AEROBRAKING MISSION ANALYSIS TOOL FOR MARS EXPLORATION MISSIONS

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ABSTRACT

In the context of Mars exploration missions, the aerobraking strategy has been brought to the fore as an alternative to a fully propulsive scenario for the insertion into the target science orbit. While technically more complicated, longer and operationally more demanding than a fully chemical orbit insertion, the aerobraking strategy is implemented because it allows for large ΔV and propellant budget savings for the science orbit acquisition.

The definition of the heat flux / dynamic pressure corridor and the heat load constraints to guarantee S/C integrity during aerobraking has a major impact on the aerobraking duration and on the number of periapsis control manoeuvres to be performed.

This paper provides an overview of the algorithms and tools developed at DEIMOS Space to enable an exhaustive analysis of the aerobraking scenario, dealing with the associated operational phases and key drivers. The application of these analysis capabilities to representative Mars missions is intended to assess the effectiveness of the embedded methods for the evaluation of the aerobraking strategy.

1. INTRODUCTION

After an interplanetary cruise, all planetary exploration missions have to deal with the challenge of achieving a final science orbit around the planet. Typically, a propulsive burn, at the incoming hyperbola pericentre, achieves insertion into a first high-energy and high-eccentricity orbit around the planet.

The following transfer to the final science orbit may be performed either in a purely propulsive manner or by a combination of smaller manoeuvres and high atmospheric passes. In the former case, a series of pericentre burns lower the apocentre to its final value, whereas in the latter case, the planet atmosphere is used for the purpose. This strategy is widely referred to as the "aerobraking" strategy.

The purpose of the aerobraking technique is to reduce the energy of a highly elliptical orbit (achieved by propulsive planetary capture), transforming it into a low-eccentricity, low-altitude orbit by successive atmospheric passes. Indeed, the S/C orbital energy, period and apoapsis altitude are progressively lowered by means of the drag force acting mainly on the S/C solar panels (and high gain antennas possibly), as it passes through the upper layers of the Mars atmosphere. The achievement of the target orbit apoapsis and period typically takes a few months.

A graphical 3-D view of the first part of a typical aerobraking scenario around Mars is shown in Fig. 1.

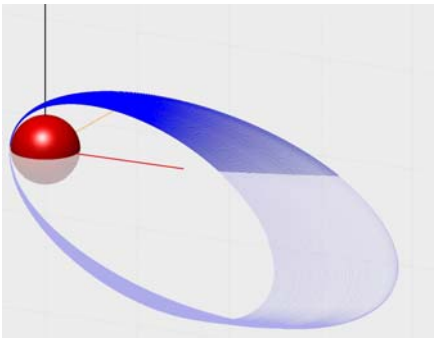

Fig. 1: Graphical evolution of the orbit during the aerobraking phase.

While **technically more complicated, longer and operationally more demanding** than a fully chemical orbit insertion, the interest in the implementation of the aerobraking strategy in Mars missions stems from the possibility to allow **large ΔV and propellant budget savings** to achieve the science orbit around Mars.

The definition of the **heat flux / dynamic pressure corridor and the heat load constraints** to guarantee S/C integrity during aerobraking has a key impact on the aerobraking duration and on the number of periapsis control manoeuvres to be performed. Thermal and lifetime limits (which generally require higher altitudes to increase safety margins) are traded with aerobraking duration and number of drag passes (which require lower altitudes for minimisation). The primary means to deal with these margins is the **apoapsis manoeuvre strategy** that raises or lowers the

periapsis altitude to adjust the drag achieved on each pass, taking into account the changing Mars atmospheric conditions.

In the recent past, three NASA Mars missions have successfully implemented the aerobraking strategy, thus demonstrating the feasibility and the effectiveness of this technique.

The NASA Mars Global Surveyor ([1], [2]) in 1997 and Mars Odyssey ([3]) in 2001 were launched with propellant deficits and relied upon the aerobraking technique to lower the orbit apoapsis to the desired altitude for the science mission. To perform a successful and effective aerobraking strategy, these two missions had to tackle a challenging operational scenario due to the high orbit-to-orbit variability of Mars atmosphere. The propellant savings provided by aerobraking allowed these missions to launch on Delta II 7925 vehicles, providing important cost savings relative to the larger launch vehicles that would have been required if purely propulsive orbit insertion had been implemented. For these two missions aerobraking was an enabling technology and a critical factor to mission success.

Most recently, the NASA Mars Reconnaissance Orbiter ([4]) completed a 6-month aerobraking phase before the start of the science mission in 2006. Also in this case, the aerobraking strategy was included in the baseline mission profile as a key element to guarantee mission success.

In Europe, the analysis of the aerobraking strategy as a potential mission enhancing or enabling technique is more recent and it has been assessed, though not yet validated in-flight, for ESA Venus Express and Mars Express missions. The future ESA ExoMars mission envisages the use of the aerobraking strategy, which is currently included in the baseline ExoMars mission profile, as an alternative to a fully propulsive insertion into the Mars science orbit for the ExoMars Orbiter.

The heritage of past Mars missions that successfully implemented the aerobraking sequence and the increasing interest in the application of this technique in future exploration missions have brought to the fore the need for design and analysis tools that allow the mission analysts to design an aerobraking scenario and to assess the impact and the effectiveness of the aerobraking strategy. To address this need, DEIMOS Space has developed a suite of methods and algorithms and has embedded them in a dedicated **Aerobraking Mission Analysis Tool**. This tool is intended to enable an exhaustive analysis of the aerobraking scenario, dealing with the associated operational phases and key drivers.

This paper yields an overview of the Aerobraking Mission Analysis Tool functionality for the analysis of the aerobraking scenario for a Mars exploration mission, streamlining the aerobraking phases and highlighting the main issues and constraints to be taken into account in each phase. The application of the analysis capabilities provided by this tool to representative ExoMars-like mission scenarios is intended to assess the effectiveness of the embedded methods for the evaluation of the aerobraking strategy.

2. AEROBRAKING OPERATIONAL PHASES

The aerobraking complexity derives from both the need of respecting a certain number of constraints and from the uncertainty and unpredictability of the Mars atmosphere. Indeed, it is important to assure that the S/C be not structurally stressed more than allowed (dynamic pressure constraint) or get too much heated (heat flux and heat load constraints). Thus, the most operationally intensive trajectory analysis task during aerobraking consists in providing information used to manage the aerobraking margins.

The aerobraking scenario implies a high operational risk since generally the atmosphere density changes dramatically at subsequent pericentre passages (because of its strong dependence on altitude, longitude, latitude and stochastic events like temporal variability, dust storms or gravity waves perturbations). It is therefore necessary to control the pericentre passage density through the implementation of periodic burns at apocentre, which control the pericentre altitude and hence adjust the drag to some target value.

Given the changing atmospheric conditions at Mars, the phase-dependent constraints and the risk management trade-offs associated with each decision, the manoeuvre strategy is continually monitored and adjusted throughout aerobraking to react to variations with respect to foreseen or nominal conditions. The guiding philosophy of the manoeuvre strategy is typically to reduce orbit period as quickly as possible while maintaining acceptable margins and manoeuvre frequencies.

In order to comply with all these issues, three different aerobraking phases are normally implemented, each one differing from the others in terms of constraints applied and goals to be achieved. These phases are named respectively walk-in, main-phase and walk-out.

2.1 Walk-In Phase

Because of the uncertain knowledge of the planetary atmosphere, at the beginning of the aerobraking, a gradual lowering of the pericentre altitude is executed.

This is a conservative approach, which allows reaching the operational aerobraking working conditions in the safest way. In addition, walk-in permits to tune the available atmosphere model to the actual atmospheric conditions through the definition of scale factors, which are the ratios between the measured density values and the model predicted ones. These adaptations are paramount for the density predictions and the aerobraking control during mission operations.

During the walk-in phase a first pericentre passage at a safe high altitude above the planet is typically performed (approximately 150 km in the case of Mars) and then the pericentre is gradually lowered to obtain increasing values of the peak dynamic pressure or heat flux at pericentre passage. The last walk-in manoeuvre aims at reaching the operational value of the peak dynamic pressure or heat flux, which triggers the beginning of the main phase.

2.2 Main Phase

The main phase is the longest phase of the aerobraking since it enables most of the apocentre altitude reduction. However, it is also the one that faces the most demanding orbit control issues, with the associated manoeuvre implementation. On one hand, the aerobraking has to be accomplished within a strict timeline, on the other hand, since the S/C does not have a thermal shield (which is the case of the aero-capture missions), care must be taken to assure that critical structural and thermal constraints be respected. These operational limitations are used as criteria for pericentre altitude control during the main phase. They include:

- **Peak value constraints at pericentre, applied to the dynamic pressure and the heat flux** (computed as in Eqs. 1-2, where ρ is the atmospheric density and *V* the velocity at pericentre passage). These control variables (or their average over more than one pericentre passage) should not step out of a pre-established control band.

$$p_{dyn_\max} = \frac{1}{2} \cdot \rho \cdot V^2 \qquad (1)$$

$$\dot{q}_{\max} = \frac{1}{2} \cdot \rho \cdot V^3 \qquad (2)$$

- **Heat load** (i.e. the integrated heat flux during each pericentre passage, computed as shown in Eq. 3), which converts into a solar panels temperature rise and must be kept always below a maximum allowed value.

$$\Delta Q = \int_{Atmospheric\ pass} \dot{q}\, dt \qquad (3)$$

During most of the aerobraking and in particular the main phase, the active constraints are the peak value constraints (dynamic pressure and heat flux), which are used as driving criteria for the pericentre altitude control, implemented by an ad-hoc apocentre manoeuvre strategy. Either the dynamic pressure or the heat flux may be chosen as control variable, since controlling one automatically means controlling the other as well. The need to respect these constraints and to assure a timely execution of the mission yields the definition of a control window. The higher boundary of this control interval is a safety threshold not to be trespassed (peak dynamic pressure translates into torque around the central body and therefore structural stress), while the lower boundary value drives the maximum duration of the aerobraking.

The control bandwidth on the peak dynamic pressure drives the number of control burns and their overall cost in terms of ΔV. A reasonable trade-off between these important factors and the overall duration of the aerobraking phase has to be performed. Indeed, an increase of the control bandwidth, while keeping fixed the higher boundary value of the interval, would yield a lower number of manoeuvres but, at the same time, a larger spread in peak dynamic pressure values and hence a longer aerobraking duration.

Towards the end of the aerobraking (endgame sub-phase) the increase of the atmospheric passes duration (due to the eccentricity lowering) is higher than the decrease of the pericentre velocity (due to the orbit shrinking), and therefore the heat load increases more and more until it becomes the driving control constraint. From that point onward, the control strategy must avoid that the heat load surpasses its maximum allowed value until walk-out phase is initialised.

2.3 Walk-Out Phase

This phase allows exiting the main aerobraking phase and achieving the desired final orbit. During the walk-out phase, a main safety issue is represented by the expected remaining lifetime of the S/C. **Lifetime** is the time required by the apocentre altitude to get below a threshold value (typically 300 km) during free orbit propagation. It is important that the lifetime be maintained above a minimum value (typically 1 or 2 days) during the whole aerobraking in order to account for possible contingency events (sudden loss of contact with the spacecraft or dust storm). So, when the expected lifetime gets below the minimum allowed, the main phase ends and the walk-out begins.

Each walk-out burn raises the pericentre altitude and yields a lower and lower peak dynamic pressure. In this way, the apocentre altitude reduces less and less at each orbit and, therefore, a fine-tuning of the final apocentre altitude can be easily achieved. Finally a last burn raises the pericentre altitude to the target final value, depending on the mission specifications.

3. AEROBRAKING MISSION ANALYSIS TOOL

3.1 Functionality Overview

The Aerobraking Mission Analysis Tool developed at DEIMOS Space is intended to simulate the whole aerobraking strategy as closely as possible to its implementation in operational mission scenarios. Therefore, it consists of three modules, each of which performs one of the three aerobraking phases described above.

The **orbit propagation** can be executed taking into account many perturbation effects such as:

- Non-spherical gravity (up to order and degree 50).
- Third bodies gravitational effects.
- Atmospheric drag (with possibility of selecting the atmospheric density model between MARSGRAM and EMCD V4.3).
- Solar radiation pressure.

The **pericentre control** is based on propagation predictions of the orbit evolution, taking into account the full set of perturbations. The methodology used to analyse the aerobraking phases is described below.

3.1 Walk-In Implementation

The walk-in is executed by specifying a set of input parameters. First of all, the user must specify the pericentre altitude to aim at after the first apocentre burn. This simulates the first approach with the Mars atmosphere. Secondly, the user must select the series of peak dynamic pressure values to be achieved after the corresponding walk-in burns, including the last peak dynamic pressure to be achieved at the end of the walk-in. The timing of the manoeuvres is given in input as well, by specifying at which apocentre number to execute them, counting from the beginning of the aerobraking simulation.

3.2 Main Phase Implementation

During the main phase, control on both the peak dynamic pressure at pericentre and heat load per pericentre pass is performed at the same time.

Referring to the block scheme of Fig. 2, the user must firstly specify a control interval (typically 1 or 2 days), which takes the meaning of minimum time gap (or minimum number of orbits) between control burns. The algorithm checks whether, during each control interval, either the peak dynamic pressure or the heat load constraints are violated. If that is the case, a burn at the initial apocentre of the control interval, makes the peak dynamic pressure and the heat load evolution comply with the control band. If no constraint has been violated, the algorithm propagates up to the next control interval where a similar check is performed.

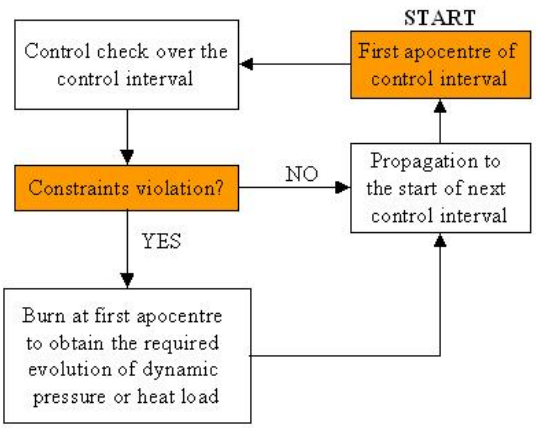

Fig. 2: Pericentre control loop scheme during aerobraking

While only one control action is foreseen for the **heat load compliance**, there exist two different strategies for the peak dynamic pressure control. For what concerns the former, the control burn aims at obtaining that the maximum registered heat load during the control interval be equal to the maximum allowed value. In such a way, the duration of the aerobraking is clearly minimised. The two available strategies for the **peak dynamic pressure constraint** are:

1) **Control on the average peak dynamic pressure**. It consists of checking whether the average peak dynamic pressure computed over the control interval (which generally includes more than 1 orbit) gets out of an input control band. If it does, a control burn at the initial apocentre of the control interval aims at obtaining that the average peak dynamic pressure be equal to some input target value (e.g. the mid point of the control band).

2) **Control on the highest peak dynamic pressure**. In this case, the algorithm checks whether the maximum registered peak dynamic pressure over the control interval gets out of an input control band. If it does, the control strategy aims at obtaining that the maximum registered peak dynamic pressure be restored equal to the maximum allowed value (which is the higher bound of the peak dynamic pressure band).

Though the algorithm can switch from a control on the heat load to a control on the dynamic pressure, this is not the case for real missions. Indeed, when the heat load constraint becomes active (towards the end of the aerobraking) it never turns off because of the natural evolution of the S/C orbit. When both constraints are violated, precedence is given to the heat load constraint. Only one exception to this rule applies, that is when the highest or average (depending on the strategy) dynamic pressure overcomes the higher control band boundary by a larger relative amount than the heat load. In that case a manoeuvre is executed to control the peak dynamic pressure evolution.

The algorithm always implements **control burns** by applying the ΔV parallel to the velocity at apocentre and its size is found through the use of a mathematical method aimed at achieving the target conditions (in terms of heat load or peak dynamic pressure) after manoeuvre execution.

The **remaining lifetime** is monitored during the final part of the aerobraking in order to trigger the transition from the main-phase into the walk-out when it gets below a given input value.

3.3 Walk-Out Implementation

The walk-out is executed according to a selected list of input parameters. They are essentially the same as those of the walk-in, except for one aspect. Instead of giving an initial pericentre altitude to be attained, here the user specifies which is the final altitude to be achieved after the last walk-out burn. Dynamic pressure values to be achieved and the time sequence of the burns present the same logic as in the walk-in execution. Care must be taken by the user to assure that the lifetime stays above a safety margin during the whole walk-out manoeuvre sequence and that the peak dynamic pressure values selected do not lead to heat loads higher than allowed. The latter case may occur since, towards the end of the aerobraking, heat load tends to increase almost monotonically.

4. ANALYSIS OF REPRESENTATIVE AEROBRAKING SCENARIOS

Two representative (ExoMars-like) aerobraking scenarios for the achievement of a target orbit around Mars have been analysed using the modelling and simulation capabilities of the Aerobraking Mission Analysis Tool. The results obtained are presented and analysed in order to show the tool potentialities.

4.1 Definition of the Aerobraking Scenarios

The representative aerobraking scenarios analysed are characterised by the following input definition data:

- Initial orbit apocentre altitude: 33310 km.
- Initial orbit pericentre altitude: 483 km.
- Initial inclination: 74.28º (Mars equator reference).
- Target science orbit: circular with 400 km altitude.
- Spacecraft initial mass: 1400 kg.
- Spacecraft aerodynamic cross section: 17.5 m^2.
- Free molecular flow drag coefficient: 2.0.

Both scenarios simulated present the same walk-in and walk-out profile, which is shown in Table 1.

Table 1: Input values for walk-in and walk-out phases

	Walk-in	**Walk-out**
Nº burns	6	3
Initial pericentre altitude (km)	150	N/A
Final pericentre altitude (km)	N/A	400
Dynamic pressures (N/m^2)	[0; 0.10; 0.15; 0,20; 0.25; 0.30]	[0.05; 0.025; 0.0]
Control burns time sequence (apocentre)	[1st; 3rd; 5th; 7th; 9th; 11th]	[1st; 20th; 40th]

The walk-in consists of six burns, the first of which yielding a pericentre altitude of 150 km and occurring at the first apocentre of the aerobraking. Then, respectively at the 3rd, 5th, 7th, 9th and 11th apocentre, control burns gradually raise the peak dynamic pressure at pericentre to respectively 0.10, 0.15, 0.20, 0.25 and 0.30 N/m^2. For what concerns the walk-out, the control burns occur at the 1st, 20th and 40th apocentre since the end of the main phase and yield peak dynamic pressures of respectively 0.05, 0.025 and 0.0 N/m^2. The final pericentre altitude achieved is 400 km.

For what concerns the main phase, the two scenarios analysed differ in terms of the dynamic pressure control strategy, as shown in Table 2.

The chosen control interval duration is 2 days, meaning that, during the main phase, control burns are separated in time by at least 2 days.

Table 2: Main-phase parameters for the 2 scenarios.

	Scenario Nº1	Scenario Nº2
Control interval duration (days)	2	2
Dynamic pressure controlled variable	Average peak dynamic pressure	Highest peak dynamic pressure
Dynamic pressure control band (N/m^2)	[0.25, 0.30]	[0.27, 0.32]
Dynamic pressure target value (N/m^2)	0.275	0.32
Maximum allowed heat load (MJ/m^2)	0.25	0.25
Minimum allowed lifetime (days)	1.5	1.5

For the scenario Nº1, a control strategy based on the average peak dynamic pressure has been chosen. The control band has been set to [0.25, 0.30] N/m^2, whereas, when activated, the control aims at obtaining an average value of the peak dynamic pressure of 0.275 N/m^2 during the control interval. For the scenario Nº2, the control strategy based on the highest registered peak dynamic pressure has been selected. In this case the control band is set to [0.27, 0.32] N/m^2, but, this time, it acts over the maximum peak dynamic pressure in the control interval. Whenever the control is applied, the highest peak dynamic pressure is restored to 0.32 N/m^2.

For both scenarios, a maximum allowed heat load of 0.25 MJ/m^2 and a minimum allowed lifetime of 1.5 days (triggering the exit from the main phase) have been selected.

Orbit propagation takes into account the following effects:

- Non-spherical gravity due to Mars J2.
- Sun gravity perturbation.
- Atmospheric drag modelled with EMCD V4.3 Mars atmosphere model ([5]).

4.2 Aerobraking Analysis Results

The evolutions of the pericentre altitude, of the peak dynamic pressure / heat load and of the longitude / latitude of the sub-satellite point at pericentre passage are presented and analysed for each of the two simulation scenarios.

Fig. 3 shows the evolution of both the longitude and the latitude of the sub-satellite point at pericentre passage.

At each pass, the longitude generally changes by a great amount and without any recognizable pattern, except when there is a resonance between the spacecraft orbital period and the Mars sidereal rotation period. This occurs at the beginning (where the orbit period is slightly lower than 1 sol, or one Mars sidereal day), but also later on when 1/2, 1/3, 1/4, 1/5 (and so on) resonance occurs.

For what concerns the latitude, it starts from an initial value close to the equator, then it increases up to a maximum value of around 73º and finally decreases down to approximately 20º. Fig. 4 shows a very similar evolution for both the latitude and the longitude for scenario Nº 2.

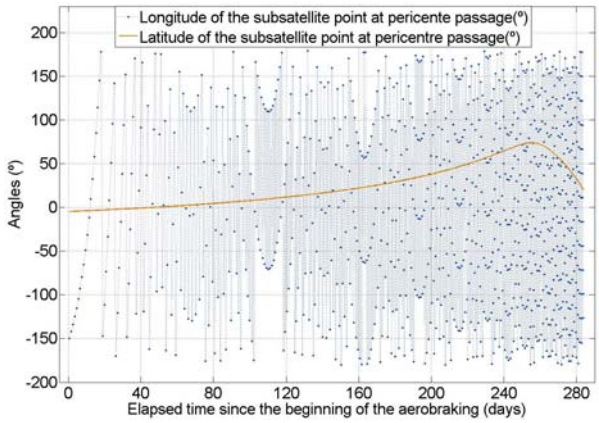

Fig. 3: Evolution of the sub-satellite point location on Mars at pericentre passage for scenario Nº1.

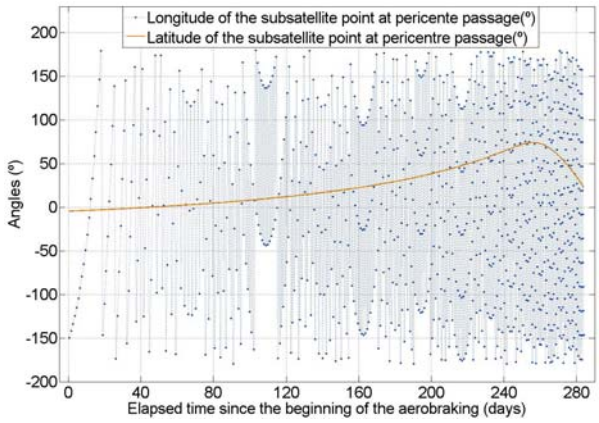

Fig. 4: Evolution of the sub-satellite point location on Mars at pericentre passage for scenario Nº2.

Fig. 5 and Fig. 6 show the evolution of the pericentre altitude during the whole aerobraking for scenarios 1 and 2. The evolution is similar, except for the total number of control burns, which is slightly higher in scenario Nº 2. Every vertical line represents one control burn, whose effect is a pericentre altitude leap (towards higher or lower values). The pericentre altitude is both shown as height above Mars equatorial reference radius (3395.515 km) and height above the local Mars areoid (Mars equipotential surface).

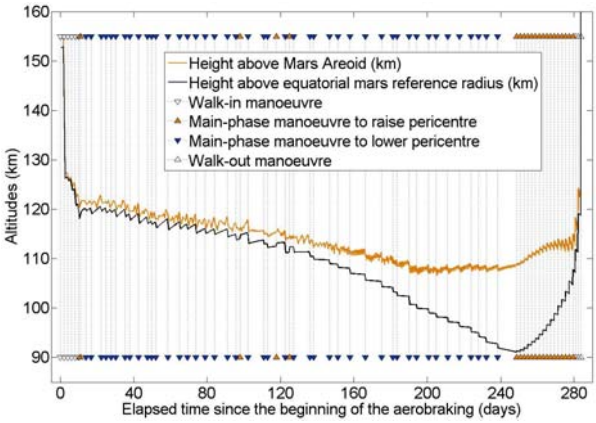

Fig. 5: Evolution of the pericentre altitude during the aerobraking for scenario Nº1.

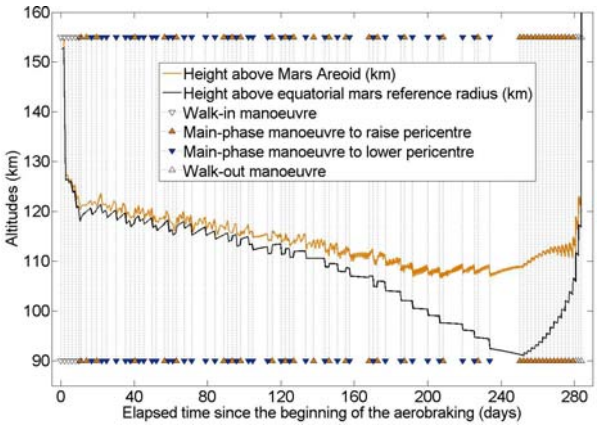

Fig. 6: Evolution of the pericentre altitude during the aerobraking for scenario Nº2.

During the walk-in, the pericentre altitude decreases from a first value of approximately 150 km (as indicated in Table 1) to a starting main-phase altitude of around 120 km. Then, the majority of burns tend to lower the pericentre altitude, as shown by the down pointing cursors at the manoeuvres epochs in Fig. 5 and Fig. 6.

In scenario Nº1 only 4 upward control burns are applied before the endgame starts (this is the final part of the aerobraking main phase when the heat load becomes the driving constraint). The pericentre altitude above the reference radius lowers almost monotonically and reaches its minimum exactly when the latitude of the pericentre is highest. Here the difference with respect to the altitude above the Mars areoid is highest. The reason for this behaviour is that Mars presents an ellipsoid shape and hence lower radiuses at higher latitudes. Therefore, as far as the latitude increases, in order to achieve a nearly constant atmospheric density or altitude above the areoid, the pericentre altitude above the reference radius must diminish.

The situation reverses when the heat load becomes the driving constraint and therefore the pericentre altitude is constantly increased through upward manoeuvres. The endgame lasts approximately 30-35 days and it ends once the lifetime limit is reached. Then the main phase is exited and the walk-out executed. The final burn yielding a pericentre altitude of 400 km is partially displayed because out of scale.

Fig. 7 shows the evolution of the controlled variables during the aerobraking for scenario Nº1, i.e. the scenario where the average peak dynamic pressure is controlled. Both the evolution of the peak dynamic pressure and heat load is shown. The aerobraking strategy controls the average of the dynamic pressure value bringing it to the mid point of the control band [0.25, 0.30] N/m^2 whenever it would otherwise step out of this interval. The effect is a nearly constant mean dynamic pressure, though the punctual value may occasionally rise to values as high as 0.37 N/m^2, or as low as 0.19 N/m^2. This noise is due to the extremely variable atmospheric conditions with longitude.

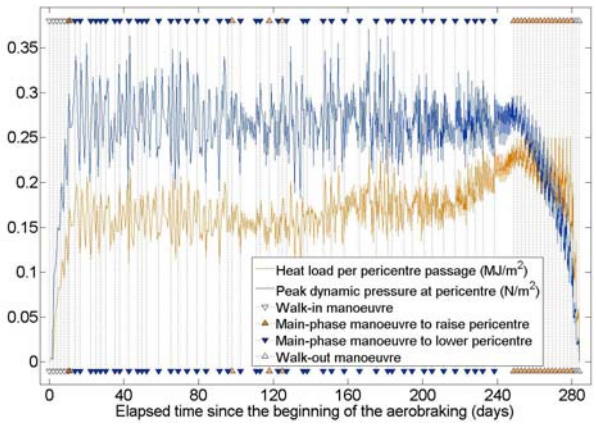

Fig. 7: Peak dynamic pressure and heat load evolution during the aerobraking for scenario Nº 1.

Near day 250, the heat load becomes the driving constraint and control is always executed every control interval (2 days) because this aerobraking phase is characterized by a monotonic increase of the heat load. Therefore, control aims at reaching the highest allowed heat load at the end of each control interval. The effect on the dynamic pressure is to lower it from the mid point of the control band to values as low as 0.1 N/m^2, when the main phase is exited and the walk-out begins.

The first walk-out burn brings the peak dynamic pressure to 0.1 N/m^2 and after 20 orbits a second burn further lowers it to 0.05 N/m^2. Finally, after another 20 orbits, the pericentre is raised to the 400 km science orbit altitude and both the peak dynamic pressure and the heat load drop to 0.

A similar behaviour characterizes the scenario Nº2, shown in Fig. 8. Here the controlled variable is the highest registered peak dynamic pressure in the control interval. After each burn, the peak dynamic pressure assumes the value 0.32 N/m^2. With respect to scenario Nº1, more upward burns are executed. Indeed, while in scenario Nº 1 the control trigger is the mean dynamic pressure evolution over 2 days, in scenario Nº 2 no such an averaging-out effect exists and control is executed any time a single dynamic pressure value would get out of the control band during the control interval. Though the overall cost and number of manoeuvres is slightly higher than in strategy Nº 1 (the whole aerobraking takes 7 manoeuvres and 2 m/s more), strategy Nº 2 allows controlling exactly the highest punctual values of the peak dynamic pressure.

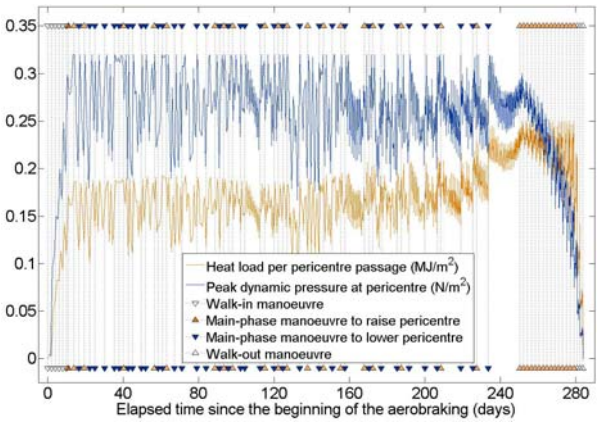

Fig. 8: Peak dynamic pressure and heat load evolution during the aerobraking for scenario Nº 2.

Fig. 9 shows the evolution of the heat load and peak dynamic pressure during the walk-in phase. The gradual increase of the dynamic pressure to respectively 0.1, 0.15, 0.20, 0.25 and 0.30 N/m^2 can be clearly identified. The heat load curve is shifted half a day to the right, because heat load is updated at the following apocentre, half an orbit later than the peak dynamic pressure, which is evaluated at pericentre.

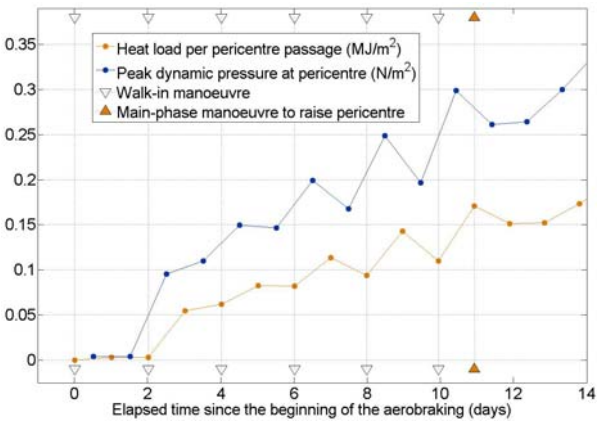

Fig. 9: Walk-in zoom for scenario Nº 1.

Fig. 10 shows a zoom into the endgame and walk-out phases for the scenario Nº1. The natural increase tendency of the heat load between the control burns and the walk-out control burns execution are highlighted.

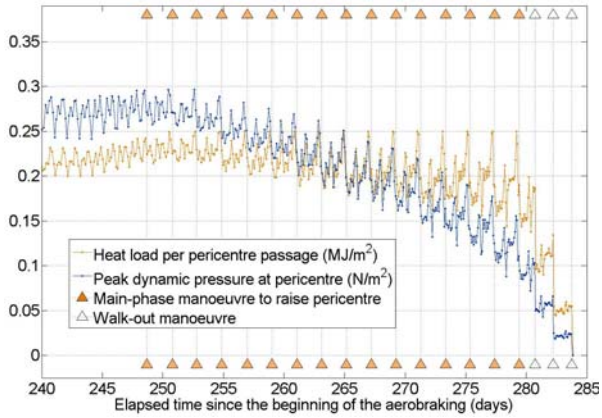

Fig. 10: Endgame and walk-out zoom for scenario Nº 1.

Finally, a summary with the overall performance statistics for both aerobraking scenarios is shown in Table 3.

Table 3: Summary of the analysis results for both scenarios

	Scenario Nº1	Scenario Nº2
Aerobraking duration (days)	**283.8**	**283.8**
Walk-in ΔV (m/s)	21.1	21.1
Total number of main-phase control burns	64	71
Average time gap between main-phase control burns (days)	4.2	3.8
Main-phase ΔV (m/s)	10.1	11.4
Walk-out ΔV (m/s)	67.5	68.0
Overall aerobraking ΔV (m/s)	**98.6**	**100.5**

5. CONCLUSIONS AND FOLLOW-ON DEVELOPMENTS

The Aerobraking Mission Analysis Tool developed by DEIMOS Space has been used to perform a set of analyses of representative aerobraking scenarios for ExoMars-like missions, dealing with the associated phases, key drivers and relevant operational constraints.

The results obtained encompass aerobraking ΔV budget, duration and operational implications, and they

are intended to draw the roadmap for an exhaustive assessment of the aerobraking scenario for future Mars exploration missions. In particular, the analysis capabilities provided by the Aerobraking Mission Analysis Tool have yielded the following relevant achievements:

- Operational-like simulation of the aerobraking strategy with subdivision into walk-in, main phase and walk-out.
- Predictive algorithm implementation for checking constraints and executing control burns.
- Definition of two control strategies on the peak dynamic pressure at pericentre passage: one controlling the average peak dynamic pressure, the other the highest peak dynamic pressure.
- Automatically computed switch from peak dynamic pressure constraint to heat load constraint to trigger the corresponding control method.
- Results yielding a relatively low number of control burns (60-70) and a low ΔV cost (approximately 10 m/s plus walk-in and walk-out cost).

The results presented in this paper are based on a single-shot aerobraking simulation. However, since the knowledge of the Martian atmosphere is affected by considerable uncertainties (which become patent when one compares the predicted values of the density with the measured ones during real mission operations), this single shot simulation is useful only to build a nominal aerobraking mission scenario.

Future developments and enhancements of the Aerobraking Mission Analysis Tool are envisaged to include the following additional functional components:

- Monte Carlo module, which would run a certain number of aerobraking simulations, handling random generated perturbations of the Mars atmosphere, random burn implementation errors (which are now assumed to be zero), etc. Such a statistical analysis would provide a very good sensitivity assessment about the environment and system conditions expected in an operational aerobraking scenario.
- Navigation module, which would cover measurement modelling, covariance analysis, orbit determination, and potentially also a Periapsis Time Estimation (PTE) algorithm to be used for the simulation and analysis of aerobraking scenarios based on an increased autonomy level (currently put forward for future Mars exploration missions).

6. REFERENCES

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