GUIDANCE, NAVIGATION, AND CONTROL TECHNIQUES AND TECHNOLOGIES FOR ACTIVE DEBRIS REMOVAL

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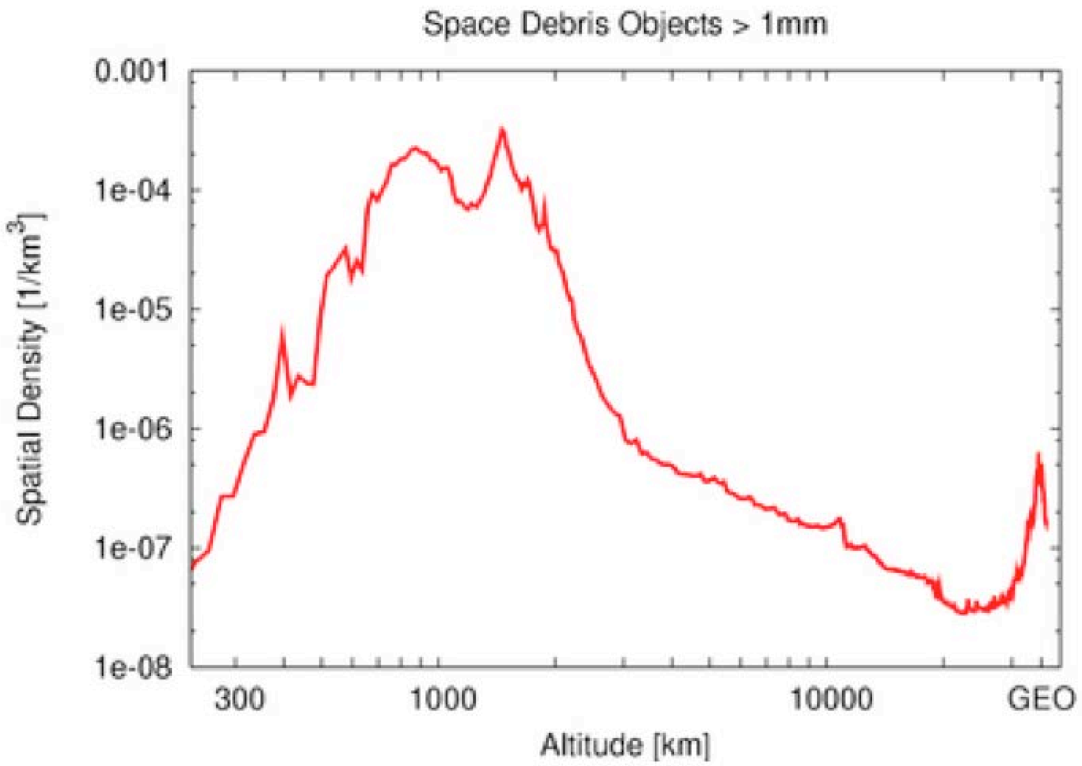
NON-FUNCTIONAL SATELLITES AND UPPER STAGES

- The size, distribution and observability of space objects is given by the ESA MASTER catalogue.

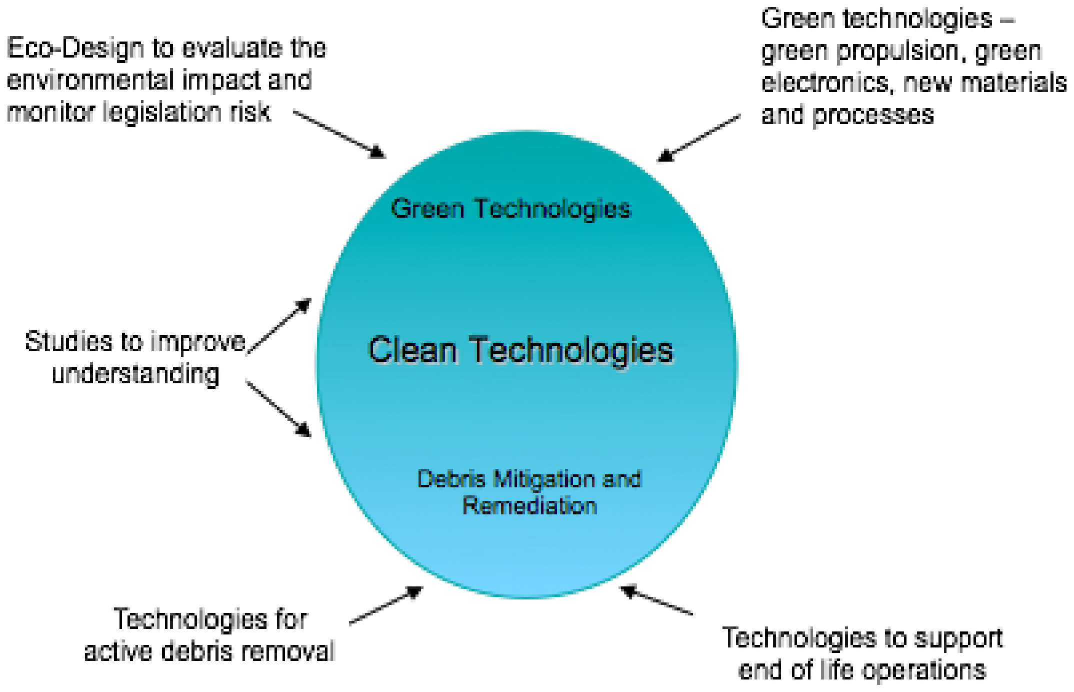
- The analysis of the density distribution of space debris as a function of altitude shows that **debris is mostly concentrated at altitudes below 3000 km** with a local peak around GEO.

- Several of those big satellites are currently located at orbits with an altitude of around 700 to 800 Km corresponding to a semi-major axis of more than 7000 Km. The related **risk of a collision is very high and potentially catastrophic**, given the large mass of those dead objects.



THE ESA'S CLEAN SPACE PROGRAM

- The ESA's "**Clean Space" program** is introduced as a cross-cutting theme within ESA's Technology programmes.
- Clean technologies are defined as those that **contribute to the reduction of the environmental impact of space programmes**, taking into account the overall life-cycle and the management of residual waste and pollution resulting from space activities.



THE ESA'S CLEAN SPACE PROGRAM

- The ESA's Clean Space initiative, organizes the implementation around four distinct branches:
  - 1. **Eco-design**: the development of tools to monitor and evaluate the environmental impact and legislation compliance of programmes.
  - 2. **Green technologies**: the development and qualification of new technologies and processes to mitigate the environmental impacts of space activities.
  - 3. **Space debris mitigation**: the study and development of affordable technologies required for managing the end-of-life of space assets.
  - 4. Technologies for **space debris remediation**: the study and development of the key technologies for active debris removal.

DESIGN OF A REMOVAL MISSION

- The design of the chaser mission to remove a non-functional satellite of big dimensions with a controlled re-entry can be broken down in several mission arcs: **ascent, far rendezvous, close approach and fly around, capture, and finally de-orbiting.**

- The **ascent phase** has the aim to inject the chaser into a **neighbouring orbit** that will lay down underneath and behind the non-functional satellite with a true anomaly that provides a distance of about **20 Km below and 50 Km behind the target**

  - The arrival to this point is performed in two steps: first the **injection of the launcher** into an elliptical orbit with the node coincident with the target orbit followed by a **circularisation** to acquire the proper anomaly. With this latest circularisation burn the launch phase is concluded.

DESIGN OF A REMOVAL MISSION

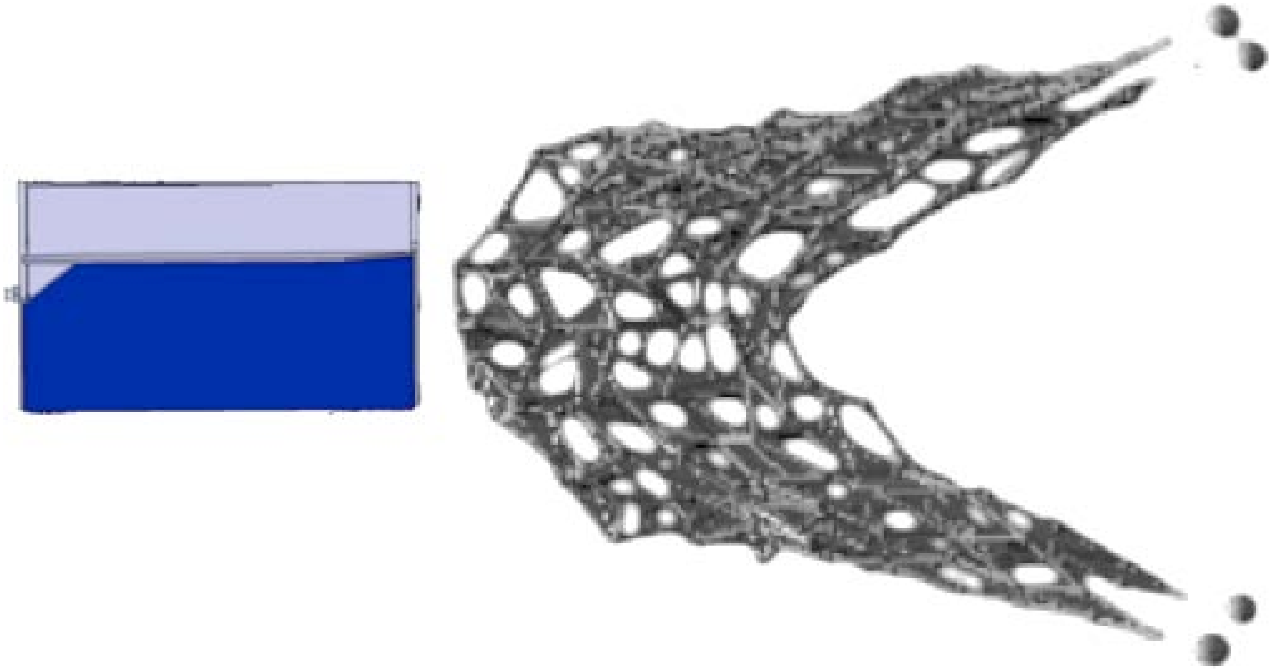
- The **far rendezvous phase** has the aim to move the chaser from its launched parking orbit **to an orbit closer to the non-functional satellite** of big dimensions just behind it.
  - This phase ends with the chaser much closer now to the target and **ready to initiate the relative navigation**.
- The **close approach phase** allows arriving to a **very close distance to the target** (e.g. 50 meters). The objective is to arrive close to the target and hold the chaser in a point to allow the activation of the sensing suite to initiate the next phase.
- The **fly-around phase** is used to **determine the attitude rate of the target and match it.** This phase is needed to identify the best possible place to initiate the capture. This phases uses 3D vision and image processing techniques to accurately and autonomously determine the best capture pose.

DESIGN OF A REMOVAL MISSION

- The **capture phase** is devoted to capture the target:
  - This phase will see the activation of the **deployment mechanism** and the final capture.
- The **de-orbiting phase** starts after the capture and stretches all along the required manoeuvres to de-orbit the target
  - The period of time can vary depending on **the strategy of de-orbiting** used. In general, several impulsive ΔV may be required to de-orbit the compound chaser-target

CAPTURE MEANS DESIGN TRADE-OFFs

- For this analysis, two capture means are under study: the tentacles and the net.
  - **The net** is assumed to be similar to a fish net of about 25x25 m^2 in surface. The net is deployed by bolts located on a single side of the chaser. The **deployment is at "once"**. This means that there is only **one chance** of deployment. The mass of the net is assumed to be about 25 kg of weight

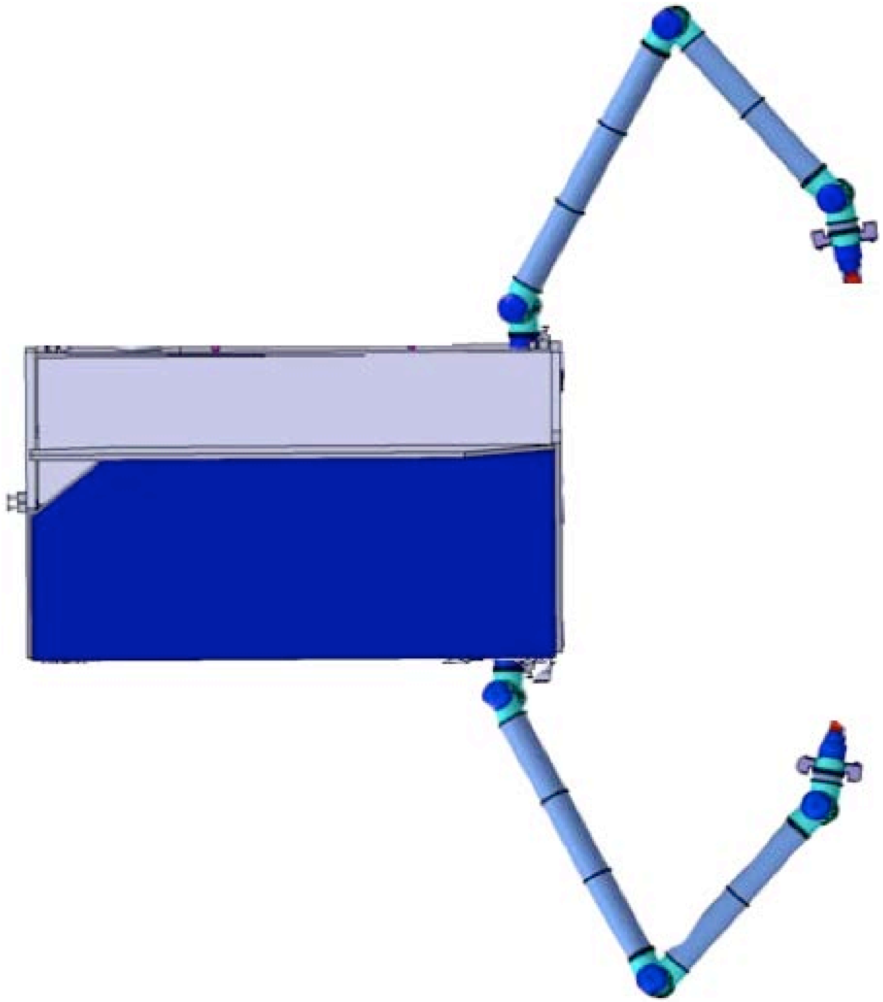


CAPTURE MEANS DESIGN TRADE-OFFs

- **<u>The tentacles</u>** are assumed to be **two identical arms** collocated in each side of the chaser. The length of each arm is ±3 m, its mass is about 10 kg and each arm exerts a grip force of 10 N per tentacle.

- For the analysis shown in this article, the tentacle arms re assumed to be like the DEOS manipulator.

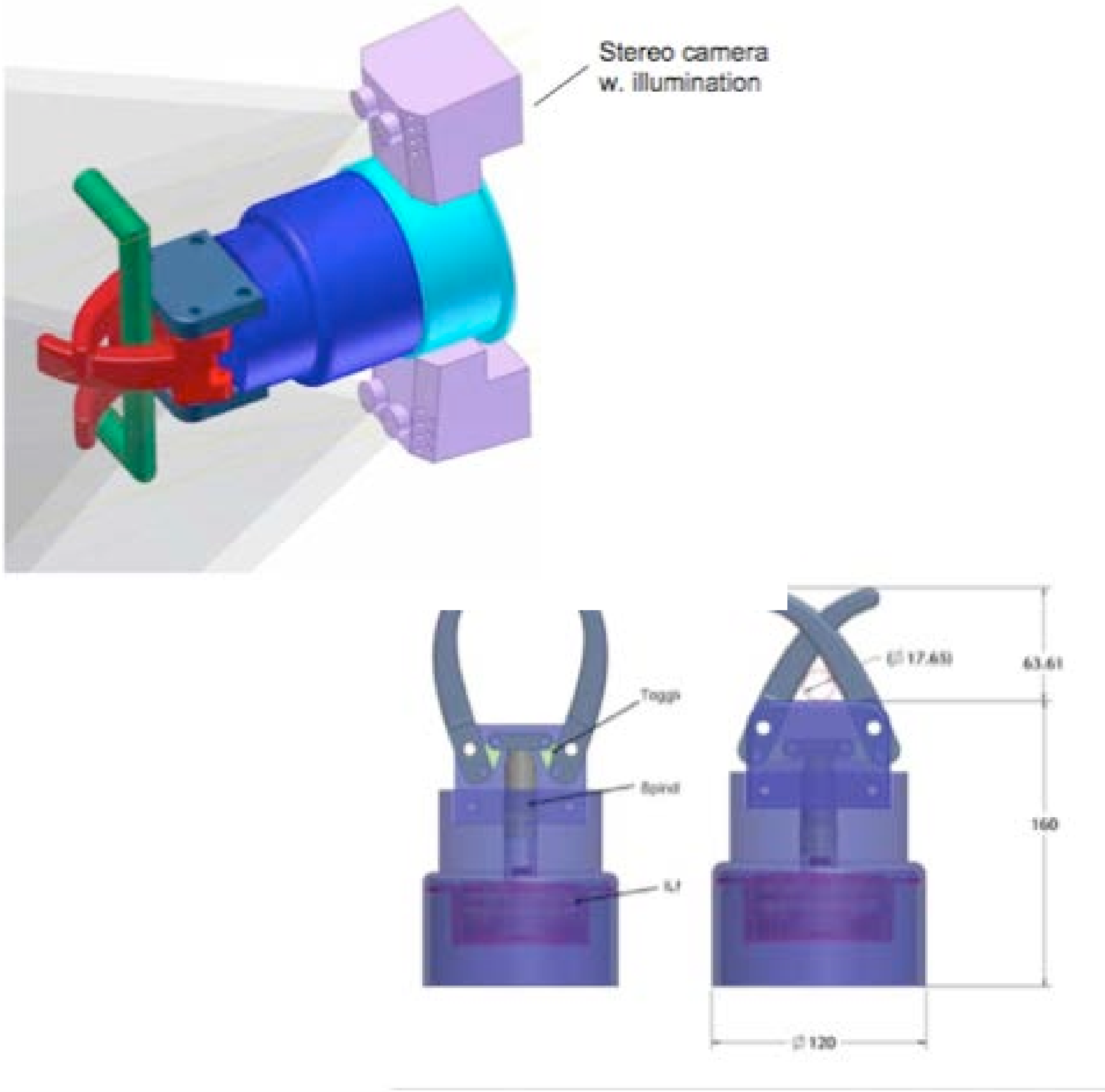
- One of the manipulators has a **holder ring** as end effector. The other manipulator has a **gripper**. The gripper “holds” the ring of the other manipulator across the target.



CAPTURE MEANS DESIGN TRADE-OFFs

- The gripper manipulator has 2 **cameras** (redundant) with illumination. The gripper is assumed to be identical to the one of the DEOS mission.

- Both tentacles **encircle the target along the body Z-axis**. The chaser is positioned along the centre of **centre of gravity**. Then both tentacles close around the target at the same time. The plume on the target must be compensated by the control of the chaser.



Gripper for the tentacle arm. Courtesy of Kayser-Threde and DLR

GUIDANCE

- The guidance analysis comprises the **study of the rendezvous strategies and trajectories** for far, intermediate and close approach, the fly-around manoeuvres, the capture, the towing, and de-orbiting.

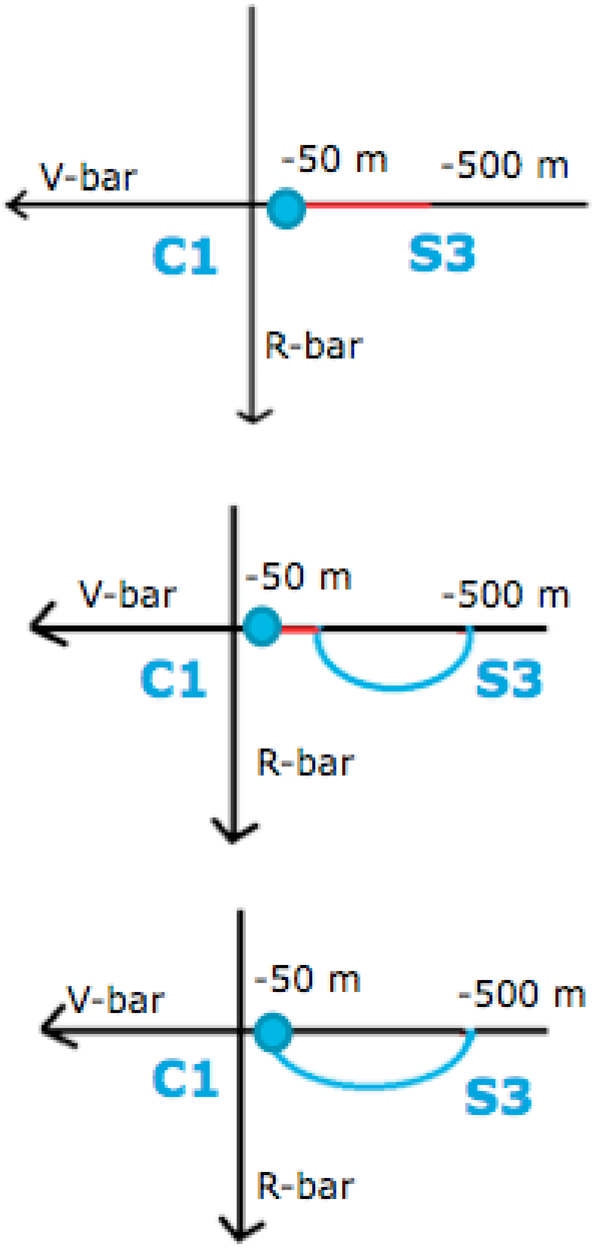
- For this part, several **trade-offs** have been performed: rendezvous on V-bar (positive and negative), and rendezvous in R-bar (positive and negative). The analysis reported here used the **Local Vertical Local Horizontal** (LVLH) coordinate system.
  - In this system, the centre of coordinates is located on the centre of mass of the target, being positive in the direction of its velocity and positive as well in the direction of the Earth. The third axis complements the triad providing the out-of plane component.

GUIDANCE

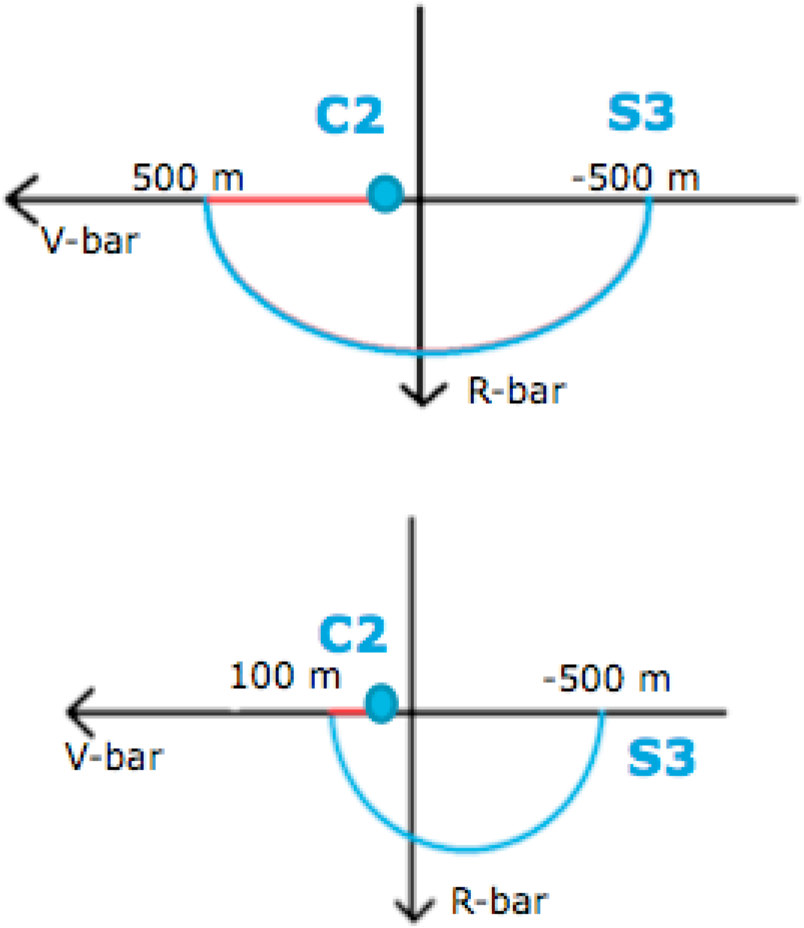
- **Special points** (C1, C2, C3, C4) have been defined in the guidance of the chaser as to activate and deploy the capture means.
  - The distance of these points to the target have been **parameterised** to compare and trade-off time to capture and the fuel required.
- The **safety** of the guidance strategies has also been investigated in both axes (V-bar and R-bar). A **safety corridor** with a cone half angle of 2 degrees has been assumed for all approaches. The safety Collision Avoidance Manoeuvre (CAM) was computed as a safe ΔV of 0.15 m/s in the most demanding case.

GUIDANCE: V-bar approach

Net Capture

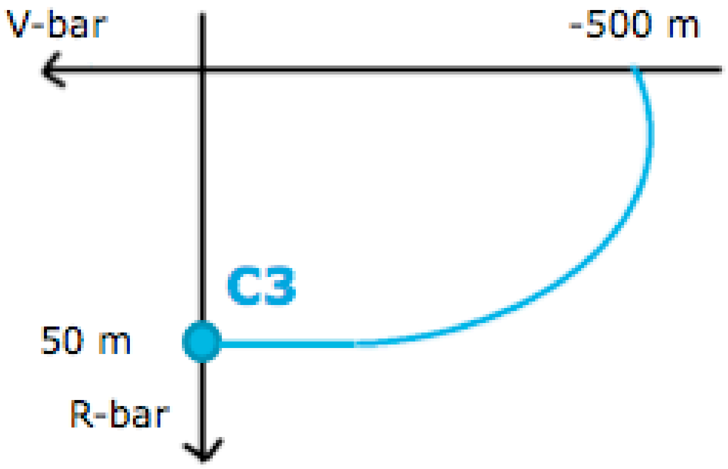


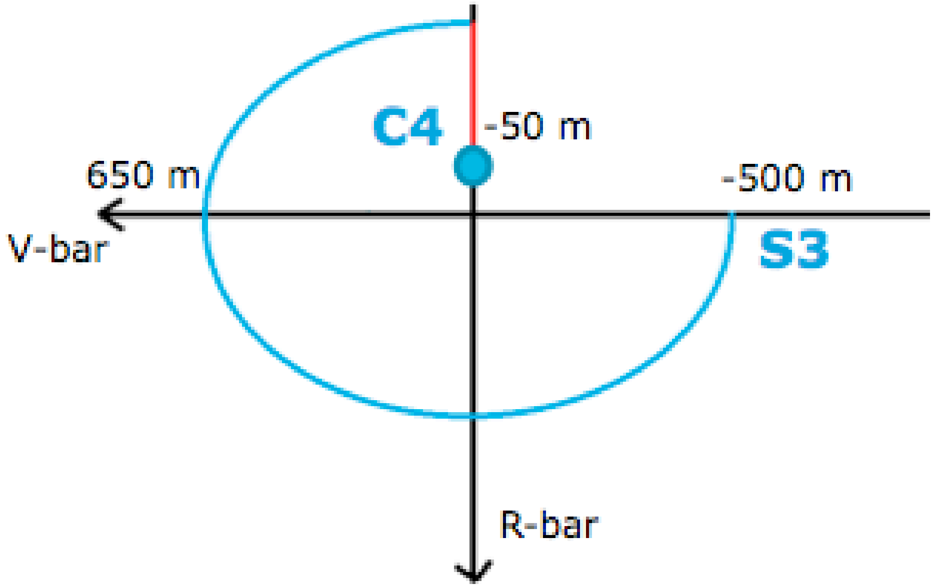
Tentacles Capture

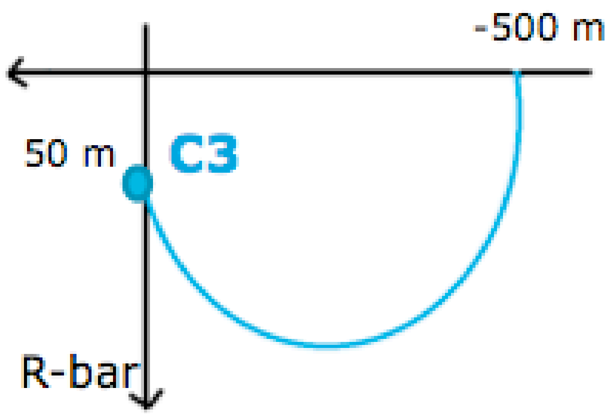


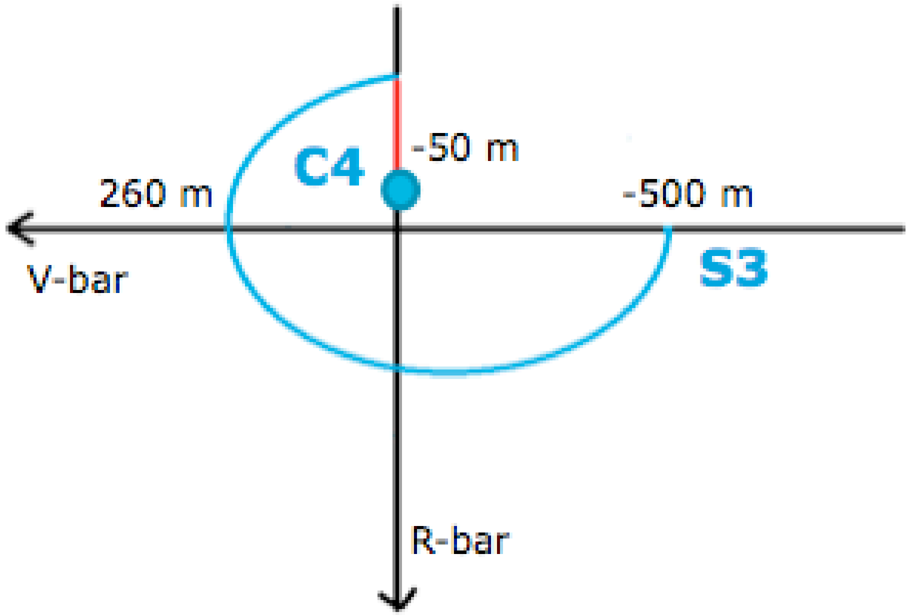
GUIDANCE: R-bar approach

Both Net and Tentacles Capture





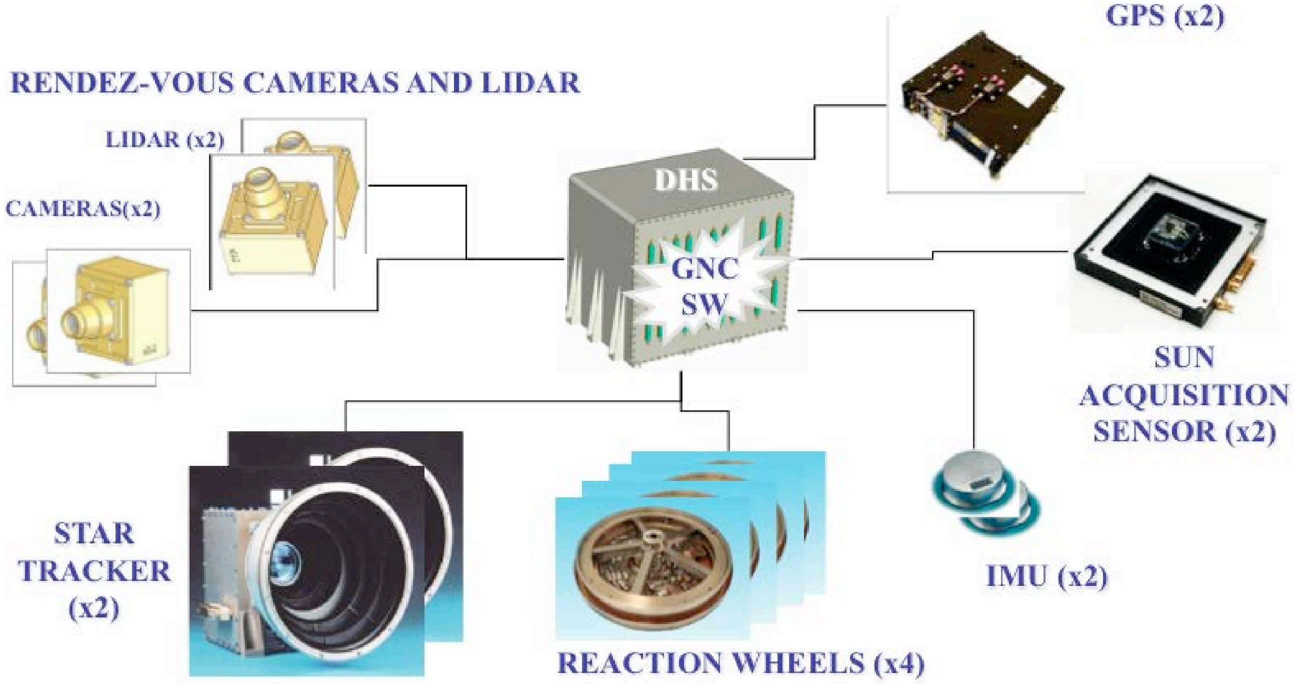




NAVIGATION

- The navigation analysis comprises the selection of the **navigation strategies** and the trade-off of the **sensor suite** to board the chaser.

- For this part, a special point **S2** has been defined on which the **navigation turns from absolute to relative**. The types of sensors under study have been classified into long range, medium range, and close range.



NAVIGATION

- The sensing suite selected is composed of two redounded star trackers (**STR**), two Inertial Measurement Units (**IMU**), two cameras (**CAM**), two Light Detection And Ranging (**LIDAR**) units, and two Global Positioning Service (**GPS**) receivers. Sun acquisition is obtain by the mounting of Digital Sun Sensors (**DSS**).
  - The IMU and the STR will provide classic **absolute navigation** as well as redundancy for the phasing part of the rendezvous and the fly around part.
  - The cameras and the LIDARs deliver the information to a Data Handing System (DHS) unit. The DHS will host the required **image processing algorithms** to extract and obtain the attitude pose and rate of the target during **relative navigation**.

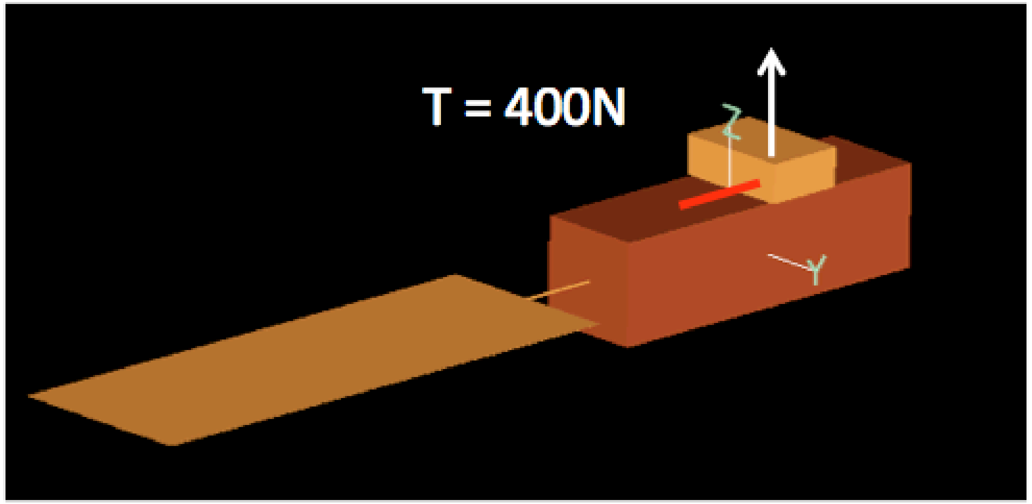
CONTROL

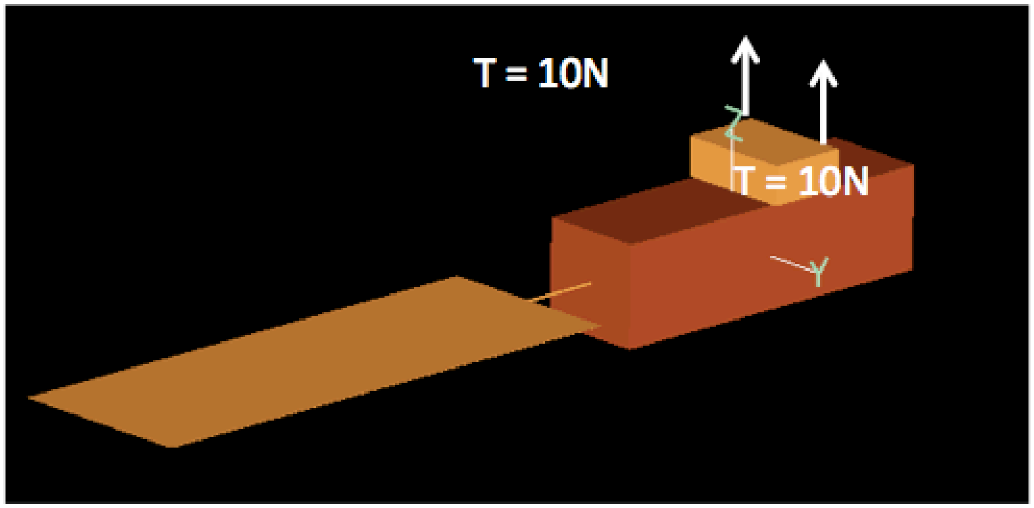
- The control algorithms have to cope with **not well-defined tumbling rates**, and the need to synchronise and align with the target true angular momentum.
- The control specifications need to **avoid** the **target's solar arrays**, which narrows the approach corridor.
- Control algorithms for chaser **agility**, and **manoeuvrability** are required to approach safely and finally capture the target.

Capture Dynamics:
Net Deployment and Compound Control

- Once the **net** is extended, the **firing of the de-orbit engine may affect the material of the tether**: a) depositing materials over the tether and b) damaging the tether (cut)

- A comfortable solution for the problem of plume impingement may be a so-called **Thruster Re-orientation Mechanism** (TOM). Further, with TOMs the torque authority is increased in the chaser allowing **improved pointing of the thrust vector** through the instantaneous Centre of Gravity (CoG).





Capture Dynamics: Tentacles Deployment and Compound Control

- A parametric assessment of **time needed to de-tumble** the compound has been performed assuming an initial angular rate of 0.5˚/s in the three different axes. The maximum amount of time was found to be about **50 seconds** assuming an accommodation of six clusters with a total of twenty 10N AOCS thrusters.

- For the assessment of **disturbance torques**, it was also taken into consideration that the main engine thrust vector would **not** be perfectly pointing towards the centre of gravity (CoG) of the mated system. A **misalignment** along x-axis of 0.15 m has been taken into account. This large value assumes the effect of contact dynamics and slippage during tentacle closing. Further, a misalignment along y-axis of 0.03 m has been considered.

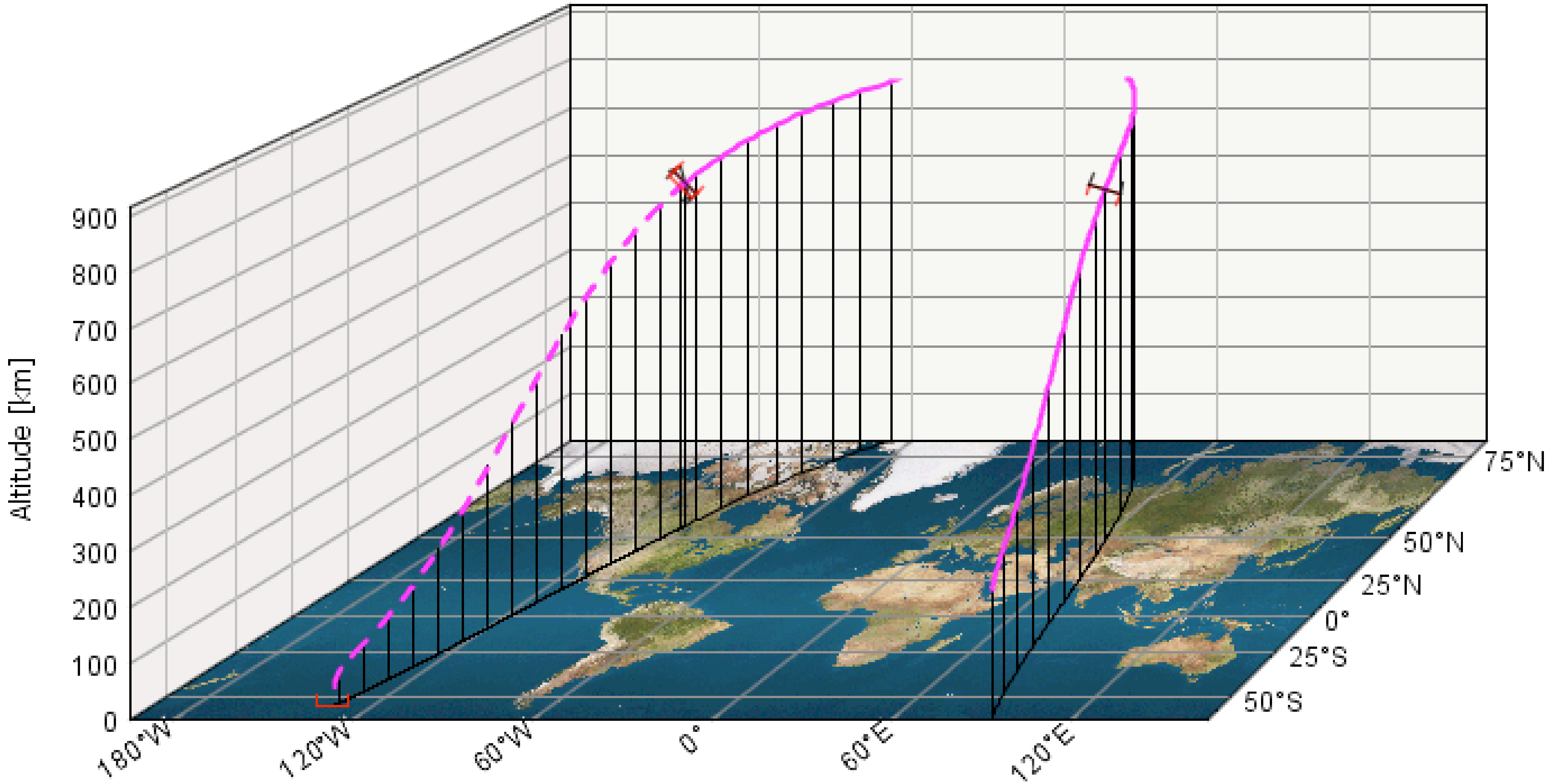
DE-ORBITATION

- Two scenarios have been traded-off for the de-orbitation strategy: a single burn or a multi-burn approach:
  - The single arc scenario contemplates **one long and single manoeuvre**. In an idealised manoeuvre, the energy required to bring the perigee to 0 km is about 215 m/s that can be achieved through a burn of about 1200s applying 1600N thrust. The burn propellant mass is about 600kg. Any type of **cosine losses** in thrust effectiveness will drive the propellant budget to a higher value.

DE-ORBITATION

- Two scenarios have been traded-off for the de-orbitation strategy: a single burn or a multi-burn approach:
  - The **multi-burn scenario** contemplates more **gradual reduction of the perigee** to 200km by having a sequence of burns, followed by a final burn that brings the perigee to 0km and results in controlled re-entry. In this way, effectiveness losses can be minimised while reducing the required thrust magnitude. The ΔV needed to get to 200km perigee is about 156m/s. The final burn with a 400N thruster would be about 1250s with a ΔV of 59m/s.

DE-ORBITATION



CONCLUSIONS AND RECOMMENDATIONS

- The paper explained the guidance strategies to **launch, rendezvous, close-approach, and capture the target**.
- The **guidance strategy** uses chaser manoeuvres, hold points, and collision avoidance trajectories to **ensure a safe capture**. It also details the guidance profile to de-orbit it in a controlled re-entry.
- The **navigation** analysis has comprised the selection of the navigation **strategies** and the trade-off of the **sensor suite** to board the chaser.
- The paper has also analysed the **control strategies to deploy and use towing means.**
- **Advanced control techniques** are shown as required, since the compound chaser + target is in fact a **multi-body system** whose dynamics is mathematically complex.

CONCLUSIONS AND RECOMMENDATIONS

- From the point of view of the **guidance and navigation analysis**, the same strategies and hardware sensing suite can be selected for both approaches: the net or the tentacles.

- The provided calculations presents a rough order of magnitude (ROM) assessment and more **detailed design is required**, once requirements, for instance, concerning centre of gravity **misalignment** (from mechanical perspective, not GNC) are more detailed or the **tumbling rate** of the target is finally derived.