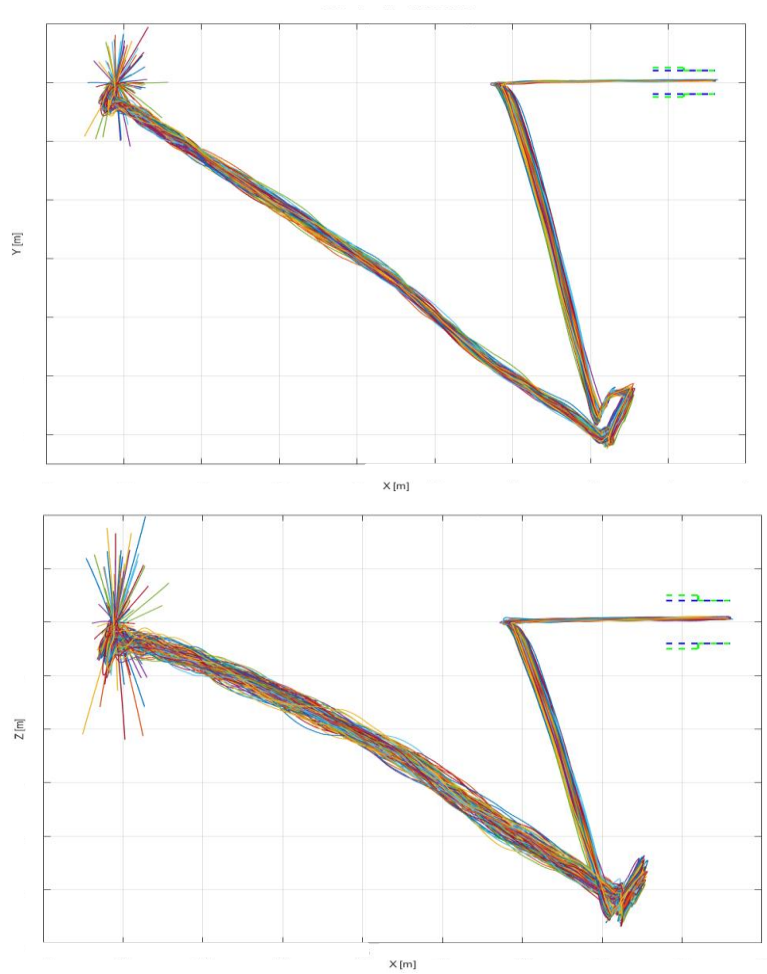
- ✓ The servicer safely approaches the target both in true anomaly and fly-around radius of ROE
- ✓ Approach Zone is avoided

Far rendezvous



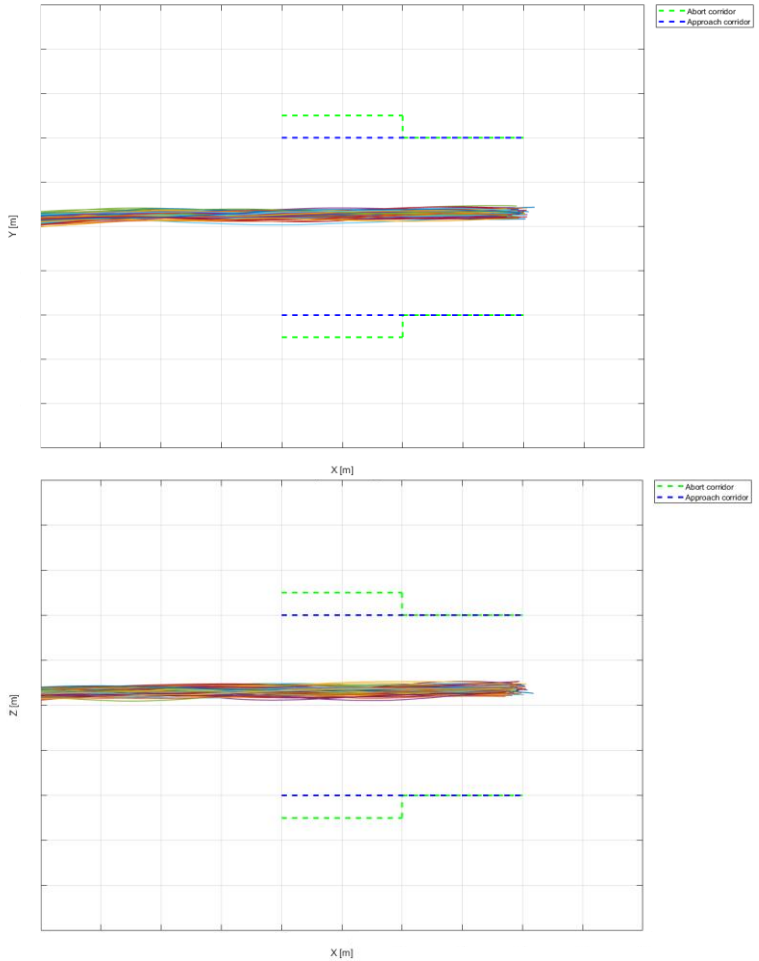
- ✓ Performed within Approach Zone
- ✓ KOZ is avoided without requiring active control
- ✓ Client inspection is performed with natural ROE

Close rendezvous



- ✓ Forced motion solution, with active safety
- ✓ Trajectory inside the KoZ
- ✓ Servicer successfully performs 6DoF control

Capture

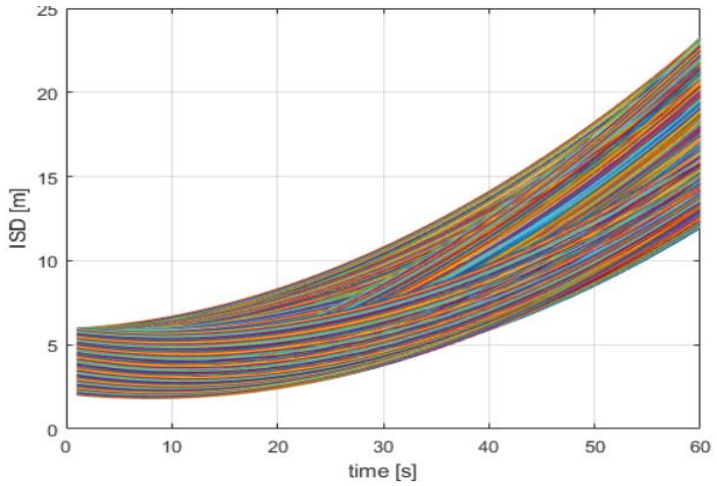


- ✓ Trajectory within Approach Corridor
- ✓ Compliance with respect to corridor is obtained with margin

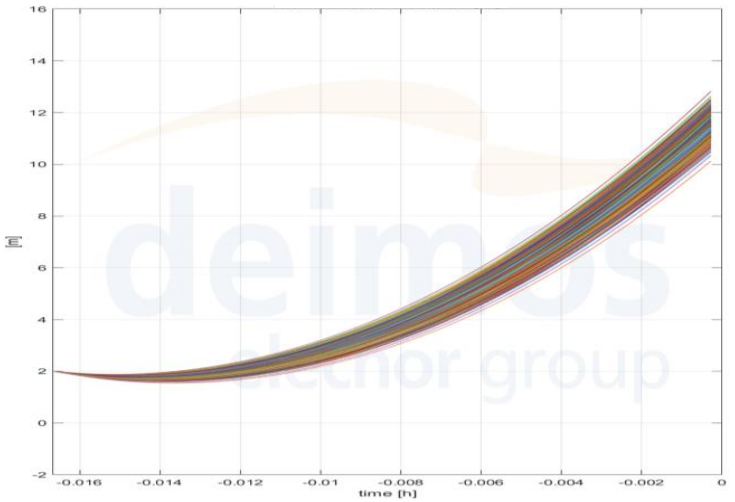
Active safety

Abort

Inter Satellite Distance Evolution (Fast Simulator)



Inter Satellite Distance Evolution (FES)

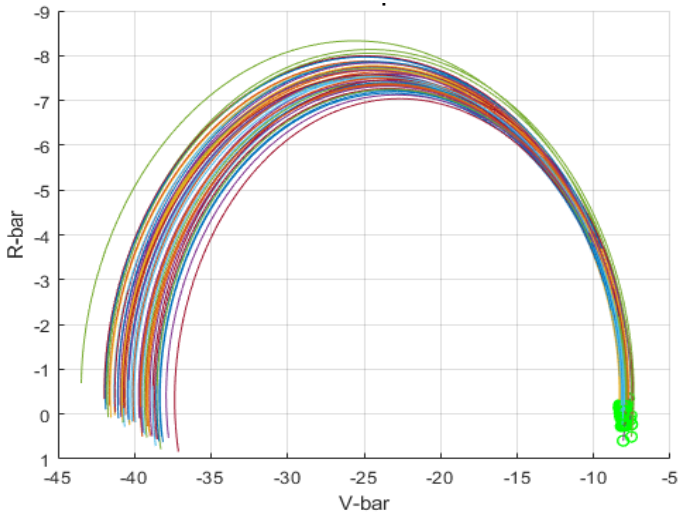


- ✓ Abort solution is demonstrated for the case of single thruster failure when in KoZ
- ✓ Abort applies a sequence of boost to drift away from the client both in short and long term
- ✓ Validated with two tools:
  - Fast simulator for intensive testing, identifying worst-case conditions
  - High-fidelity simulator (FES) for MC around worst-case conditions

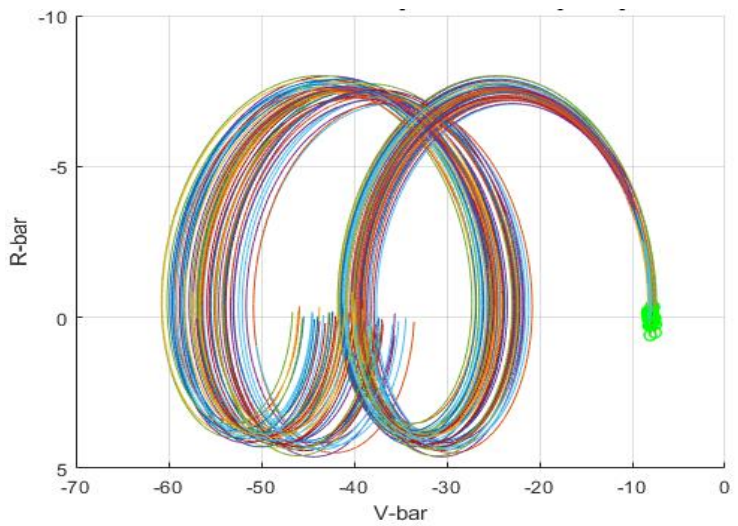
Active safety

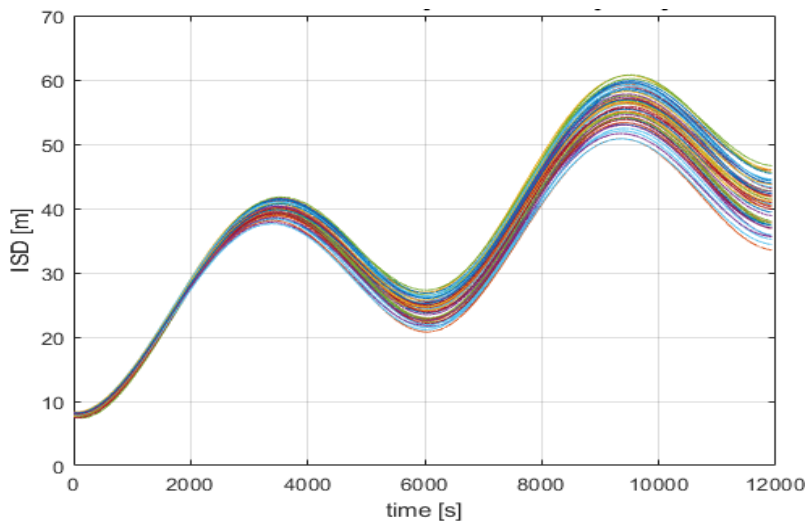
Cancel

Cancel with stop hop



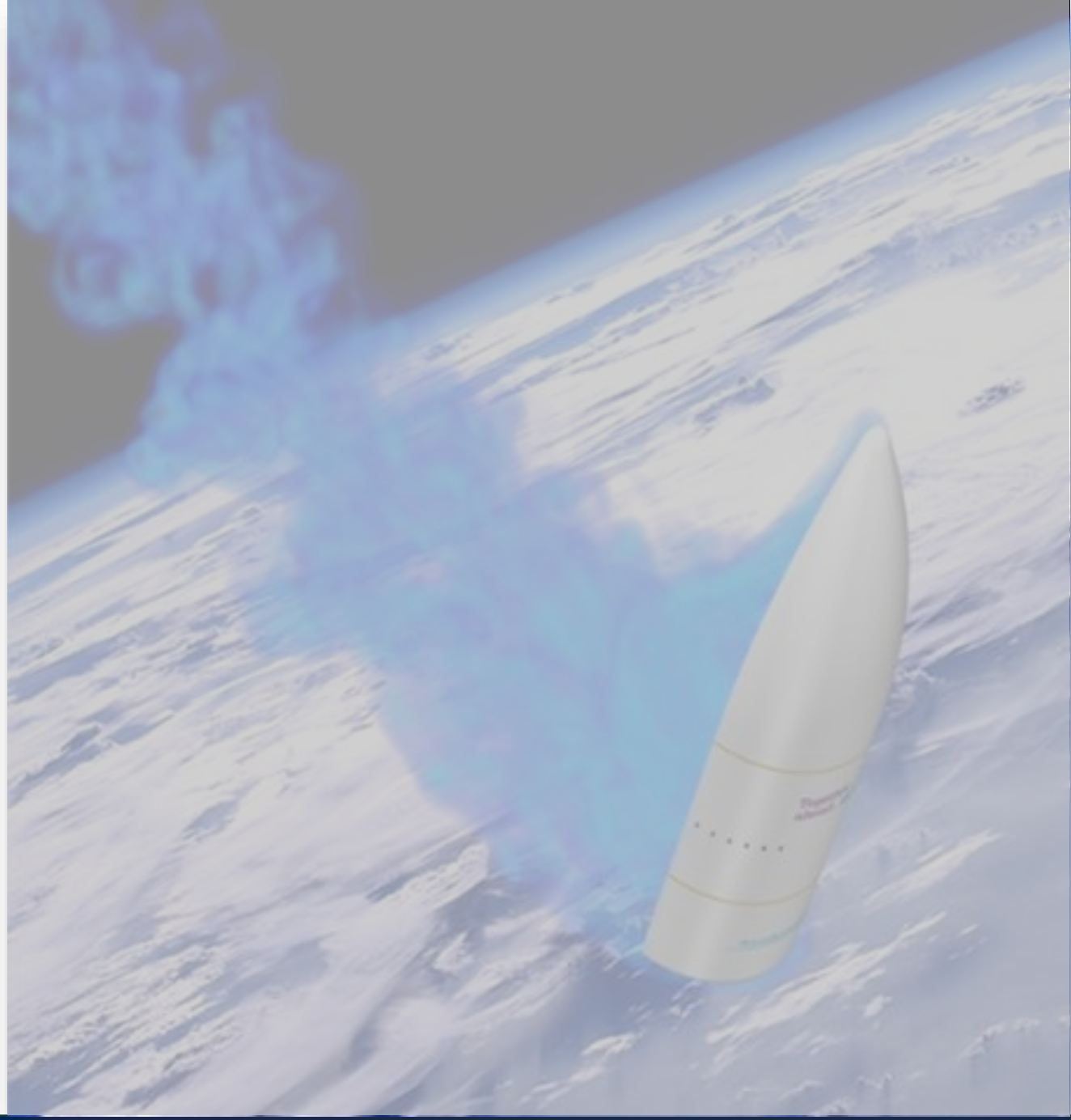
Cancel with failed stop hop





- ✓ Cancel will boost back to a reference point
- ✓ Passively safe: if the stop hop fails, the servicer will continue to drift away from the target
- ✓ Both abort and cancel are effective and place the servicer in a passively safe trajectory

Conclusions



Conclusions

Demonstrated the V&V of **requirements for Close proximity operations;**

Several approaches adopted (**design, analysis and test**) for a given **use case**, Clearspace-1;

The **guidelines are well posed**:

- can be adopted in general, providing methods for **V&V in other missions**;
- cover the topics of GNC, Mission Analysis and Concept of Operations.

Selected lessons learned:

- For active safety (CAM) sizing and validation, a **dedicated simulator** proved effective:
  - enabled extensive testing of initial states;
  - identified worst-case (WC) configurations;
  - complemented with high-fidelity simulations around WC configurations.
- For passive safety, careful selection of points of interest for the validation was key. Simulations starting from every possible state would be computationally impeditive.
- A **dedicated tool** allowed for controllability analysis of the rendezvous profile.

Future work may address generalization to RV to other scenarios, such as small asteroids and small bodies, which have similarities (forced approach for capture, combination of simulators for validation) but challenges (very limited ground communication and hence high GNC autonomy).

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