GNC design and validation for rendezvous, detumbling, and de-orbiting of ENVISAT using a clamping mechanism (CLGADR study)

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SCOPE AND OBJECTIVES OF CLAMP ADR

Main Objective of the Study

To evaluate an autonomous **GNC** system, for the **ADR** scenario of rendezvous, capture, detumbling and de-orbiting of an **uncooperative target** using a **clamp** mechanism, to derive requirements for future missions within the **Cleanspace** initiative.

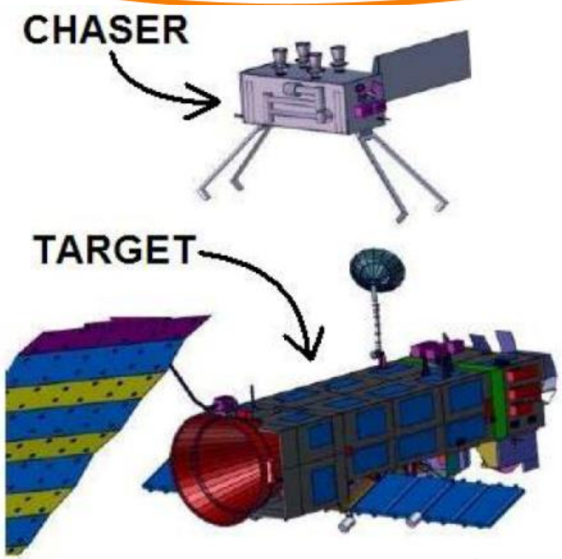

Image source: ESA/ESTEC

Key Objectives

- Develop **a GNC concept and algorithm** that is able to deal with the **multi-body dynamics** of the composite chaser-clamp-target system during capture, stabilization, detumbling and De-orbiting phases;
- Theoretically **analyze the robustness and performance** of the GNC algorithm for the chaser (pre-capture phase) and the coupled chaser-clamp-target stack (post-capture);

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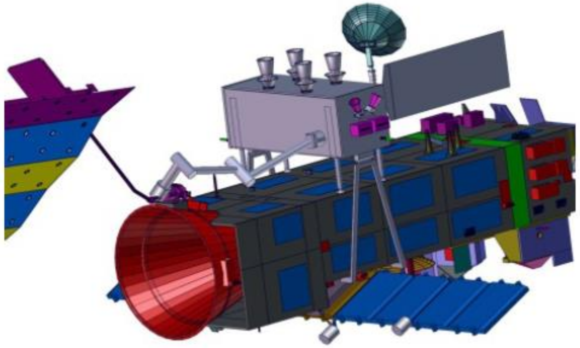
Key Objectives (cont)

- Develop a **MIL simulation** framework for **performance assessment** of the GNC concept, supporting GNC and mission trade-offs.
- **Assess the GNC concept performance**, especially with what relates to G&C, sensor characteristics and the clamping mechanism.



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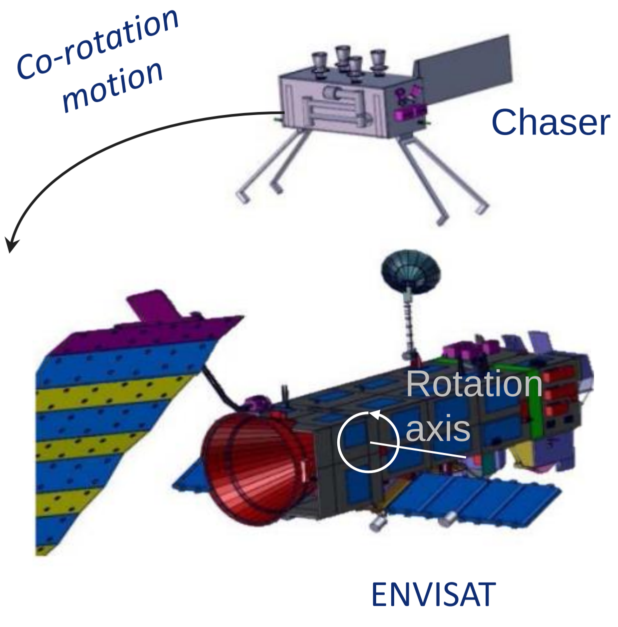
- Provide **lessons learnt** on the suitability of the clamp ADR approach and suitable technical GNC solutions.
- Derive **a set of requirements** for future ADR GNC solutions using the Clamp.

Contents

Pre-Capture Phase

Perform a final rendezvous to acquire capture configuration:

- phase starts at station keeping (SK);
- chaser acquires null relative velocity (co-rotation motion);
- finalized by a forced approach to reach capture distance wrt target body;

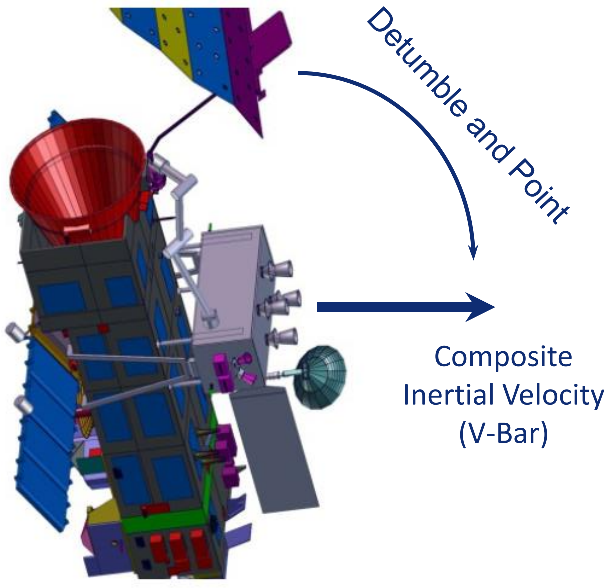


Target Stabilization Phase

Immediately after the clamp deployment, the chaser is clamped to the target and applies torque commands to:

- detumble the target, nullifying its angular velocity;
- point the composite to the attitude required for de-orbiting;

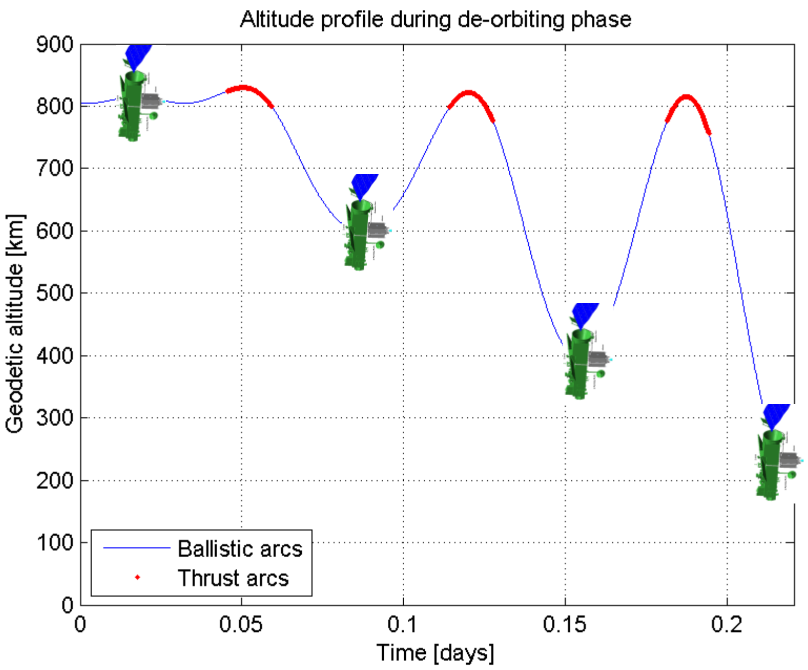
Detumbling and Pointing



Stack Orbit Transfer and Disposal Phase.

The objective is the de-orbiting and disposal of the composite.

A gradual perigee lowering strategy is adopted, with de-orbit boosts at apogee.



GNC Requirements

Design requirements define design specifications of the GNC, such as design method and parameters, and are thus verified by review of design.

The design requirements that establish the GNC must:

- Use modern **MIMO robust techniques** that:
  - provide **analytical stability** characterization;
  - by design, can cope with **uncertainties** in the model;
- Be **autonomous** (using ground only for high-level decisions) and **generic** (with respect to orbit radius);
- Effectively **attain and perform co-rotation**, with a final relative distance between 2m and 3m point-to-point;
- **For pre-capture**, control the translational and rotational states of (6-DoF) chaser relative to the target;
- **For post-capture**, control the rotational state of the composite (3-DoF).

Robustness requirements define what are the effects to which the GNC must be robust.

The robustness requirements that establish the GNC must:

- Be robust to:
  - **Sensor and actuator** errors considered in the model;
  - **Sloshing and flexible modes** of both S/C (chaser and target);
  - **Air-drag**, that is significant at lower altitudes of de-orbiting;
  - **De-orbiting boosts**, namely in the on/off commutation;
- Satisfy the following stability criteria for all phases:
  - **Structured singular value** such that $\mu<1$;
  - **Modulus margin** larger than -6dB.
- Be robust to the MCI uncertainties (3-σ)

Chaser	Target
Mass: 5%	**Mass**: 0.2%
Inertia: $\pm\begin{bmatrix}10.0\% & 20.0\% & 20.0\% \\ 20.0\% & 10.0\% & 20.0\% \\ 20.0\% & 20.0\% & 10.0\%\end{bmatrix}$	**Inertia**: $\pm\begin{bmatrix}2.0\% & 25\% & 11.5\% \\ 25\% & 2.4\% & 43.4\% \\ 11.5\% & 43.4\% & 2.3\%\end{bmatrix}$
CoM: 0.10m per axis	**CoM:** 0.01m per axis and **slippage** up to 0.10m wrt chaser during de-orbit.

GNC Requirements

Performance requirements: these define quantitatively the desired performance of the GNC.

- ❑ The performance requirements establish the accuracy of the following:
  - Positioning accuracy at pre-capture SK;
  - Positioning and pointing accuracy at capture configuration;
  - Pointing accuracy at post-capture;

Robustness and performance requirements are the focus of the CLGADR study.

- ❑ **By design,** the GNC was made compliant with the requirements.
- ❑ The requirements were validated using:
  - **robust control analysis tools**, obtaining analytical guarantees of the desired properties;
  - **extensive Monte Carlo campaign** (designed to obtain 99% confidence levels), complementing/confirming the analytical results.

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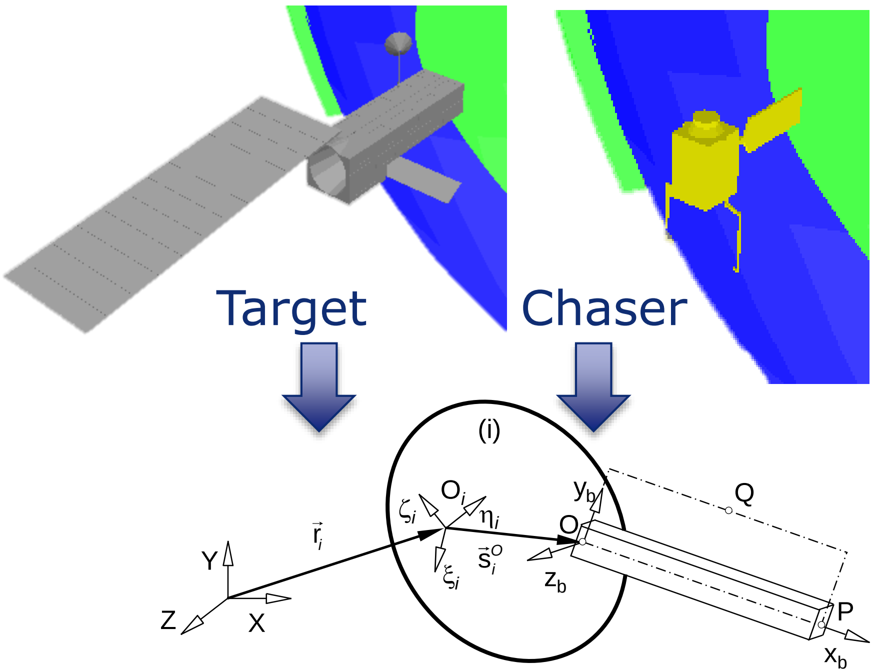
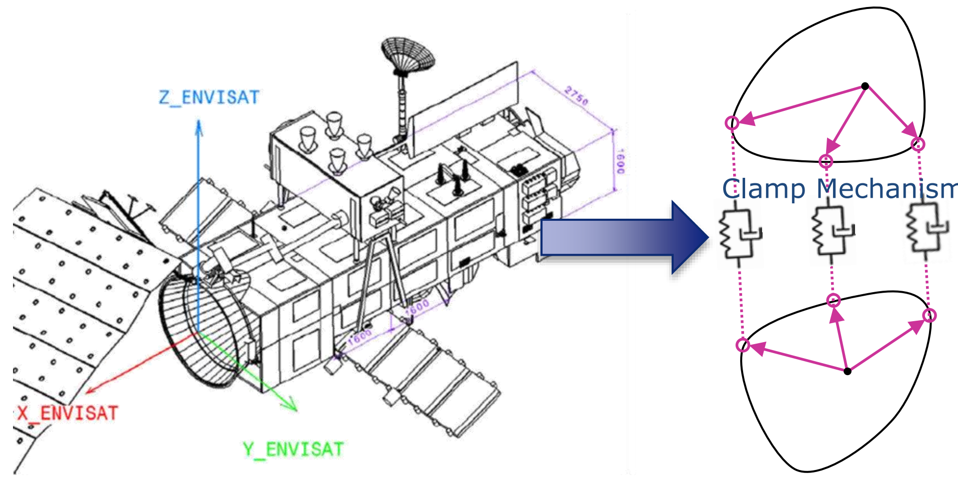
MODELS FOR GNC DESIGN AND SIMULATION
S/C and Clamping Mechanism Multi-body Dynamics

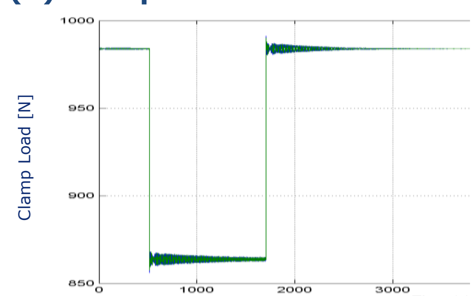
(1) Pre-capture S/C modeling



(2) Post-capture composite



(3) Clamp Mechanism Monitoring



(1) Each S/C is modeled as a rigid body with a flexible appendage and sloshing effects;

(2) For post-capture, the model considers both S/C attached by a clamping mechanism;

(3) High-fidelity modeling enables monitoring of clamp load and time-domain response.

Model-in-the-Loop (MIL) Simulator

A Model-in-the-loop (MIL) simulator was developed for time-domain validation of the GNC, being characterized by:

- **High-fidelity simulation of many configurations** considered in the study:
  - single and multi-body S/C dynamics;
  - clamping mechanism;
  - three ENVISAT rotational scenario;
  - three relative sensor performance;
  - the dynamics of the S/C appendages (flexible modes, sloshing);
  - the validation type (single-shot vs MC campaign).
- **High-fidelity simulation of environmental effects** such as third body, drag, solar radiation pressure and gravity harmonics perturbations;
- **Representative simulation of sensors and actuators models**, and associated non-idealities.

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LFT Modeling approach

For each phase (pre-/post-capture), three models are synthesized:

Nonlinear MBD model
- Highly nonlinear
- High fidelity
- Appropriate for simulation purposes

Model for closed-loop analysis
- Large number of uncertain parameters
- Intermediate complexity and conservatism

Model for controller synthesis
- Adopts a subset of the parameters and simplified models if necessary
- Model mismatch due to simplification is approximated by exogenous disturbances

LFT models (model for closed-loop analysis; model for controller synthesis)

Model Complexity (increasing from controller synthesis model to nonlinear MBD model)

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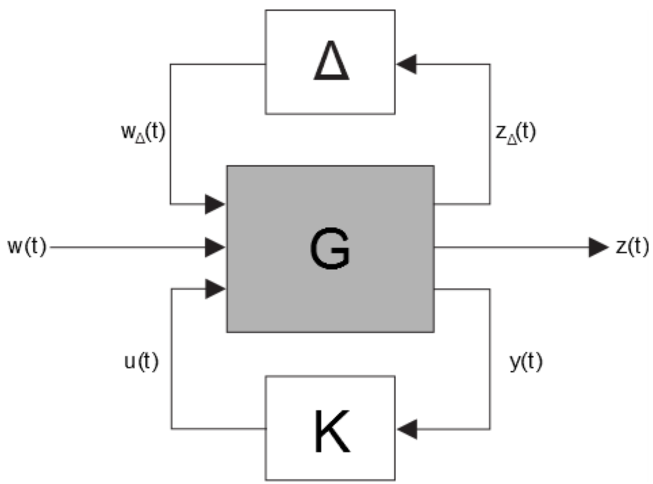
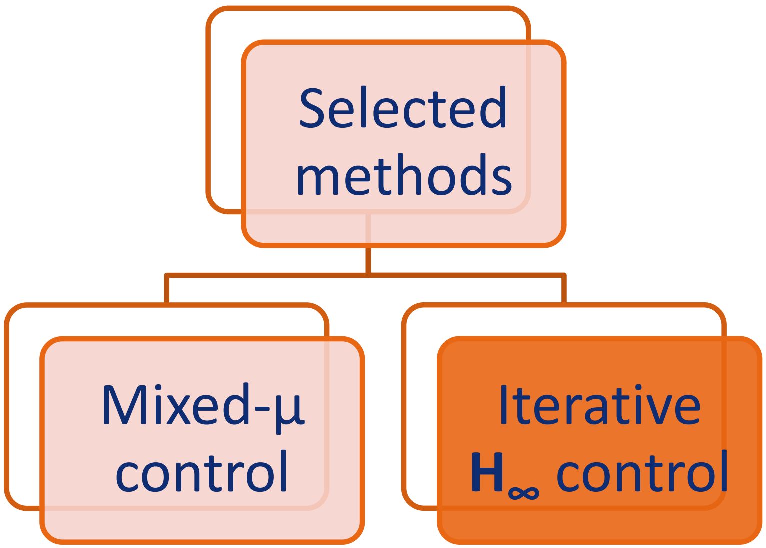
Controller Design/Synthesis

General Setup

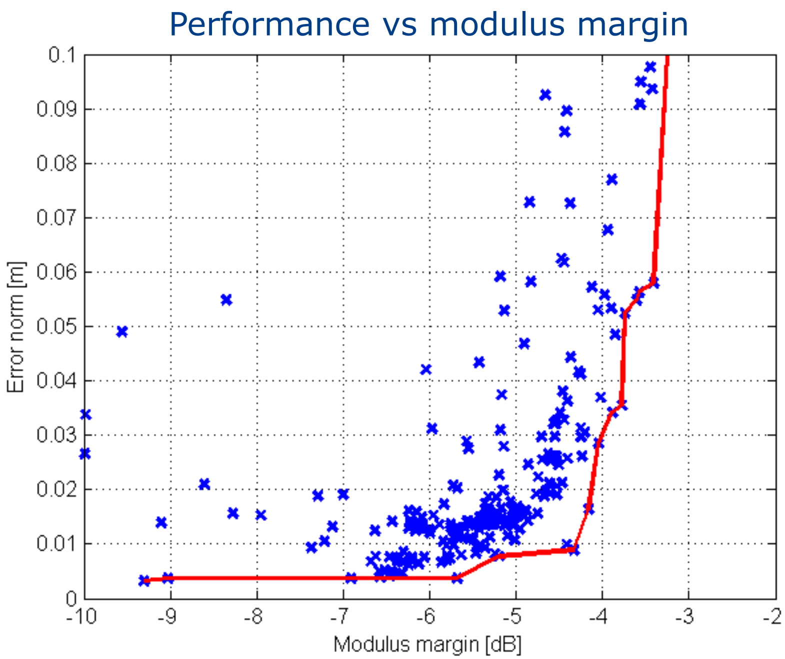


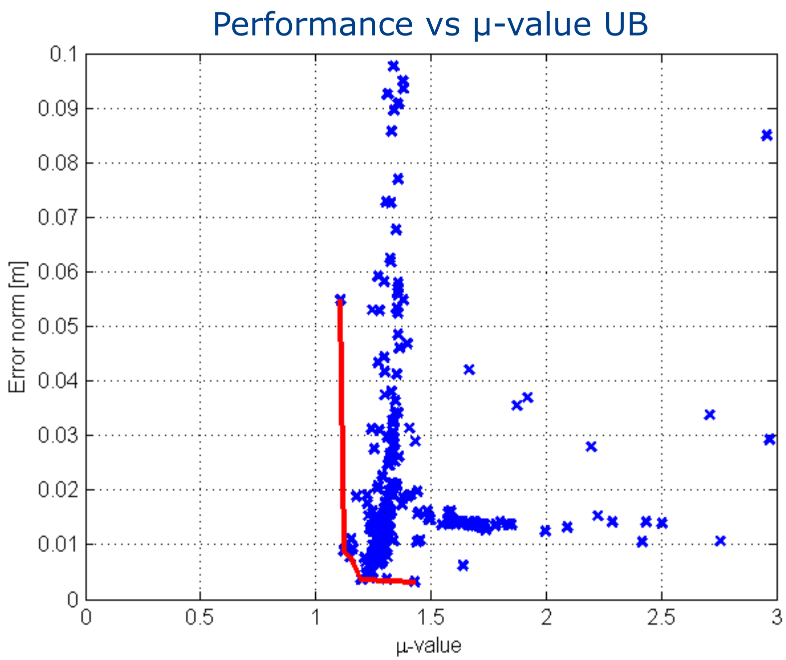


The pre-capture controller was synthesized using robust synthesis tools, as follows:

- Selected design method is an **iterative unstructured H_∞ control**, using Hybrid Differential Evolution (HDE) to tune the dynamic weights. This approach is motivated by numerical limitations associated with large pre-capture LFT, that precluded mixed-μ.
- A two-degree of freedom architecture is adopted, that computes a **robust feed-forward term**. This command improves the tracking performance (similar to Guidance classical feed-forward), but explicitly takes into account model uncertainty.

Controller Synthesis

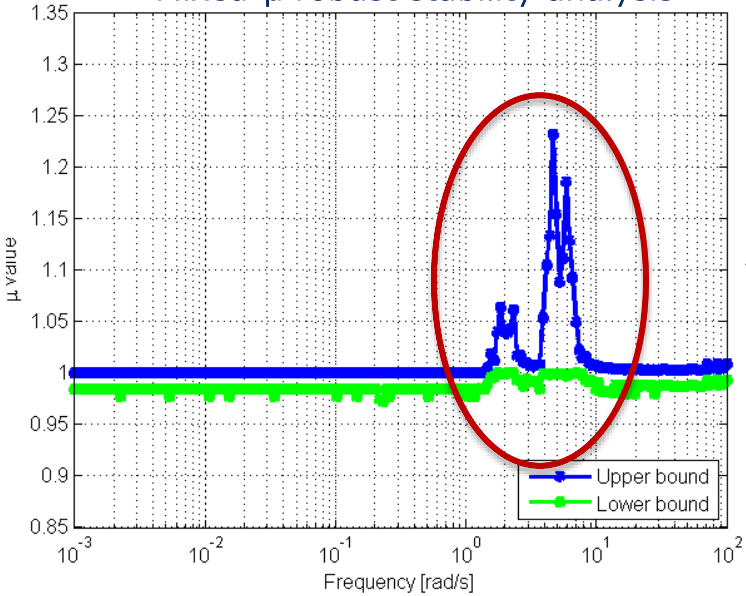




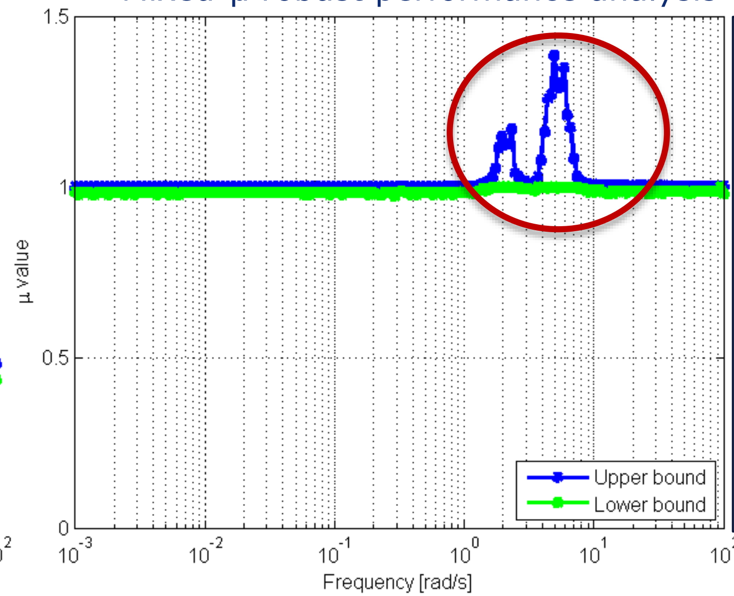
- ❑ The controller synthesis applies a global optimization algorithm to search for the dynamic weights that best comply with the requirements;
- ❑ The figures show the optimization results, depicting performance of the GNC at capture vs modulus margin (left) and vs μ-value (right).
- ❑ The selected controller ensures: the required modulus margin and μ LB, for a position tracking error below 1 cm at capture position.

Robust analysis results

Mixed-μ robust stability analysis



Mixed-μ robust performance analysis



Immediate analysis

μ-UB larger than 1, preventing validation of **robustness** property;

μ-LB smaller than 1, preventing exclusion of **robustness** property;

This gap is **inconclusive** w.r.t. GNC robustness. It is matured with complementary simulation.

- The gap between the μ-LB and UB is around the flexible modes frequency.
- The μ-gap can be interpreted as a consequence of some conservativeness associated with the adopted LFT;
- The robustness analysis is matured by finding the worst-case (WC) conditions, using μ-analysis tools. The WC are simulated in MIL, showing that the system is **stable**.
- Further confirmation of GNC robustness is obtained in MC campaign, with dispersion of parameters such that 99% confidence level is attained.

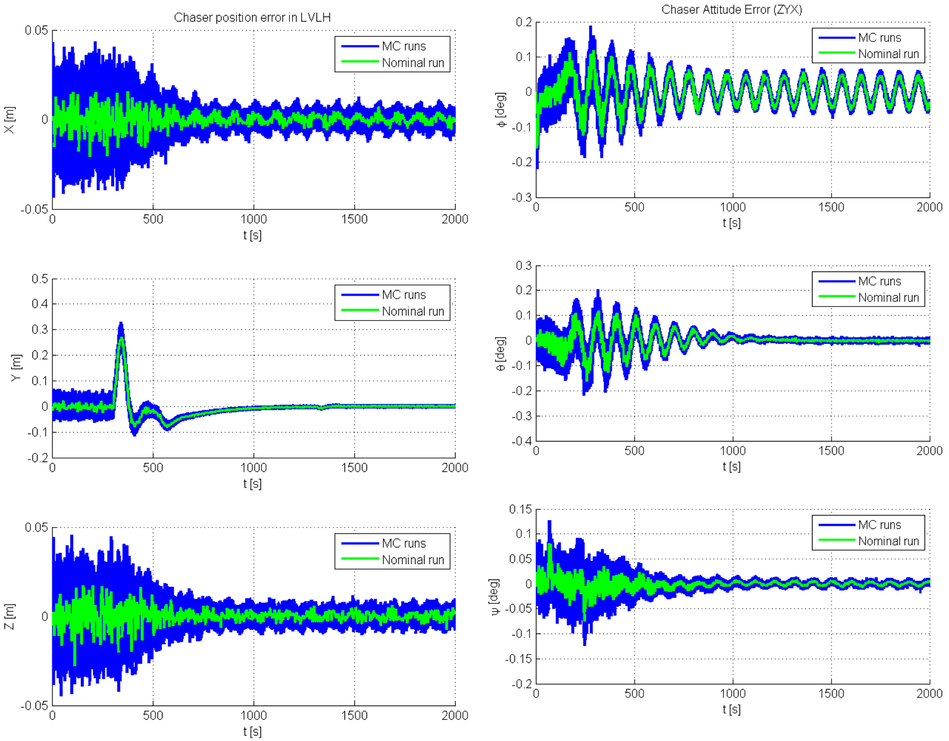
PRE-CAPTURE GNC DESIGN AND VALIDATION
Time-domain validation of GNC

GNC time-domain validation

- The results are obtained for 300 MC shots with GNC in the loop, nominal rotation scenario, and dispersion in all the parameters;

- The results show that
  - the co-rotation profile is tracked;
  - the GNC performs target pointing;
  - the applied actuation is within saturation bounds.

- The analysis of the results shows that GNC accuracy is within performance requirements allowed by the mission:

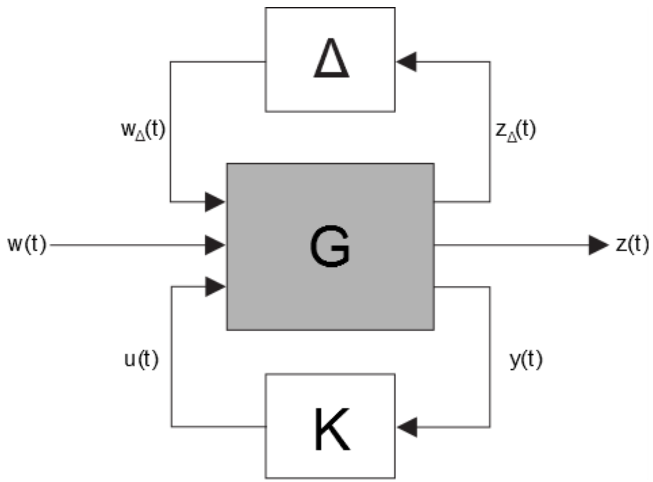


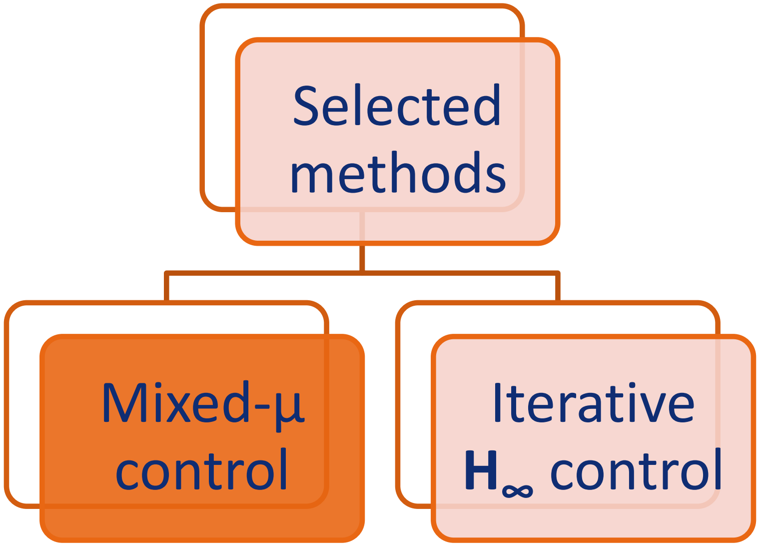
	Required/Allowed GNC Accuracy			
	Position	**Velocity**	**Attitude**	**Angular rate**
Station keeping	20.0 cm	2.0 cm/s	-	-
Capture position	1.2 cm	0.5 cm/s	1 deg	0.1 deg/s

Contents

Controller Design/Synthesis

General Setup



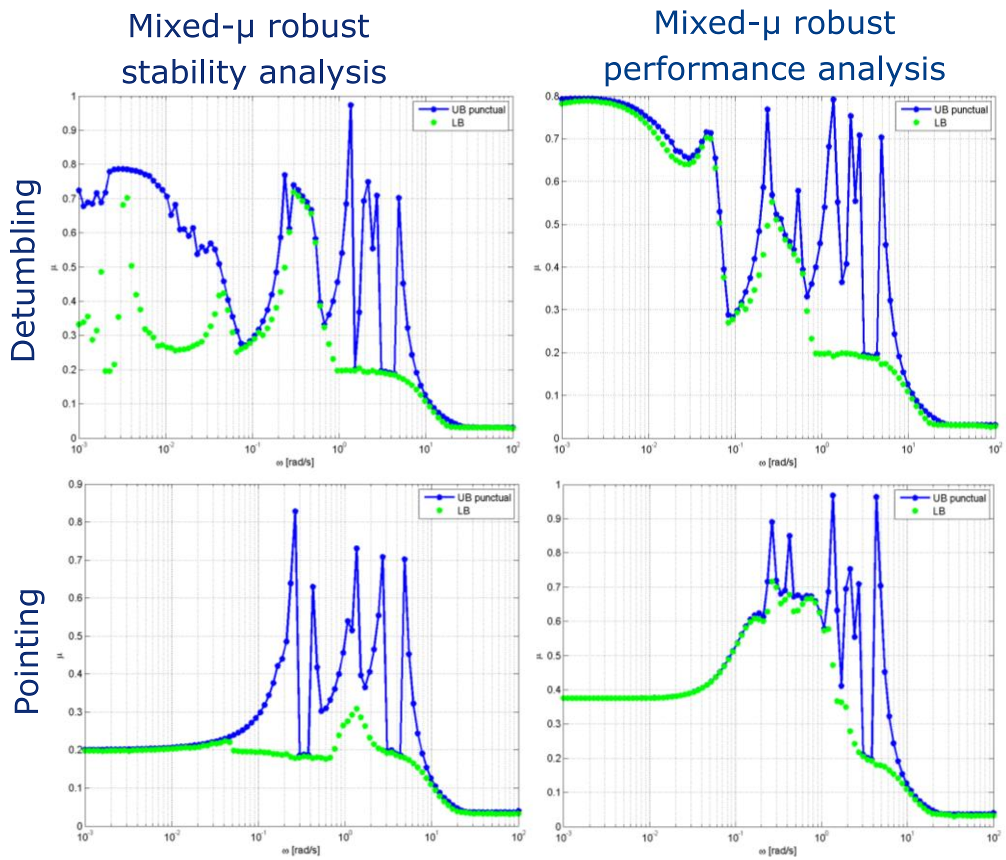


- ❑ The post-capture controller was synthesized using **mixed-μ**, being an attitude control problem with an LFT with lesser complexity than in pre-capture;
- ❑ Separate control modes are adopted for detumbling and pointing, being distinct control optimization problems as follows:

	Modeling characterization		
	Angular velocity error	Pointing accuracy	Worst-case disturbance torques (drag)
Detumbling	High	Low	Negligible
Pointing	Low	High	Increasing during de-orbiting

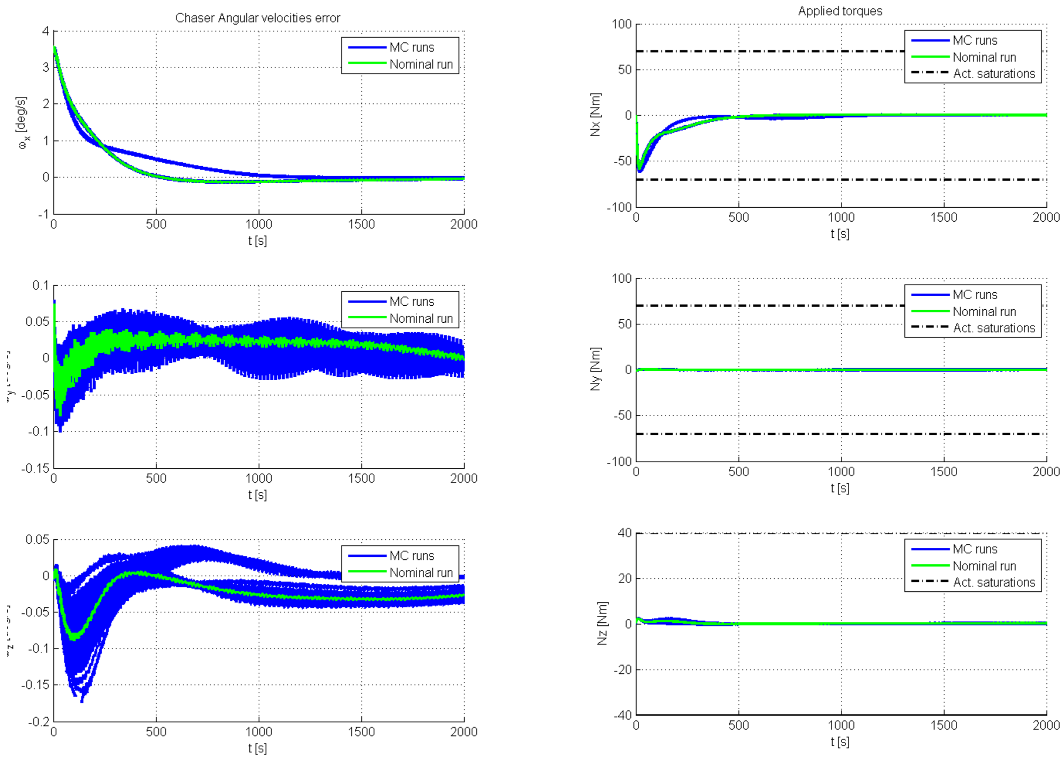
Robust analysis results

- **µ-UB<1 for all frequencies**, attaining stability and performance robustness.
- Highest values of µ-LB are around the flexible modes frequency.
- **Worst-case conditions**, computed using µ-tools, correspond to lowest damping and lowest frequency of flexible modes.
- The analysis is obtained under the assumptions that:
  - Uncertainty in target mass, chaser mass and inertia uncertainty are negligible given their magnitude and the composite configuration;
  - that angular velocity is <1 deg/s (LFT analysis results are conservative otherwise).



- Extensive Monte-Carlo campaign is adopted to show that robustness is indeed attained, resolving analytical validation limitations and justifying the adopted assumptions.

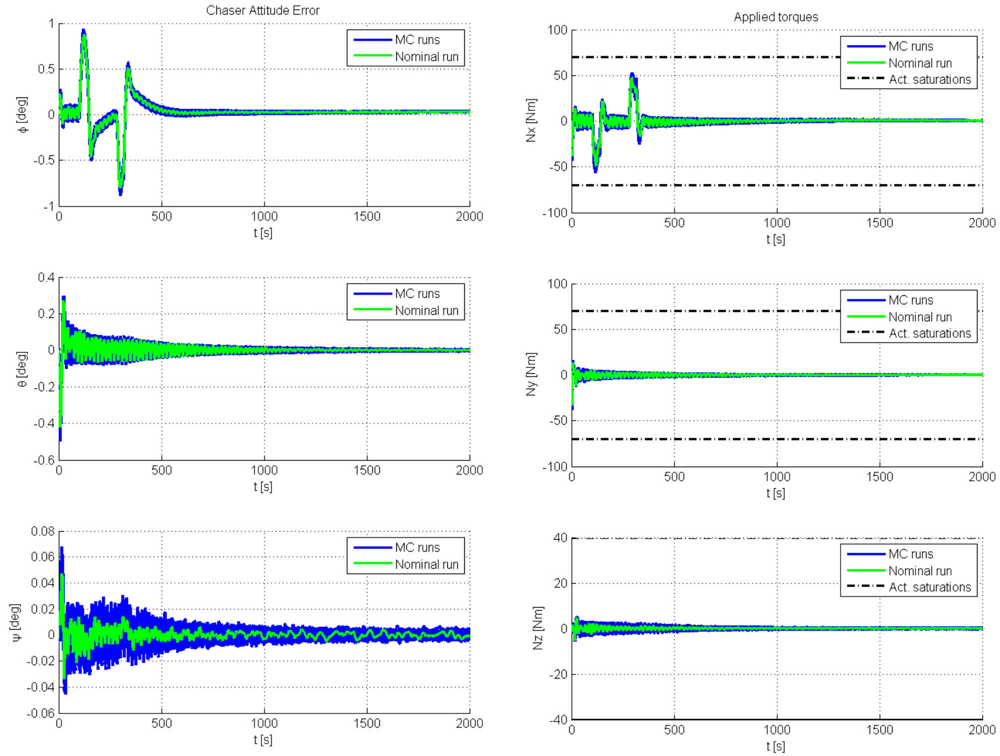
Detumbling time-domain validation



- ❑ The results are obtained for 100 MC shots with GNC in the loop, nominal rotation scenario, and dispersion in all the parameters;

- ❑ The results show that
  - the composite is effectively detumbled, with final angular rate error below 0.1 deg/s;
  - the applied torque is within saturation bounds.

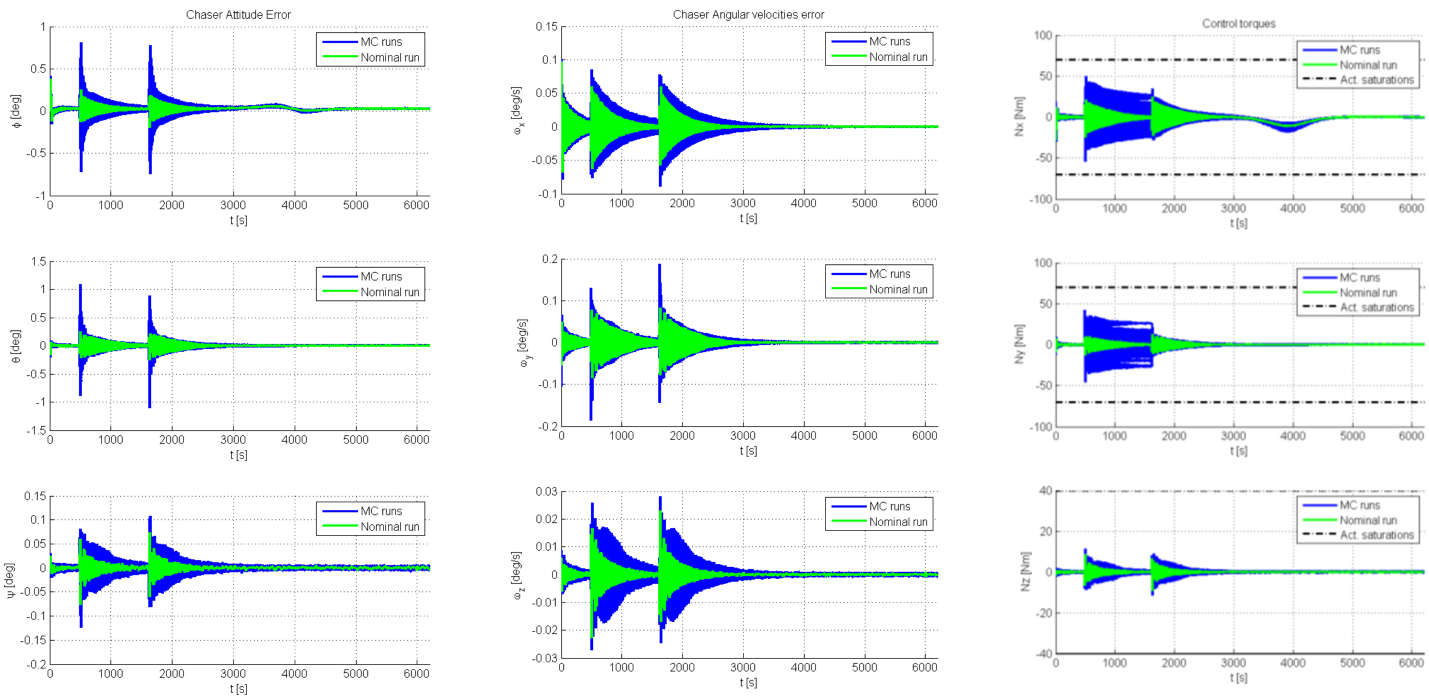
Pointing time-domain validation



- ❑ The results are obtained for 100 MC shots with GNC in the loop, nominal rotation scenario, and dispersion in all the parameters;

- ❑ The results show that
  - composite pointing is attained, with final angular error below 1 deg/s;
  - the applied torque is within saturation bounds.

De-orbiting time-domain validation



- The de-orbiting results are obtained for 100 MC shot with GNC in the loop and dispersion in all the parameters. The results, illustrated above for the 3rd burn, are similar for all burns.
- The results show that:
  - angular error is <1 deg/s for 99% of the burn, considered compatible with mission objectives;
  - Actuation torque is excited by main engine commutations and at perigee passage. Actuation is within saturation bounds for heights >150km; below this point, drag torque is above torque authority.
  - Closed-loop GNC correctly counteracts the effect of 10cm (3σ) slippage of target with respect to chaser.

Contents

CONCLUSIONS

- **ADR GNC architecture and algorithms** were designed for the capture and de-orbiting of ENVISAT using a clamp mechanism.
- The design of the GNC addressed the problems of **stability and performance** robustness, for **multi-body systems**.
- The validation of key requirements was obtained in an **advanced verification and validation framework**, that combined analytical and simulation-based validations.
- **The requirements are satisfied in general.** Some refinements to the requirements were produced.
- The representativeness of the results is supported by the **several scenarios considered**, the **adopted verification and validation framework**, the **high-fidelity simulation framework**.
- These can be considered valuable in the **context of the Cleanspace** initiative and future studies/programs.

Thank you

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