AEOLUS assisted re-entry

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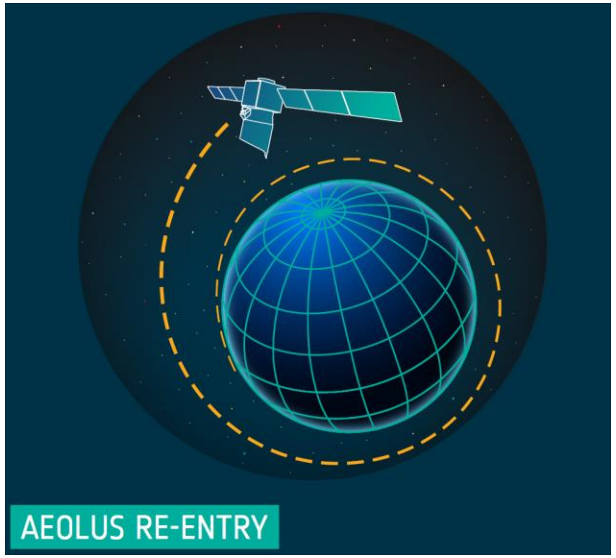


1. Introduction

Objectives

- Follow the best effort obligation to minimise the global casualty risk associated to a re-entry below the currently applicable threshold of 1/10000[1].
- Use the remaining fuel to deorbit the satellite and shorten the time spent in the protected LEO region after end of mission.
- Proof of concept of an assisted re-entry for a mission not designed for active re-entry operations.

Implementation

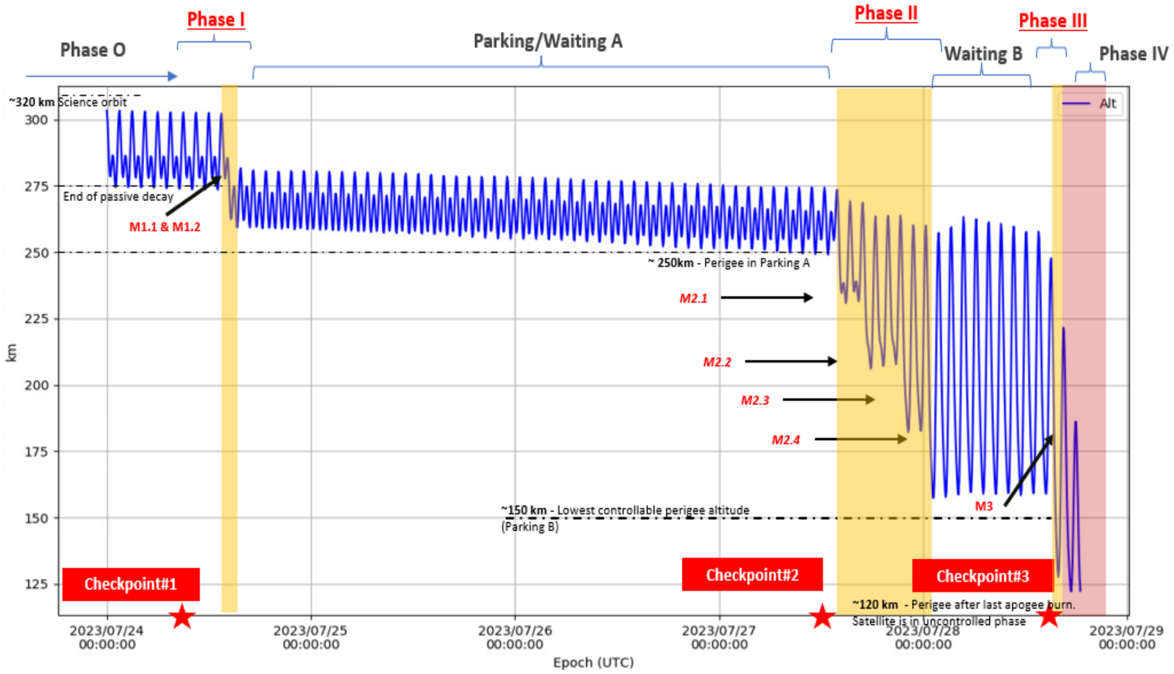
Assisted Natural Re-entry: fills the gap between controlled re-entry and uncontrolled re-entry, requiring a last controlled perigee typically around 150km. The final decay lasts less than a day, so that the associated uncertainty can be less than one orbit, making the decay phase as deterministic as possible. Perigee lowering can be done gradually and it is compatible with low-thrust propulsion.

- Natural decay to an altitude of ~275 km and then a series of retrograde manoeuvres to reduce the perigee to a point where the re-entry can be predicted within one orbit with the target re-entry location along the Atlantic Corridor.

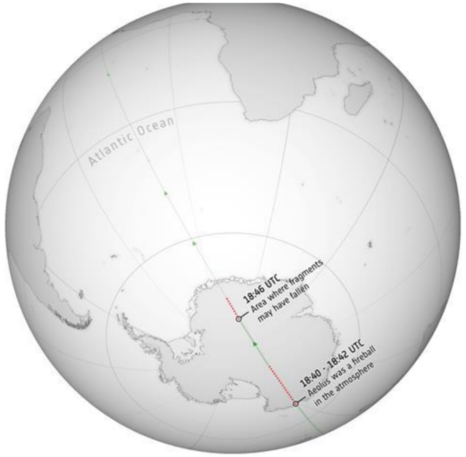
1 As per ESA/ADMIN/IPOL(2014)2. Note that the Aeolus phase B, C/D &E1 contract was kicked-off in 2001 with the Satellite PDR taking place in 2003, i.e., well before the current ESA Admin on Space Debris Mitigation Policy for Agency projects entered into force.

2. Re-entry phases

	Date	Duration	Perigee at start of phase	Total burn time	Manoeuvre	ΔV [m/s]
Phase 0	19/6/2023 - 24/7/2023	35 days	320 km	-	-	-
Phase 1	24/07/2023	11h	275 km	40 min	M1.1	-9
					M1.2	-0.75
Waiting A	24/7/2023 - 27/7/2023	2.5 days	270 km	-	-	-
Phase 2	27/7/2023 - 28/7/2023	18h	250 km	144 min	M2.1	-9.38
					M2.2	-9.38
					M2.3	-9.38
					M2.4	-9.38
Waiting B	28/07/2023	7h	160 km	-	-	-
Phase 3	28/07/2023	6h	160 km	1h	M3	-12.27



Assisted re-entry phases. Source: ESA



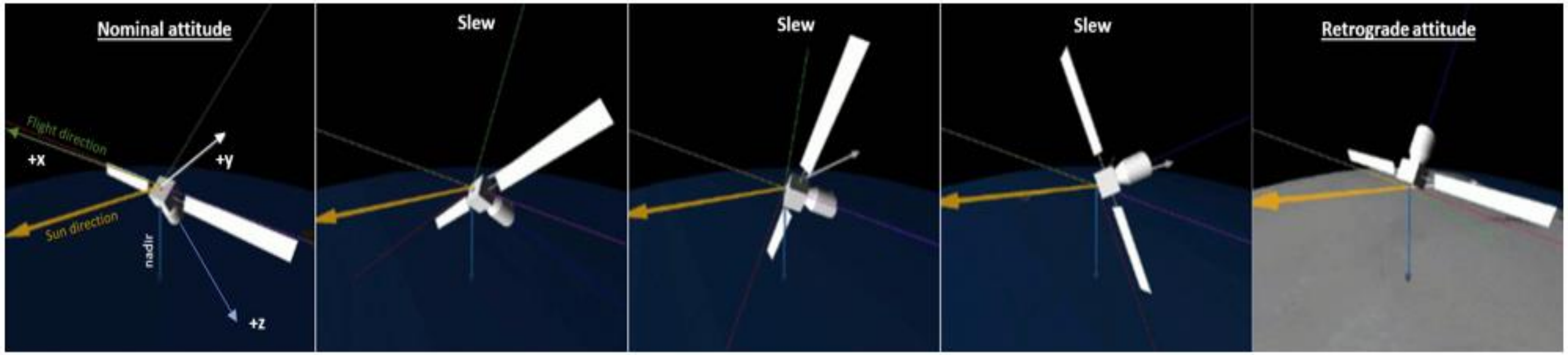
Re-entry area. Source: ESA

- Preparation of a “reversed LEOP” involving different ESA departments and requiring industry support.
- Specific FDIR configurations for the different phases of the re-entry to avoid safe mode or any monitoring triggering unwanted system/unit reconfigurations.
- Execution of 7 anti-flight manoeuvres with a total ΔV of 59 m/s.
- Initial perigee of ~275 km → Perigee of ~125 km after the last manoeuvre (M3)
- Re-entry on 28/07/2023 at ~18:40h UTC, 3h (~ 2 orbits) after the end of M3.

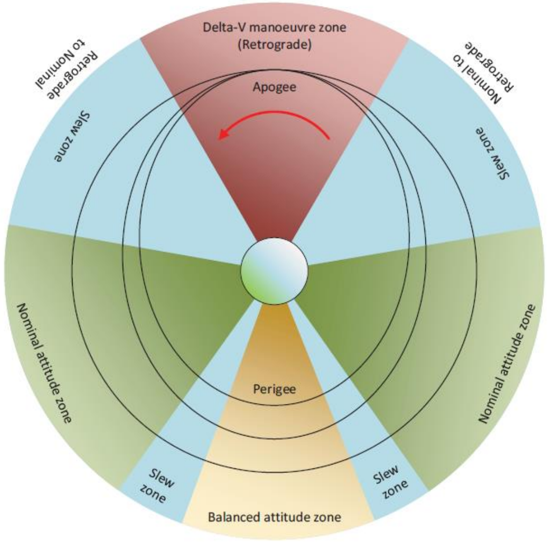
3. Retrograde manoeuvre

Retrograde manoeuvre

- Thruster in the –X direction since their primary function is to perform manoeuvres to counteract the drag force on the spacecraft.
- 180deg rotation of the spacecraft around the Y axis to keep the solar arrays sun-pointing and the instrument radiator anti-sun-pointing.
- X-band antenna, Star Trackers and GPS antennas are Earth pointing→ internal orbit propagation during part of the slews and manoeuvres.
- Between manoeuvres it is necessary to return the spacecraft to its nominal attitude→ Use of STR, GPS and X-band antenna for mass memory dumps.



Slew from nominal attitude to retrograde attitude. Source: ESA

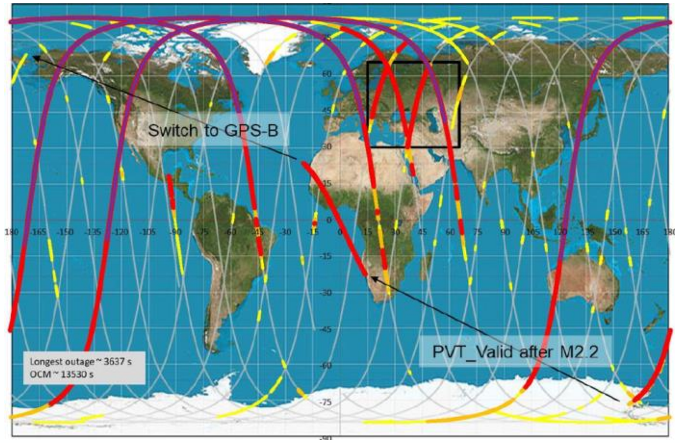


Attitude zones during manoeuvres.
Source: Airbus

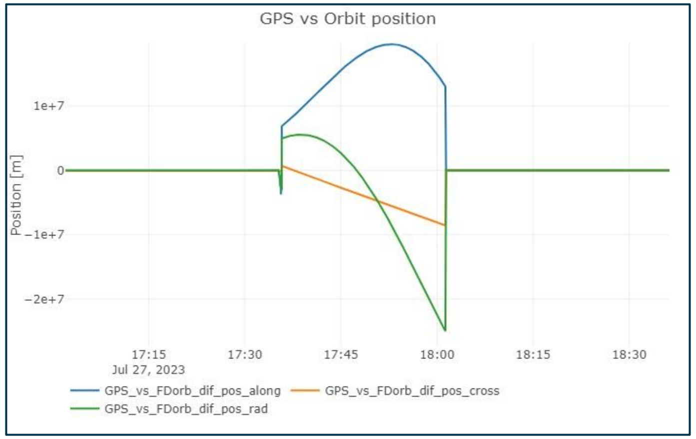
4. GPS issues after manoeuvres

With the nominal settings of the Kalman filter, new range information from the GPS satellites was given a low weighting compared to the existing navigation solution since the difference between the calculated and expected range was too large. This prevented the navigation solution from adjusting itself towards the real orbit after the manoeuvre. The longer the orbit solution stayed unmodified then the further away the pseudo ranges were from the expected ones, the RAIM flags were raised, and the GPS satellite information excluded. Relaxation of the navigation parameters, to the maximum possible values, proposed by industry:

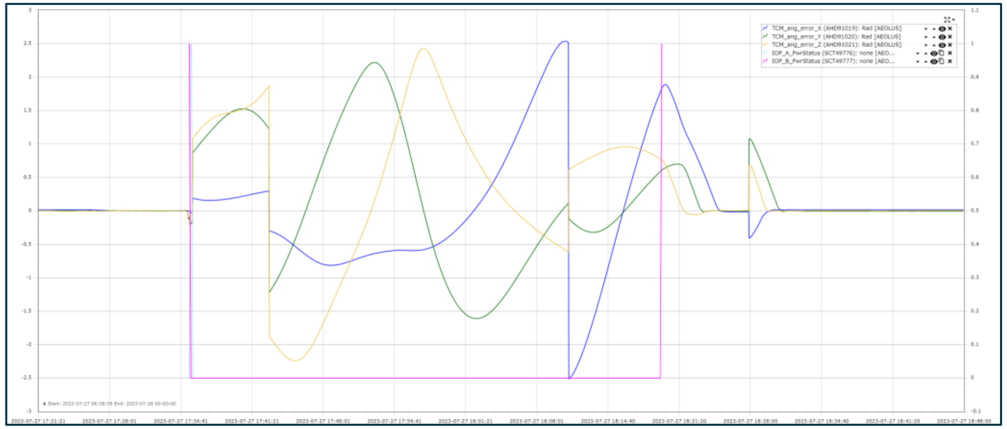
- RAIM: Residual Range Test Threshold updated from 500m to 100km.
- Navigation Filter: Covariance of Position and Covariance of Velocity changed to 1.



Orbit position jump due to wrong PVT data accepted. Source: Airbus



Orbit position jump due to wrong PVT data accepted. Source: ESA

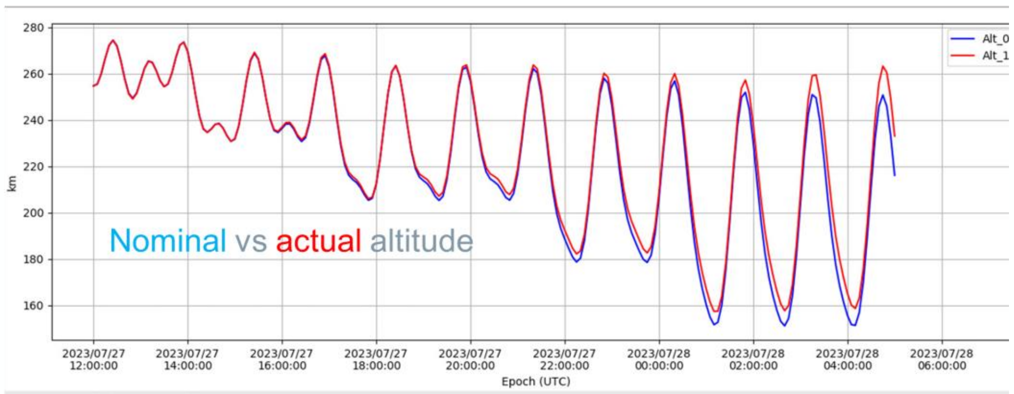

Attitude errors and RCS reconfigurations. Source: ESA

- Wrong GPS data received after the manoeuvre M2.2, flagged as valid due to the new wide margin and wrongly propagated internally by the GPS.
- Due to the error in position (>10000 km along-track) the new estimated attitude differed significantly from the target attitude (~11 deg in Pitch), commanding a slew to correct the pointing error.
- RCS reconfiguration due to saturation of one of the thrusters → Same problem with the other branch→ 45 min without RCS.
- M2.3 and M2.4 executed without any issues; GPS flag correctly set to INVALID. GPS data out of the AOCS processing loops for M3.

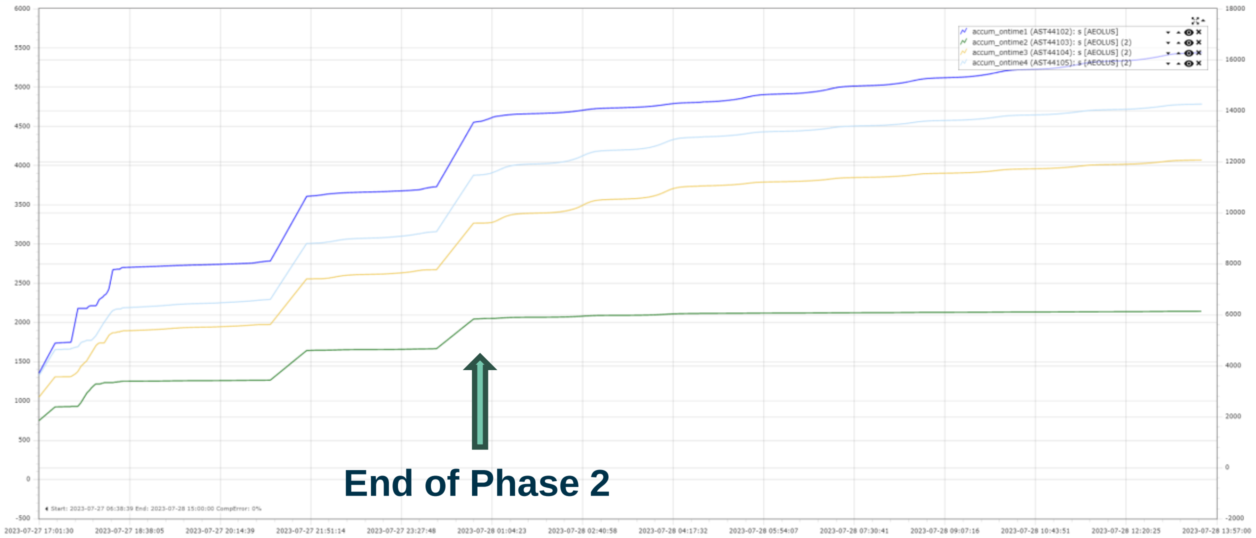
5. Unexpected orbit raise - Equilibrium attitude

- Due to the low altitude (perigee below 250 km) from Phase 2 onwards and the uncertainty on the behaviour of the RWs in Normal Mode the AOCS was permanently transitioned to TCM (Thruster Control Mode).
- At the end of Waiting B the expected perigee altitude was 150km but the real one was 160km.
- The air drag and torques were higher than expected, increasing the use of thrusters for attitude control and adding an in-flight deltaV that raised the orbit by 10km.
- The fuel consumption was ~3kg/orbit for attitude control → Not enough fuel to execute the last manoeuvre and finish the re-entry if we would have continued at this rate.

Phase ii – Situation in Waiting B



Difference nominal and actual altitude after Phase 2. Source: ESA



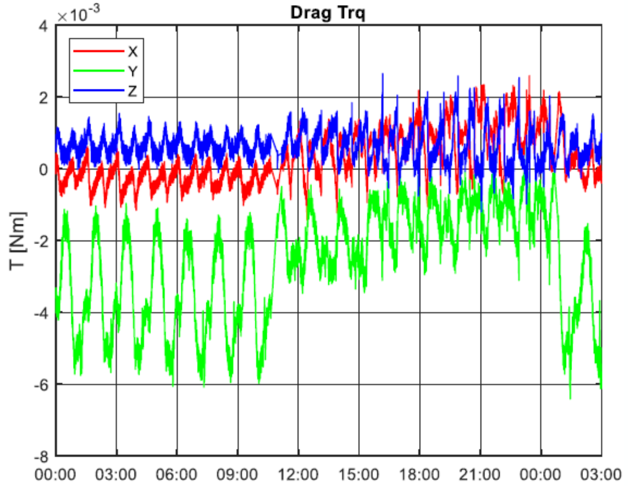
Increase of thruster firing after Phase 2. Source: ESA

- Thrusters 3 and 4 highly used to provide a positive pitch torque and counteract the drag force on the instrument baffle which created a negative pitch torque.
- It was decided to implement the <u>equilibrium attitude</u> to reduce the external pitch torque and the required amount of firing/fuel consumption during Waiting B.

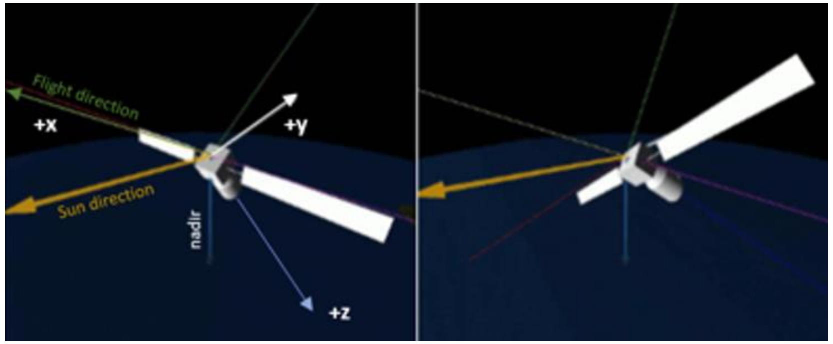
5. Unexpected orbit raise - Equilibrium attitude

Equilibrium attitude

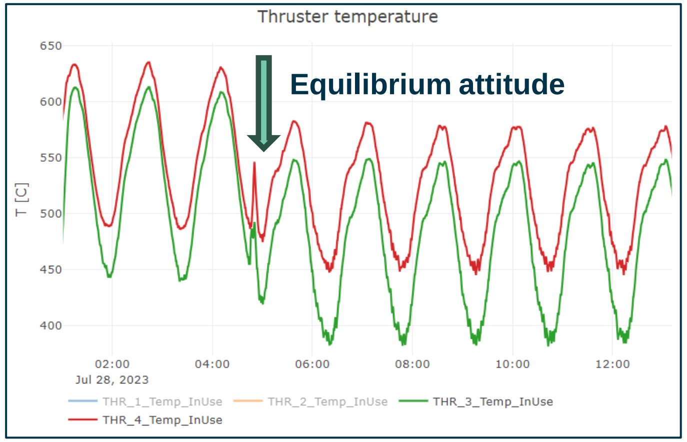
- Attitude close to the nominal value that reduces the drag torques and allows Normal Mode to operate at lower altitudes and TCM to save fuel.
- Tested during routine operations before the re-entry campaign, commanding different bias attitudes and analysing the effect on the torque required by the Reaction Wheels.
- Initially planned to be applied only in Normal Mode if the load of the RWs was high (> 30 Nms or 3000 rpm) → Values below that limit during the re-entry (maximum of 24 Nms at ~250km)
- Negative pitch of 28.8 deg implemented → ~60% reduction of the fuel used for attitude control, from 3kg/orbit to 1kg/orbit.

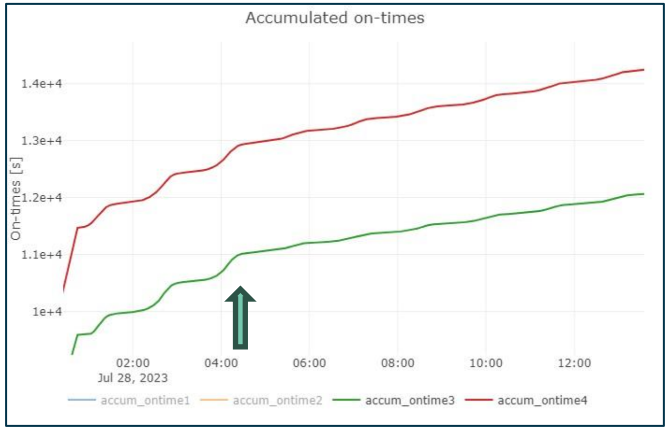


Reduction of torque during the Equilibrium Attitude test before the re-entry. Source: Airbus



Equilibrium attitude rotation. Source: ESA





Equilibrium attitude effect on thrusters #3 and #4 temperature and accumulated on-time. Source: ESA

Thank you for your attention!