ROBUST AND AUTONOMOUS AEROBRAKING STRATEGIES

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ABSTRACT

The Robust & Autonomous Aerobraking Strategies project (RAAS) represents the first European attempt to investigate systematically mission operations and GNC strategies for aerobraking, which fulfil specific autonomy and robustness requirements. DEIMOS Space and TAS-F have cooperated to propose a robust mission approach enabling S/C autonomies of up to one week, by means of an onboard Pericentre Time Estimator, an Atmosphere Estimation function and a precise timeline for onboard and ground activities.
Innovative orbit control approaches and an autonomous GNC mode management for attitude control were proposed and tested at simulation level to meet the robustness and autonomy requirements. This paper will describe these new strategies in detail together with the results of the tests performed for their validation.

1. INTRODUCTION

Aerobraking is clearly emerging as a mission enabling technique to reach, at low propulsive cost, a low energy, low altitude orbit around a planet with atmosphere. In the recent past, various NASA exploration missions achieved their final science orbit by means of an aerobraking manoeuvre which lasted several months but enabled the orbit insertion of a much heavier S/C with respect to what possible with a purely chemical insertion. The success of the Venus Magellan [1], the Mars Global Surveyor ([2] and [3]), the Mars Odyssey ([4]) and the Mars Reconnaissance Orbiter ([5]) scattered any doubts about the technical feasibility of a mission technique which still remains quite complex from a technical and operational point of view.

For the above reasons, interest in aerobraking has also been growing in the European space community, as testified by the ESA exploration programme, which envisages this technique in the baseline scenario of several future missions to Mars such as Exomars, Mars Sample Return Orbiter and NetLander. Since little expertise is currently available in Europe (no European mission has ever executed an aerobraking manoeuvre), ESA has also fostered investigation on mission operations approaches and GNC strategies (Guidance Navigation & Control) by financing several R&D projects. Among these, the Robust and Autonomous Aerobraking Strategies (RAAS) represents an important attempt to tackle this technique systematically and with a realistic approach to real operations planning.

The main goal of the RAAS project was to investigate mission and GNC strategies for both S/C attitude and pericentre altitude control, which fulfil, at the same time, specific autonomy and robustness requirements. In particular, a S/C autonomy of 7 days and a control robustness to dust storm events (for Mars scenarios) without interruption of operations, were the two most challenging requirements.

DEIMOS Space developed orbit guidance and control strategies, which were validated on a long-term basis (the whole aerobraking duration), while TAS-F was involved in the development of GNC algorithms and modes management for S/C attitude control, validated on a short-term basis (a few orbits).

Finally, a test campaign was carried out to validate the overall mission approach, assuming as reference mission the Mars Sample Return (MSR) aerobraking.

2. PERICENTRE ALTITUDE GUIDANCE

Orbit control for aerobraking essentially deals with pericentre altitude control and it is achieved through aerobraking manoeuvres at apocentre (ABMs) to either raise or lower the pericentre of the orbit. A **predictive corridor** approach was developed:

- ABMs are computed on the basis of predictions of orbit and atmosphere conditions
- ABMs are applied to fulfil a control corridor, which is defined in terms of one or more surrogate control variables (**heat flux** or **dynamic pressure** at pericentre, **heat load** per drag pass)

The choice of a predictive control approach was justified by dedicated orbit dispersion analyses around Mars, aimed at assessing the quality of the orbit predictions throughout time intervals as long as one week (which is the RAAS autonomy target). The effect of Mars atmosphere unpredictability on the evolution of the pericentre altitude was assessed by means of orbit simulations featuring the perturbed EMCD (European Mars Climate Database) atmosphere model. The pericentre altitude 3-sigma dispersion for Warm scenario simulations was found to be much lower than the typical Mars atmosphere density scale height (0.150 km Vs 7-8 km) and, hence, it was assumed that pericentre altitude predictions could be reasonably trusted for orbit guidance computation.

The next sub-sections will describe in detail the developed control corridor concepts and guidance logic.

2.1 New Control Corridor Definitions

The control corridors developed within the RAAS project were presented at the IPPW8 in 2011 (refer to [6] for a detailed description). The major innovation consists in the fact that these corridors adapt themselves to the changing geometry of the orbit.

Past aerobraking missions ([1] to [5]) have always featured constant corridors defined in terms of dynamic pressure or heat flux at pericentre which were updated on a regular basis throughout the mission after complex and real time analyses of S/C thermal telemetry and atmospheric readouts.

The idea proposed within RAAS is to build offline a control corridor with a detailed solar array thermal analysis, extending over all possible drag pass geometries of the aerobraking. In this way, a corridor upper boundary may be defined as the locus of points yielding a maximum allowed solar array temperature, whereas the lower boundary as the locus of points corresponding to a minimum dynamic pressure to be reached at pericentre to achieve the target orbit within a maximum time. According to the variables chosen for the definition of these loci of points, two different approaches were developed:

- **1-D Approach**: Corridor defined in terms of the allowed range of pericentre heat flux (or dynamic pressure) as a function of the apocentre altitude (which univocally specifies the drag pass geometry)
- **2-D Approach**: Corridor defined in terms of the allowed 2-D region in the heat flux-heat load (integrated heat flux) control plane

2.2 Atmosphere Estimation Algorithm

In order to increase the orbit predictions robustness, an onboard atmosphere estimation algorithm was proposed, which is based on the use of an onboard heat flux sensor. The measured convective heat flux at each pericentre is compared with that predicted using a nominal atmosphere model to evaluate a scale factor, as shown in Eq. 1, where $\Phi_{measured}$ and $\Phi_{nom\ atm}$ represent respectively the measured heat flux and that predicted with a nominal atmosphere model:

$$SF_{drag\ pass} = \frac{\Phi_{measured}}{\Phi_{nom\ atm}} \qquad (1)$$

A 3-days moving average of the measured scale factors is then considered to filter out short term oscillations. Finally, this filtered scale factor value is applied to the nominal atmosphere model for orbit predictions, as shown in Eq. 2, where $\rho_{nom\ atm}$ is the predicted atmosphere density with a nominal atmosphere model and $SF_{filtered}$ is the above described filtered scale factor.

$$\rho_{predictions} = \rho_{nom\ atm} \cdot SF_{filtered} \qquad (2)$$

2.3 Baseline and Correction Guidance

Pericentre altitude is controlled with a **two-fold guidance approach**, which features baseline and correction ABMs. The former are required to comply with the aerobraking control corridor on the middle term (a few days), thus compensating predictable orbit evolution effects (e.g. pericentre altitude deterministic trends). The latter are computed and executed, if required, to compensate atmosphere density variations in the short term (a few orbits). This division into baseline and correction ABMs helps improve the overall performance and robustness of the control.

The baseline guidance logic is the following: *baseline ABMs ensure that the predicted evolution of the control variables during each control interval fulfils as much as possible the aerobraking corridor*. In this definition, the **control interval** is the predictions time span over which baseline ABM decisions are based. Thence, no more than one ABM per control interval is executed.

Fig. 1 and Fig. 2 show relevant examples of the baseline ABM effect when upper and lower boundary violations are predicted for respectively 1-D and 2-D control corridor cases. In short, if a corridor violation is predicted in the coming control interval (red dots), the baseline guidance aims at lowering or raising the pericentre altitude to bring the "worst orbit" control variables to the corridor upper boundary (blue dots). In this way, not only is the aerobraking corridor complied with, but also the aerobraking duration is minimized.

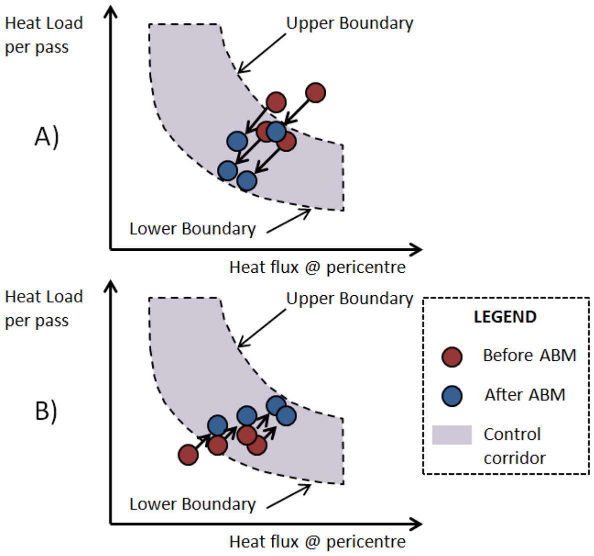

Fig. 1. Baseline Guidance Logic for 2-D Corridor

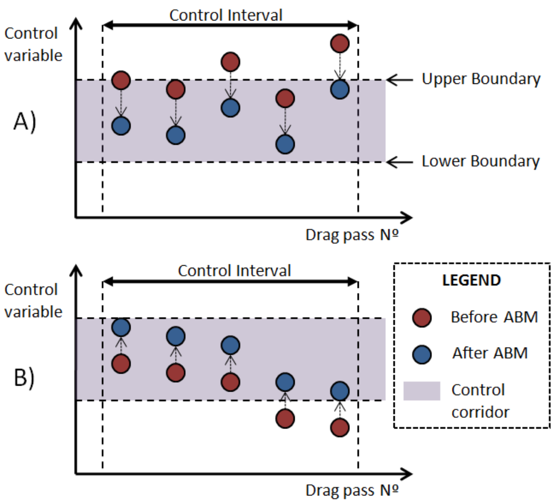

Fig. 2. Baseline Guidance Logic for 1-D Corridor

Prediction of baseline manoeuvres is made with a frequency not higher than one per control interval (a few days). Therefore, a short term control is needed to compensate rapid changes in atmosphere conditions, such as a dust storm insurgence. Typical build-up periods of dust storms into the higher layers of the Mars atmosphere are only a few days and therefore, the corresponding density change may not be considered at the time of baseline guidance prediction. For this reason, correction ABMs were included to enhance the overall control robustness.

The guidance logic is the following: *correction ABMs reproduce the baseline predicted evolution of the control variables, whenever the onboard predicted control variable for the coming pericentre pass falls outside the control corridor* (due to short-term atmospheric variations). Fig. 3 shows the effect of a correction ABM, executed after detecting a sudden density increase at pericentre. The black circles represent the predicted values of the pericentre control variable (e.g. pericentre heat flux) at the time of the baseline predictions. The atmosphere scale factor used for such baseline predictions is SF_0. A sudden density increase is detected in the form of a quick atmosphere scale factor increase (bottom plot of Fig. 3). After each drag pass, an onboard prediction of the coming pericentre control variable is obtained by comparing the current scale factor value SF to that used at the time of baseline predictions SF_0, as shown in Eq. 3, where $\Phi_{next\ pass}$ and $\Phi_{baseline}$ are respectively the onboard predicted control variable and the baseline control variable for the coming pericentre pass.

$$\Phi_{next\ pass} = \Phi_{baseline} \cdot \frac{SF}{SF_0} \tag{3}$$

In Fig. 3, these onboard predictions are shown as grey circles and tend to depart progressively from the baseline values as the atmosphere scale factor increases. When a control variable is predicted to fall out of the corridor, a correction ABM is applied to bring it back to its baseline value.

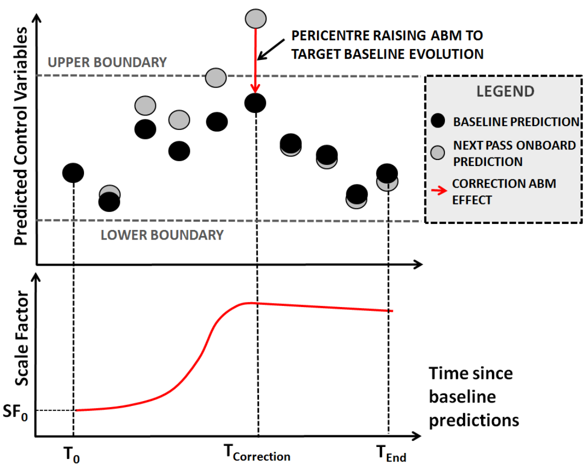

Fig. 3. Pericentre Raising Correction ABM

3. MISSION OPERATIONS APPROACH

In addition to control robustness to a dust storm insurgence event (tackled with the baseline/correction control approach), another challenging requirement to be fulfilled was the 1-week autonomy requirement. The S/C must be capable of keeping nominal aerobraking operations at least for one week without ground intervention. In order to achieve this autonomy, it was necessary to implement an autonomous in-orbit timing sequence update. During aerobraking, in fact, attitude switch manoeuvres must be performed periodically and with a precise timing, as shown in Fig. 4. In particular, attitude switch manoeuvres from vacuum attitude (solar arrays normal to the Sun direction) to drag pass attitude (drag surfaces normal to the wind direction) or aerobraking manoeuvre attitude (thrusters aligned with the inertial velocity at apocentre) and vice versa have to be performed on a 1 orbit time scale.

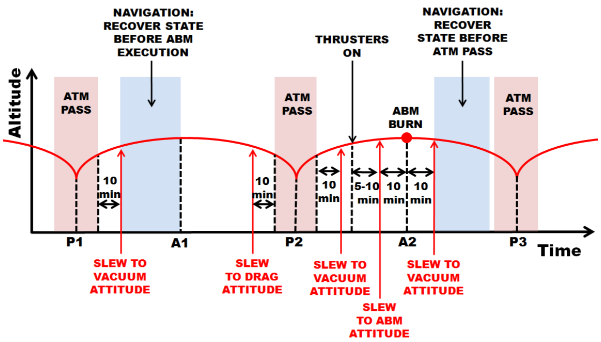

Fig. 4. Typical In-Orbit sequence of manoeuvres

If the triggering times were merely predicted on ground and uplinked to the S/C, they would become obsolete after a short time (not more than a few orbits) because of the unpredictability of atmosphere density. For example, Mars Global Surveyor and Mars Odyssey missions relied only on ground predictions and hence required a very high frequency of sequences built and uplinked to the S/C (several per day). On the contrary, the Mars Reconnaissance Orbiter mission started to use an onboard Pericentre Time Estimator (PTE) towards the end of the aerobraking, achieving a frequency of sequences uplinks as low as one every five days ([7]).

A PTE algorithm, which is described in [8] and [9], was then included in the mission operations approach, as it enabled autonomies (at least from the point of view of in-orbit sequence update) of several days.

Regarding the overall operations approach, the activities loop of Fig. 5 was proposed. Just before the start of each **autonomy interval** (also named **upload interval**), predictions of the S/C orbit are carried out on ground to produce a data package to be uplinked to the S/C, which contains relevant data for the autonomous onboard algorithms execution. Then, throughout each upload interval (7 days at most), real time operations are performed, featuring the execution of a precise sequence of onboard algorithms on a 1-orbit time scale (PTE algorithm, atmosphere estimation function, correction manoeuvres planner etc...). Finally, towards the end of each upload interval, a S/C tracking campaign is required to estimate the S/C state vector and initialize a new loop of orbit predictions and real-time operations.

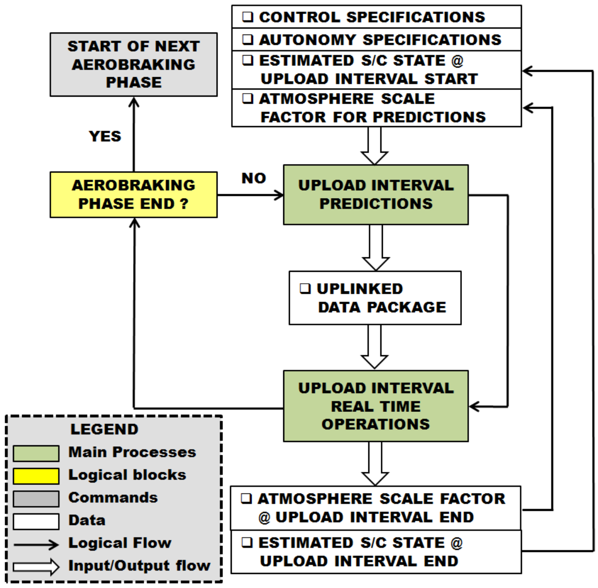

Fig. 5. Mission Operations Activities Loop

According to the platform allocation for baseline and correction guidance, two mission autonomy levels were identified:

- **Autonomy Level 1**: Baseline ABMs are predicted on ground throughout the entire autonomy interval (7 days at most) and uplinked to the S/C. Correction ABMs are planned directly onboard
- **Autonomy Level 2**: Baseline ABMs are computed onboard every control interval (2 days typically) throughout the autonomy interval. Correction ABMs are planned directly onboard

For both autonomy levels, orbit evolution predictions are always performed on ground, since it was deemed too expensive from a computational point of view to predict onboard the S/C orbit with a complex atmosphere model such as EMCD.

3.1 Upload Interval Predictions

The Upload Interval Predictions are performed on ground before the start of each upload interval (or autonomy interval). Their goal is to build a data package to be uploaded to the S/C containing the relevant data necessary for the autonomous onboard algorithms execution throughout such interval. Fig. 6 shows the main algorithms necessary for the generation of such data package for both autonomy levels.

For autonomy level 1, a ground manoeuvre planner computes, for each control interval contained within the upload interval, the baseline ABMs necessary to comply with the control corridor and the corresponding predicted evolution of pericentre pass variables: heat flux, heat load, altitude, atmosphere scale height, epoch and inertial velocity. These variables are required by the onboard PTE, atmosphere estimation and onboard correction algorithms.

For autonomy level 2, a simple predictive propagation algorithm predicts the above described pericentre variables throughout the entire upload interval without considering any orbit guidance, which is computed directly onboard.

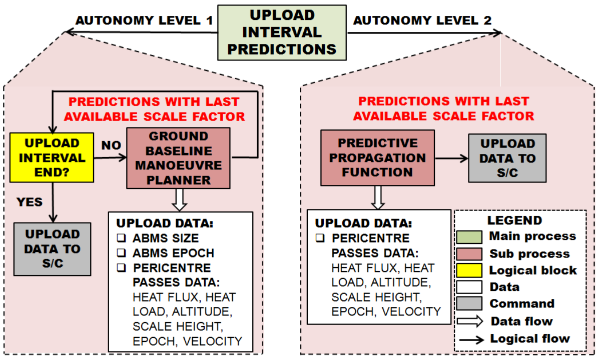

Fig. 6. Upload Interval Predictions Scheme

3.2 Upload Interval Real Time Operations

The real-time operations consist of a precise loop of activities executed for each orbit of the upload interval. Fig. 7 shows this operational loop, where attitude switch manoeuvres have not been included for the sake of clarity. Conventionally, the start of each orbit has been chosen to be just after the end of the drag pass.

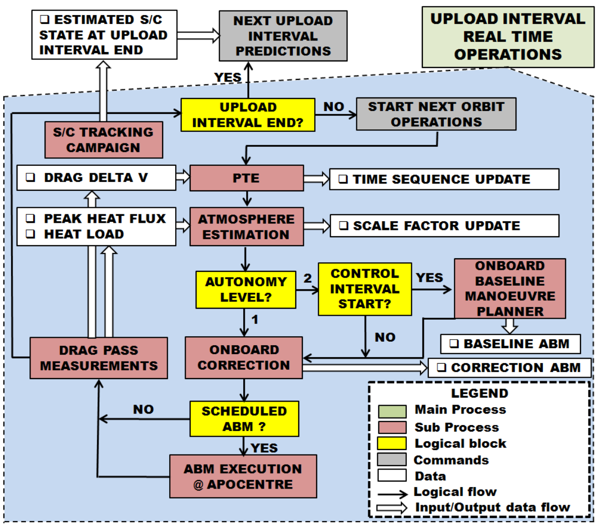

Fig. 7. Upload Interval Real-Time Operations Scheme

The first onboard algorithm to be executed is the PTE, which updates the in-orbit timing sequence (epochs of next apocentre and pericentre) by means of the measured drag delta V in the previous orbit Then, the atmosphere estimation function updates the value of the filtered scale factor for orbit predictions, with the heat flux and heat load data measured in the previous drag pass (Eq. 1). If the autonomy level is 2 and the current orbit corresponds to the start of a control interval for baseline guidance, then an onboard baseline manoeuvre planner is triggered to compute the required ABM size to comply with the control corridor. Finally, an onboard correction algorithm checks the need and computes the size of a correction ABM, if required. All the above described onboard algorithms require the upload data package generated during the upload interval prediction phase.

If a correction or baseline manoeuvre is planned, then it is executed at the coming apocentre. Finally, during the coming pericentre pass, measurements of heat flux, heat load (heat flux sensor) and drag delta V (inertial measurements unit) are obtained as inputs to the atmosphere estimation and PTE algorithms at the start of the following orbit. This loop is followed until the last orbit of the current upload interval has been reached, when a new upload interval prediction phase starts. Finally, as illustrated on the top left corner of Fig. 7, a S/C tracking campaign towards the end of the upload interval is carried out to estimate the S/C state vector for the next interval predictions.

4. ATTITUDE GNC MODE MANAGEMENT AND FDIR STRATEGIES

The operations approach described above clearly required specific GNC algorithms to command the S/C attitude changes on a 1-orbit time scale, and an autonomous GNC mode management compliant with an autonomy of several days. Therefore, the RAAS project also investigated GNC algorithms covering both normal operational and safe modes, implementing, at the same time, FDIR strategies to comply with potentially very stringent planetary protection requirements.

4.1 Autonomous Mode Management

The GNC subsystem must perform a number of tasks autonomously during the upload interval duration (or autonomy interval duration). The most significant are:

- Attitude control during the atmospheric drag pass, to maximize overall drag ΔV
- Perform ABMs at apocentre, respecting epoch, inertial direction, and amplitude
- Routine attitude control outside atmosphere, to keep solar generators sun-pointed, or perform scheduled communication sessions

These different tasks require the GNC subsystem to switch repeatedly, within one single orbit, among several attitude estimation, guidance and control functions, and among several types of sensors. To this end, the GNC includes an autonomous mode management function. Taking as inputs the mission plan – predicted atmospheric drag pass epochs, and command ABMs – it provides three flags to other GNC functions:

- **Guidance Flag** which determines the guidance profile to follow
- **Navigation Flag** which determines the estimation functions to be activated or reset
- **Controller Flag** which determines the control function or set of gains to activate

4.2 Attitude Control in Atmospheric Pass

The drag passes are characterized by:

- High disturbance torques around the pericentre
- Duration of about 1000 seconds at most
- Possible unavailability of any star tracker sensor, due to the high aspect angle of the planet and high inertial angular rates

Any deviation from the target attitude causes a loss of efficiency of the atmospheric forces, reducing the drag ΔV. However, strong disturbance torques can overwhelm the capacity of reaction wheels, and render a thruster-based attitude control scheme costly in fuel.

The baseline control scheme requires a highly stable aerodynamic configuration, with the plane of the solar generators having sufficient offset with respect to the S/C center of gravity. In this stable configuration, atmospheric torques keep the S/C around its most stable attitude, and the ΔV loss is not significant as long as attitude deviations do not exceed about 20 degrees. To avoid this, a simple thruster rate damping controller was chosen, for a minimal fuel cost.

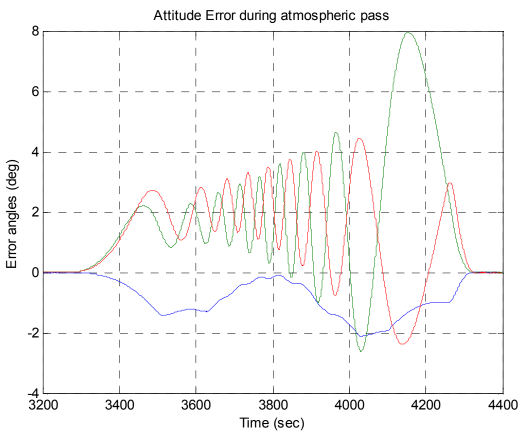

Fig. 8. Attitude angles throughout atmosphere pass

A scheme to take advantage of strong disturbance torques to unload the reaction wheels system was also tested. It allowed to eliminate the need for thruster-based reaction wheels (RWs) unloading, for additional savings of fuel.

4.3 FDIR Concepts for Aerobraking

The following sub-sections describe the proposed Fault Detection, Isolation and Recovery (FDIR) concepts for autonomous aerobraking.

4.3.1 FDIR Alarms

FDIR levels specific to autonomous aerobraking and their associated contingency procedures were defined.

The most dangerous fault is an **unexpectedly high heat flux** during the atmospheric pass (e.g. due to faulty pericentre altitude control or exceptional atmospheric conditions). High temperatures can irreversibly damage solar cells and cause the loss of the mission. Monitoring is performed by thermistors placed on the most temperature-sensitive parts of the spacecraft, and by dedicated heat flux sensors. The contingency response to a **thermal alarm** is a **pop-up manoeuvre**, raising the pericentre to a 'safe' altitude above a pre-defined threshold, typically 150 km.

A pop-up manoeuvre is costly in fuel, and is not warranted in other alarm cases. The most significant other types of alarm are:

- **Communication Black-Out**: failure to establish ground contact in a scheduled communication session
- **Power Alarm**: excessive battery depth of discharge
- **Rate Alarm**: excessive attitude angular rates

In the aforementioned cases, a pop-up manoeuvre is generally not warranted, and a **safe mode** is entered. Both safe mode and pop-up manoeuvre will be described in the next sub-sections

4.3.2 Safe Mode

The safe mode requirements are to minimize power consumption, to maximize solar exposition and to avoid the use of star trackers and reaction wheels. Specifically to aerobraking, it must withstand several atmospheric passes.

The attitude control is the same as in normal mode. However, unlike normal mode, the GNC subsystem must autonomously detect atmospheric entry and exit in order to switch to rate damping. This detection function is based on IMU acceleration measurements. The tuning of the measurement filter and the detection threshold present a trade-off between avoiding false positives and fuel over-consumption due to delay. Fig. 9 shows an example of atmosphere detection based on IMU acceleration measurements.

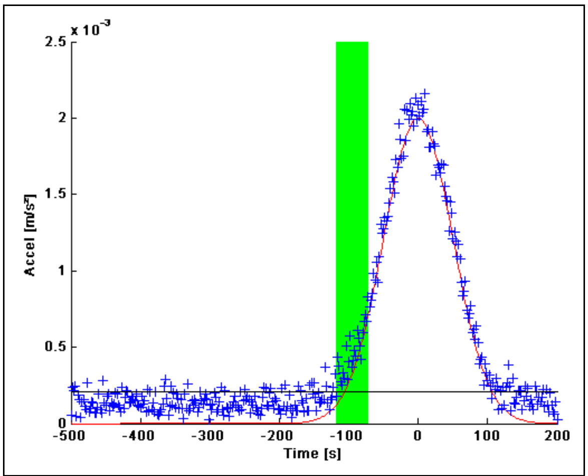

Fig. 9. Atmosphere detection on IMU

Safe mode should not in any case last for more than the orbit lifetime requirement, which was set to 4 days.

4.3.3 Pop-Up Manoeuvre

In addition to the Fail Safe approach, the FDIR includes an automatic pop-up capability, which can be performed in either normal or safe mode. The pop-up is activated in case of **thermal alarm** and if this happens, a pop-up manoeuvre is targeted for the next apocentre.

The immediate execution of a pop-up is warranted by the risk of losing the mission at the next pass. But even if the solar arrays (and thus the mission) are lost on the thermal alarm, the pop-up is still executed to avoid an uncontrolled crash. The inclusion of this pop-up is therefore critical for planetary protection compliance requirements.

In normal mode this manoeuvre is performed like any other ABM. On the other hand, if in safe mode, the S/C must be capable of performing it with sufficient precision without absolute 3-axis attitude measurements (no star tracker available). To cope with this, IMU acceleration measurements during the drag pass are integrated to derive the total aerodynamic ΔV direction, which is then propagated through gyrometer measurements for one half-orbit, until the next apocentre. Since the pop-up ΔV inertial direction is approximately equal to the measured aerodynamic ΔV inertial direction, this propagation allows the spacecraft to perform the boost with sufficient precision.

5. GNC ALGORITHMS VALIDATION

The validation of the GNC strategies described in the preceding sections was carried out with two different simulators:

- **Mission Analysis Simulator** (**MAS**) to emulate the evolution of the S/C state and simulate the mission operations approach over the time scale of the whole aerobraking, using 3-DOF (degrees-of-freedom) high-fidelity dynamics integration. This tool is described in [10]
- **High-Fidelity Aerobraking Simulator** (**Hi-FAS**), to integrate the high fidelity 6-DOF dynamics at 10 Hz over a time scale of a few orbits.

In particular, MAS was used for the long term validation of the orbit guidance and mission operations approaches described in chapters 2 and 3. The Hi-FAS was used to validate the attitude GNC algorithms and FDIR (Fault Detection Isolation & Recovery) concepts, described in chapter 4.

5.1 Long Term Validation

The long term validation consisted of three sets of tests, as described below:

- **Reference Scenario**: Assumption of a perfect knowledge of atmosphere, orbit evolution and manoeuvres execution. The goal was to evaluate the performance of the baseline guidance approach described in chapter 2 for both autonomy levels
- **Montecarlo**: Assumption of non-perfect knowledge of atmosphere and orbit evolution, implementation errors in ABMs execution, errors in onboard measurements and S/C state estimation. The goal was to test the robustness and performance of the guidance and mission operations approach for real scenarios from a statistical point of view
- **Worst Scenario**: Assumption of worst conditions in terms of atmosphere unpredictability (e.g. global dust storm event), manoeuvres execution, onboard measurements and S/C state estimation. The goal was to test robustness of guidance and operations strategies against worst conditions and to build sizing worst cases for the definition of the control corridor security margin

The mission scenario, the success criteria and the results of the three set of validation cases are presented in the following sections.

5.1.1 Mission scenario and success criteria

The aerobraking mission scenario for the long-term validation was a MSRO-like aerobraking scenario, which is synthesized in Tab. 1. The initial orbit is a 0.5 Sol orbit (roughly 12 hours) with a 45° initial inclination. The physical S/C properties, in terms of drag force, are synthesized by a ballistic coefficient of 56.5 kg/m^2.

Tab. 1. MSRO-like aerobraking mission parameters

Mission parameters	Unit	Value
Initial orbit period	hrs	12.0
S/C ballistic coefficient	kg/m^2	56.5
Initial orbit inclination	deg	45.0
Altitude targeted by ASIM	km	150.0
Number of Walk-In burns	N/A	8
Final value of pericentre heat flux achieved at Walk-In End	W/m^2	1450.0
Walk-In phase duration	days	14.0
Control interval for Main-Phase	days	2.0
Type of control corridor	N/A	2-D
Control Interval for Walk-Out phase	days	1.0
Minimum allowed orbit lifetime	days	4.0
Final orbit apocentre altitude	km	600.0
Final orbit pericentre altitude	km	600.0
Safe altitude during solar conjunction	km	150.0
Time gap between re-entry burns at solar conjunction end	days	2.0
Heat flux increase targeted at each re-entry burn at solar conjunction end	W/m^2	300.0

The first operational phase is the Walk-In phase, featuring an ASIM (Aerobraking Step-In Manoeuvre), which targets an initial pericentre altitude of 150 km. The goal of the Walk-In phase is to reach operational pericentre altitudes with a series of pericentre lowering manoeuvres (8 in 2 weeks for this scenario) in a safe and gradual way, in order to tune the atmosphere model for predictions with the evaluation of an atmosphere scale factor, as shown in Eq. 1 and 2.

After the Walk-In phase, the Main Phase begins, during which a 2-D corridor (heat flux and heat load) is used for pericentre altitude control. The control interval for baseline guidance decisions is 2 days (1 manoeuvre every two days at most).

At the end of the aerobraking, the Walk-Out phase begins when the predicted S/C lifetime approaches a minimum allowed value of 4 days. The lifetime is approximately the expected life of the S/C before atmospheric re-entry (as the apocentre altitude lowers, the drag pass duration increases and the orbit decay increases exponentially). During the Walk-Out phase, a manoeuvre every day is executed to maintain the lifetime above 4 days, until an apocentre altitude of 600 km is reached. Then, a final ABM raises the pericentre altitude to 600 km, thus achieving a circular orbit with a period of slightly less than 2 hours.

Tab. 1 also gives control specifications for solar superior conjunction handling. When the Sun-Earth-S/C angle gets below 5º operations are interrupted and the pericentre altitude is raised to 150 km. At the end of the solar conjunction (i.e. when the above angle becomes again higher than 5º), operations are restored through a series of pericentre lowering manoeuvres (one every 2 days) aiming at raising the pericentre heat flux by 300 W/m^2 each. Re-entry phase ends when control corridor is resumed.

The success criteria for the validation campaign were:

- **AB-THERM-1**: No solar array thermal damage. 2-D control corridor upper boundary corresponds to a peak temperature of the solar array of 95ºC, quite below the maximum tolerable temperature of 150º C. This success criteria is satisfied if no drag pass violates the 150º C damage curve in the control corridor 2-D plots (due to atmosphere prediction errors)
- **AB-OPER-1**: Aerobraking duration (excluding solar conjunction period) lower than 9 months
- **AB-ORB-1**: Real S/C lifetime never below 4 days, throughout the aerobraking

5.1.2 Reference Scenario Cases

Tab. 2 summarizes the main assumptions made for the reference scenario simulations. Two cases were run, one for each autonomy level, to test performance of both ground and onboard baseline ABM planner, when perfect orbit and atmosphere predictions are assumed on ground. The EMCD scenario Nº 7 (Warm Scenario) was assumed for both predictions and true orbit propagation.

Tab. 2. Reference Scenario Simulations Assumptions

Assumptions	Unit	Value
Total number of simulations	N/A	2
Autonomy level	N/A	1, 2
Autonomy interval	days	4.0, 7.0
Atmosphere model for predictions and true orbit simulation	N/A	Deterministic EMCD Scenario Nº 7

Tab. 3 shows the performance for the two reference scenario simulations, in terms of duration, delta-V cost and total number of ABMs. Performances are very similar for both autonomy levels and **all success criteria were met**.

Fig. 10 shows the evolution of the pericentre altitude throughout the aerobraking for the autonomy level 1 case (autonomy level 2 is very similar). The Walk-In phase, Main Phase, Walk-Out phase, solar conjunction and re-entry phase may be easily identified in the plot.

Tab. 3. Reference Scenario Simulations Results

Performance Variable	Autonomy Level 1		Autonomy Level 2	
	Unit	Value	Unit	Value
Overall duration	days	273.6	days	274.9
Overall delta-V cost	m/s	148.3	m/s	147.3
Overall number of ABMs	N/A	101	N/A	96

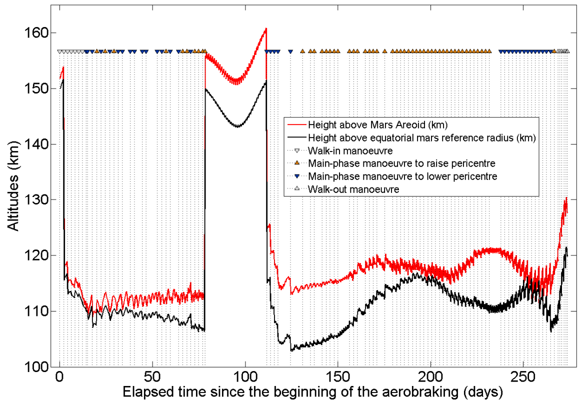

Fig. 10. Pericentre altitude evolution (autonomy lev.1)

Fig. 11 shows the controlled evolution of pericentre heat flux and heat load per pass throughout the aerobraking for autonomy level 1. Since ground baseline ABM planner predicts the orbit with a high fidelity integrator, compliance with the control corridor upper boundary is perfect (no point above the red curve). Fig. 12 shows the same plot for the autonomy level 2. Although ground predictions feature perfect knowledge of atmosphere and orbit perturbations, the onboard baseline ABM planner predicts the ABM effect with a simplified scale height model and upper boundary compliance is not perfect, though quite good.

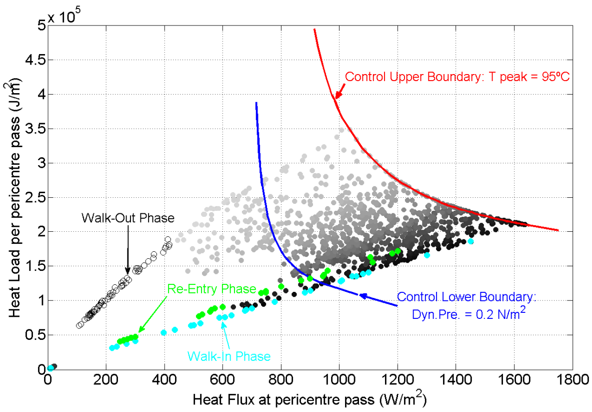

Fig. 11. Control variables evolution (autonomy lev.1)

Finally, Fig. 13 represents the evolution of the S/C lifetime during the Walk-Out phase for autonomy level 1 (again, the other autonomy case presents a very similar evolution). No violation of the 4 days requirement (AB-ORB-1) was detected.

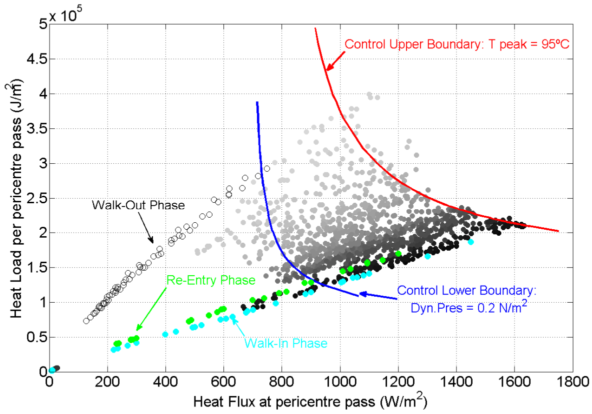

Fig. 12. Control variables evolution (autonomy lev.2)

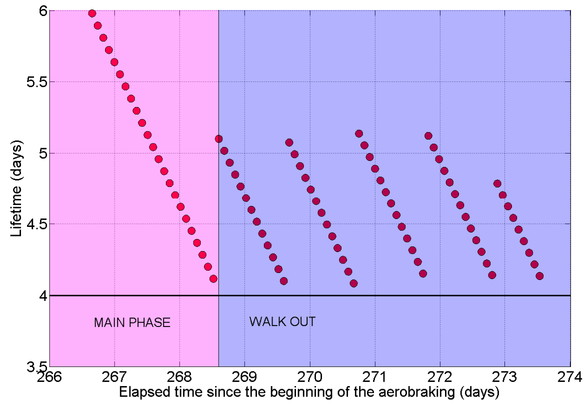

Fig. 13. Lifetime at aerobraking end (autonomy lev.1)

5.1.3 Montecarlo Cases

The assumptions for the Montecarlo cases are summarized in Tab. 4. A total of 100 aerobraking simulations were run, featuring a propagation world model for predictions different from that used for true orbit simulation, in order to emulate real mission scenarios. Different atmosphere models, NGAs (Non gravitational accelerations), ABM implementation errors, onboard measurements errors (for both drag delta-V and peak heat flux) and S/C state estimation errors were considered. For atmosphere density predictions, the nominal atmosphere model was corrected with the measured filtered scale factor using Eq. 2.

All success criteria were successfully met and the results are summarized in Tab. 5. The average value and the standard deviation of several performance variables such as overall duration, minimum registered S/C lifetime, overall cost and number of manoeuvres are provided.

Tab. 4. Montecarlo Simulations Assumptions

Assumption	Unit	Value
Total number of simulations	N/A	100
Autonomy level	N/A	2
Autonomy interval	days	7.0
Atmosphere model for predictions	N/A	Deterministic EMCD scenario Nº 7
Atmosphere model for true orbit simulation	N/A	Perturbed EMCD scenarios Nº 1, 2, 3, 7, 8
NGA acceleration components for true orbit simulation	km/s^2	10^{-11}
ABM magnitude errors	%	0.4 (3-sigma)
ABM direction errors	deg	2.0 (3-sigma)
Onboard measurements errors	N/A	performance models
S/C state estimation errors	N/A	performance model

Tab. 5. Montecarlo Simulations Results

Performance Variable	Unit	Average value	Standard deviation
Overall duration	days	286.6	4.2
Overall duration (excluding solar conjunction)	days	253.4	4.2
Overall delta-V cost	m/s	154.7	2.4
Overall number of ABMs	N/A	112.1	6.2
Minimum registered lifetime	days	4.3	0.1

Fig. 14 shows the dispersion of the pericentre altitude for the 100 simulations. Clearly, simulations featuring the cold atmosphere model for true orbit propagation also presented the lowest operational altitudes. In fact, the calmer the atmosphere, the lower is the density at a given altitude.

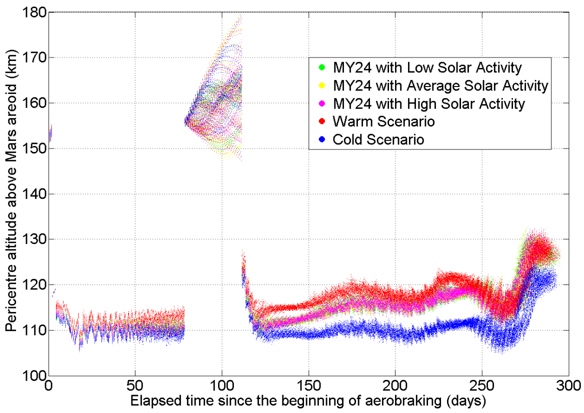

Fig. 14. Montecarlo pericentre altitude dispersion

Fig. 15 shows the worst orbit per simulation in the control variables plane (heat flux-heat load). Clearly control upper boundary violations are detected because of the atmosphere unpredictability. Nevertheless, the purple damage curve is never reached (corresponding to a solar array temperature of 150 ºC) thus fulfilling AB-THERM-1 criteria.

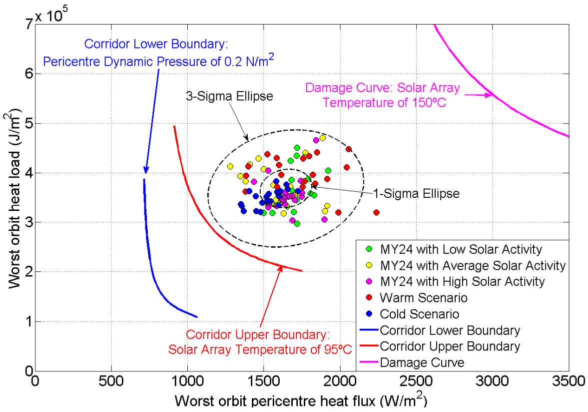

Fig. 15. Worst orbits per Montecarlo simulation

Fig. 16 finally shows the performance of the autonomous onboard PTE for all simulations. A slight dependence on the true orbit atmosphere model was detected (the calmer the atmosphere, the lower the average error) and no prediction errors higher than 80 seconds were found.

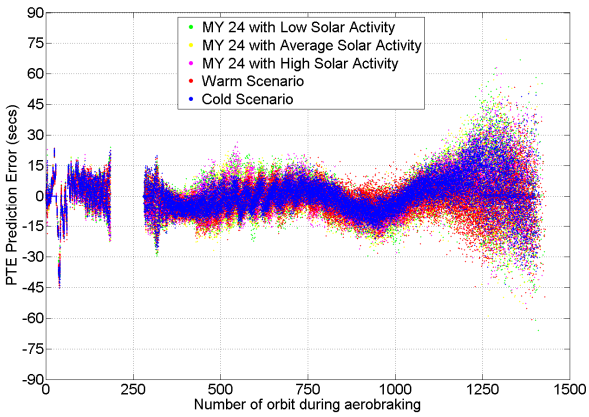

Fig. 16. Pericentre time prediction errors

5.1.4 Worst Scenario Cases

The assumptions made for the Worst Scenario simulations are summarized in Tab. 6. A total of 96 deterministic simulations were carried out considering 2 autonomy levels, 2 initial orbital periods, 12 initial LST (local solar times) at pericentre and 2 ABM magnitude errors (± 0.4% of the ABM magnitude). Regarding heat flux and drag delta-V measurements and S/C state estimation errors, 3-sigma values from available performance models were adopted.

Tab. 6. Worst Scenario Simulations Assumptions

Assumption	Unit	Value
Total number of simulations	N/A	96
Simulation duration	days	60.0
Autonomy level	N/A	1, 2
Autonomy interval	days	4.0, 7.0
Local solar time at pericentre	hrs	0:00 to 22:00 (2 hours step)
Initial orbital period	hrs	12.0, 6.0
Atmosphere model for predictions	N/A	Deterministic EMCD scenario Nº 7
Atmosphere model for true orbit simulation	N/A	LMD Global Dust Storm Scenario 2001
ABM magnitude errors	%	+0.4, -0.4
ABM direction errors	deg	2.0
Measurements errors	N/A	3-sigma error (performance models)
S/C state estimation errors	N/A	3-sigma error (performance model)

The true orbit atmosphere model considered in these simulations, is the LMD (Laboratoire de Météorologie Dynamique) model of a Mars global dust storm registered in 2001.

For these validation tests, the dust storm insurgence is detected through the measurement of the atmosphere scale factor, computed with Eq. 1. Fig. 17 shows the evolution of this important variable throughout one specific worst case simulation. In particular, the red dots are the measured values after each drag pass, the blue line is the filtered scale factor used for onboard predictions and the black line is the value used for upload interval ground predictions.

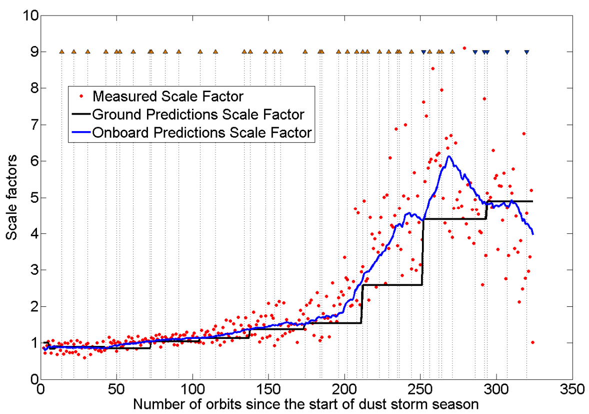

Fig. 17. Scale factor evolution (pericentre LST: 16:00, autonomy level 2, orbital period 6 hrs)

Fig. 18 shows the evolution of the controlled variables for all worst scenario simulations. A few simulations violated the purple damage curve (10% of cases in no more than one pericentre pass per case).

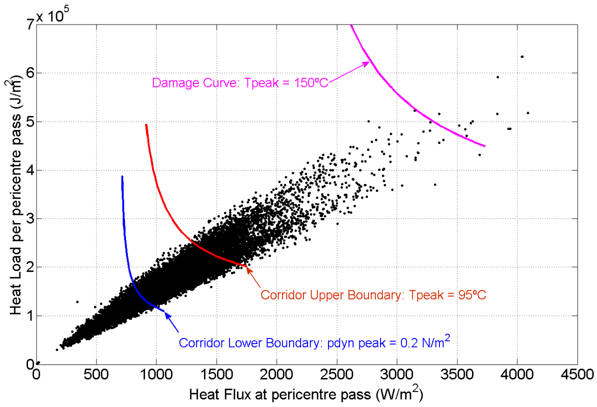

Fig. 18. Control variables evolution for the 96 sims

In order to avoid the detected violations, it was suggested to reduce the control upper boundary curve from 95ºC to 80ºC during the dust storm season (solar longitudes between 180º and 360º). The worst case simulations run with this conservative corridor are shown in Fig. 19. Although no further violation were detected, such conservative corridor resulted in a degradation of the overall aerobraking performances. Dedicated reference scenario simulations featuring this new corridor during the dust storm season period only, permitted to assess the performance deterioration: 50 days in overall duration, 10 m/s in total cost and 30 additional control manoeuvres.

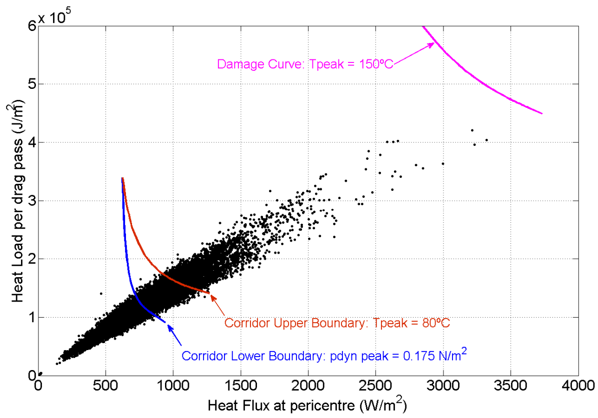

Fig. 19. Control variables evolution for the 96 sims and the conservative 2-D corridor

5.2 Short Term Validation

The short term validation of the GNC modes and FDIR strategies featured the same types of tests of the long-term validation (reference scenario, montecarlo, worst scenario cases) but on a much more shorter time scale (a few orbits). The validation campaign was successful and demonstrated the general applicability of the proposed strategies for autonomous aerobraking.

6. CONCLUSIONS AND WAY FORWARD

Aerobraking is a relatively new technique which is still open to an incredible variety of mission approaches and control corridor definitions. The Robust and Autonomous Aerobraking Strategies project represented a great opportunity to study systematically and in a comprehensive manner this mission scenario permitting to:

- Classify the different aerobraking phases, in terms of their relevant constraints and goals
- Analyze the main factors limiting the autonomy and robustness of an aerobraking mission, such as the atmosphere prediction uncertainty and the possible insurgence of a dust storm
- Improve the efficiency of the pericentre altitude control by investigating control corridor concepts, which adapt to the changing geometry of the orbit
- Improve the robustness of pericentre altitude control by proposing a two-fold guidance concept, featuring baseline and correction ABMs
- Improve the reliability of orbit predictions, by proposing the use of heat flux sensors to measure the atmosphere conditions
- Propose and validate two mission operations approaches with different autonomy levels
- Propose and validate a preliminary design of a full GNC subsystem for autonomous aerobraking
- Explore FDIR concepts and strategies specific to autonomous aerobraking
- Develop and validate new guidance and navigation algorithms, reaching a TRL of 2-3 (Technology Readiness Level)
- Develop new tools to tackle with aerobraking mission design on the long term (MAS) and short term (Hi-FAS)

Future work should aim at raising the TRL of the proposed GNC technologies. In particular, ground algorithms will need to be integrated into real ground stations architectures and the mission operations approaches will require testing with additional real-time effects (radio communications delays, communications black-outs etc...). Regarding the onboard algorithms, additional theoretical investigation should be fostered to improve the proof-of-concept with the final goal of validating them on a space-qualified computer.

To conclude, although a great amount of work still has to be done, the RAAS project represented a significant step forward in the understanding of the aerobraking concept and it paved the way for future implementation of new technologies for real space missions.

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