Funded by ESA and EU

CIMR

COPERNICUS IMAGING MICROWAVE RADIOMETER

## 2022 Clean Space Industry Days

# CIMR END-OF-LIFE CONTROLLED RE-ENTRY STRATEGY

OCTOBER 13TH 2022

# CIMR end of life controlled re-entry strategy

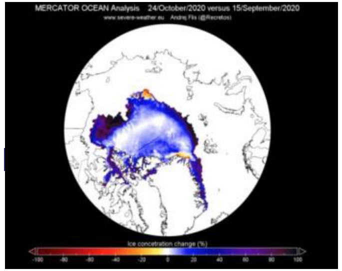
- CIMR introduction
- Cleanspace Driving Requirements
- Re-Entry Strategy
    - Firing Strategy
    - GS coverage
    - Attitude Control Strategy
    - FDIR
- Updated DRAMA Analsys and Reached Compliance
- Active Debris Removal
- Conclusions

# CIMR Overview: Mission

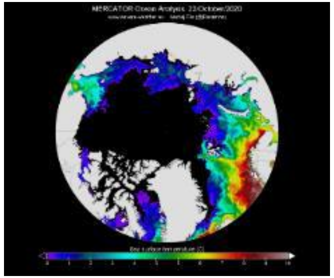
/// **C**opernicus **I**maging **M**icrowave **R**adiometer will carry a wide-swath conically-scanning multi-frequency microwave radiometer to provide observations of **:**

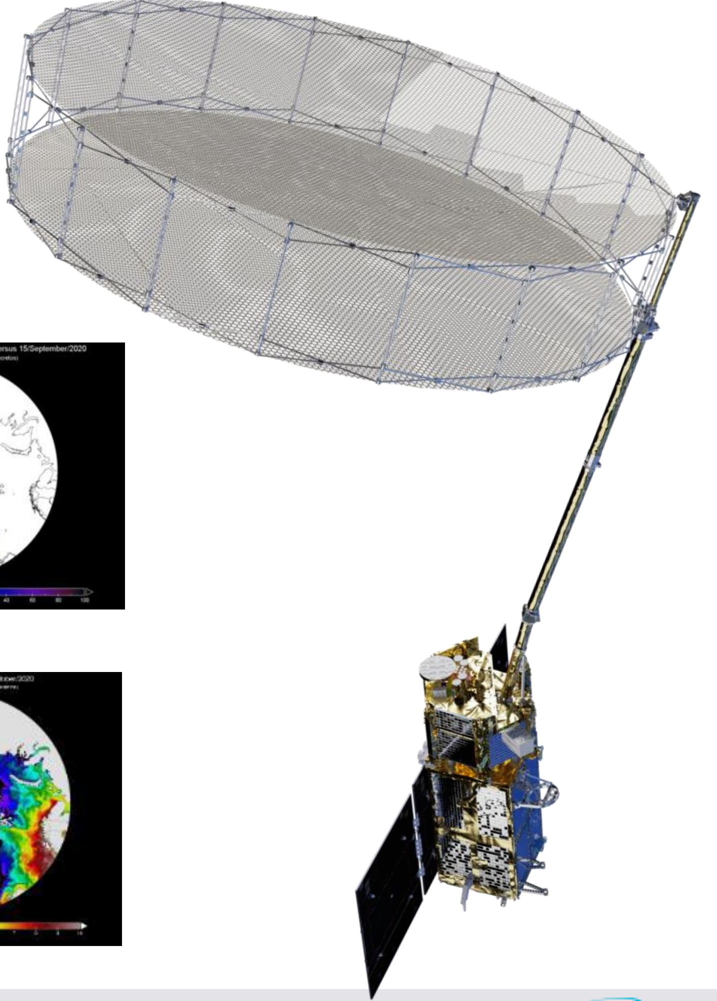
- **Sea Ice Concentration/Extension –SIC/SIE**
  (+ Sea Ice Thickness/Drift/Type …)
- **Sea Surface Temperature –SST**
  (+ Sea Surface Salinity, …)
- … plus many other variables (Soil Moisture, Thin Sea Ice, Sea
  Ice Surface Temperature, Snow Depth on Sea Ice, Sea Surface
  Speed over Ocean…)

SIC/SIE




SST





/// CIMR Space Segment consists **:**

- PFM
- FM2
- FM3 (optional)

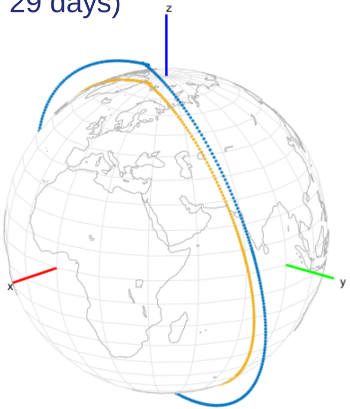


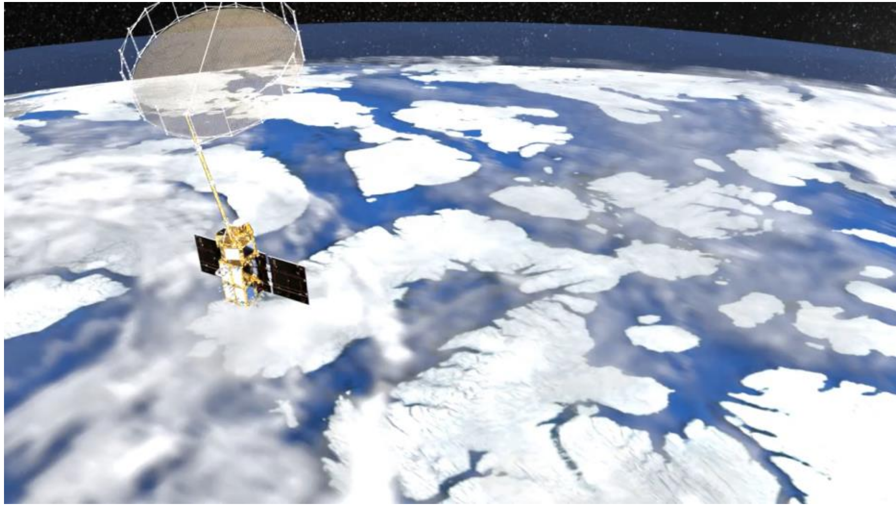
**Ref:** CIRR-HO-TAI-PM-0012 – PART 4
**Template:** 83230347-DOC-TAS-EN-008

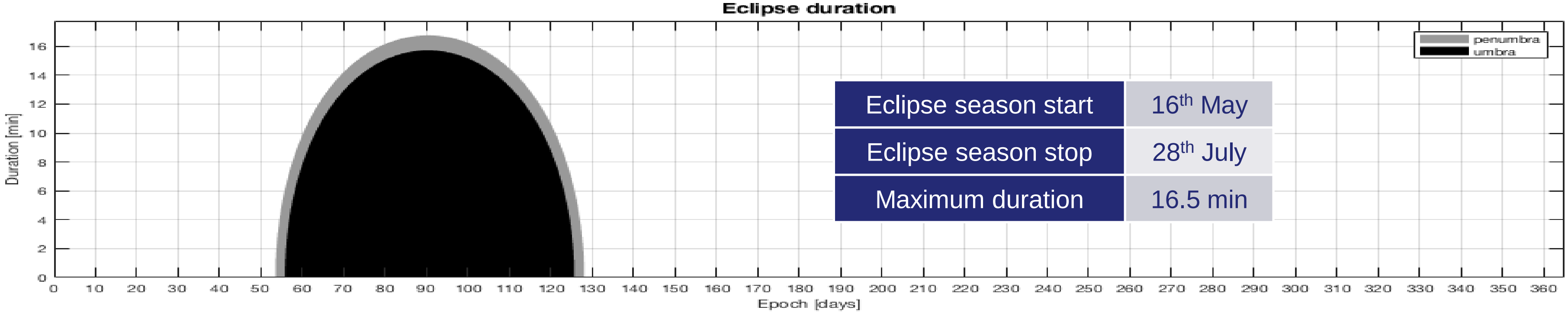
# CIMR Overview: Operational Orbit

- SSO dawn/dusk
- Frozen
- Repetitive ground track (Repeat cycle = 29 days)

| | Nominal Orbit |
|---|---|
| Semi-major axis | 7195.605 km |
| Eccentricity | 0.001141 |
| Inclination | 98.7021° |
| Argument of Perigee | 90° |
| Mean LTAN | 18:10:00 |






| | |
|---|---|
| Eclipse season start | 16th May |
| Eclipse season stop | 28th July |
| Maximum duration | 16.5 min |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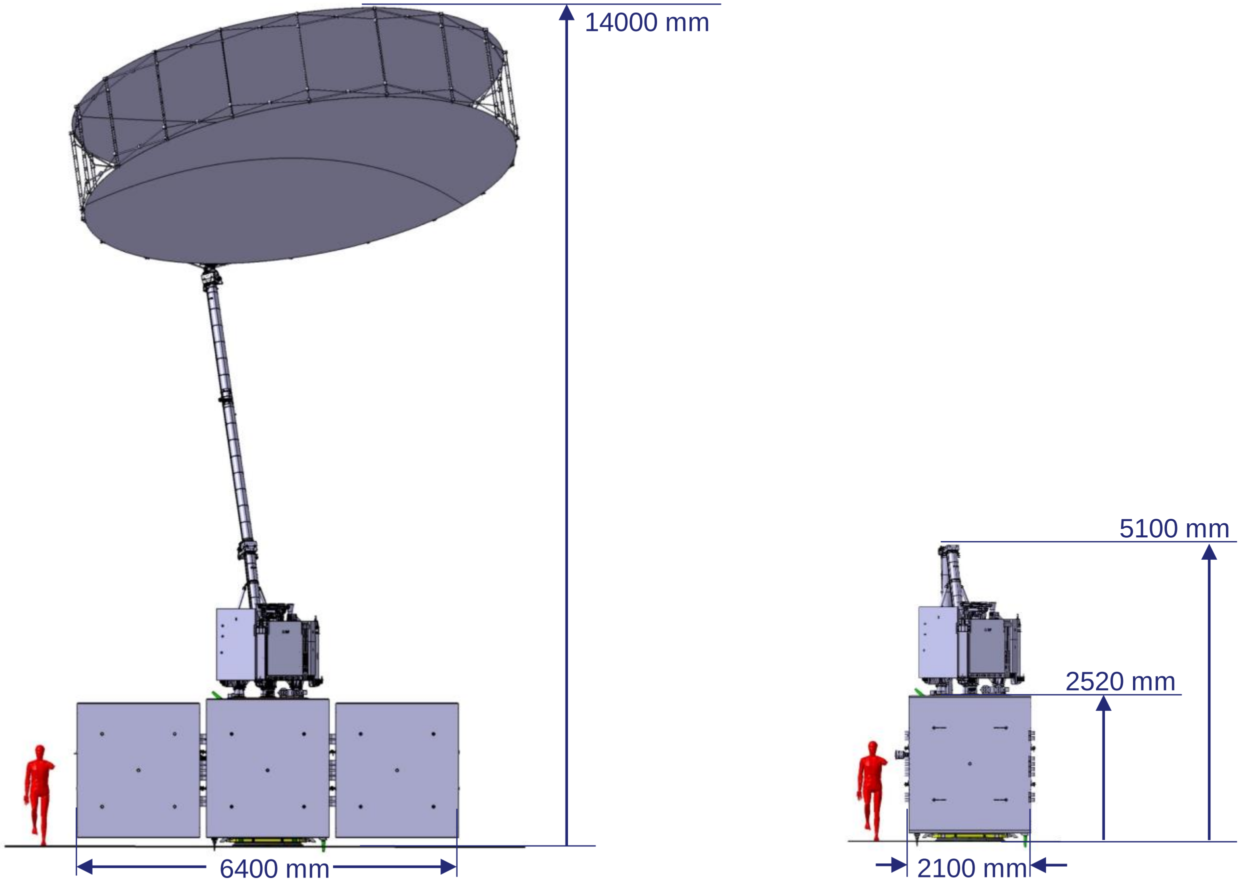
# CIMR Overview: S/C Configuration



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# Space Debris Compliance - Driving Req.'s

- CIMR Satellite design complies to Space Debris Mitigation Requirements (ISO 24113 – 2019).
- The compliance is achieved by implementing several design choices regarding:
  - Electrical passivation
  - Propulsion system capabilities to enable controlled re-entry at EoL
  - Reliability of involved S/Ss to guarantee successful disposal at EoL
  - Implementation of dedicated AOCS modes for re-entry
- and demonstrated by means of the following analyses:
  - Casualty risk analysis for Uncontrolled re-entry
  - Controlled re-entry study
  - Debris and meteoroids impact analysis

# Space Debris Compliance – Casualty Risk Analisys

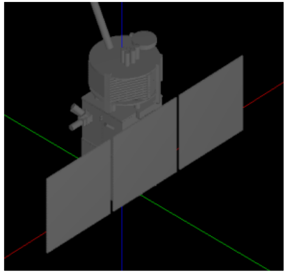
## ///Uncontrolled Casualty Risk Analysis

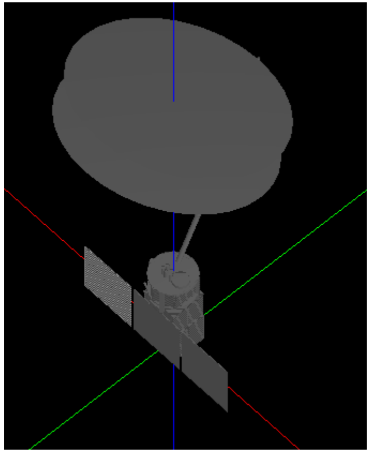
- The casualty risk analysis for CIMR has been performed using DRAMA version 3.0.4

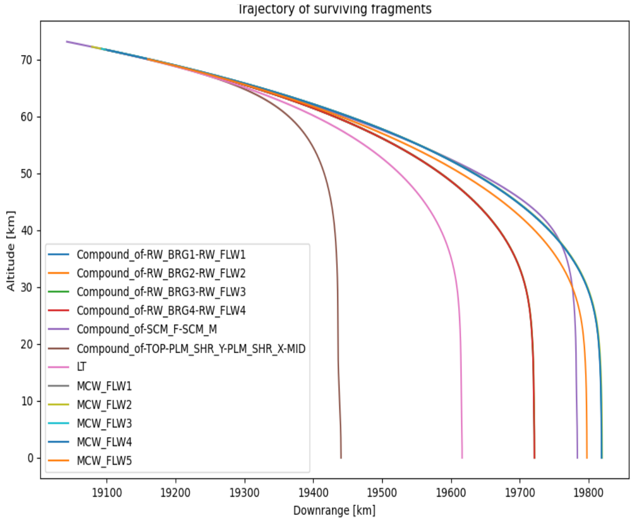
- 12 fragments survive re-entry with a casualty area ~ 16m$^2$.:
  - Steel parts for RW and MCW (bearing and flywheel)
  - The titanium propellant tank
  - Some parts CFRP parts of the structure
  - Aluminum made parts of the  Scan Mechanism

- Assuming a re-entry in 2060 for FM 2 resulting casualty risk is 2.412 e-4 > 1 e-4

- → **need for controlled re-entry**







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# Space Debris Compliance – General Strategy

Perigee Altitude

824 km

**Re-entry High Altitude Phase :**

Short and efficient firing at apogees for perigee lowering

Nominal AOC mode for attitude control

Nominal FDIR

250 km

**Re-entry Medium Altitude Phase :**

Short and efficient firing at apogees for perigee lowering

Specific AOC mode for attitude control (THRUST_REM)

Specific FDIR 1 (relaxed thresholds) *

180 km

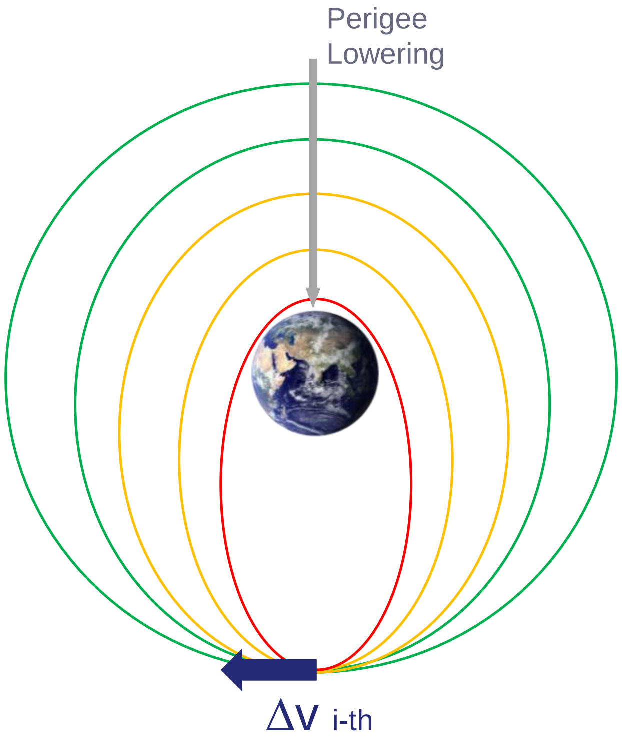
**Re-entry Low Altitude Phase :**

Long Last Burn for South Pacific Ocean Unhabited Area splasdown

Specific AOC mode for attitude control (THRUST_REM)

Specific FDIR 2 (online M → R swap, no SW restart, no HW FDIR) *

50 km



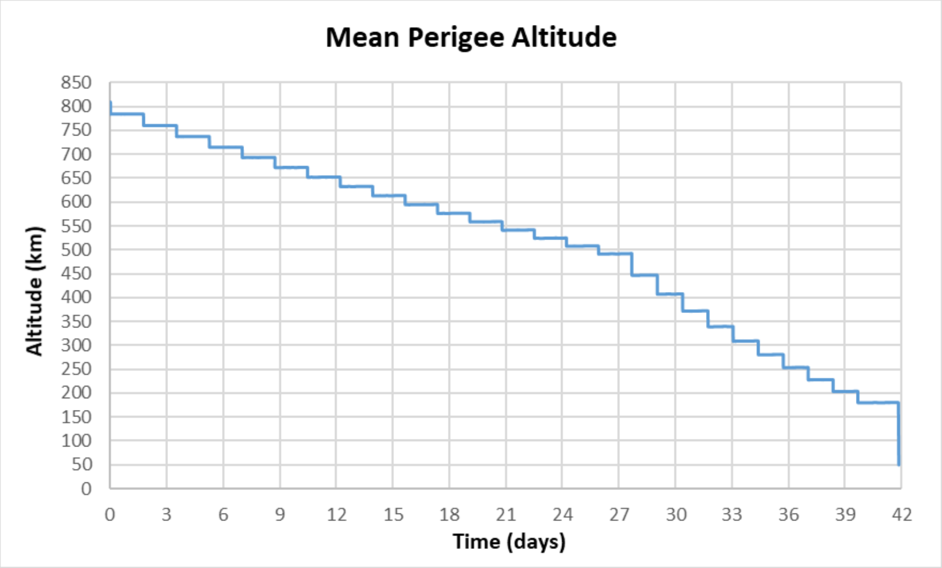

** purpose is to have a more and more failure tolerant S/C with the lowring of the perigee*

# Space Debris Compliance – Firing Strategy

- Firing strategy defined with the following driving requirements
  - Propellant budget minimization
  - Minimization of single firing duration for efficiency
  - Minimization of entire phase
  - South Pacific Ocean Unhabited Area

**Firing Strategy**

- Burns 1 to 26:
  - Duration = ~5 min each @apogee
  - Final perigee altitude = 180 km
- Last burn:
  - Duration = 37.5 min
  - Final perigee altitude = 50 km



# Space Debris Compliance – Firing Strategy: Last Burn

## Last Burn Initial Orbit

- Mean Perigee Altitude = 180 km
- Mean Apogee Altitude = 798 km
- Orbital Period = 94.4 min

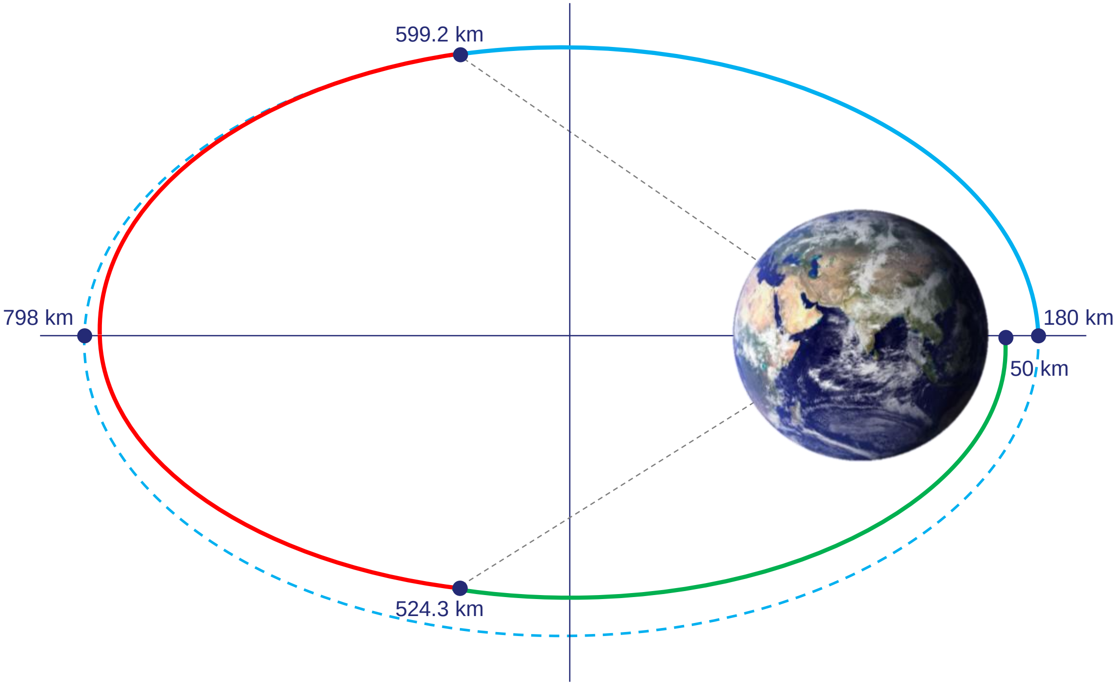
## Last Burn Firing Arc

- Burn duration = 37.5 min

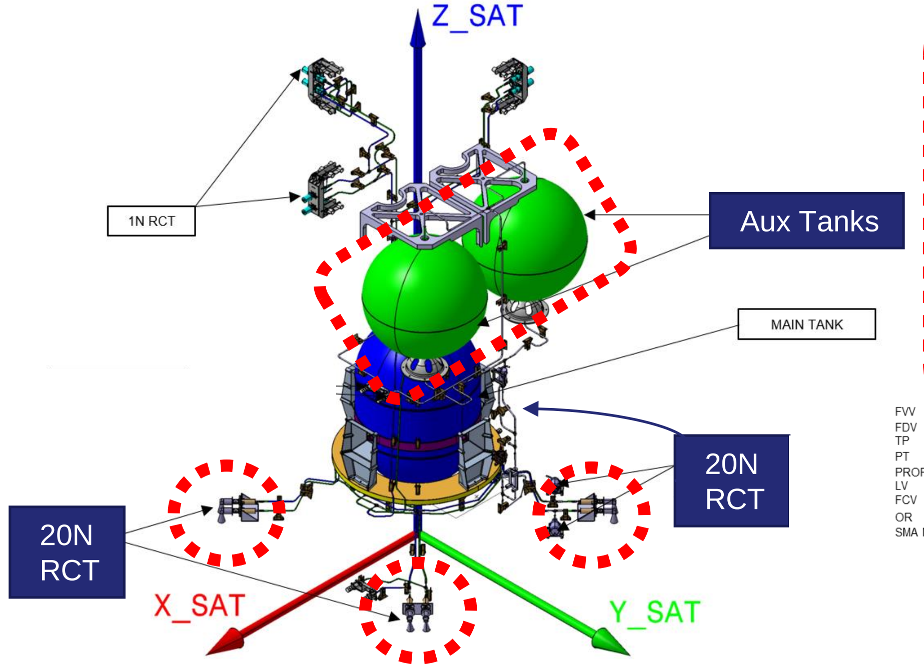
  → less than half orbit

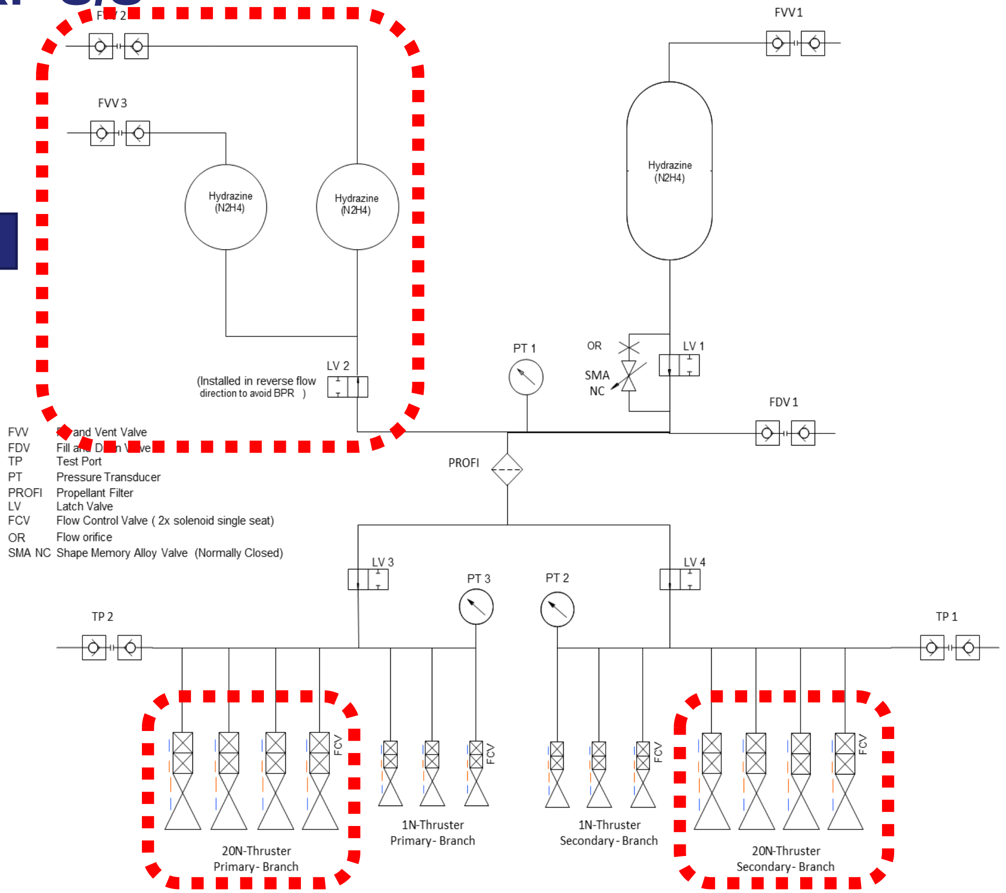
## Final Coasting Arc

- Duration = 33.6 min



# Space Debris Compliance – PRP S/S



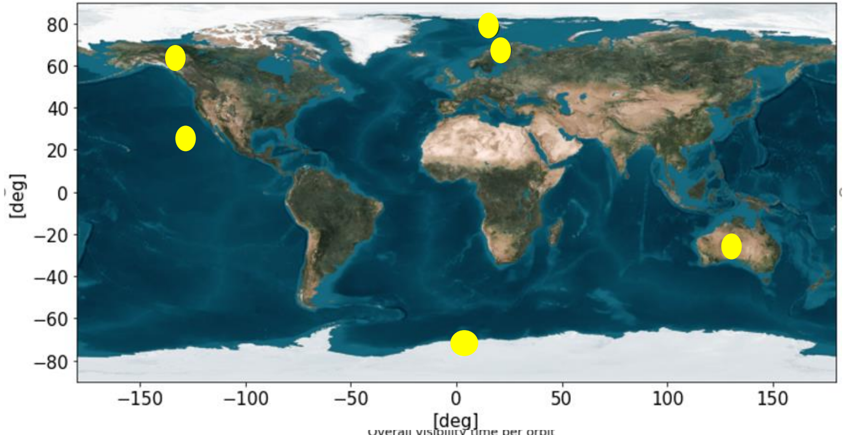




Propellant budget for re-entry **201Kg**:

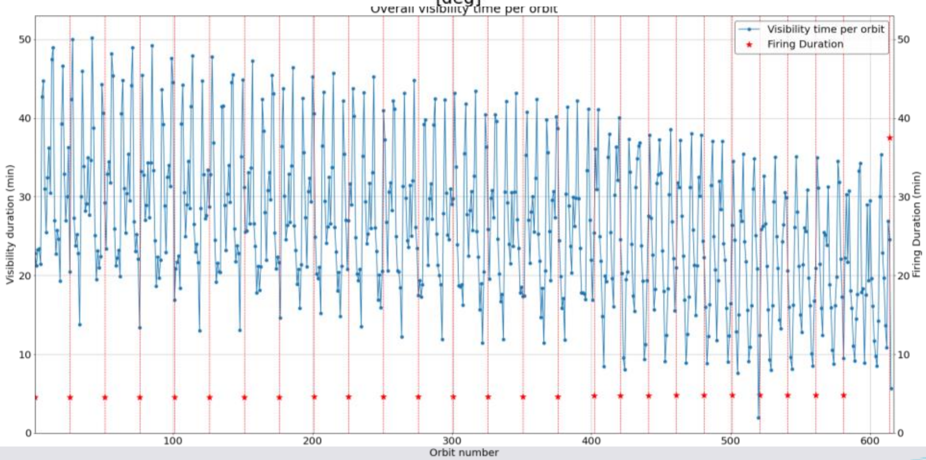
- Perigee lowering - 161Kg
- Final Burn: 40Kg

# Space Debris Compliance - GS Coverage: visibility timeline

- Ground Stations Network:
  - Kiruna
  - Svalbard
  - North Pole (USAK01)
  - Troll
  - Australia (AUWA01)
  - Hawaii (USHI01)




- Firing strategy:
  - Firing #1 to #26
    - Interval between firings: **1.6** days average
    - Firing duration: **4.7** min on average
  - Firing #27
    - Interval between firings: **2.2** days
    - Firing duration: **37.5** mins



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# Space Debris Compliance - GS Coverage: Last Burn Visbility

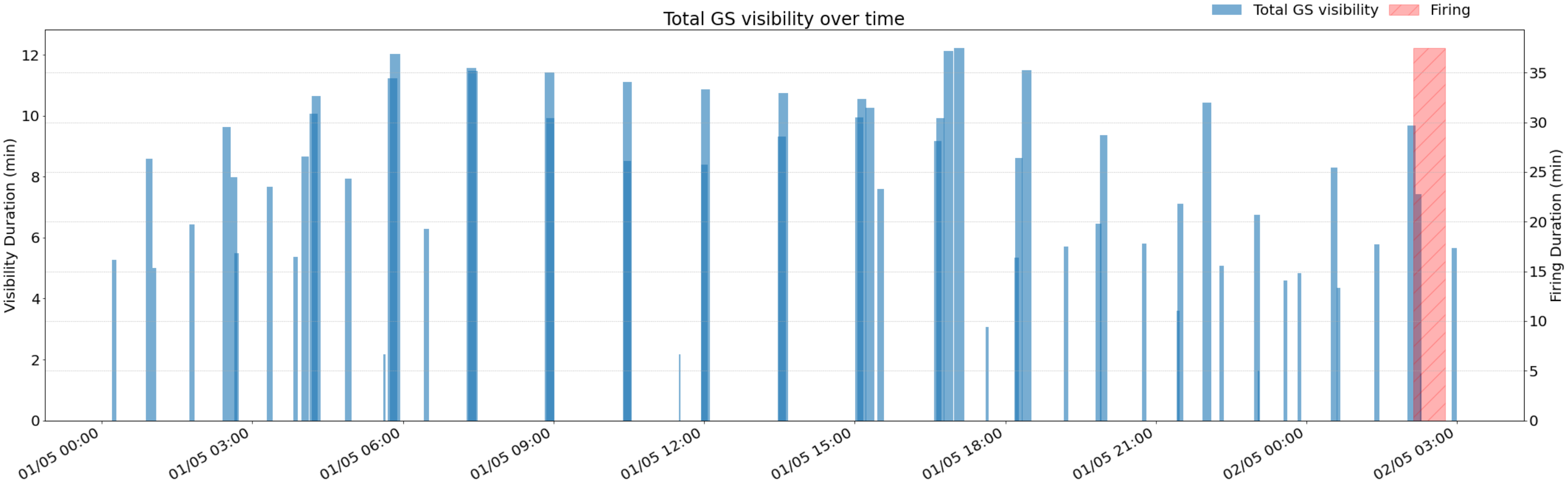
## LAST BURN

### /// GS total visibility time and overlaps during 27th firing

- Firing duration: **37.49** min.
- **10 minutes** of total GS visibility during last burn

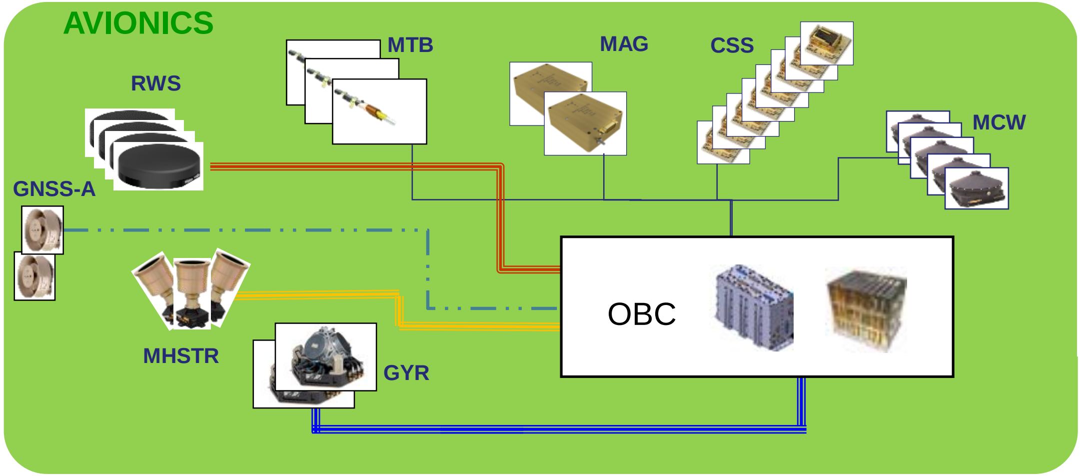
| Firing | Start Time (UTCG) | Stop Time (UTCG) |
|---|---|---|
| 27 | 2/5/27 2.07 | 2/5/27 2.45 |

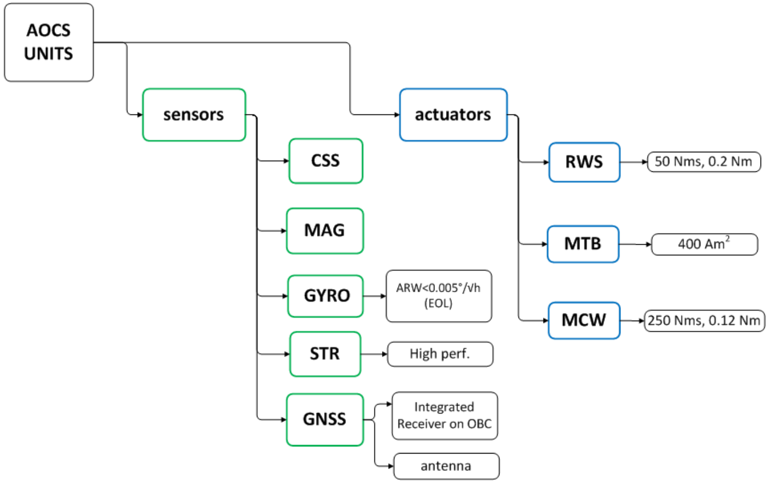
| Ground Station | Access Start (UTCG) | Access End (UTCG) |
|---|---|---|
| North Pole | 2/5/27 2.00 | 2/5/27 2.10 |
| Svalbard | 2/5/27 2.10 | 2/5/27 2.17 |
| Kiruna | 2/5/27 2.15 | 2/5/27 2.17 |



# Space Debris Compliance – Avionic Subsystem Architecture

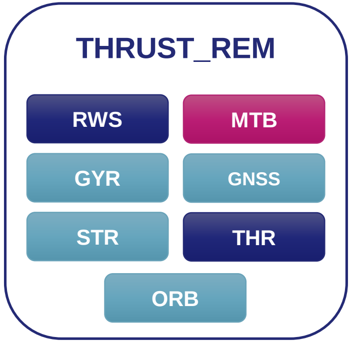
## Avionics S/S HW Architecture

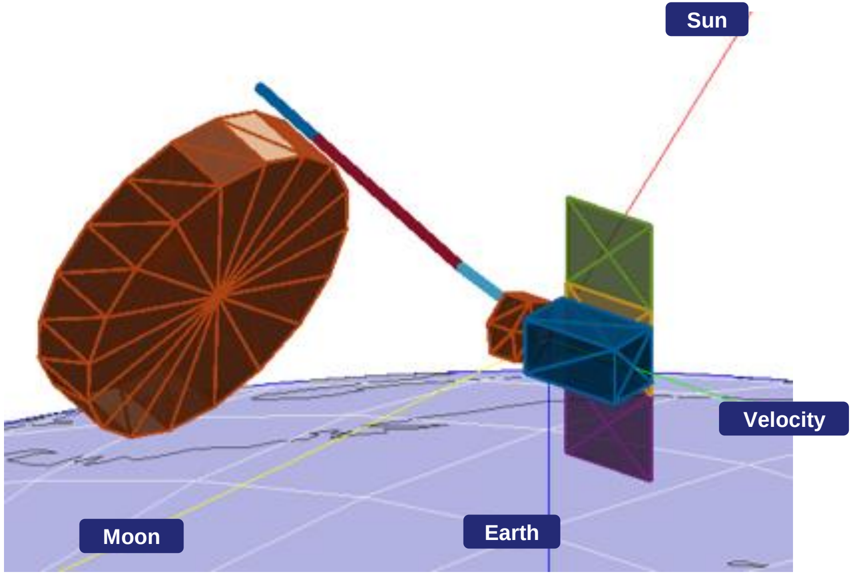


# Space Debris Compliance – AOCS Strategy

- **THRUST_REM** Specific AOCS mode defined for re-entry phase, driven by
  - Robust attitude control capability also against high drag phases
  - Maneuvering capability
  - 20N thrusters commanding and off-modulation (due to the S/C CoG offset)
- During the re-entry phase
  - instrument rotation is stopped to a controlled and given angular position in order to minimize the atmospheric drag effects
  - Nominal attitude is tilted 90deg in pitch in order to get the 20N RCTs firing directions against the orbital velocity still getting the same sun illumination
- Active HW for the mode
  - Reaction Wheels
  - Magnetorquer
  - GNSS Receiver
  - Star Tracker
  - Gyroscope
  - Thrusters

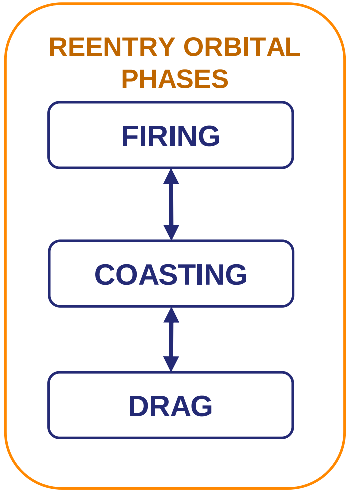


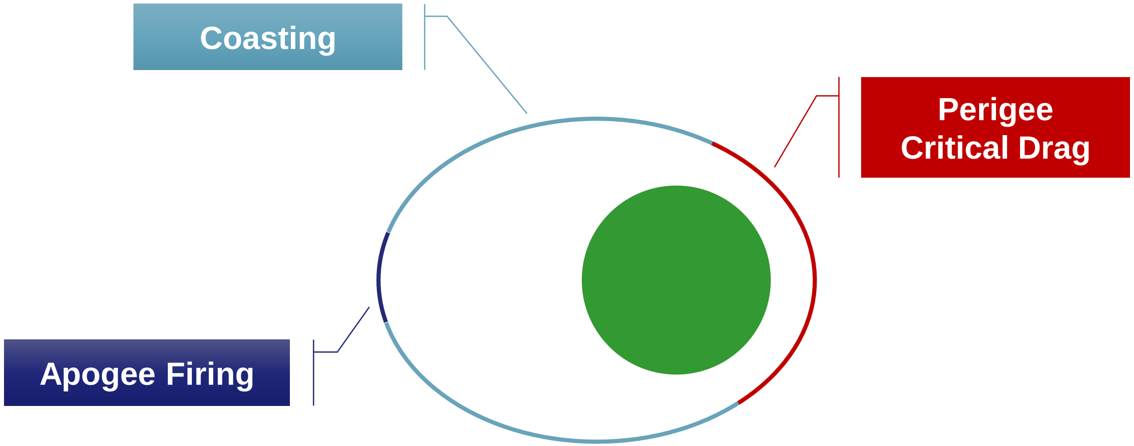



# Space Debris Compliance – AOCS Strategy

## /// AOCS acknowledges 4 sub-phase during the re-entry

- **SLEW** phase: attitude maneuver to reach the firing pointing (-90 deg pitch)
- **CRUISE** phase: maintains the target attitude during the coasting trajectory
- **FIRE** phase: performs high delta-v maneuvers by using the 20N thrusters with an off-modulation strategy to slow down orbit inertial velocity minimizing torque disturbances
- **DRAG** phase: handles the high drag torque that the spacecraft will sustain at lower altitude





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# Space Debris Compliance – AOCS Strategy: High Drag phase control

The most demanding requirement for AOCS is the robustness against the high drag phase, occuring at low perigee passing

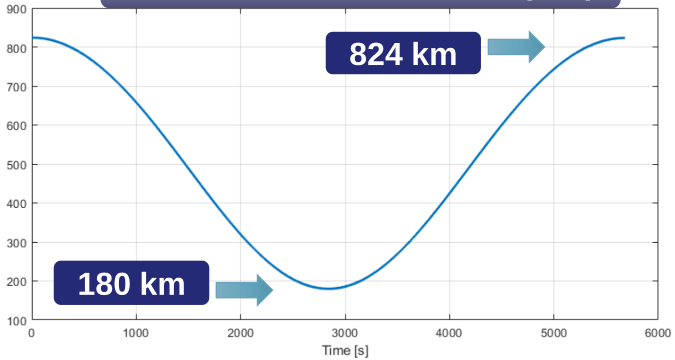
## /// Overview

- During reentry, when perigee becomes lower than 210 km, the **drag torque disturbance** is no longer sustainable by AOCS actuators (with nominal control performances)
- Mission analysis needs to reach a perigee of 180 km for maneuvers **delta-v optimization**
- During coasting AOCS does not have **pointing accuracy requirements** of nominal mission phase (payload is off)

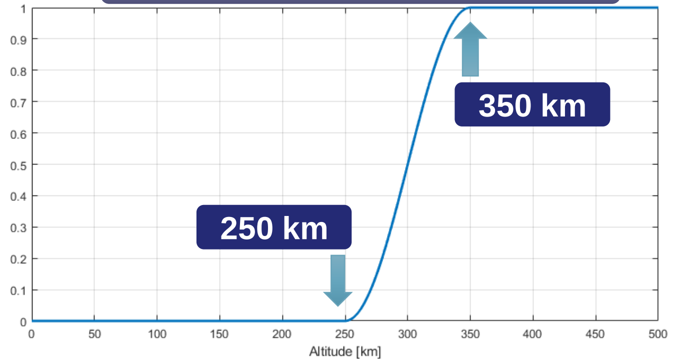
## /// Strategy

- The **feed-back gains of attitude controller** are attenuated through a smooth switching function (using altitude as argument) to avoid reaction wheels angular momentum saturation
- The same switch is implemented at the exit of drag phase, coming back to reentry nominal control law, **recovering attitude error** in time for the next firing phase

Last Orbit Altitude Profile (WC)




Switch Coefficient Function



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# Space Debris Compliance - Casualty Risk Analysis: Compliance

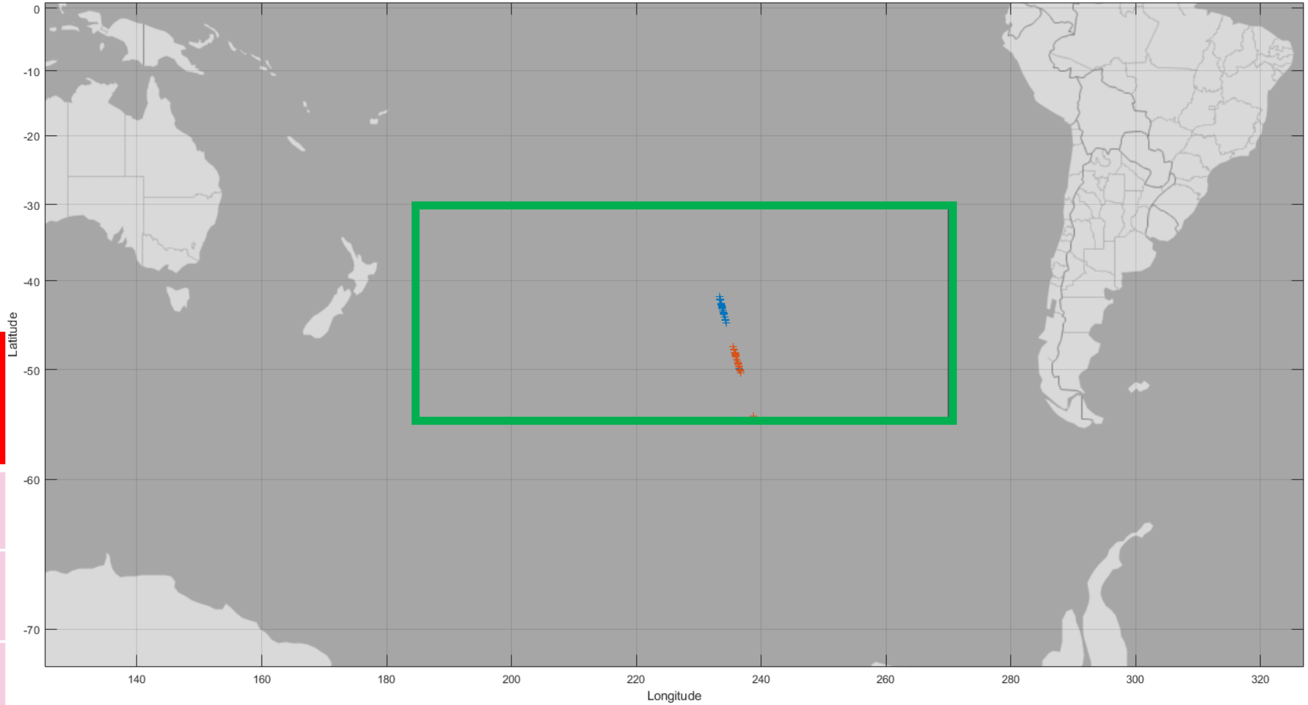
**Compliance:** The resulting splashdown in the South Pacific Ocean Unhabited Area.

Two **extremal** cases have been studied, as they are considered worst cases:

**Case 1**: thrusters under performing, minimal Solar activity and drag;

**Case 2**: thrusters over performance, maximal Solar activity and high drag.

| | Case 1 (blue marks) | Case 2 (red marks) |
|---|---|---|
| **Thrust Magnitude** | -5% wrt nominal | +5% wrt nominal |
| **Solar Activity** | 120 | 180 |
| **Drag Coefficient** | 2.2 | 3 |



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# Space Debris Compliance - Active Debris Removal Compatibility

- **Active Debris Removal (ADR)** vehicle mission's objective is to perform the de-orbiting of Client satellite after its end-of-mission
- There are two different scenarios were a removal service may be required:
  - Uncooperative – whereby the satellite is non-operational (either completely or with respect to attitude control) and tumbling.
  - Cooperative – whereby the satellite is operational but unable to perform the end-of-life functions with respect to removal from orbit.

## 2D Navigation Aids

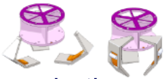
ground-tracking and attitude reconstruction based on Laser Retro-Reflectors corner cubes

for rendezvous, with signature on visual and infrared wavelength, to improve pose and attitude determination from 50 m down to 5 m distance

## 3D Navigation Aids

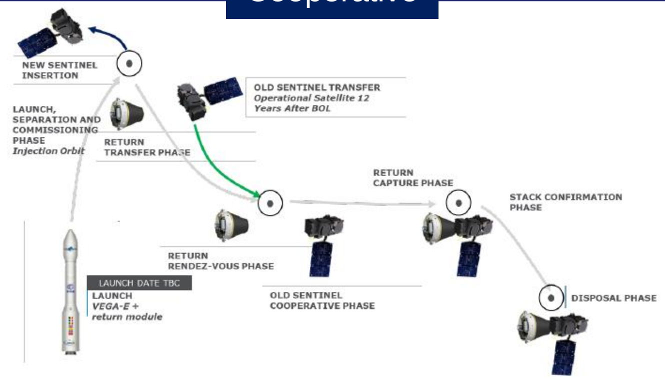
for rendezvous, with signature in visual, to improve pose and attitude determination from 5 m down to 0 m distance

## Mechanical Capture I/F

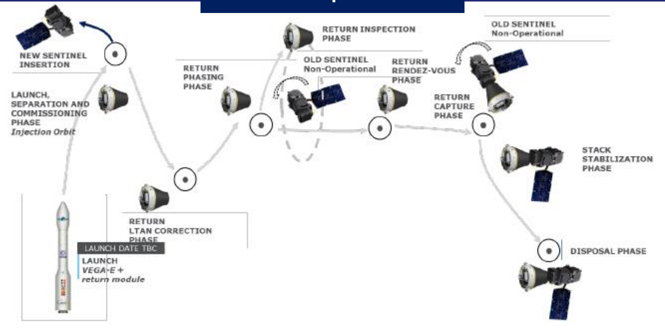


Passive metallic part mounted on Spacecraft's structure to allow its capture with a robotic gripper before rigidization of the compound Spacecraft and removal vehicle.

## Cooperative




## Un-Cooperative



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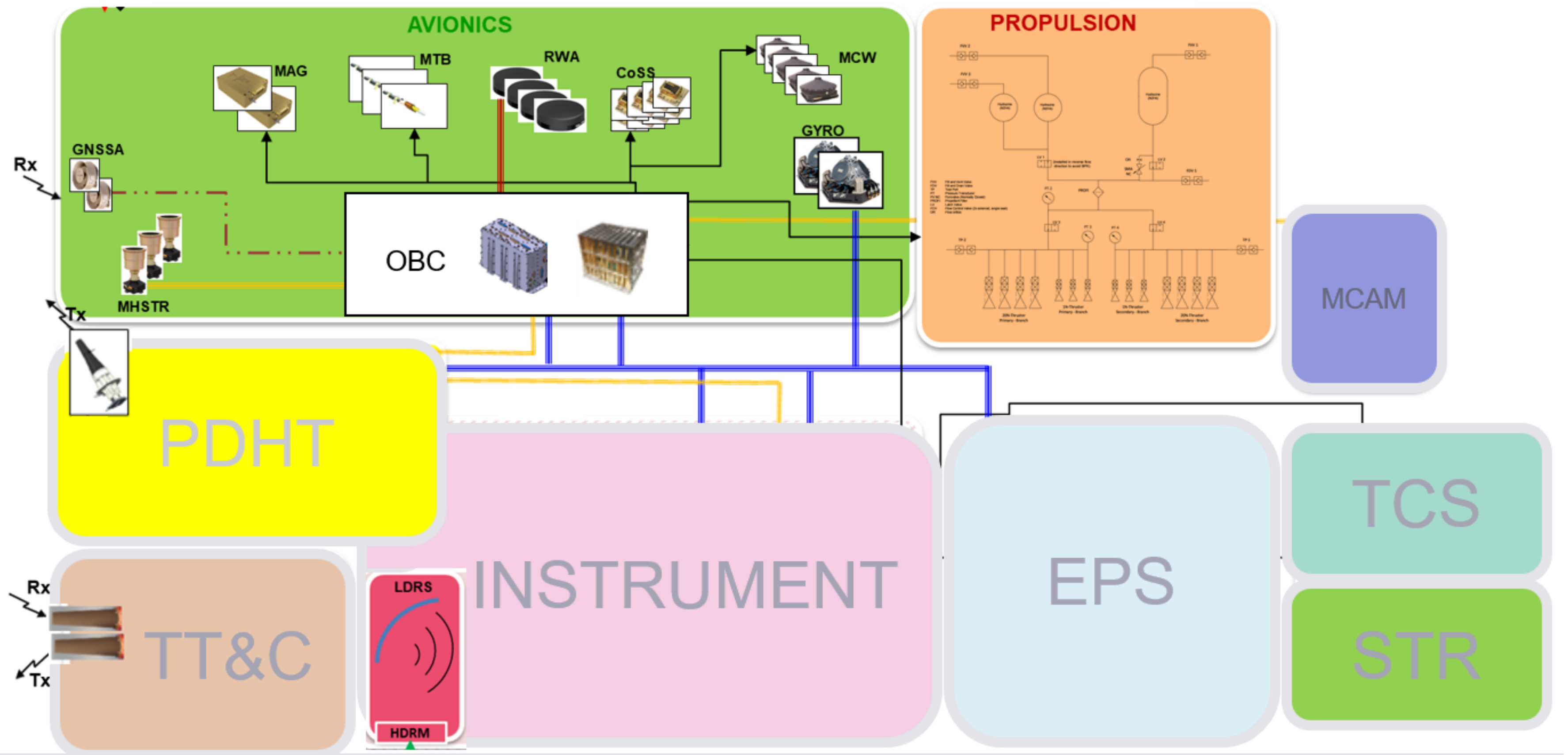
# Space Debris Compliance - Conclusions

- Un-controlled re-entry showed non-compliances wrt casualty risk analysis
- Proper strategy has been designed for a compliant controlled re-entry
  - Dedicated design for propulsion sub-system
  - Dedicated AOCS modes and strategy for the re-entry phase
  - Dedicated FDIR
- CIMR Project is currently facing the PDR:
  - design maturity is according to the actual project phase.
  - General consolidation of design and verification is expected for the next project phase
- Despite the capability of controlled re-entry, CIMR is also compliant with the de-orbiting performed by the Active Debris Removal as requested by ESA, both in a cooperative and un-cooperative scenarios

# CIMR end of life controlled re-entry strategy

Questions ?

# CIMR Overview: Satellite Architecture



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# Space Debris Compliance – PRP S/S

///Four 20 N thrusters are used during the controlled re-entry phase:

- Thrust = 24.5 N @ 24 bar
  7.8 N @ 5.5 bar
- Specific Impulse = 231 sec @ 24 bar
  223 sec @ 5.5 bar

///Propellant used for perigee lowering up to 180 km = 161 kg

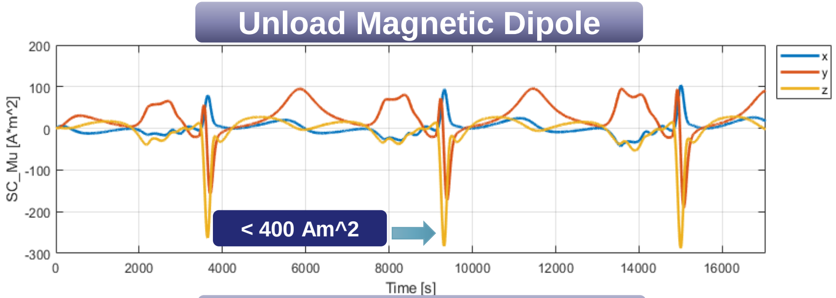
///Propellant used for last burn = 40 kg

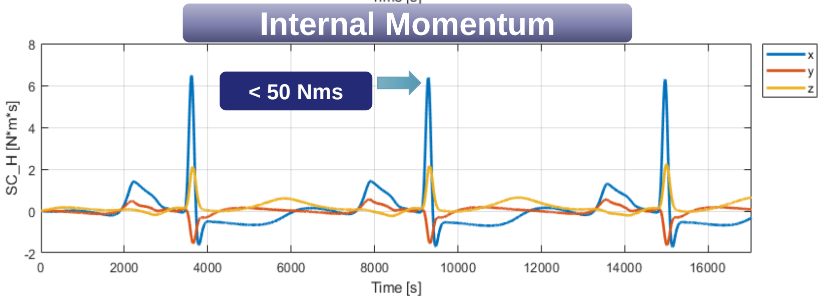
→ Total propellant needed for re-entry = **201 kg**

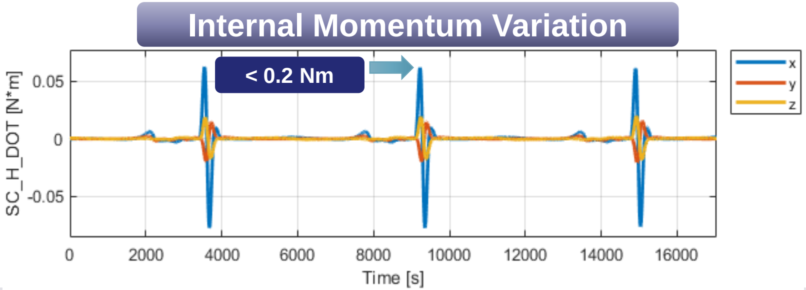
# Space Debris Compliance – AOCS Strategy: High Drag phase control

## /// Verification: RW

- The **internal angular momentum** is always inside the RWS envelope at the worst case (one RW in failure)
- **Torque Authority** granted
- The **peak** corresponds to the attitude recovery at the exit of Drag Phase (when controller see a high error)
- During the Drag Phase the **unloading** of RWS continues to be performed through MTB magnetic dipole and feed-forward contribute of control request



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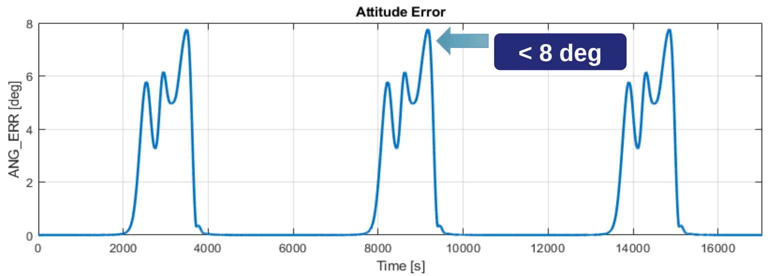
# Space Debris Compliance – AOCS Strategy: High Drag phase control

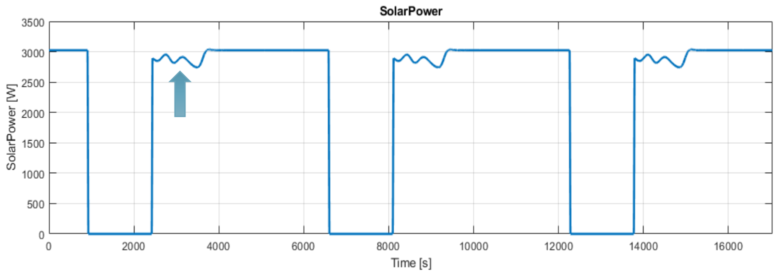
## /// Verification: Platform Dynamic Stability

- During Drag Phase relaxation of the attitude pointing **error requirement** is needed in order to limit the usage of the RW
- Simulation shows a **maximum error** of about 8 degrees (with respect to the nominal reference attitude)




## /// Verification: Solar Power

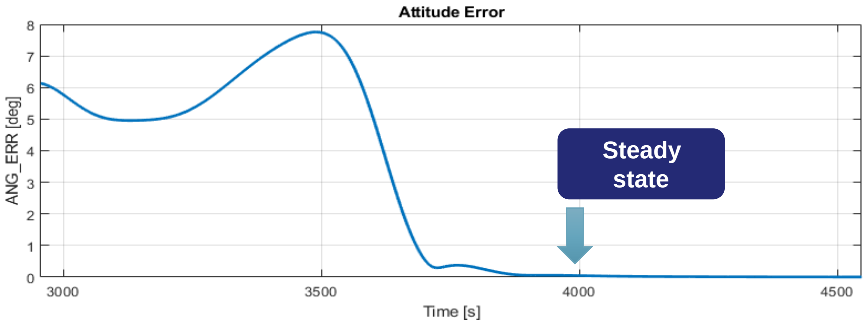
- **electrical power** supply provided by the solar panels in a worst case scenario of summer solstice (i.e. eclipse for CIMR)
- The **off-nominal behavior** negligible (payload OFF)

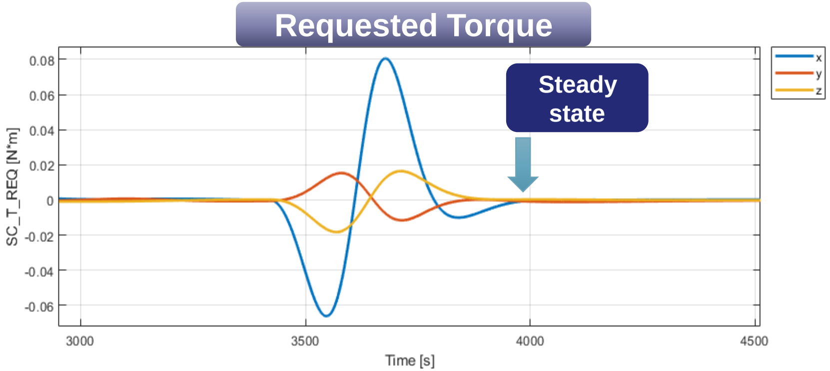


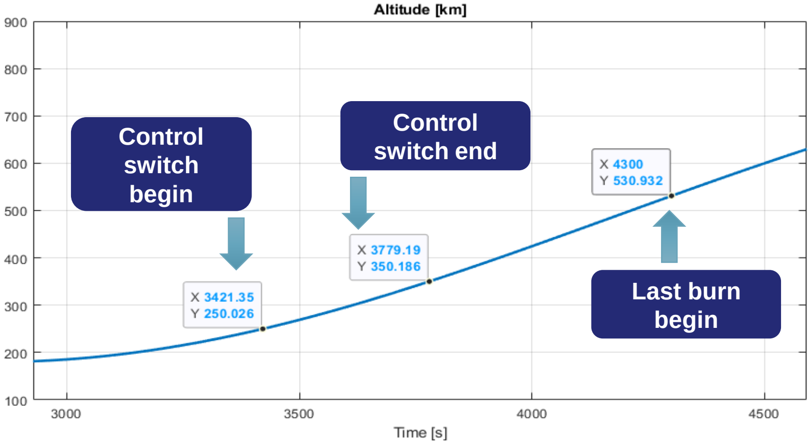
# Space Debris Compliance – AOCS Strategy: High Drag phase control

## /// Verification: Control Transient Time

- **Steady state** status achieving after control gain switching is achieved before each next burn ignition
- Last Burn is worst case due to its longest duration
  For last orbit we have:
  - Gains relaxation @perigee lasts from 3421s  to 3779s
  - Steady state is achieved @4000s
  - Last burn starts @4300s



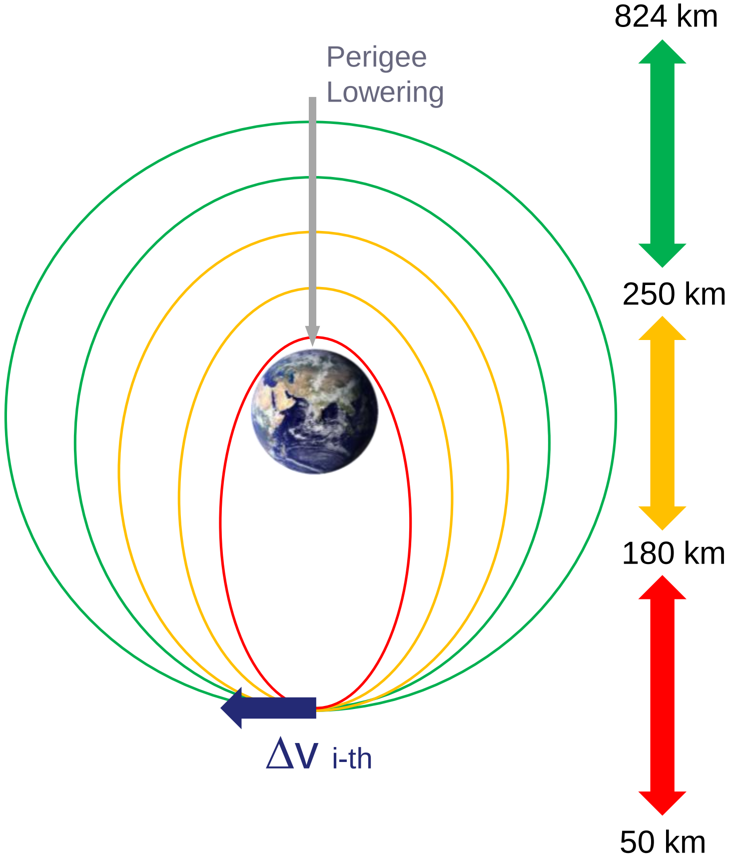
# Space Debris Compliance – FDIR

- General idea is to have a more and more failure tolerant S/C with the perigee lowering → FDIR relaxation

- Re-Entry_High Altitude Phase
  - Nominal FDIR

- Re-Entry_Medium Altitude Phase
  - Same FDIR strategy as nominal mission but with lowered thresholds for attitude and rate error (according to THRUST_REM mode)

- Re-Entry_Low Altitude Phase
  - For the final burn, many FDIR monitorings will be disabled:
    - No SW restart in case of AOCS unit failure: online M → R swap
    - Propagation of last navigation and attitude data in case of failure
    - All hardware FDIR will be disabled (except for SW crash recovery)
  - Only parameter to be monitored during last burn is S/C attitude. In case of tumbling recovery actions in case are TBC
    - Transition to safe mode
    - Temporary firing stop untill attitude is recovered



# Space Debris Compliance - Casualty Risk Analysis: Compliance

- Risk analysis for controlled re-entry has been updated considering the uncertainty over delta-V estimation, Solar activity, and drag coefficient.
- Errors on the estimated delta-V that have been considered for the analysis are:
  - Uncertainties on the thrust magnitude because of over or under performances
  - Non-null pitch angle for thrust direction because of errors on the mounting of the thrusters (considered misalignment = ± 0.2 deg.).
- A comparison has been done between the minimum thrust and the average thrust at EoL. It results that the minimum thrust is 4% smaller than the nominal, and therefore, in order to consider under and over performance at EoL, a ±5% variability with respect to nominal thrust has been considered.
- The effect of a ± 0.2 deg. pitch angle is very small and it is considered negligible.
- Solar activity values of 120 and 180 sfu have been used, considering a variation of ±20% over the nominal value of 150 sfu.
- For atmospheric drag values of 2.2 and 3 have been considered.

# Space Debris Compliance - Casualty Risk Analysis: Compliance

- Two **extremal** cases have been studied, as they are considered worst cases:
  - Case 1: thrusters under performing, minimal Solar activity and drag;
  - Case 2: thrusters over performance, maximal Solar activity and high drag.

| | Case 1 | Case 2 |
|---|---|---|
| Semi-major axis [km] | 6782.23 | 6775.37 |
| Eccentricity | 0.05136 | 0.05215 |
| Inclination [deg] | 98.799 | 98.799 |
| RAAN [deg] | 138.502 | 138.502 |
| Argument of perigee [deg] | 306.617 | 306.607 |
| True anomaly [deg] | 328.875 | 326.636 |

- The DRAMA model employed in the simulation is the same used for uncontrolled re-entry, but all the temperature triggers have been removed from the connections. This results in a more conservative case with about 40 surviving fragments.


Ref: CIRR-HO-TAI-PM-0012 – PART 4
Template: 83230347-DOC-TAS-EN-008

# Space Debris Compliance - ADR: I/F Compatibility