ThalesAlenia Space — a Thales / Leonardo company

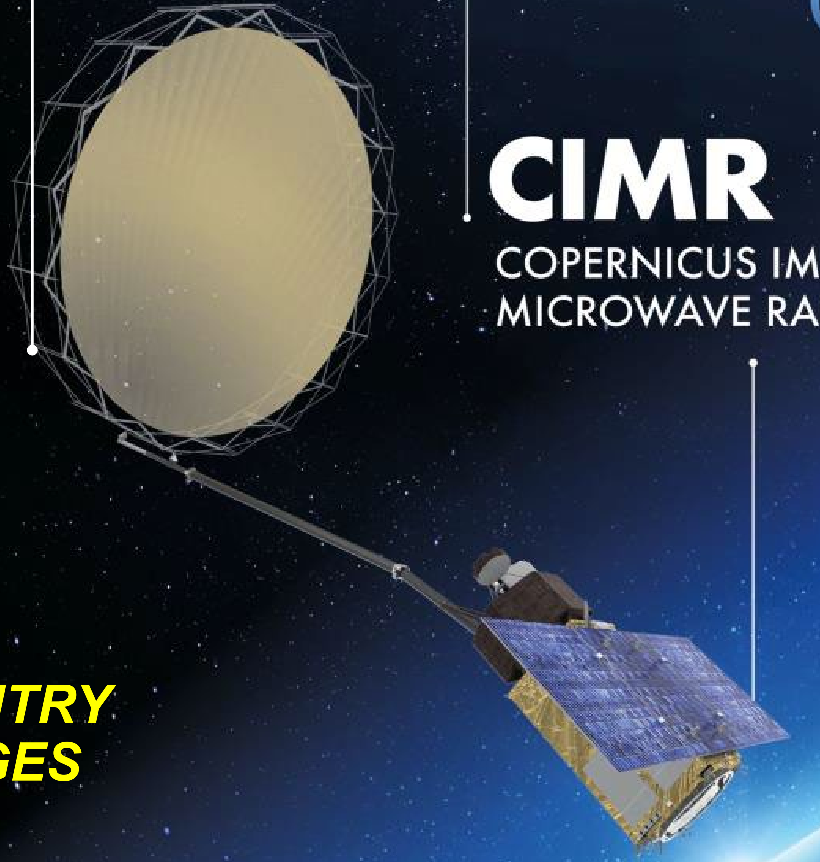
esa

OHB ITALIA

HPS High Performance Space Structure Systems GmbH

LSS Large Space Structures

copernicus — Europe's eyes on Earth



CIMR

COPERNICUS IMAGING MICROWAVE RADIOMETER

CIMR MISSION:

AOCS CONTROLLED RE-ENTRY STRATEGY AND CHALLENGES

PRESENTATION OUTLINE

Programme of the European Union
Cofunded with
17th ESA Workshop on Avionics, Data, Control and Software Systems (ADCSS2023)

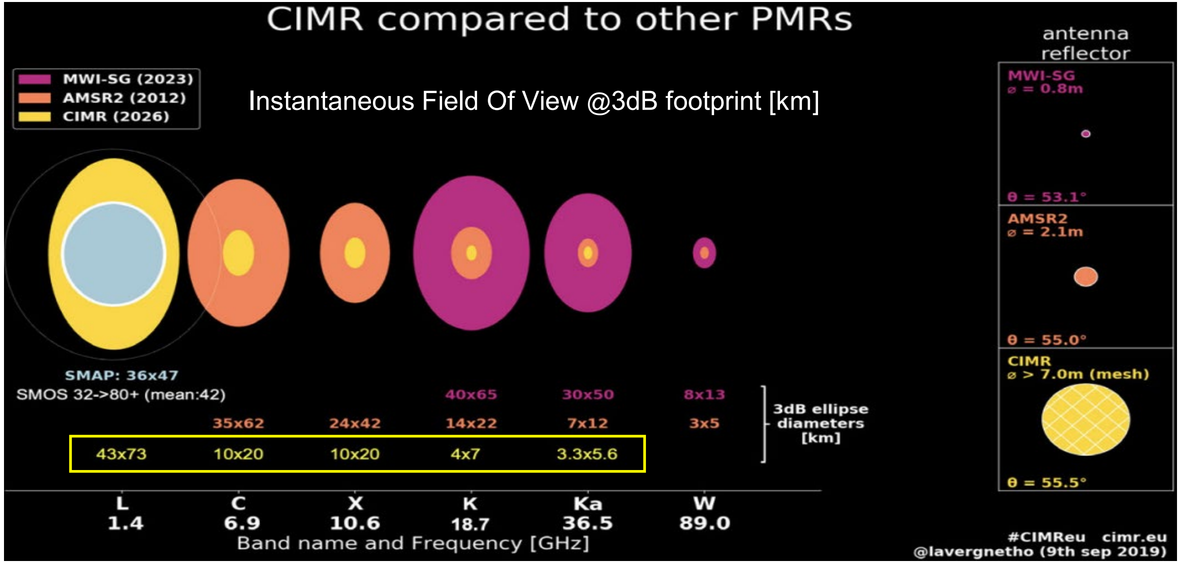
CIMR Project Overview: Introduction

/// Copernicus Imaging Microwave Radiometer project:

- within the **European Copernicus Expansion** (CopExp) program
- implemented by the **European Space Agency** (ESA) and the **European Commission** (EC)
- currently in the C/D phase with **Thales Alenia Space** as prime contractor

/// CIMR: a “game changer” in Polar regions monitoring

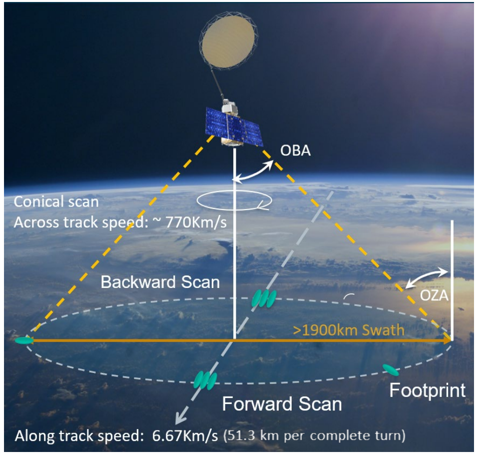
- **Observations**:
  - Sea Ice Concentration/Extension (SIC/SIE)
  - Sea Ice Thickness (SIT)
  - Sea Surface Temperature (SST)
  - Sea Surface Salinity (SSS)
- **Performances**:
  - Multi-frequency, simultaneous acquisitions
  - Unrivaled spatial resolution → 5 to 60 km
  - Excellent radiometry accuracy/resolution
  - Global coverage → 95% daily
  - sub-daily revisit → 6h

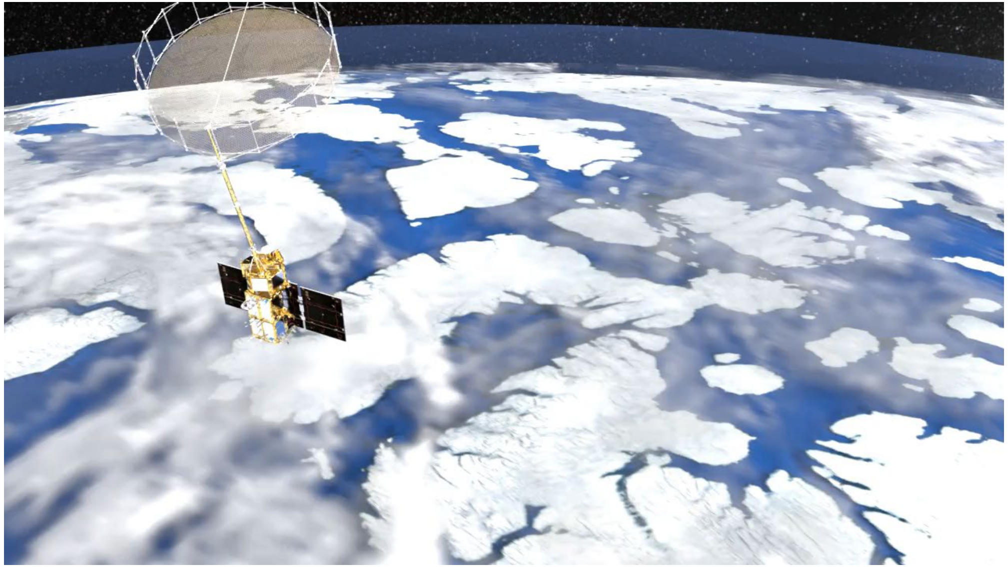


CIMR Project Overview: Mission concept

/// Orbit and Payload characteristics:

- **Sun-synchronous** dawn/dusk operational orbit with:
  - semi-major axis is such that the **ground track** is repeatable (orbital cycle duration of **29 days**)
  - **frozen eccentricity** and average altitude of ~ 817 km
- **Off-Zenith Angle** (OZA): ~ 55 deg
- Instrument rotation **speed**: 7.8 rpm
- **Ground Swath**: 1900 km





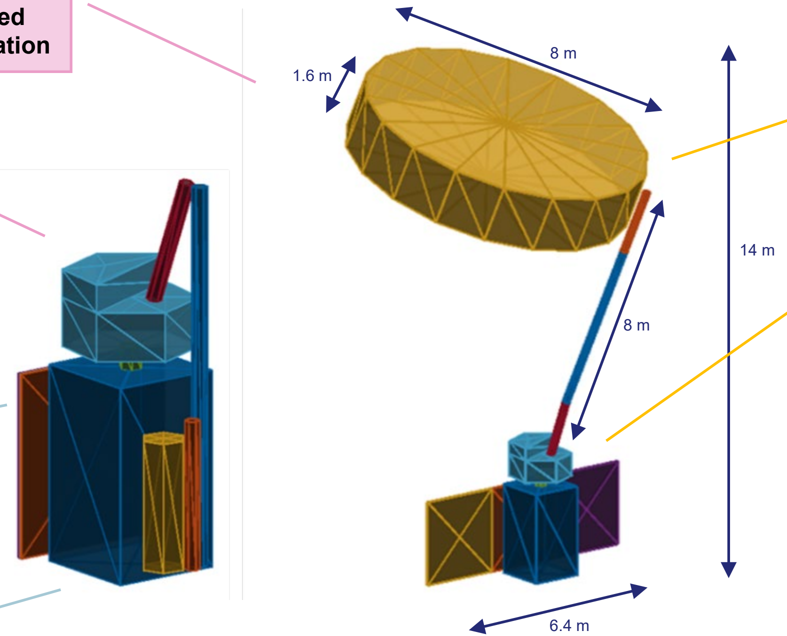
Programme of the European Union
Copernicus Europe's eyes on Earth
Cofunded with esa
17th ESA Workshop on Avionics, Data, Control and Software Systems (ADCSS2023)
ThalesAlenia Space a Thales / Leonardo company

CIMR Project Overview: Spacecraft Multibody Layout

Deployed Configuration

Stowed Configuration

Solar Panels



Instrument

- **LDRS** (Large Deployable Rotating System)
- **Crate**

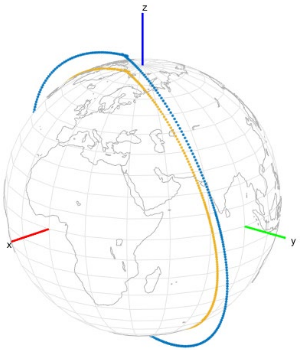
Platform

AVS	EPS	PDHT
PROP	TCS	TTC

CIMR Project Overview: Space Debris Mitigation

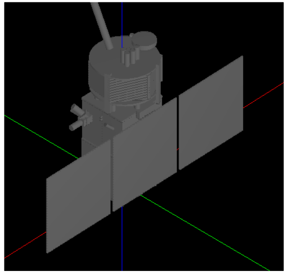
/// Space Debris Mitigation:

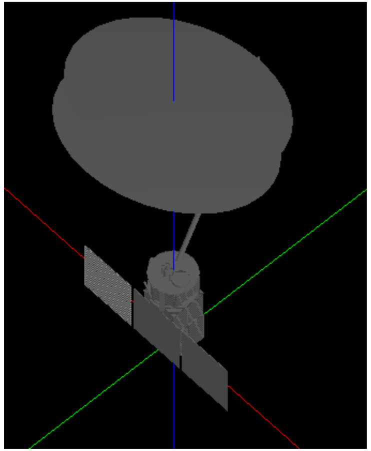
- CIMR Satellite design complies to **Space Debris Mitigation Requirements** (ISO 24113 – 2019)
- **Casualty Risk Analysis** results for Uncontrolled Re-entry are not compliant with the standard
- Need for a **Controlled Re-entry** at EOL



/// Design impacts:

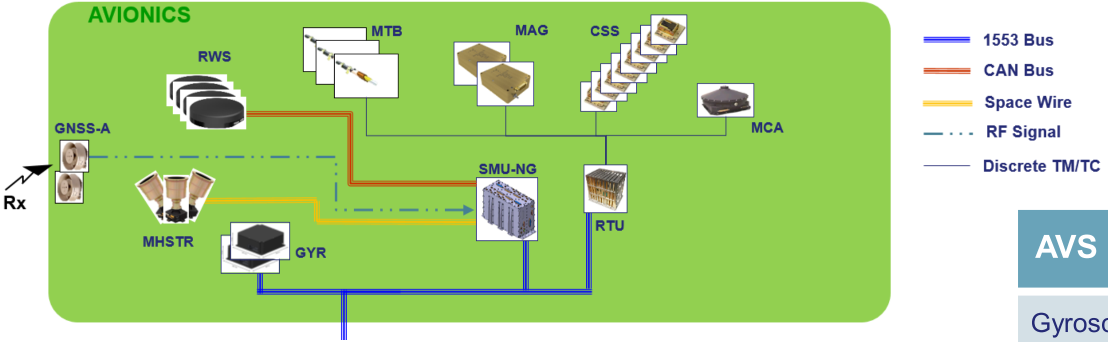
- **Propulsion** system capabilities (thrust level and propellant)
- Implementation of **AOCS** dedicated mode
- Subsystems **reliability** for additional functionalities and environment

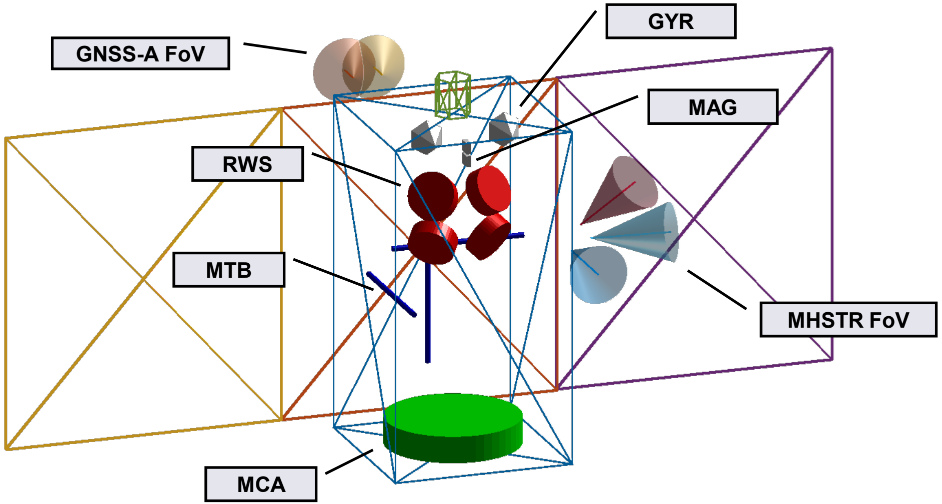




Programme of the European Union
Cofunded with esa
17th ESA Workshop on Avionics, Data, Control and Software Systems (ADCSS2023)

AVS/AOCS Architecture: Avionics Subsystem





/// Actuators Sizing:

- **RWS:** 0.2 Nm, 50 Nms
- **MTB:** 400 Am^2
- **MCA:** ~1250 Nms

AVS Units	N. Items
Gyroscope (**GYR**)	2
Magnetometer (**MAG**)	2
Multi-Head Star-Tracker (**MHSTR**)	3
Cosine Sun Sensor (**CoSS**)	8
GNSS Antenna (**GNSS-A**)	2
Reaction Wheel System (**RWS**)	4
Magnetic Torque Bar (**MTB**)	3
Momentum Compensation Assembly (**MCA**)	1

AVS/AOCS Architecture: Propulsion Subsystem

/// Reaction Control Thrusters:

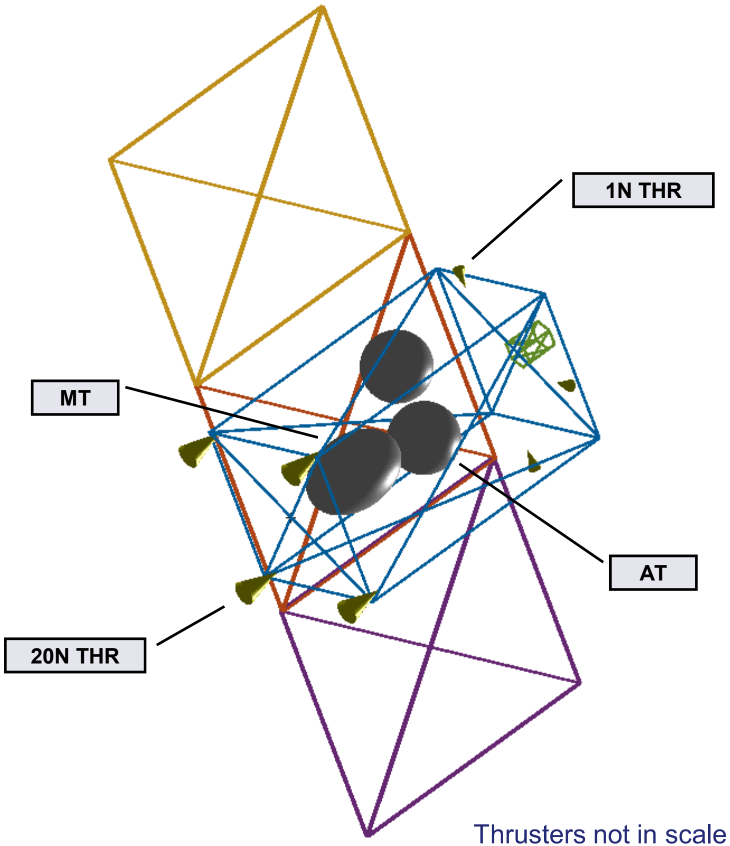
- 6 x **1 N thrusters** (3 main + 3 redundant) directed towards ±X axis and +Y axis → used for **Orbital Correction Manoeuvres** (OCM)
- 8 x **20 N thrusters** (4 main + 4 redundant) directed towards +Z axis with a tilt angle (to obtain torque authority around all the axis) → used for **High-Rate Damping Safe Mode** and **Re-Entry Mode**

/// Propellant tanks:

- **Auxiliary tanks**: 2 x 104 l tanks, used in parallel for the satellite operational life and the first phase of perigee lowering
- **Main tank**: 177 l tank, entirely dedicated to re-entry for the second phase of perigee lowering and the last burn.

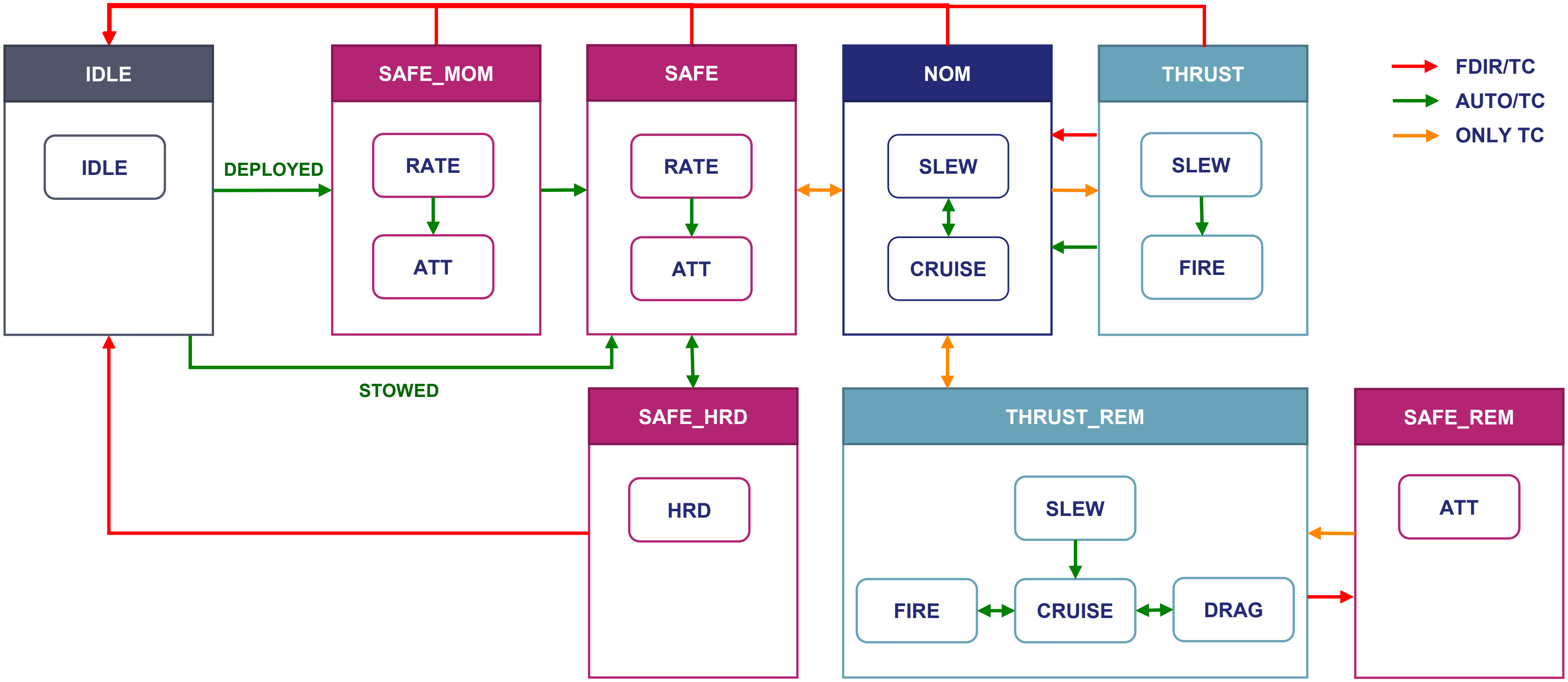
/// 20N THR performances (blowdown mode):

- **Thrust level:** 24.5 N @ 24 bar, 7.8 N @ 5.5 bar
- **Specific Impulse**: 231 s @ 24 bar, 223 @ 5.5 bar



Thrusters not in scale

AVS/AOCS Architecture: AOCS Modes & Phases



Controlled Re-entry Mode

/// THRUST_REM Mode:

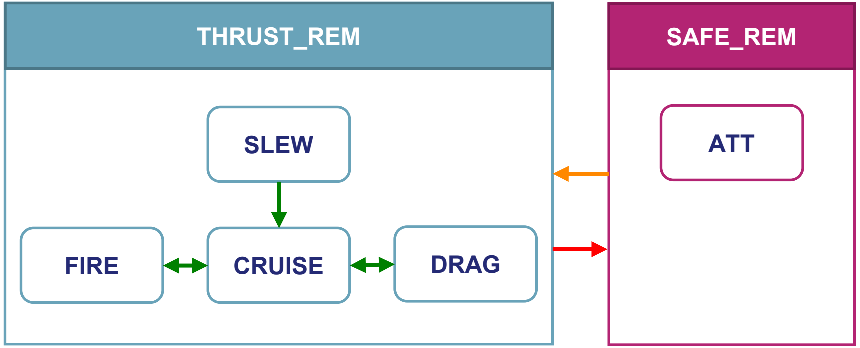
- implements a robust technique to perform the re-entry manoeuvre, given **Delta-V program** uploaded by ground (resulting from trajectory optimization)
- it can be entered only from NOM by **ground tele-command**
- on-control **units**:
  - MHSTR and GYR for **attitude estimation** (kinematic filter)
  - 20N THR for **attitude and orbital control** during firing phase
  - RWS for **attitude control** and MTB for **momentum unloading** during slew, cruise and drag phases

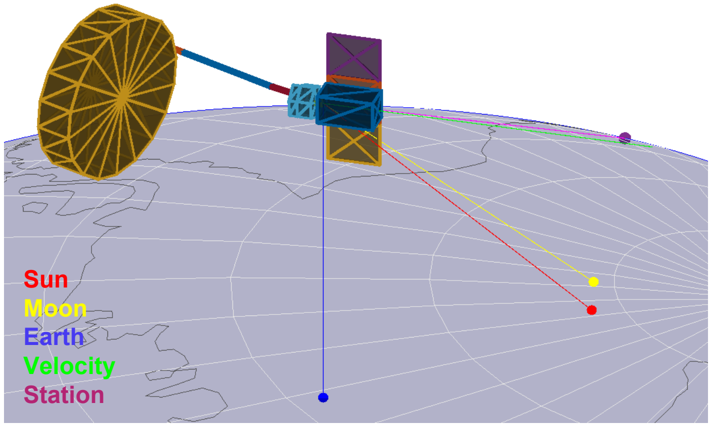
/// SAFE_REM Mode (FDIR):

- guarantees the platform stability, solar illumination of solar panels and communications with ground
- on-control **units**:
  - MAG/CoSS triad or MHSTR/GYR for **attitude estimation**
  - RWS **low bandwidth** attitude control and MTB for **momentum unloading**

/// Re-entry Reference attitude

- spacecraft –Z axis (thrusters' force) towards velocity
- spacecraft +Y axis (solar panels) towards orbital momentum (close to the Sun direction)



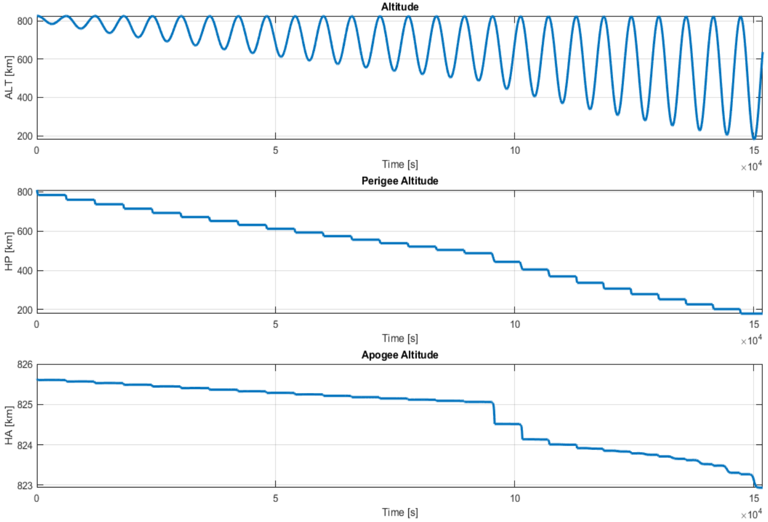


Programme of the European Union
Copernicus Europe's eyes on Earth
Cofunded with esa
17th ESA Workshop on Avionics, Data, Control and Software Systems (ADCSS2023)
ThalesAlenia Space a Thales / Leonardo company

Controlled Re-entry Mode: Reference Trajectory

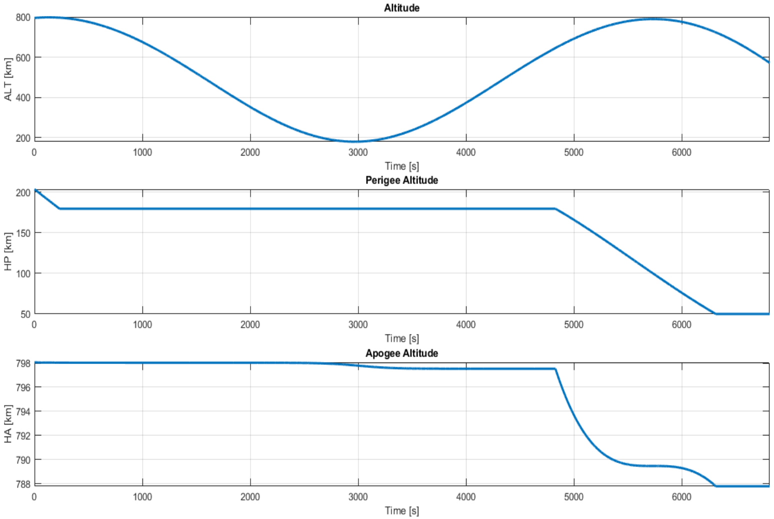
/// Perigee lowering:

- series of **short** (efficient) controlled retro-burn manoeuvers at apogee for perigee lowering
- **perigee** altitude from 800 km to 180 km
- all manoeuvers last about **5 minutes**



/// Last burn:

- final **long** (inefficient) firing phase (FDIR inhibited)
- **perigee** altitude from 180 km to 50 km
- manoeuvre duration is about **40 minutes**
- South Pacific Ocean inhabited area **splashdown**

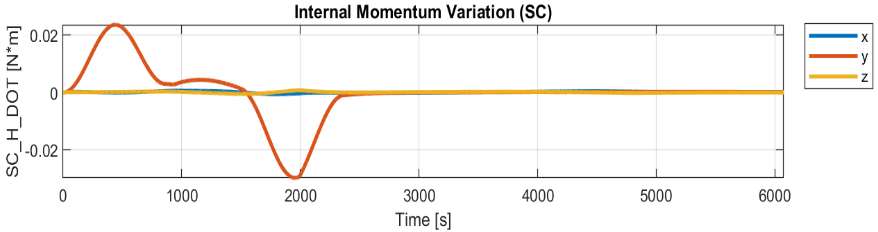


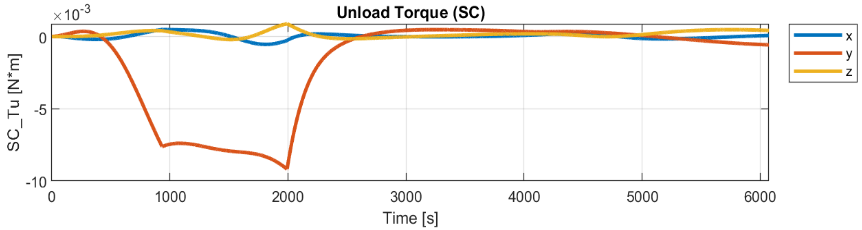
Programme of the European Union
Europe's eyes on Earth
Cofunded with
17th ESA Workshop on Avionics, Data, Control and Software Systems (ADCSS2023)
a Thales / Leonardo company

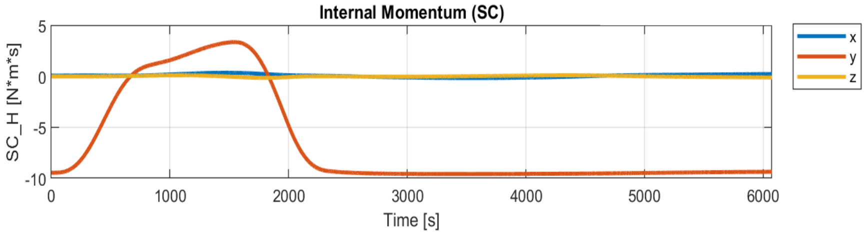
Controlled Re-entry Mode: Slew phase

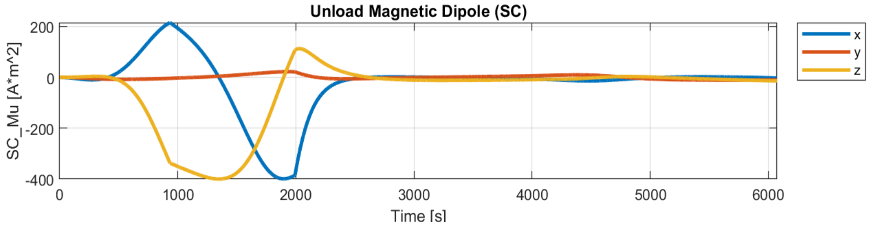
/// To change the spacecraft attitude in order to reach the firing pointing

- **pitch** manoeuver of -90 deg (predefined time profile)
- **disturbance torque** (mainly gravity gradient) counter-reacting → RWS torque/momentum verified ✓
- internal angular momentum **unloading** → MTB command verified ✓









Programme of the European Union

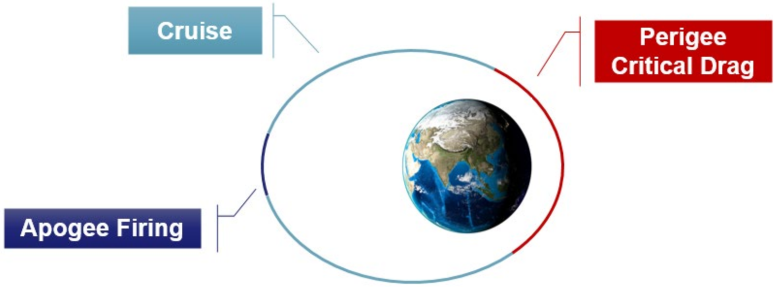
Cofunded with

17th ESA Workshop on Avionics, Data, Control and Software Systems (ADCSS2023)

Controlled Re-entry Mode: Orbital phases

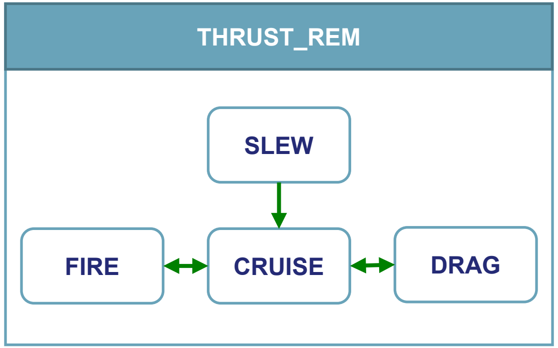
/// Orbital phases → AOCS Phases:

- **Apogee passages** → retro-burn firing (FIRE)
- **Perigee passages** → high drag torque (DRAG)
- **Coasting** → maintaining the attitude (CRUISE)



/// During the entire re-entry phase:

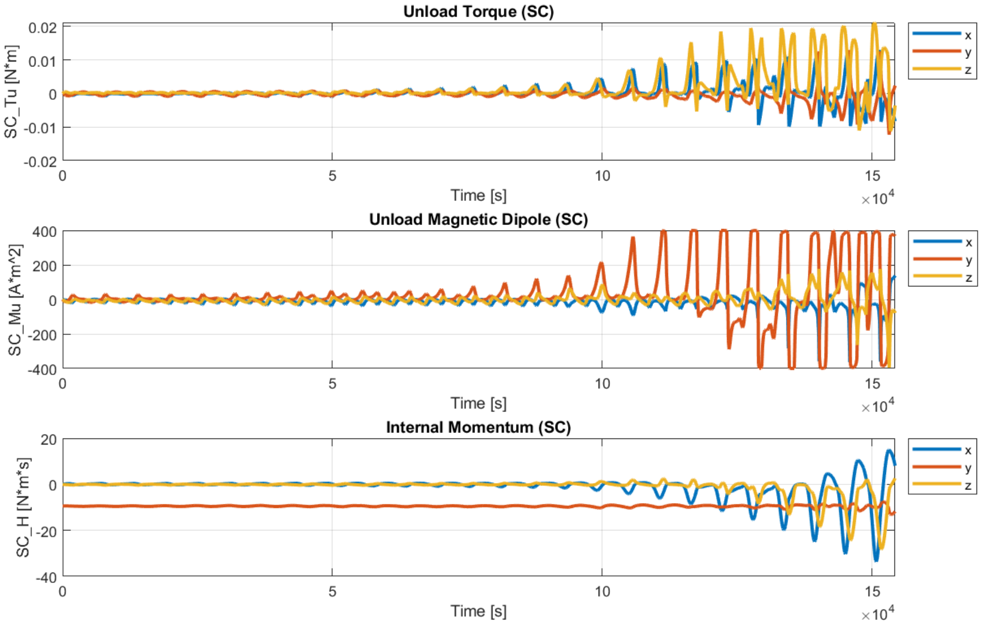
- 27 **manoeuvers** are performed
- the **payload** is off (no pointing accuracy requirements)
- the instrument is controlled to a constant angular position (**no rotation**) → to minimize drag effects
- always the same **reference attitude** is adopted → to minimize slew maneuvers and operation complexity



Controlled Re-entry Mode: Trajectory Simulation Test

/// Environmental disturbances analysis:

- **drag torque** gives the main contribution especially at low altitudes
- **hypothesis** for conventional attitude control:
  - RWS low control frequency (0.001 Hz)
  - unloading through MTB
- **results**:
  - MTB not able to fully de-saturate internal angular momentum at low altitudes
  - internal angular momentum cumulates during the orbital period
- the **outcome** is the need of the DRAG phase



Programme of the European Union
Copernicus Europe's eyes on Earth
Cofunded with esa
17th ESA Workshop on Avionics, Data, Control and Software Systems (ADCSS2023)
ThalesAlenia Space a Thales / Leonardo company

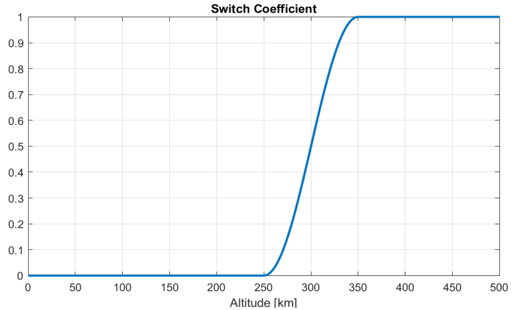
Controlled Re-entry Mode: Critical Drag phase

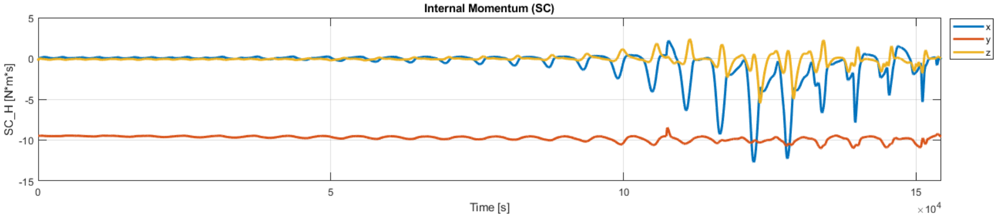
/// Drag handling during perigee passages

- the thrusters are not used, AOCS needs are related to **solar power and communi**cation
- high disturbance drag torque reached during perigee passages is **controlled through RWS**
- tuning through a **PID controller** with a preliminary control frequency of 0.001 Hz

/// Last manoeuvers: drag becomes too high

- attenuation of controller gains through a smooth **switch function** to avoid internal angular momentum saturation ✓
- target attitude is quickly restored within requirements ✓





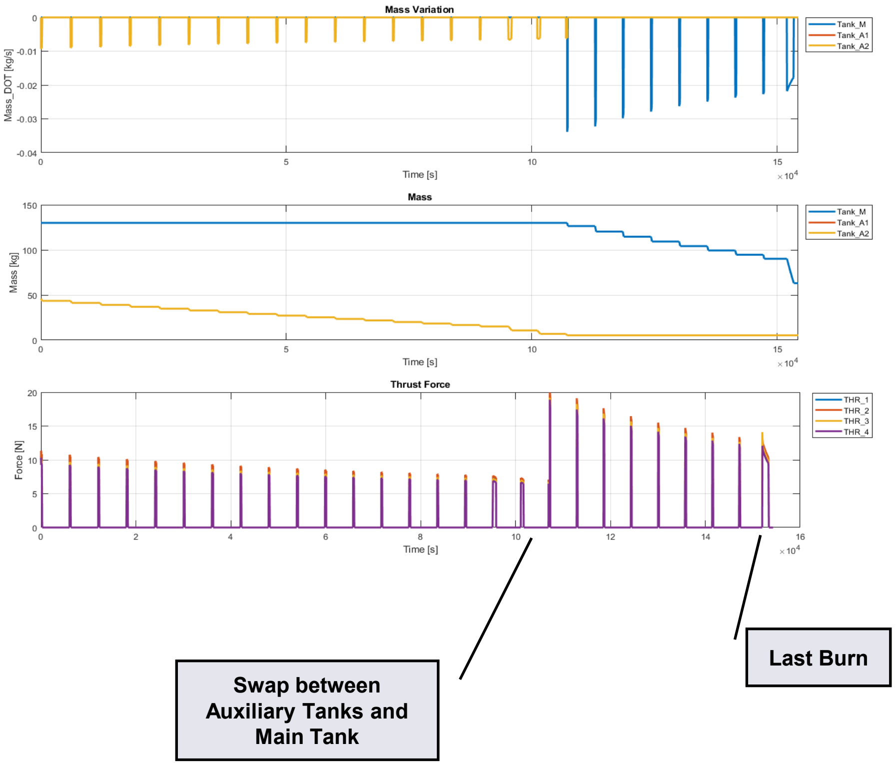
Controlled Re-entry Mode: Firing phase

/// Thruster torque:

- a **disturbance** torque is produced because of
  - spacecraft **mass properties** knowledge
  - spacecraft **center of mass** offset (variable with propellant mass)
  - **mounting** position and orientation error
- RWs are **not able** to compensate it (> 1 Nm)
- is **counteracted** by using a portion of the thrust force, tuning a PID controller, where:
  - preliminary **control frequency** is 0.01 Hz
  - **integral term** is able to find and compensate the disturbance torque ✓

/// Thruster force:

- follows the **blow-down** model: decreases with the pressure inside the tanks
- **last burn** lasts around 40 minutes



Programme of the European Union
Cofunded with
17th ESA Workshop on Avionics, Data, Control and Software Systems (ADCSS2023)

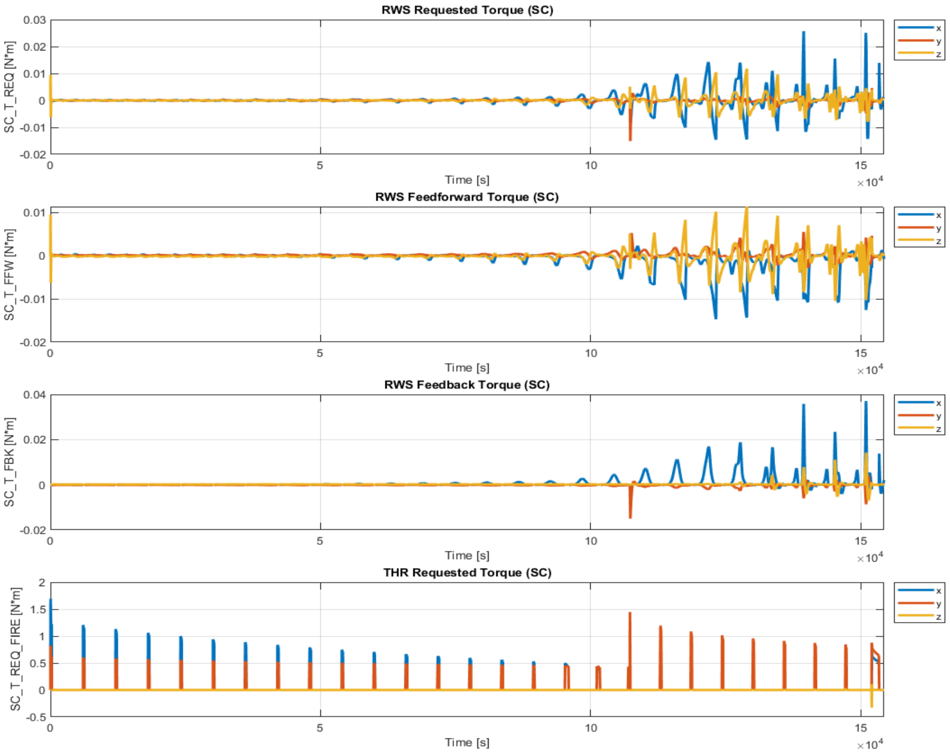
Controlled Re-entry Mode: Final Simulation Results

/// RWS requested torque:

- **feed-forward** contributions:
  - estimated gyroscopic torque
  - estimated gravity gradient torque
  - angular momentum unloading (through MTB)
- **feed-back** contribution:
  - switching function for critical drag management
  - disabled during firing

/// THR requested torque:

- PID attitude control during firing



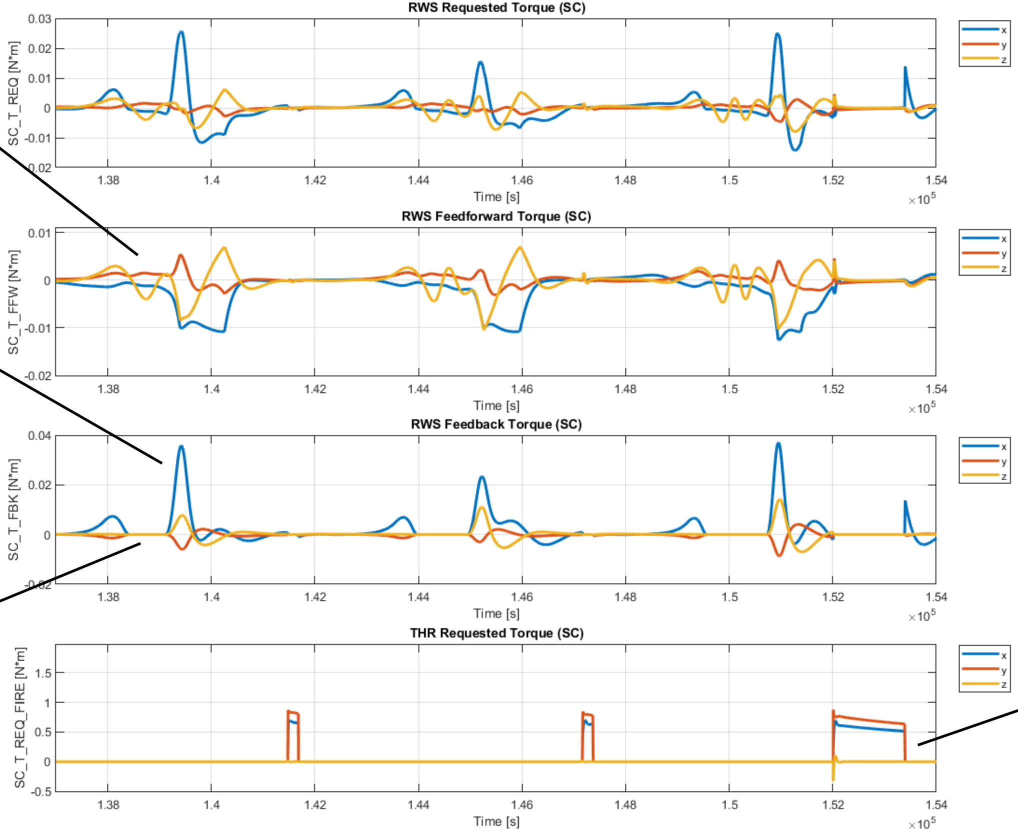
Controlled Re-entry Mode: Final Simulation Results

/// Zoom on last manoeuvres

Switching function is not applied on feed-forward contribution

Attitude recovery after perigee passage and before next firing phase

Switching function during critical drag phases



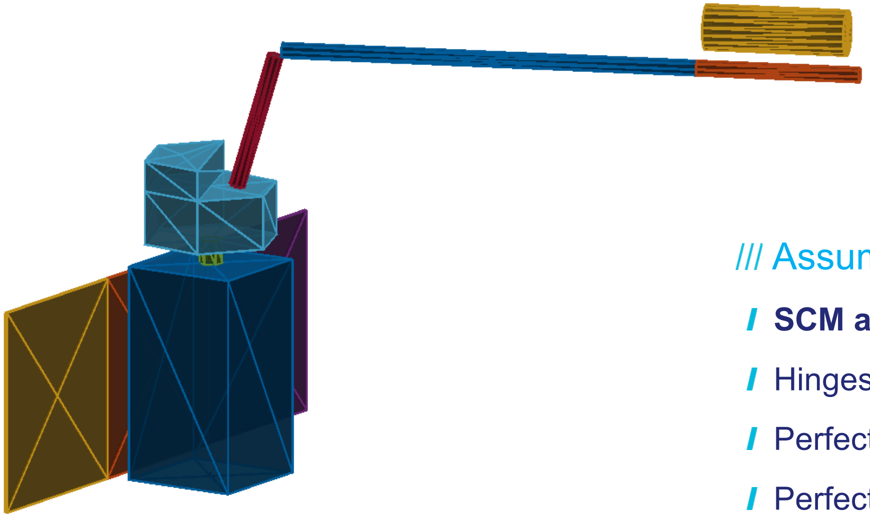
Last Burn

Programme of the European Union
Copernicus Europe's eyes on Earth
Cofunded with esa
17th ESA Workshop on Avionics, Data, Control and Software Systems (ADCSS2023)
ThalesAlenia Space a Thales / Leonardo company

Controlled Re-entry Mode: Deployment Failure

/// Failure during deployment at BOL

- **Worst case scenario** chosen in terms of higher center of mass displacement during the deployment phases
  - boom 2 stuck at 90 deg from stowed position



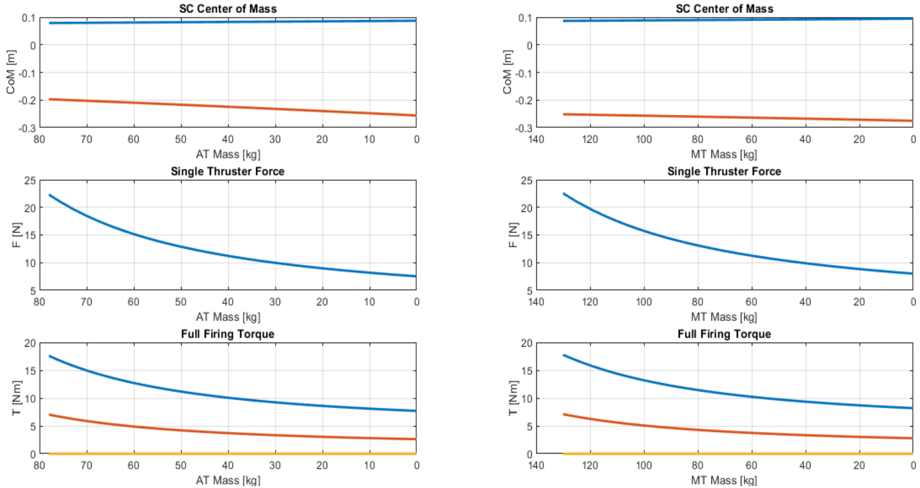
/// Assumptions for this analysis:

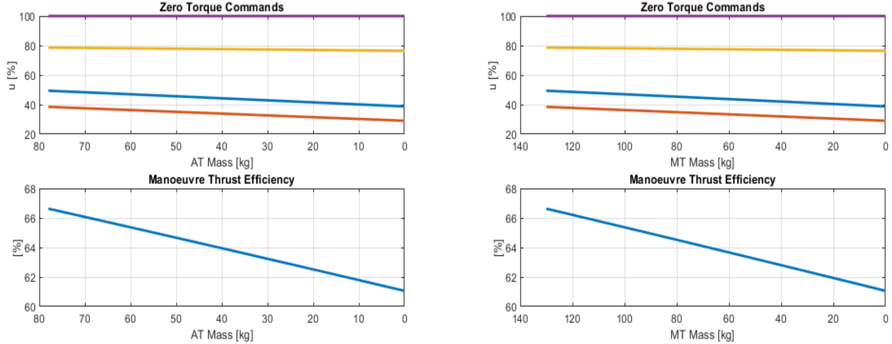
- **SCM angle** equal to zero (stowed default angle)
- Hinges blocked with **infinite stiffness**
- Perfect knowledge of **thrusters** position and orientations
- Perfect knowledge of **center of mass** position

Programme of the European Union
Cofunded with
17th ESA Workshop on Avionics, Data, Control and Software Systems (ADCSS2023)

Controlled Re-entry Mode: Deployment Failure

- **S/C center of mass** position offset (X and Y axis) → 200-300 mm towards –Y axis.
- Single **thruster force** → decreases in accordance with the blow-down model
- Produced **disturbance torque** with THR in a full firing mode → up to 20 Nm on X-axis





- Thrusters **modulation command** → fully compensate the unbalance
- Manoeuver **thrust efficiency** → the ratio between the real applied force and the nominal force

Conclusions: re-entry challenges and solutions

/// Propellant consumption

- To **minimize the propellant mass** → solution: to extend perigee lowering phase
- but attitude control cannot withstand with **high drag torque** → solution: trade-off result is **180 km** as min perigee altitude

/// Drag management

- Disturbance **drag torque** at perigee passages → solution: tuning PID controller using RWS
- Internal **angular momentum** saturation → solution: controller gains' attenuation through a smooth switch function

/// Firing management

- Thrusters **disturbance torque** during firing phase → solution: tuning PID controller using THR

Programme of the European Union
Cofunded with
17th ESA Workshop on Avionics, Data, Control and Software Systems (ADCSS2023)

THANK YOU!