ESA GNC Technologies and Test Beds for ADR and Space Tug Applications

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GNC Section of ESA

Clean Space Industrial Days

24-26 October 2017

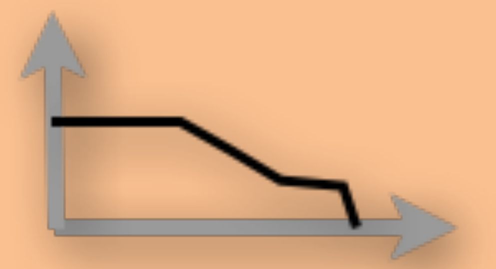
Guidance, Navigation, and Control

establishment of the desired path to follow

establishment of the current and future state

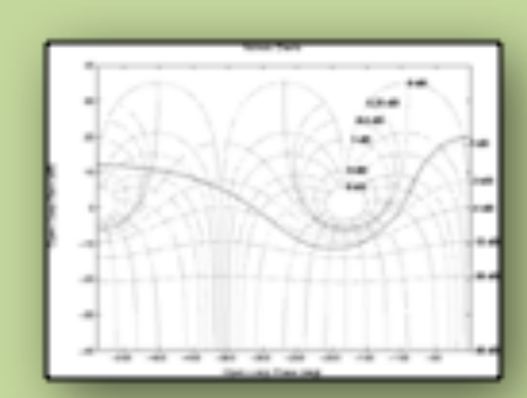
actions to match the current state (navigation) with the foreseen path (guidance)

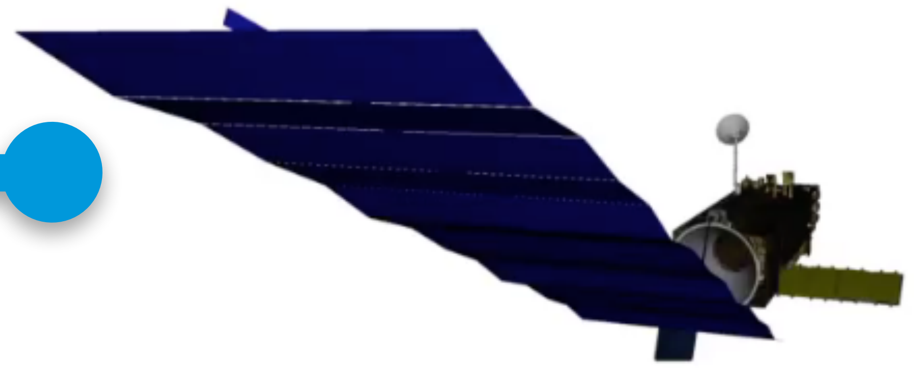
G



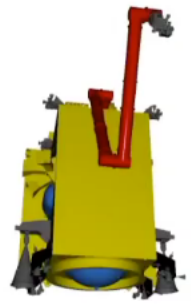
N

C

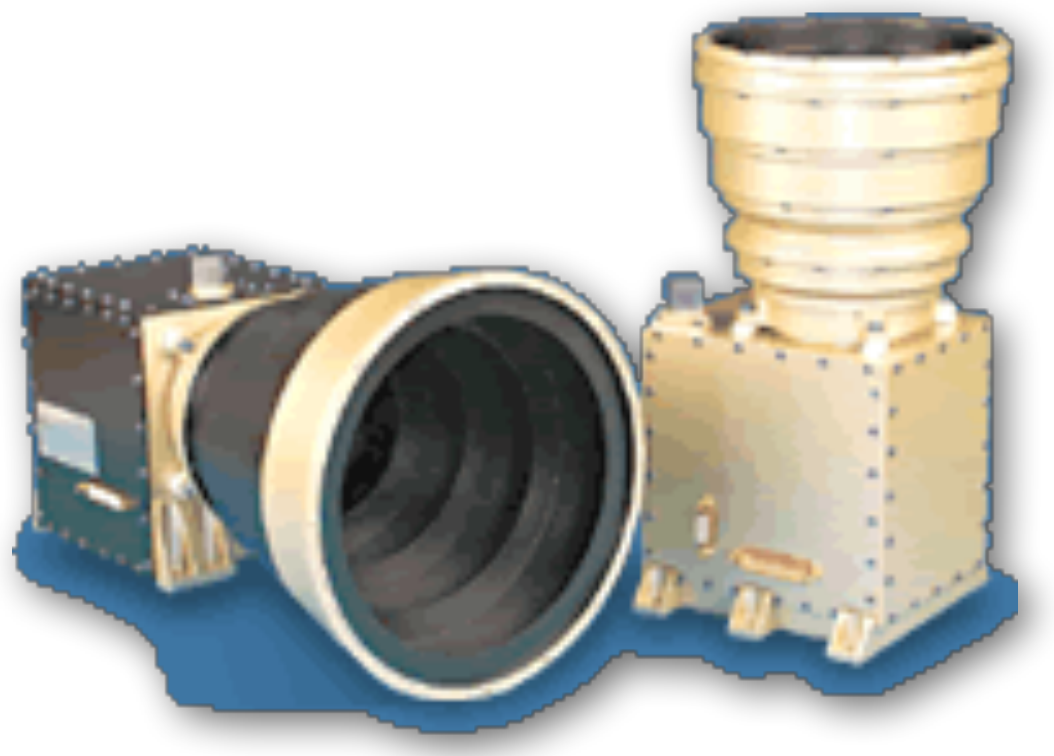


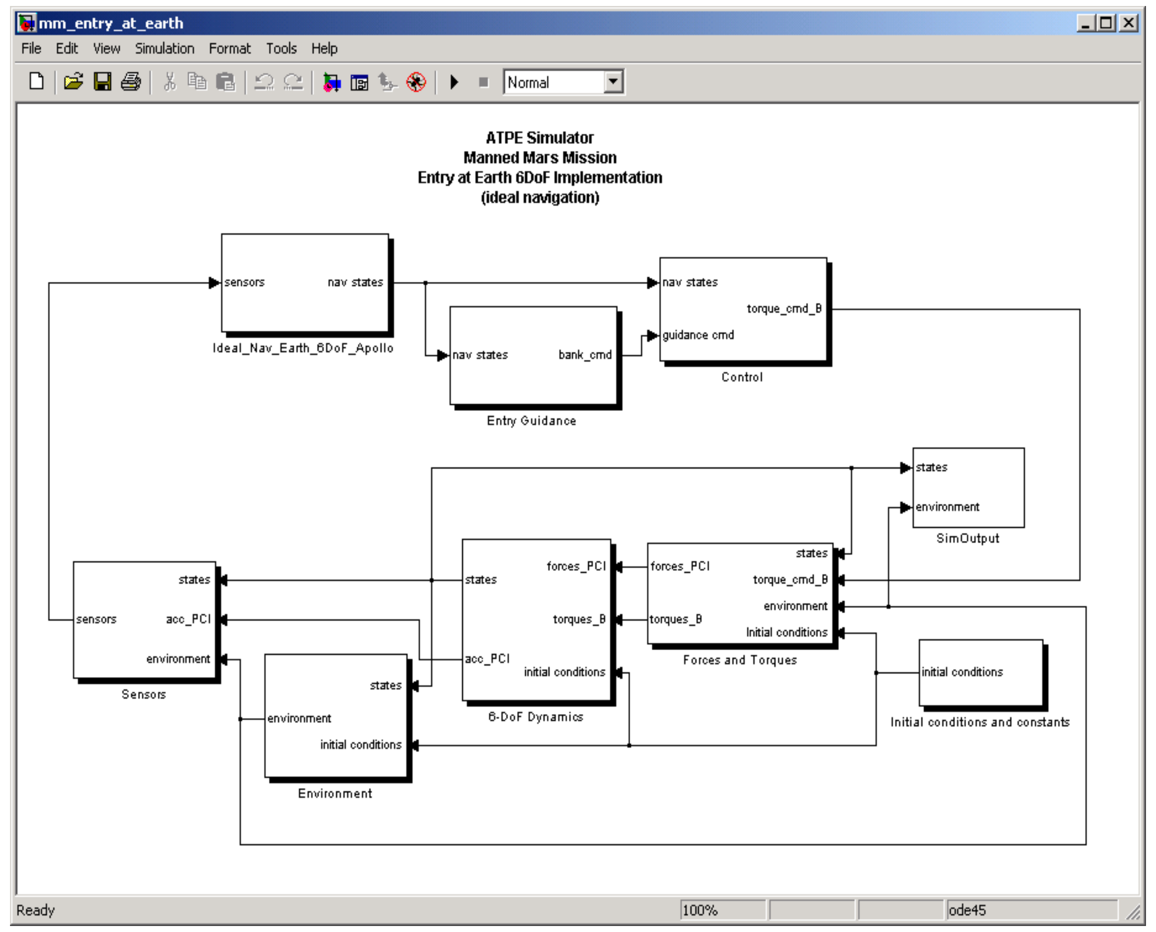


DKE



Products from GNC Systems Engineering Life Cycle

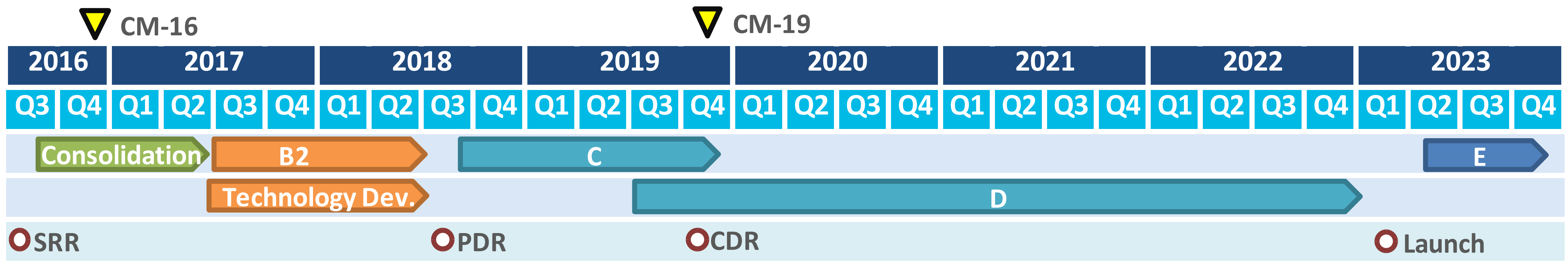




- Two main products are obtained out of the complete GNC engineering process
  - **P1**: GNC hardware configuration
    - Procurement of sensors set, positioning and mounting in the spacecraft, interconnection (sensors are considered part of the GNC subsystem)
    - Support to the procurement, placement, and interconnection of the actuators (actuators are not considered part of the GNC subsystem)
  - **P2**: GNC framework
    - The GNC simulation tools (MIL, SIL, PIL, HIL expressions)
    - Surrounding software used to initialise, launch, monitor, and store GNC simulations
  - **P3?**: More and more often, the on-board software is now automatically derived from the GNC framework (auto-coding). On-board SW could also be a product of the GNC, depending on the mission
- The cost of the complete process in a project may represent between 15% to 30% of the total cost of the project
- The GNC cost for Small Body missions is higher that average

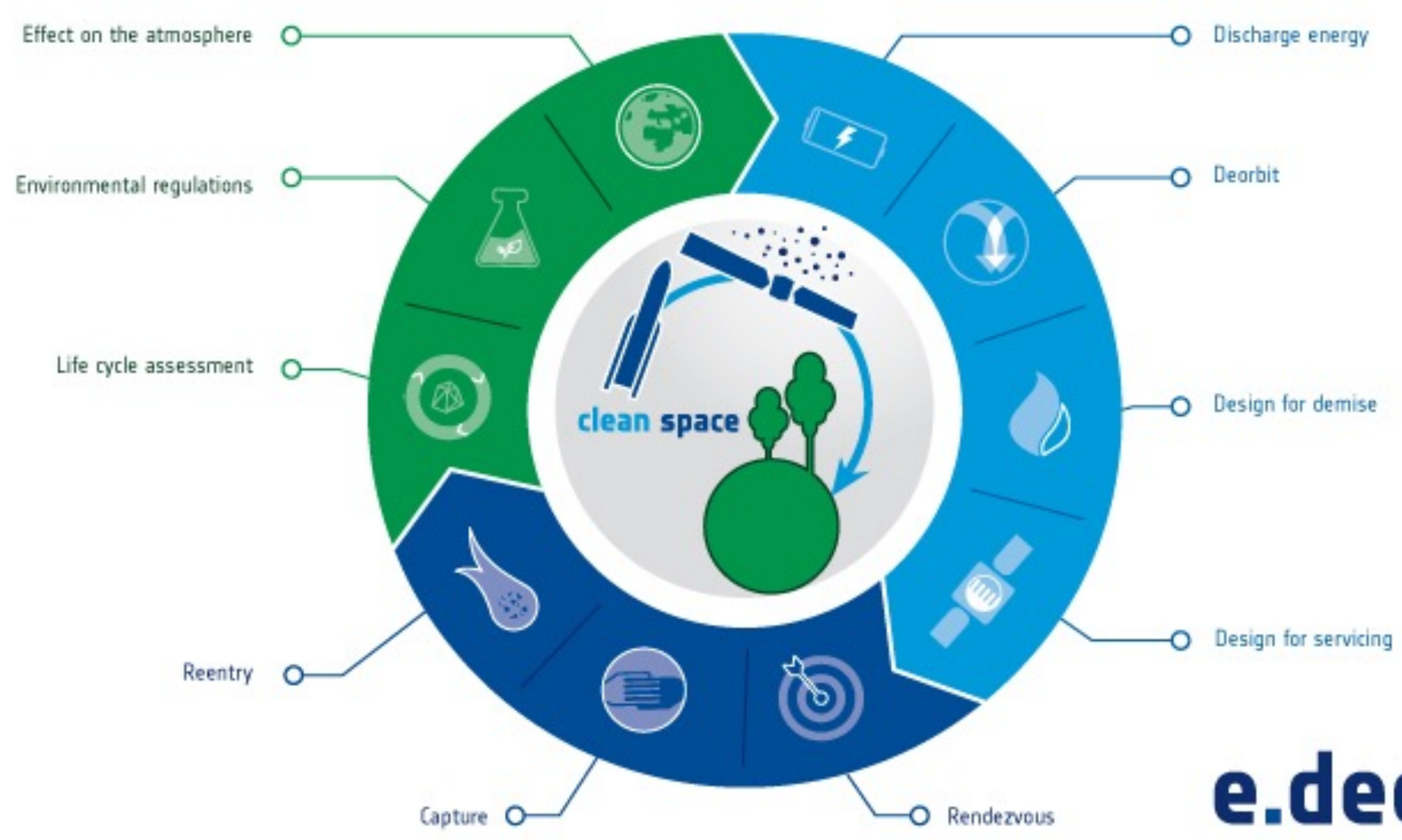
GNC in Clean Space

- CleanSAT (de-orbiting systems) and e.Deorbit (grave-yarding ENVISAT)
- Very complex GNC with a launch in 2023
- Phase 1 – e.Deorbit Delta B1
  - To close the open trade-offs following Consolidation
  - Develop the system design in order to complete the Systems Requirement Review (SRR)
- Phase 2 – e.Deorbit Phase B2
  - Consolidate the preliminary design of the chaser and payload
  - Elaborate on the definition of the critical subsystems such as GNC, Robotics and Communications
  - Develop the system design in order to complete the Preliminary Design Review (PDR)



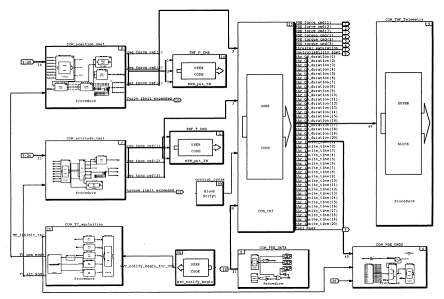
ecodesign
➔ REDUCING IMPACTS

cleansat
➔ SPACE DEBRIS REDUCTION



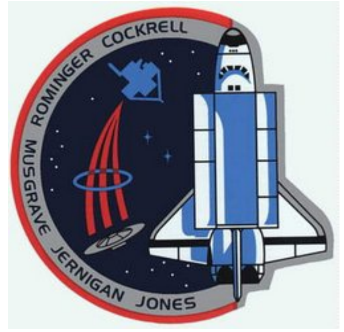
e.deorbit
➔ ACTIVE DEBRIS REMOVAL

GNC for on-orbit servicing



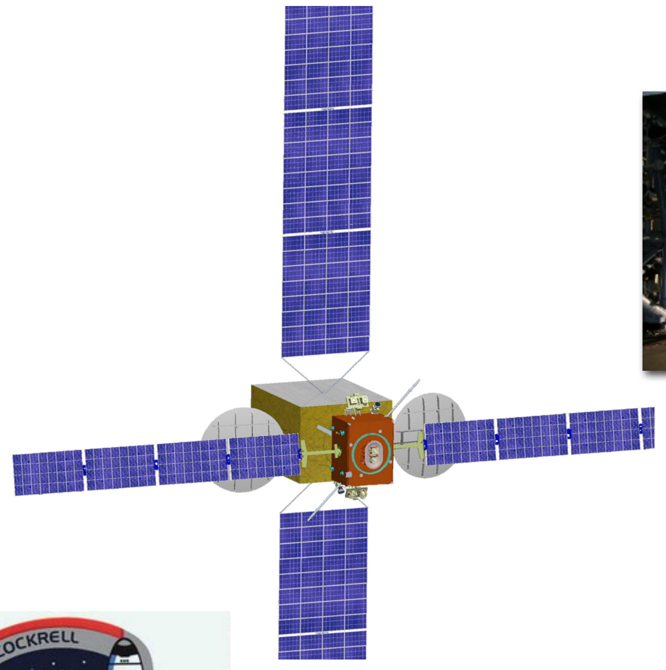
ARP-K

1992-1994



STS-80 Columbia
STS-84 Atlantis
STS-86 Columbia

1996-1998



ConeXpress

rendezvous in GEO for on-orbit servicing

2008-2010

Ground validation of on-orbit servicing

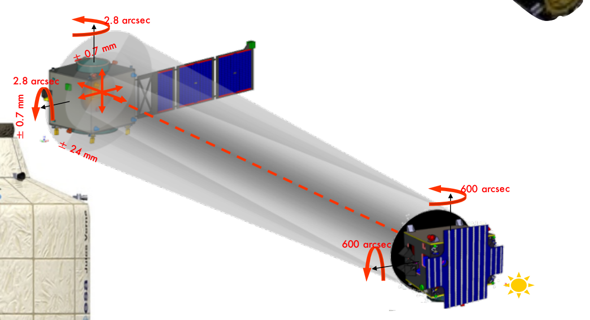
large scale testing facilities in Germany

1992-2015

ATV-1
ATV-2
ATV-3
ATV-4
ATV-5

Rendezvous in GEO with ISS

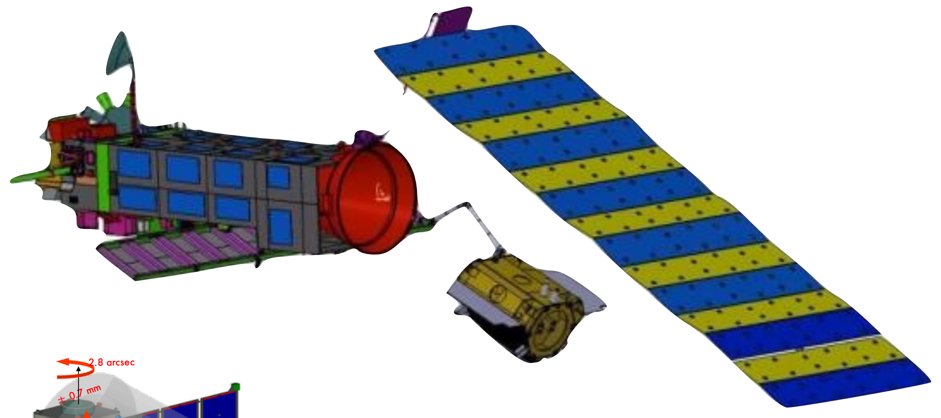
2008-2015



PROBA-3

Demo of formation flying in high elliptical orbit

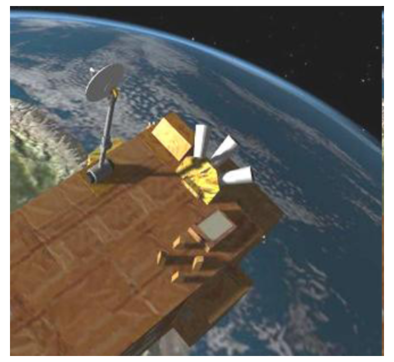
2014-2019



e.Deorbit

inspection, rendezvous and capture of ENVISAT with the purpose of de-orbiting it

2015-2023

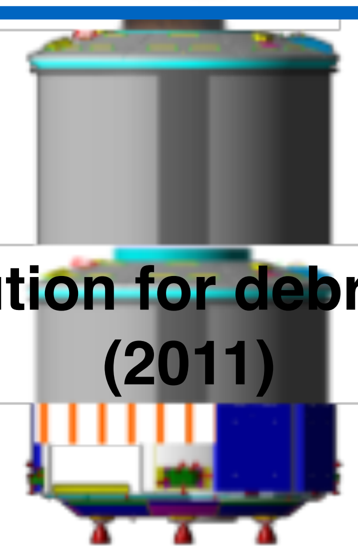


Servicing vehicles

SSV and similar vehicles based on low thrust propulsion

2018-2030

ESA studies of on-orbit servicing with GNC

 ConeXpress (2008-2010)	The **<u>ConeXpress</u>** Orbital Life Extension Vehicle (CX-OLEV) was proposed extend the lives of large geostationary satellites for up to 12 years beyond their original product- ive lives. It can also recover satellites launched into incorrect orbits, move them along the orbital arc, or manoeuvre them into to a disposal orbit. ConeXpress is a wholly European initiative and it is the only commercial on-orbit servicing project in advanced development.
 **Versatile Autonomous Concept VAC (2009-2011)**	The **VAC** study provided a definition of a versatile concept, e.g. a set of ATV-derived vehicle modules that can be fully or partially "assembled" together, to satisfy the need of a large set of future Human Spaceflight and Exploration mission scenarios. The study also explored commonalities and complementarities of the modules above with the Service Module for NASA's MPCV (MPCV-ESM). The mission scenarios studied were 1 Space Tugs for LEO Operations, 2 Resource Modules for Free Flyers, and 3 Transportation System for Exploration. The Space Tug class included Station servicing missions, De-orbiting missions, and Technology demonstration missions. The Free Flyer class included also three missions: Resource Module for an Infrastructure based Free Flyer, Resource Module for Autonomous Free Flyer in LEO, and Resource Module for Autonomous Free Flyer in Deep Space. The Transportation class included Propulsion Modules only.
 **ATV evolution for debris removal (2011)**	This ESA study targeted an **ATV derived orbital debris removal system** as multiple mission spacecraft, with the elimination of a series of large debris, and a strategy of orbital transfers in-between. Once the ATV derived vehicle has performed rendezvous with the target, it delivers a capture and disposal package, and proceeds to the next target. The number of targets per mission depends on the characteristics (mass, volume) of the capture and disposal package as well as the delta-V budget of the multiple target mission. The feasibility was stemming from the cost per removal (Ariane, ATV derived, disposal package, operations), the accessibility of targets, technically, legally and politically, the availability of a customer (agencies, nations, private sector) and the mission scenario feasibility.
 Rendezvous and Refuelling Demonstrator (R2D3) (2010)	This **R2D3** study centred on the design of a spacecraft able to perform RDV and Refuelling demonstration. A second objective was the development of a "low-mass interplanetary carrier with high-payload mass fraction. Two other objectives were the validation of an optical communication terminal and the investigation of the debris removal. For the refuelling demonstration, various propellants were considered including liquid (storable, cryogenic), gaseous (xenon, nitrogen), solid and hybrid. For the liquid the study considered mon and bi-propellants (hydrazine, green, MON, MMH, N2O4, LH2, LOX, CH4).

GNC technologies for ADR and Space Tug

	GNC technology
G	01) Trajectory guidance
	02) Rendezvous and close approach guidance
N	03) Target acquisition and identification
	04) Image processing for navigation
	05) Estimation and data fusion for navigation
DKE	06) Environment modelling
	07) Vehicle design and knowledge
C	08) Optimal and robust control
	09) Failure detection, isolation, and recovery
	10) GNC testing facilities

	Others
MVM	01) Mode transtions
	02) Safe and failure modes
HMS	03) Health monitoring
	04) Integrity breach monitoring
FDIR	05) Failure detection and isolation
	06) Recovery

Model-base GNC design and development

- Model based design approach and auto-coding
- Modeling of GNC algorithms as well as equipment, dynamics and environment
- Tools features allowing straightforward frequency analysis and time simulation
- GNC SW code and verification activities largely automated

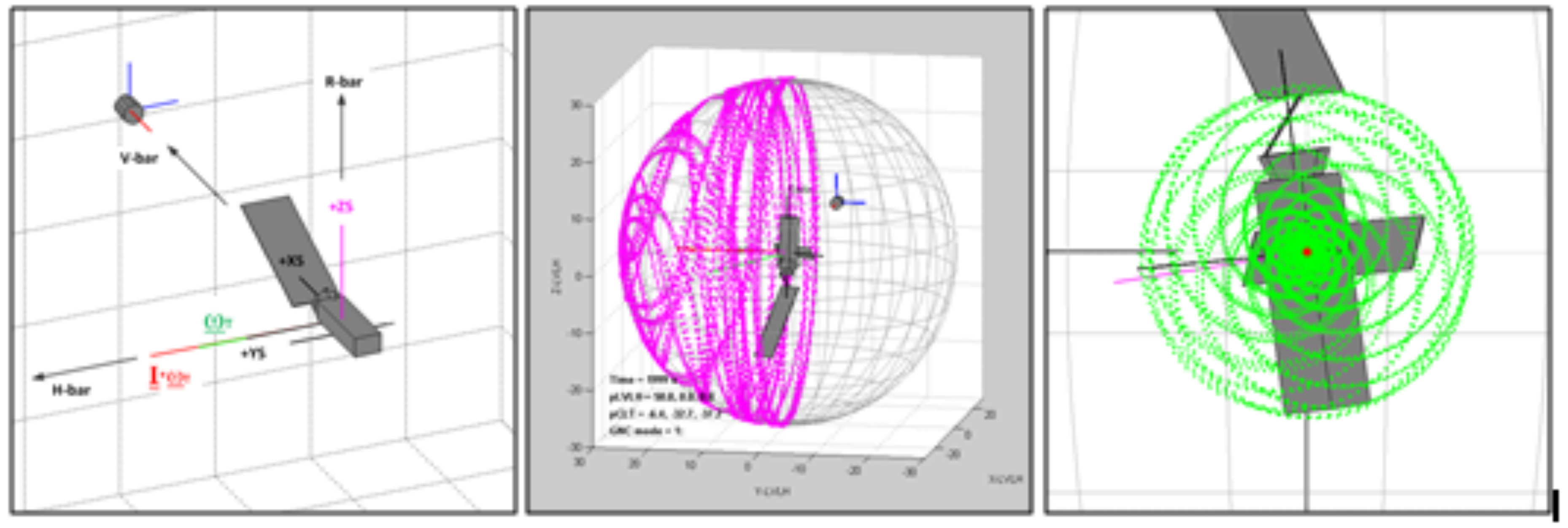


Figure 8-8: Scenario 1 results in a +/-90° cone containing the ZS figure axis motion (middle) w.r.t. LVLH and a +/-25° cone for the spin vector (right). The angular momentum vector stays very close to the H-bar

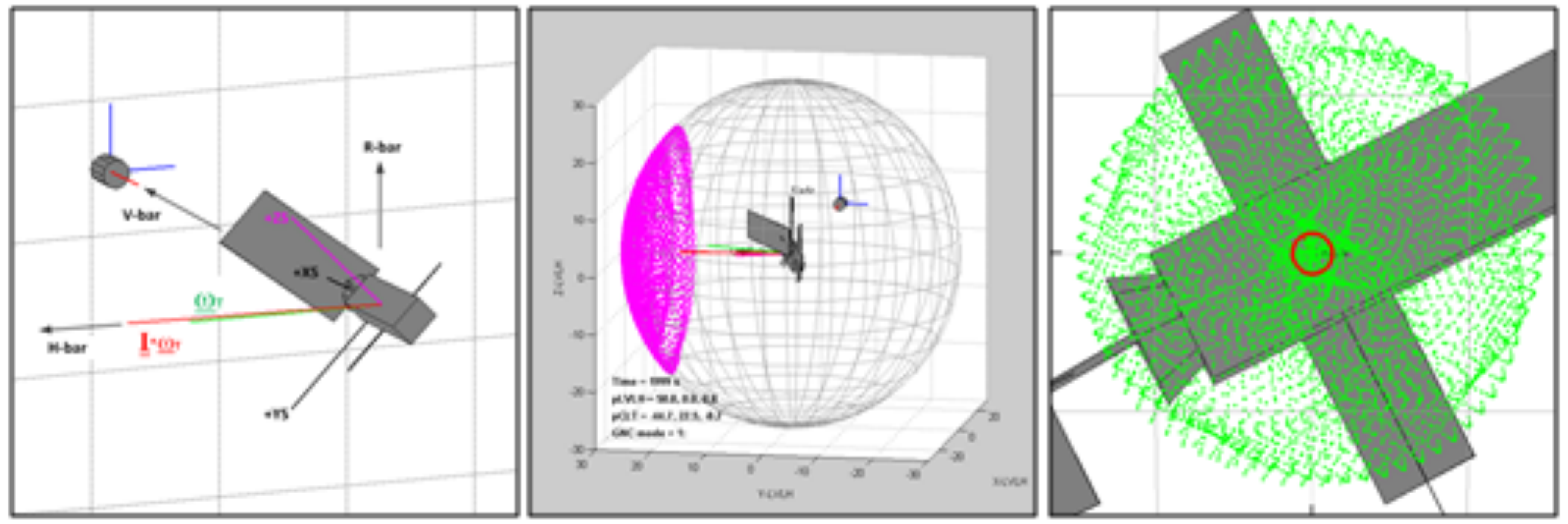


Figure 8-9: Scenario 2 results in a +/-45° cone containing the ZS figure axis motion w.r.t. LVLH and a +/-18° cone for the spin vector. The angular momentum vector stays very close to the H-bar

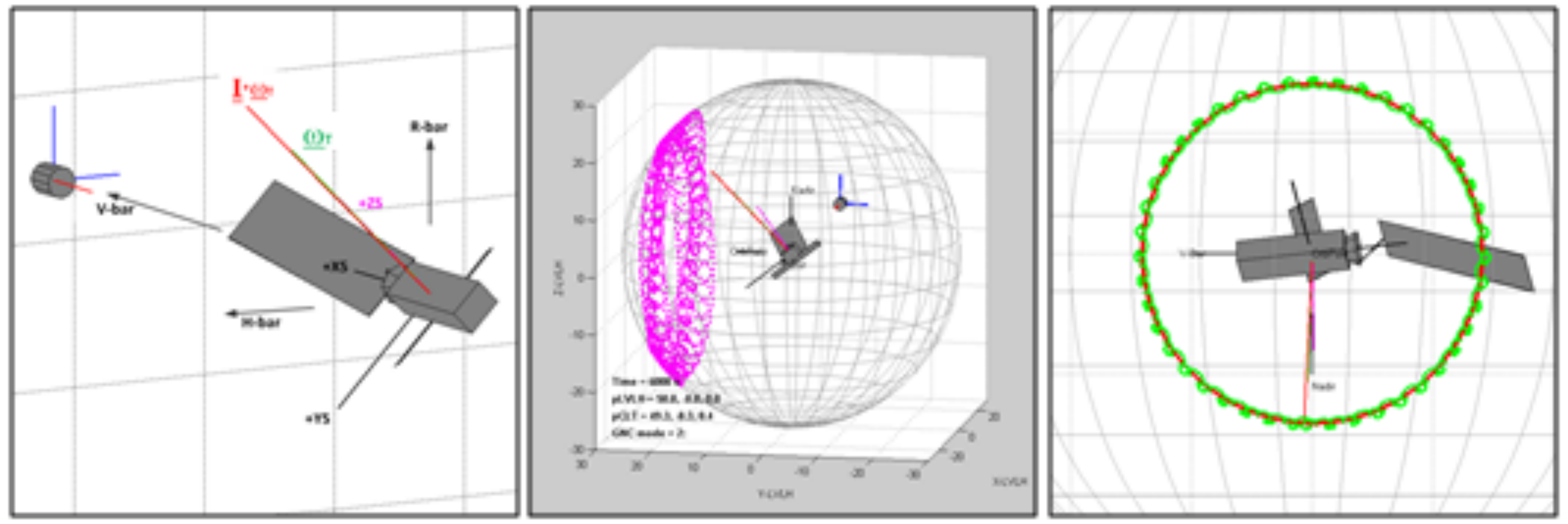
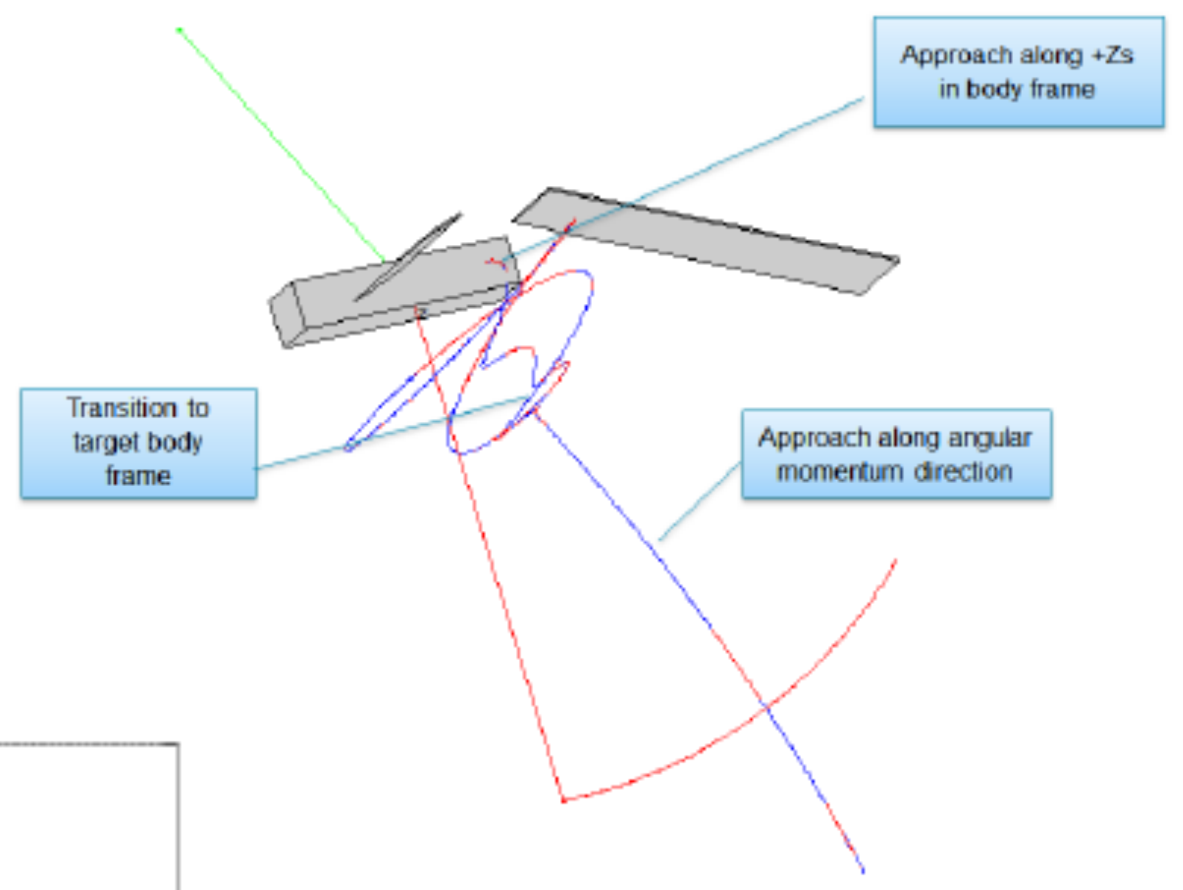
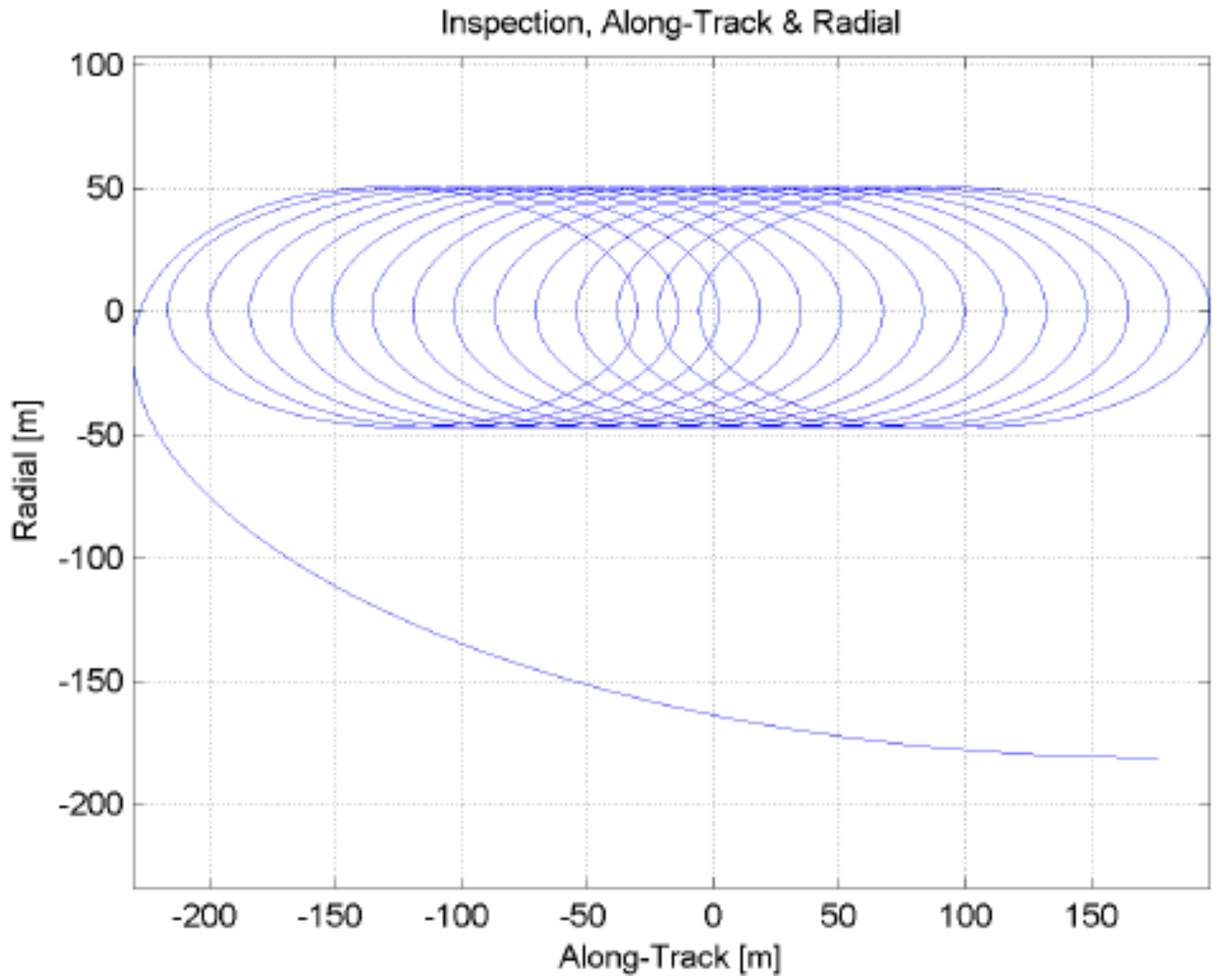


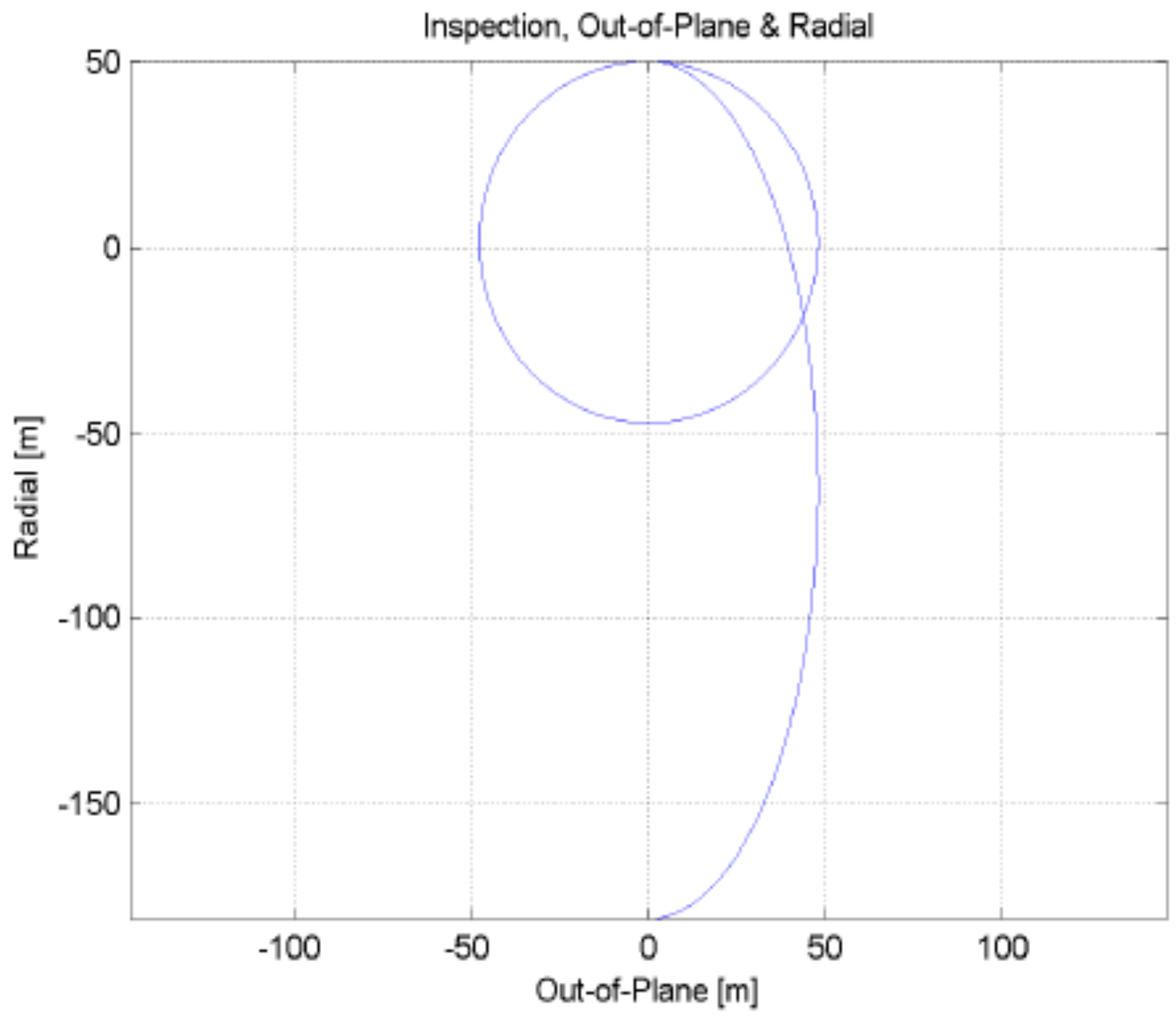
Figure 8-10: Scenario 3 results in a +/-45° virtual precession cone for the angular momentum vector (right, red). Superimposed, a small nutation of both the ZS figure axis (middle) and the spin axis (right, green) is seen

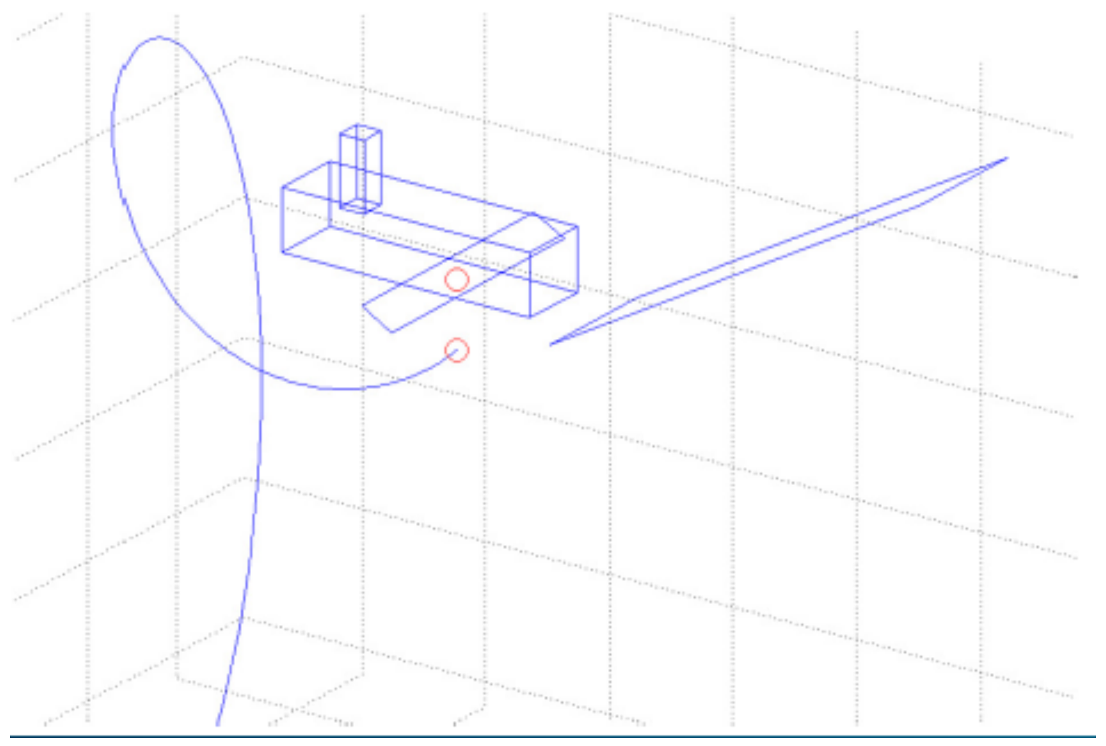
Guidance for terminal rendezvous

- Passively safe orbits
- Approach along target angular momentum and synchronization close to capture point
- Optimized approach and synchronization



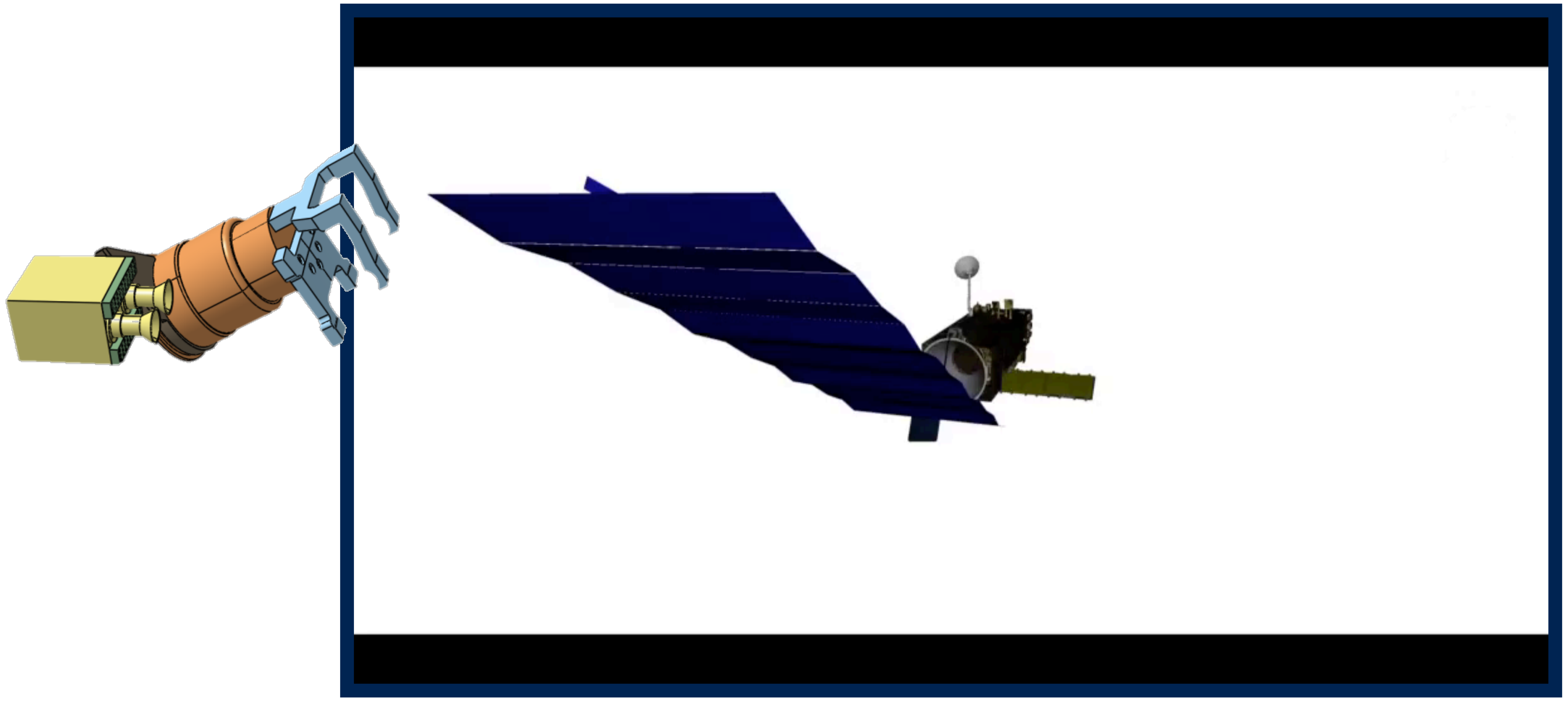






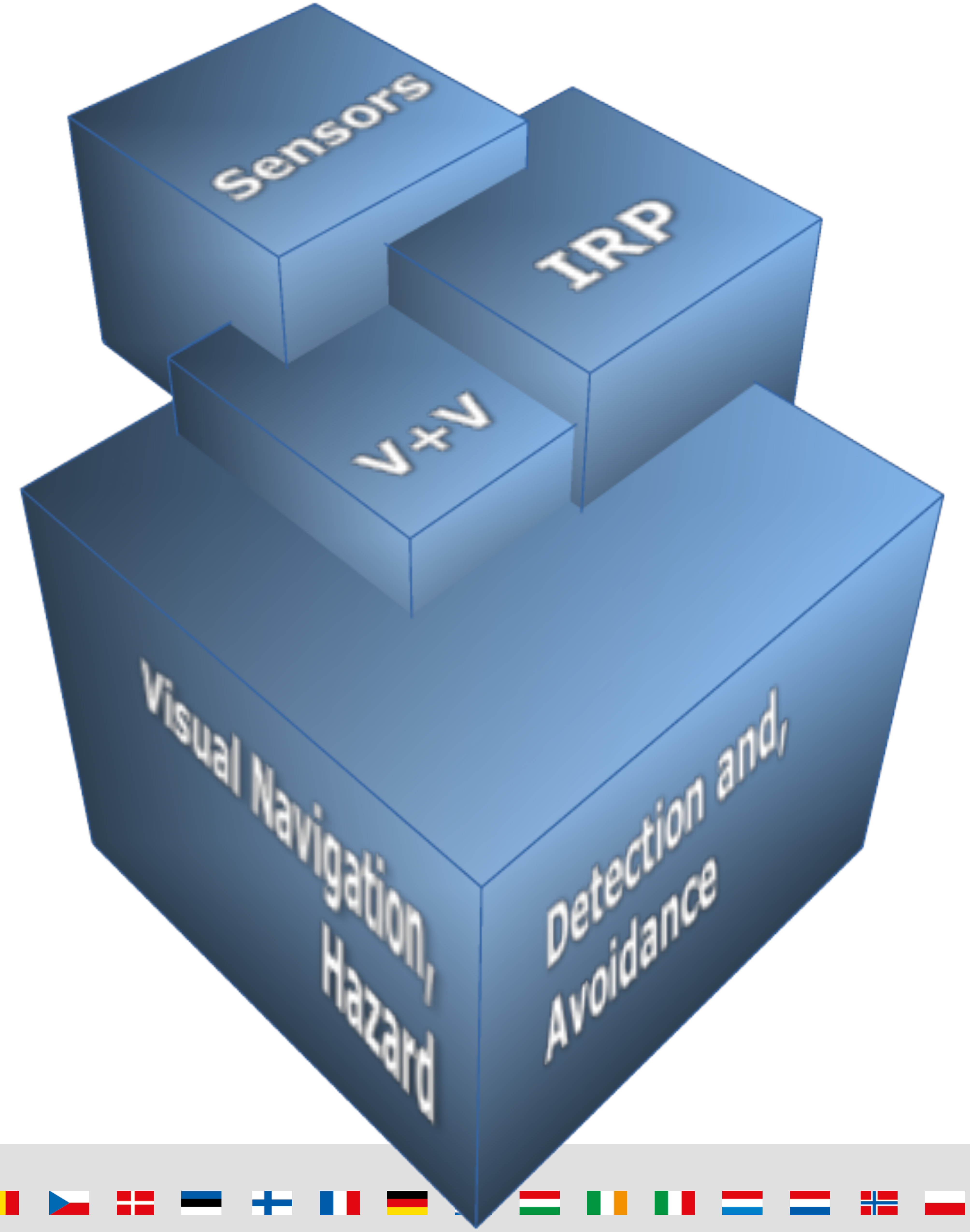
Combined control satellite+robot

- Loop shaping H-infinity combined control of satellite chaser and robotic arm
- Comparison with Linear Parameter Variant LPV controller using LFT modelling
- Satellite based on e.Deorbit specifications:
  - Dimensions: 1,45 x 1,6 x 2.2 m, Weight ~1.5 t
  - 24 control thrusters (22 N) with pulse width, pulse frequency modulation (PWPF). Force allocation on individual thrusters. Optimisation based using CLS. Additional 4 x 220 N and 2 x 425 N thrusters
  - Tanks for oxidiser and fuel with sloshing modelling

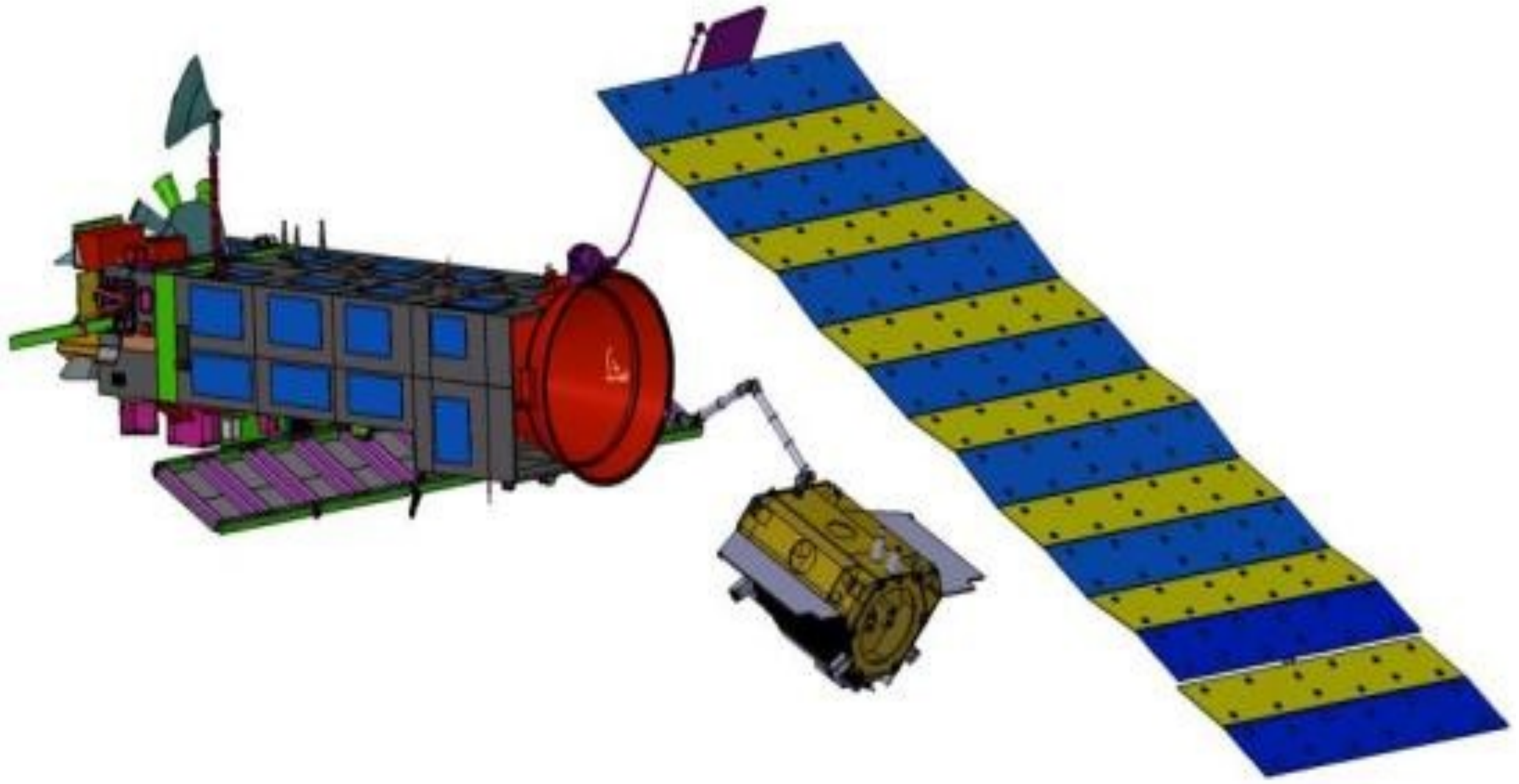


- Robotic manipulator arm with 7 degrees of freedom
  - DLR-RM ROKVISS joint design, Robot arm components as multi-body systems.
  - Large reach and low weight and modelling of joint friction and gear elasticity. Full consideration of dynamic coupling forces and torques on satellite (reaction forces) and gripper implemented as force element
  - Number of states remains constant during simulation (allows simulation of different phases with same setup, number must not change for Modelica simulation). Baumgarte stabilisation for numerical robustness

Navigation building blocks

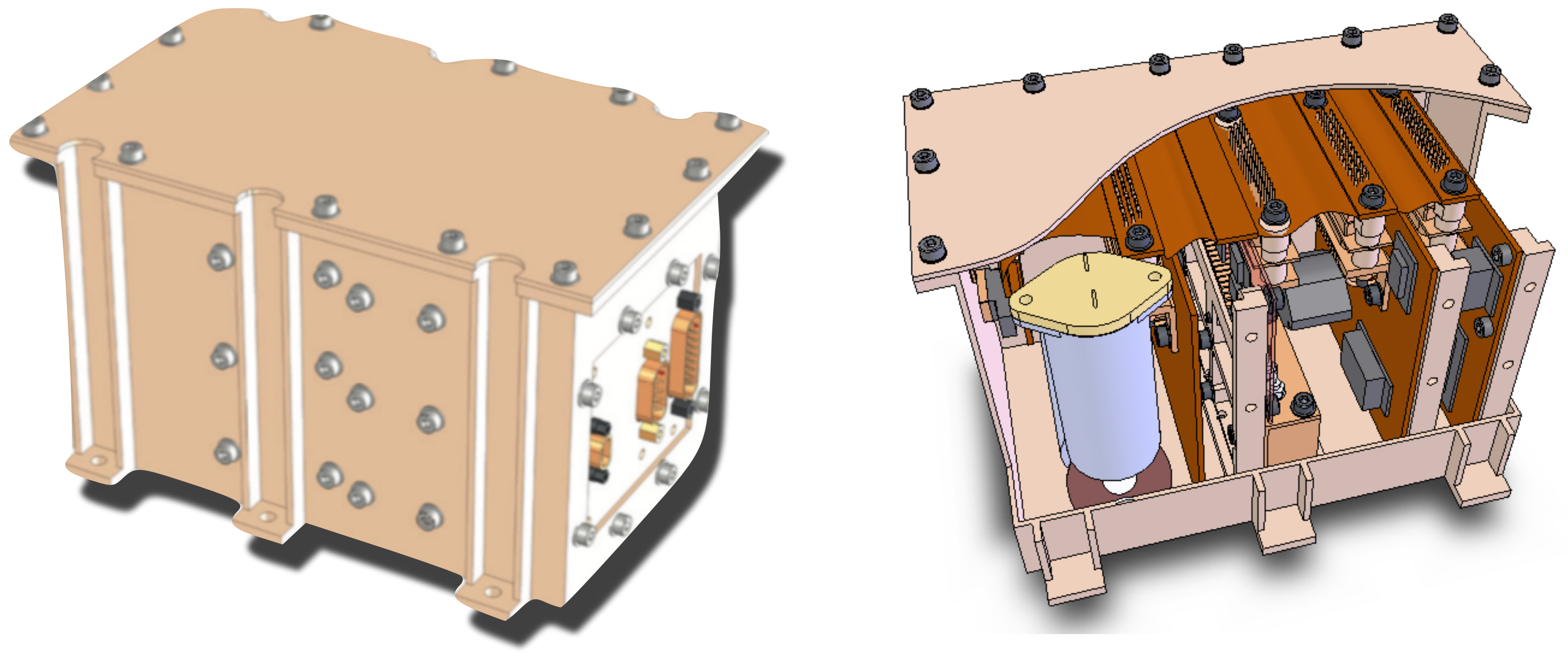


- Target acquisition and identification: vision-based cameras (wide and narrow fields of view), infrared cameras, multi-spectral, altimeters, LIDAR, IMU, STR
- Image processing for navigation: feature Extraction and image correlation, optical flow
- Estimation and data fusion for navigation: sensor data fusion, deterministic and stochastic filtering, Kalman



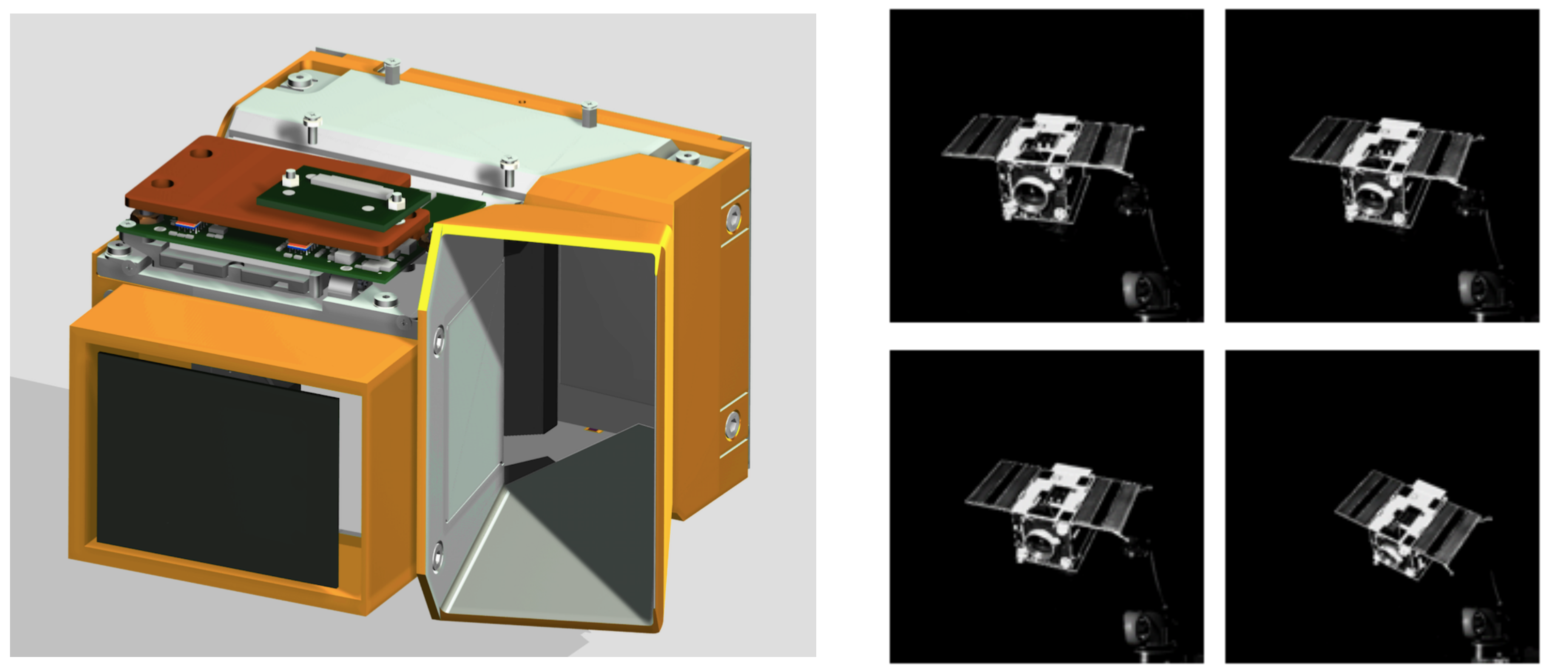
Some GNC sensors: Altimeter and Multi-spectral camera

Altimeter



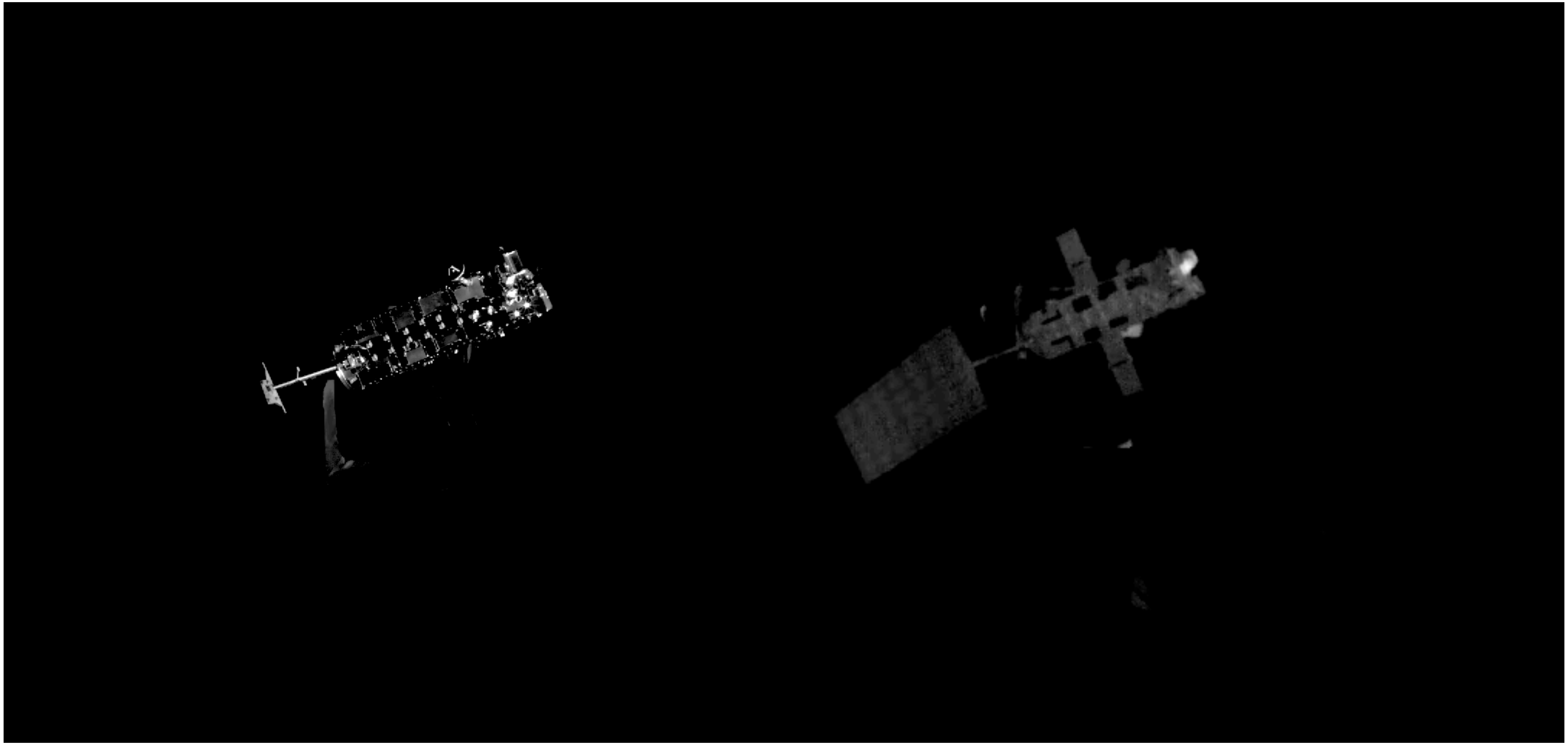
- A direct and reliable measurement of the ground distance by a terrain sensor is a key asset for any planetary descent and landing system that allows the triggering of key events of the entry, descent and landing sequence (EDL)
- Development of sensor level critical technology, and the breadboard model of a planetary altimeter
- Two technologies: radar and laser
- Reduce the mass, size, and power of its individual components

Multi-spectral camera



- Use of the combination of visible, IR, and UV wavelengths for navigation sensing
- Review existing space-qualified detectors technology which could be used for such purpose and their response in the identified spectral bands.
- Architecture and a preliminary design of a Multispectral Sensing Device called HyperNAV
- Selection of a combined VNIR (visible and near infrared) and TIR (thermal infrared) solution
- Focus on rendezvous applications (both cooperative and uncooperative)

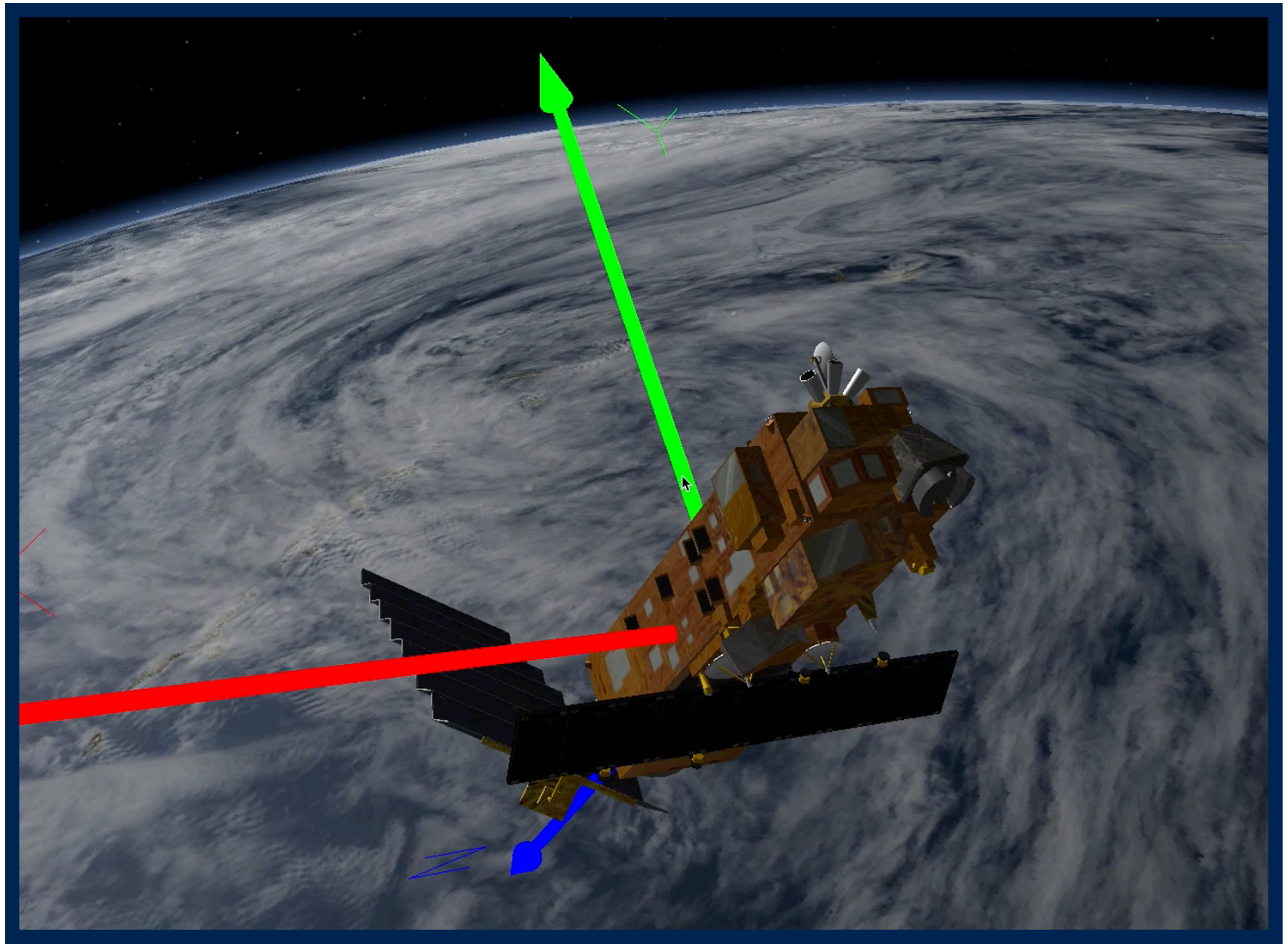
Navigation using VISIBLE vs INFRARED wavelengths



ENVISAT approach using camera in <u>VISIBLE</u>

ENVISAT approach using camera in <u>INFRARED</u>

GNC tools: synthetic scene generation with PANGU



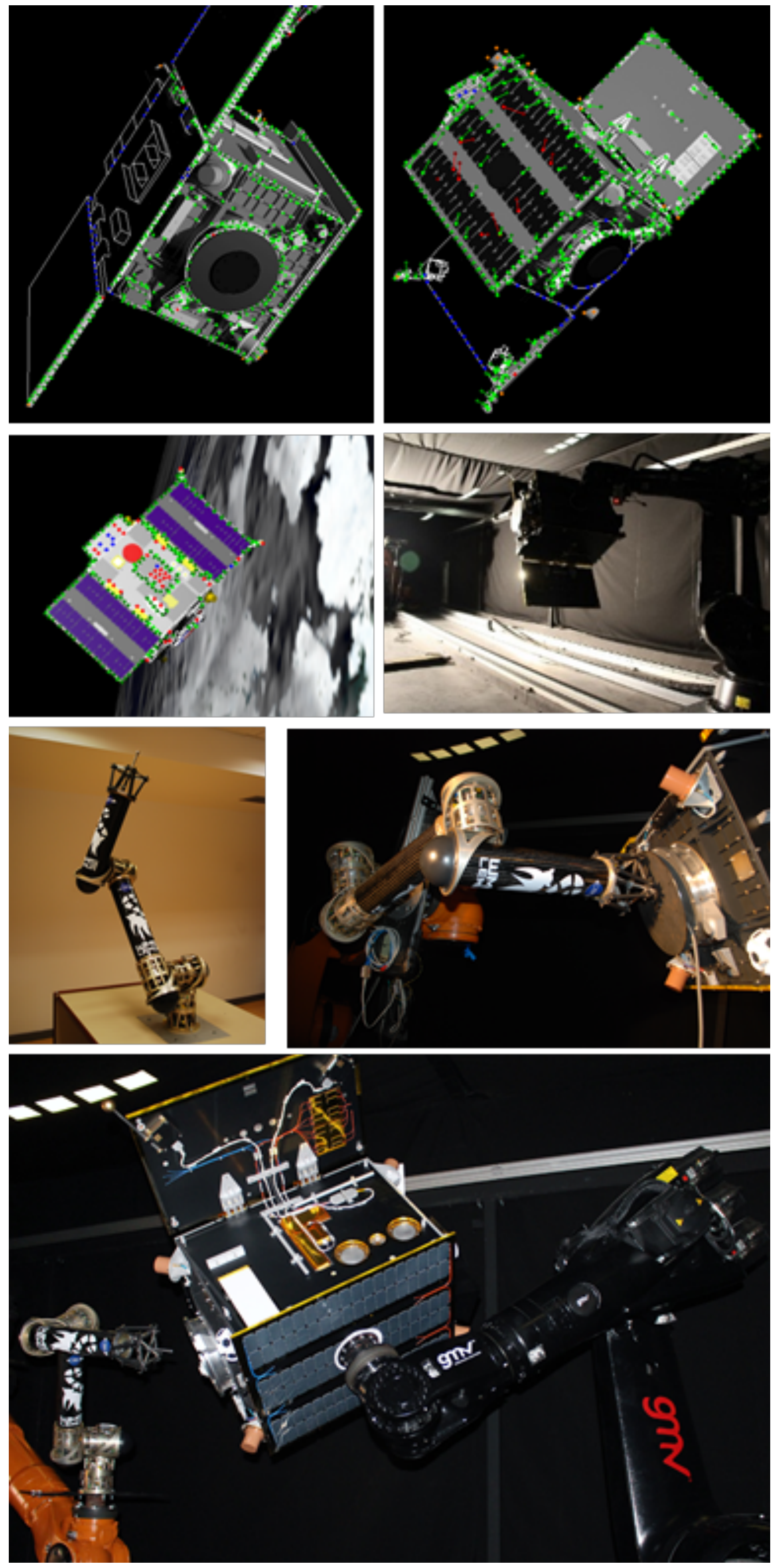
- Surface modeller: realistic surfaces (MLI, OSR, solar cells…); Generate surface file and shadow maps from scratch or from existing Digital Elevation Maps (DEM); Features available are craters, boulders and dunes
- Whole planet and asteroid models are also possible; Viewer to render the surface; Fog / atmospheric dust; Dust devils, Dust kicked off by thrusters; Sky colour, stars, Earth, moon visible
- Rendering of the surface with a shadow map; Dynamic shadows; DEM completion (filling holes, adding craters…); Surface analysis (illumination, boulder coverage…); Rover surface navigation (experimental feature)
- Asteroid simulation: Fast rendering of surface boulders on asteroid now possible, multiple bodies casting dynamic shadows
- Virtual Spacecraft Image Generator Tool
- Import of CAD/3D model

GNC Verification and Validation for e.Deorbit

- GNC **Verification** is defined as the process that demonstrates through the provision of objective evidence that the GNC product is designed and produced according to its specifications and the agreed deviations and waivers, and is free of defects.
- The GNC verification process allows to confirm that adequate specifications and inputs exist for any activity, and that the outputs of the activities are correct and consistent with the specifications and input of a GNC system.
- GNC **Validation** is defined as the process which demonstrates that the GNC is able to accomplish its intended use in the intended operational environment.
- The GNC validation process allows to confirm that the requirements baseline functions and performances are correctly and completely implemented in the final GNC product.
- GNC **Certification** is defined as the procedure by which a party gives formal assurance that a GNC system is in compliance with specified requirements.

On Ground Validation

- Advance of key technologies required to perform complex robotic scenarios (cooperative and non-cooperative) needing a rigid capture mechanism such as a robotic arm:
  - Image processing chain for relative navigation and robotic arm operation.
  - Chaser vehicle GNC for approach and for close proximity operations.
  - Robotics control
  - Simultaneous operation of two control system i.e. spacecraft GNC and robotic arm
- Combo system overall modelling/dynamic characterization, requiring multi-body models TRL 5/6 for the vision-based system, including HW (space-heritage optical and processing units have been used) and SW (performant Image Processing algorithms has been coded in VHDL and embedded in the camera processing units, working at 2Hz)
- TLR 4/5 for the full system (TRL 4/5 at functional level, TRL4 at interfacing level)

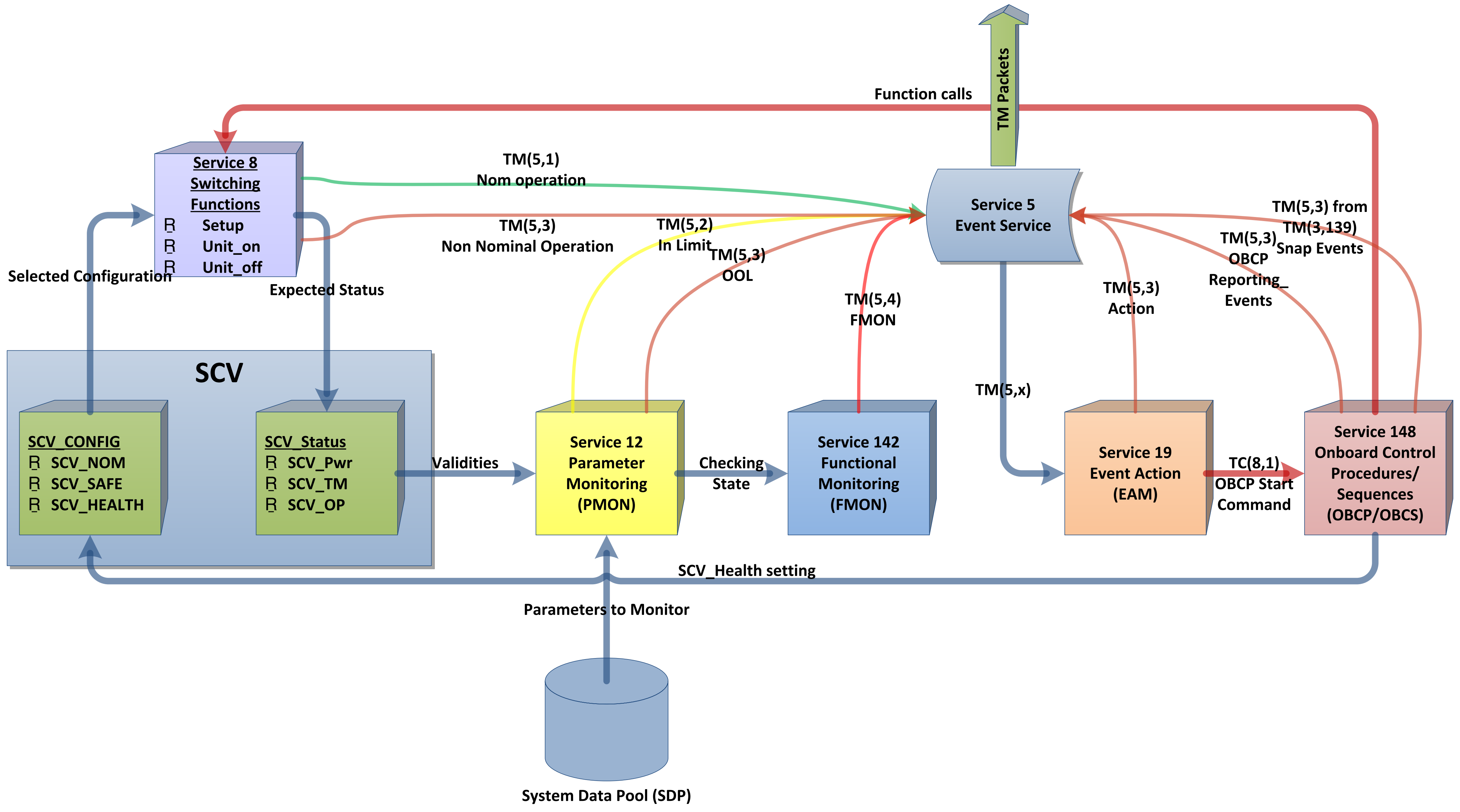



Target rotation [deg/s]


PHILIPS

FDIR for generic GNC and AOCS

- Space missions more and more complex: each mission has a “different” FDIR/FTC system
- Lack of regular processes and procedures on how to design, develop, and test FDIR/FTC systems
- Difficult to qualify FDIR/FTC systems within a “reasonable” price and time
  - Objective 1: Provision for a consistent approach, common engineering and guidelines of the FDIR/FTC design, development and testing processes
  - Objective 2: Formalisation of concepts, terminology, and vocabulary for the development of FDIR/FTC systems
  - Objective 3: Elaboration of systematic processes for the qualification of FDIR/FTC systems (including verification and validation)
  - Objective 4: Elaboration of operational aspects versus autonomy (on-board / on-ground dichotomy)
  - Objective 5: Reduction of time and funding of FDIR/FTC systems life-time design, development, and testing



Thanks for your attention