Technical Note

Executive Summary Report

Inflatable Systems for Aerocapture and Aerobraking

EUROPEAN SPACE AGENCY CONTRACT REPORT

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Prepared by:	Tiago Hormigo			Spin.Works
Revised by:	-			Spin.Works
Approved by:	Francisco Câmara			Spin.Works

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Spin.Works, S.A. **Av. da Igreja nº42, 6º** **1700-239 Lisboa** **PORTUGAL**	**European Space Research and Technology Centre (ESTEC)** **Keplerlaan 1** **2200 AG Noordwijk** **The Netherlands**	

Prepared by	*Revised by*	*Approved by*
Tiago Hormigo Spin.Works	Francisco Câmara Spin.Works	Tiago Hormigo Spin.Works

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1 INTRODUCTION

1.1 PURPOSE OF THE DOCUMENT

This technical note presents the final report for the work carried out within the WP5200 of ESA's "Inflatable Systems for Aerocapture and Aerobraking" activity and under Contract No. 4000131730/20/NL/GLC/vr.

1.2 LIST OF ACRONYMS

Acronym	Description
AOCS	Attitude and Orbit Control System
CD	Drag coefficient
CFD	Computational Fluid Dynamics
CGG	Cool Gas Generator
CMG	Control Moment Gyroscope
FEM	Finite Element Model
IPFN	Institute for Plasmas and Nuclear Fusion
IR	Infra Red
IRVE	Inflatable Reentry Vehicle Experiment
MADSIM	Mission Analysis and Design Simulator
MLI	Multi Layer Insulation
PFA	Perfluoroalkoxy alkane
SPARK	Simulation Platform for Aerodynamics, Radiation and Kinetics
TCW	Total Corridor Width
TGO	Trace Gas Orbiter
TPS	Thermal Protection System
VDA	Vapor Deposited Aluminium

Table 1: List of Acronyms

1.3 APPLICABLE DOCUMENTS

Ref.	Document Title	Code	Issue	Date
[AD1]	"19-D-S-OPS-02 Study of inflatable devices to employ atmospheric drag for orbital manoeuvres at planetary arrival"	Appendix 1 to ESA AO/1-10170//20/NL/GLC/vr	1.2	03/02/2020
[AD2]	Spin.Works' Technical Proposal in response to ESA's AO10170 – "Inflatable Systems for Aerobraking and Aerocapture"	SPIN-ISAA-TPR-001	1.0	04/05/2020
[AD3]	Kick Off Meeting	SPIN-ISAA-PRES-ESA-KOM-1.0	1.0	02/09/2020

Table 2: Applicable Documents

1.4 REFERENCE DOCUMENTS

N/A.

2 EXECUTIVE SUMMARY

Since the turn of the millennium, ESA has joined the ranks of the space agencies exploring our planetary neighbours. While European missions prior to 2000 initially targeted a minor body and the surface of the moon of an outer planet, Europe has greatly expanded its ambition in the field of planetary exploration, having since placed two orbiters around Mars (both still in operation) and one around Venus, having also carried out a lunar orbiting mission, a comet explorer and made two attempts at landing on Mars. It is currently preparing to launch yet another landing mission to the Red Planet as well as n orbiter later this decade, the latter of which as part of an ambitious partnership with the US to bring back samples from the Red Planet. Finally, it is developing its' own lunar lander and is closing in on the launch of an ambitious mission to explore the icy moons of Jupiter, which will initiate a new era not just in planetary exploration but, very likely, in astrobiology.

Planetary exploration in Europe, in summary, has been advancing significantly over the past two decades. This has also occurred at a time when multiple trends (political, technological and economical), are contributing to the boldest space agendas and the largest space-oriented private investments in history. In several fields, an intense effort towards the development of new technologies is likely to be required as Europe seeks to keep a degree of leadership in this new era of innovation in space, especially those aimed at creating new mission opportunities and scenarios.

Many such technologies have only been previously theorized, while others have been assessed to some extent but not yet tested under representative conditions. The present activity aimed at fleshing out the benefits of a potential new approach (the use of inflatable devices) to carrying out a technique often discussed and highly promising but not yet demonstrated, aerocapture, and another technique which has already proven itself in two past missions (Venus Express and Exomars Trace Gas Orbiter), aerobraking.

Our work has primarily focused on establishing scenarios where inflatable devices could be the most useful. Given that these missions rely on aerodynamic drag that results in (potentially significant) heating, we have sought to find solutions to minimize heat fluxes acting on the device surface, and especially keeping it within the limits of flexible/foldable TPS materials for the aerocapture scenario. A second key challenge has been to minimize the mass per unit area, given that the most important way in which an inflatable contributes to a lower heating is by having a large surface (ensuring aerodynamic braking occurs at a lower atmospheric density).

For each of the scenarios we have established for future Mars and Venus missions we have sought to use the simplest approaches and to change the least possible relative to past missions. The scenarios we have set up are (see chapter 3):

- S1: Accelerated Aerobraking
- S2: Aerocapture using Drag-Modulation
- S3: Aerocapture using Lift-Modulation

In the first case, we have opted with adding a large trailing ballute that would operate at a maximum dynamic pressure similar to that demonstrated with the Exomars Trace Gas Orbiter at Mars. In the second and third scenarios, and given the obvious control authority limitations caused by being restricted to a single modulation event, we have both targeted a higher post-aerocapture orbit altitude and added a short aerobraking period in each case to reach the final operational orbit.

A multidisciplinary effort with several trade-offs was carried out to investigate potentially feasible configurations taking into account multiple aspects, such as mission analysis, materials engineering, structural & thermal design, aerothermodynamics modelling (Continuous + free molecular flow) and flight stability analysis, resulting on two solutions (see chapter 4):

- Square-shaped trailing ballute for accelerated aerobraking
- Blunted sphere-cone (using stacked toroid) for aerocapture

In this study we identified the main obstacles to further improvement using these approaches. On Venus, the orbital velocity is so high (10-11km/s) - and the atmospheric density scale height for the altitudes at which aerobraking and aerocapture occurs (100-150km) so small (~5km) – that any targeting error or atmospheric density perturbation can easily translate onto excessive heating. A significant margin needs to be imposed on the nominal trajectory such that off-nominal trajectories will still stay within the allocated heat rate bounds. And as such, given the significant mass that the proposed aerocapture devices already have, little room exists for further improvement.

On Mars, peak heating is only about 1/6 of Venus for a viable inflatable aerocapture device – however, stability requirements applied to our blunted sphere-cone design impose a reference surface higher than 140m^2. This does not prevent a system mass which is competitive with chemical propulsion for orbit insertion; however, if the spacecraft to be enveloped using the proposed ballute was redesigned to place the center of mass further towards its' nose, an area of as little as 1/3-1/4 of the current size could result, something which would represent a significant improvement over both using chemical propulsion for orbital insertion and using a rigid aeroshell to protect the main spacecraft.

Finally, in the scope of this activity we have demonstrated the feasibility of using a single-event drag or lift modulation device for aerocapture. Although such devices are not as accurate as one capable of continuous aerodynamic drag or lift modulation they are also much simpler to manufacture, and have enough control authority to compensate for dispersed entry conditions, aerodynamic property uncertainties and atmospheric perturbations and to ensure that the post-insertion orbit altitude dispersion will be on the order of 100m/s (1-sigma). While already reasonably precise, the control authority can be further improved with higher pre-to-post modulation event aerodynamic surfaces (drag modulation case – currently β_1/β_2 is ~2.15) or higher lift-to-drag (lift modulation case – currently the L/D is ~0.2).

- **Key questions addressed in the study**

As part of the study we have sought to address a number of questions posed in the activity's statement of work, for which we have found the following answers at this closing point:

Q1: Is it possible to develop an inflatable device for aerocapture that incurs an overall system mass that is significantly lower than that of the propellant? In which conditions?

A1: It is possible to develop an inflatable device for aerocapture with an overall system mass lower than that of the propellant. Such is the configuration we designed for Mars and using a single-event lift modulation configuration. If stability requirements were relaxed, we could furthermore design a feasible system that would be significantly lighter than what we found, and which could perform a mass-efficient aerocapture using either drag or lift modulation.

Q2: Would an inflatable device supporting only aerobraking, not aerocapture, offer significant advantages in terms of a) mass, 2) ease of manufacturing and 3) operations?

A2: a) an improvement in mass is almost impossible if the comparison is made with missions in which long aerobraking campaigns as those in Exomars TGO (>300 days) or the one planned for Envision (>500 days) follow orbit insertion, and in which propellant expenditure is minimal. However, aerobraking campaigns can be significantly accelerated for a limited additional mass.

b) The configurations found are comparatively easy to manufacture.

c) Operations could work similarly to existing missions, without restrictions on communication. Attitude control is feasible using control moment gyros. Power production during these periods is a challenge that was not tackled.

Q3: Would it be possible to combine both by using the same device during aerocapture and later for aerobraking? Which constraints would apply in this case and how would that affect overall performance?

A3: It is possible to combine both in succession as we have suggested in scenarios S2 and S3. Constraints similar to those referred in the previous question would then apply.

The next sections in this report focus on the scenarios established for the activity (chapter 3) and the selected vehicle configurations (chapter 4). The final section (chapter 5) summarizes the outcome of our studies.

3 SCENARIOS

The scenarios elaborated for the inflatable systems designs consisted of three different types of planetary arrivals. The first scenario stems from the assumption that performing classical aerobraking with increasingly heavier spacecraft in the future will cause a large delay to the start of science operations, which can potentially be shortened to as little as 90 days for Venus and 28 days for Mars in case an inflatable aerobraking system is used instead.

The second and third scenarios focus on planetary arrivals through aerocapture, followed by a period of aerobraking (both to compensate for any dispersion in the aerocapture manoeuvre and to further reduce orbital altitude until the operational orbit is achieved). A single event has been assumed as the only means of regulating the orbit dispersion resulting from aerocapture: for the second scenario this event is a change in aerodynamic surface (the maximum tolerable change according to our calculations – this is explained next), while for the third scenario the event consists of a change in the signal of aerodynamic lift relative to the local vertical.

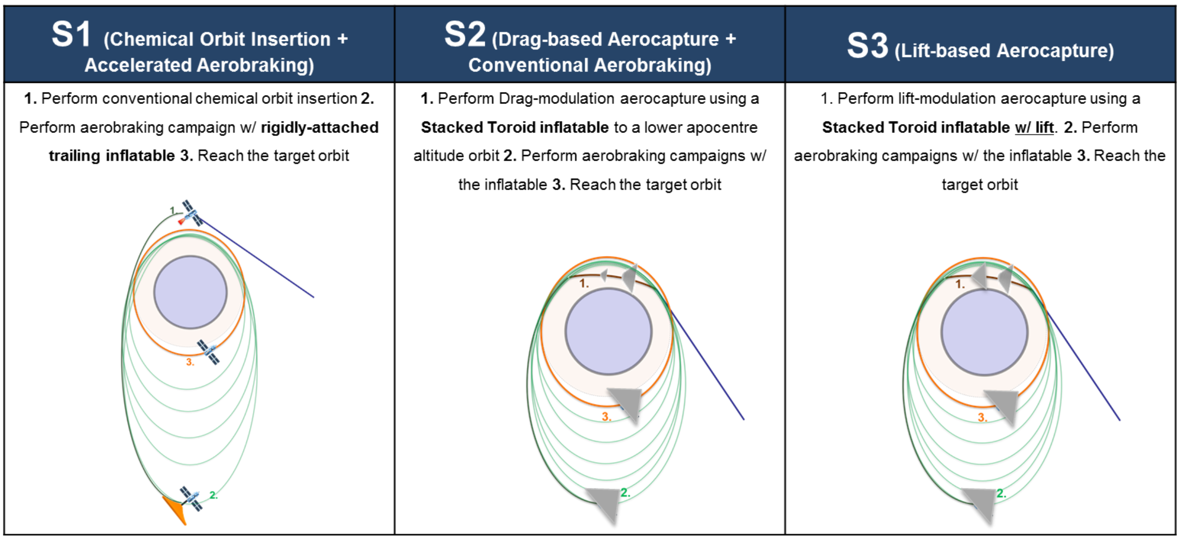


Figure 1: The three scenarios studied in the ISAA activity.

Both the first, second and third scenarios have been extensively analysed. The integrated design is presented in the next section, and the key performance indices are shown in the final section of this chapter.

3.1 ACCELERATED AEROBRAKING (S1)

In this scenario, a planetary spacecraft enters a high Martian or Venusian orbit via a chemical orbit insertion manoeuvre. Then, instead of using further propulsive manoeuvres to reach a low orbit around the planet, a large trailing inflatable is deployed (see Figure 2) to enhance aerodynamic drag.

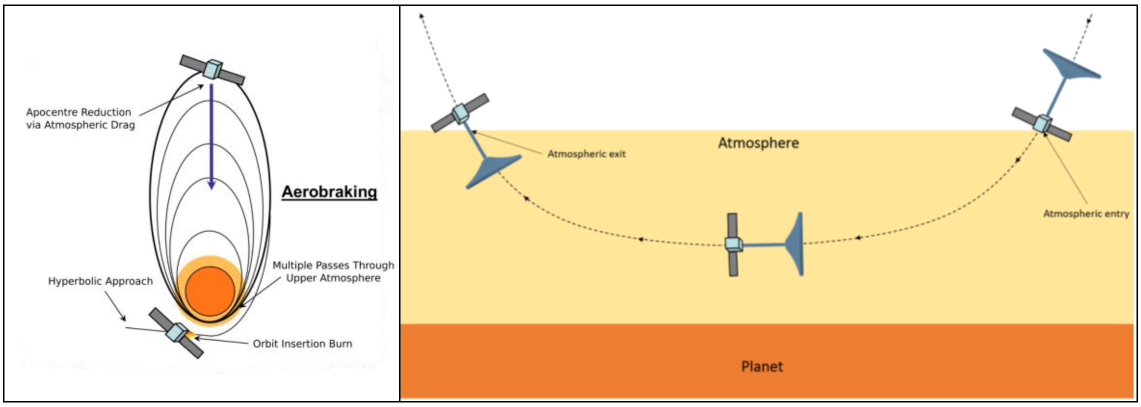


Figure 2: An aerobraking campaign (left), with each atmospheric pass during the accelerated aerobraking sequence illustrated on the right.

The final orbit would then be achieved over the course of a short aerobraking period (~90days for Venus using an Envision-like vehicle and flying at no more than 0.3N/m^2 dynamic pressure, and ~28 days for Mars using a TGO-like vehicle and the same 0.3N/m^2 dynamic pressure), in each case by performing consecutive atmospheric passes permanently attached to the device. In the periods outside the atmosphere, control moment gyros would allow for effective attitude control, namely to achieve the right attitude for communications, to perform pericentre refinement manoeuvres, and to ensure a proper attitude prior to each atmospheric pass.

The maximum dynamic pressure allowed for a Martian or Venusian accelerated aerobraking campaign would be similar to existing systems, as would heating. Accelerations would however be an order of magnitude higher (on the order of several m/s per atmospheric pass). As a result, the final science orbit would in the proposed scenario be achieved in tens of days, as opposed to the hundreds of days when using conventional means (chemical orbit insertion + aerobraking using the spacecraft solar arrays only). The mass of such a system would be about 177kg for Mars, or 190kg for Venus.

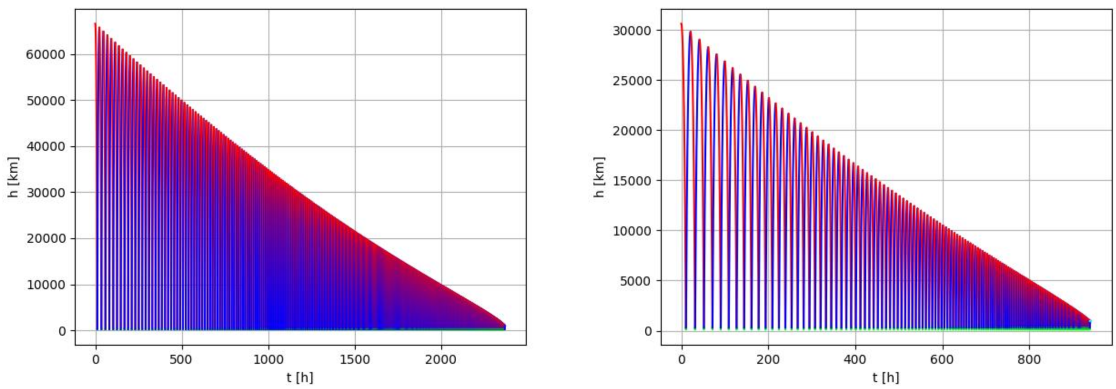


Figure 3: Aerobraking altitude evolution over time during an example of an Accelerated Aerobraking campaign at Venus (left) and Mars (right) respectively, starting from an elliptical 24hr orbit, and using the proposed trailing ballute design.

3.2 Drag-Modulation Aerocapture & Aerobraking (S2)

The second scenario studied corresponds to an arrival at the target planet where a large blunted sphere-cone inflatable in a stacked toroidal configuration is deployed by the main spacecraft, enveloping it nearly completely to protect it from the severe thermal conditions sustained in a deep atmospheric pass.

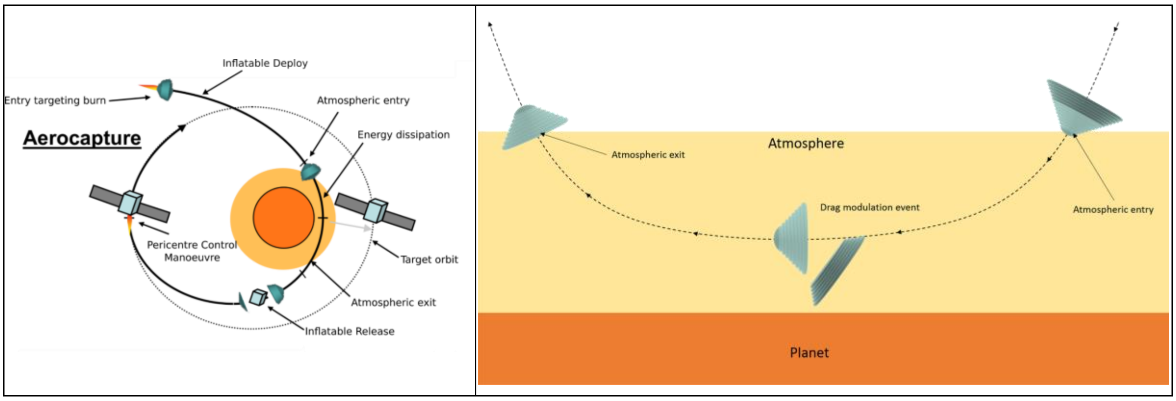
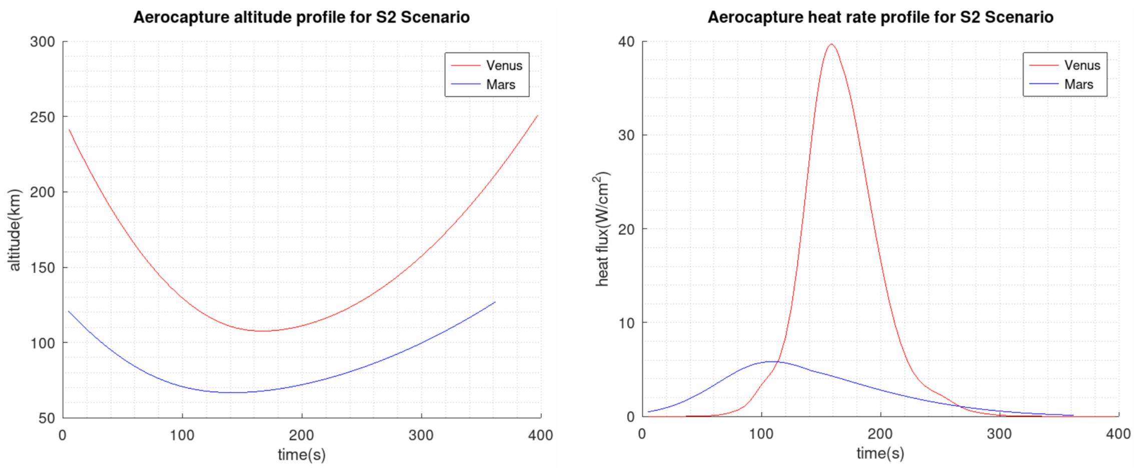


Figure 4: Aerocapture using drag-modulation scheme. The exact location of the separation event is calculated according to the measured atmospheric conditions shortly after entry.

At a specific time during atmospheric flight, a single modulation event releases a significant part of the effective area of the inflatable in order to remove most of the atmospheric drag and achieve a pre-defined orbit. A subsequent (short) aerobraking phase is used to place the vehicle in its' final scientific orbit.

Aerocapture takes approximately 350-400s at both Mars and Venus and in both cases a similar Delta-V (1.6-1.7km/s) is achieved. The associated heat rates are significantly different between Venus (about 40W/cm^2) and Mars (6W/cm^2). The accelerations are strongly modified during an atmospheric pass for both cases.



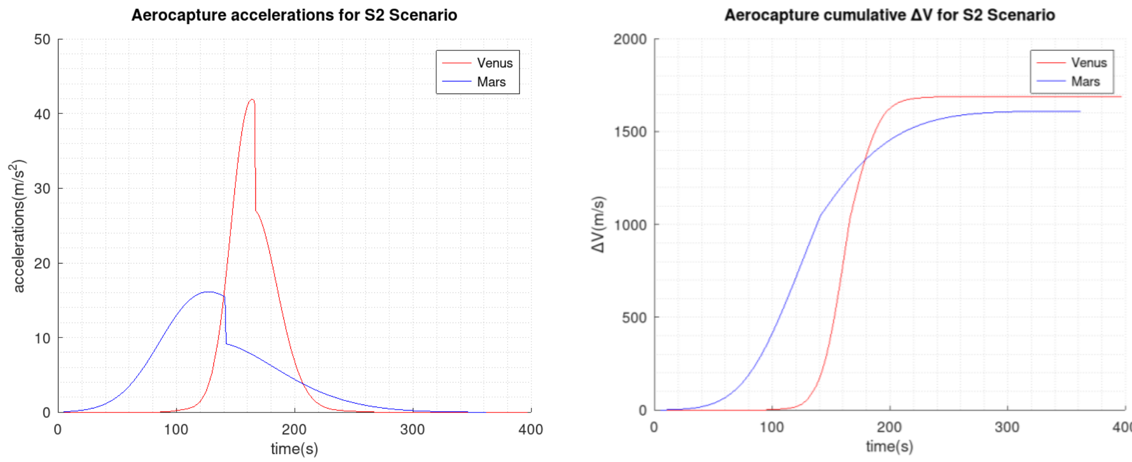


Figure 5: Nominal altitude, heating rates, accelerations and cumulative DV for S2 aerocapture scenario.

Once aerocapture is completed, an aerobraking campaign follows to reach the final operational orbits. Shorter Venus passes involving much higher heat rates for Venus contrast with slightly deeper, longer atmospheric passes at Mars with lower heating, yielding a delta-V per pass on the order of 2.6m/s at Venus and ~6m/s at Mars.

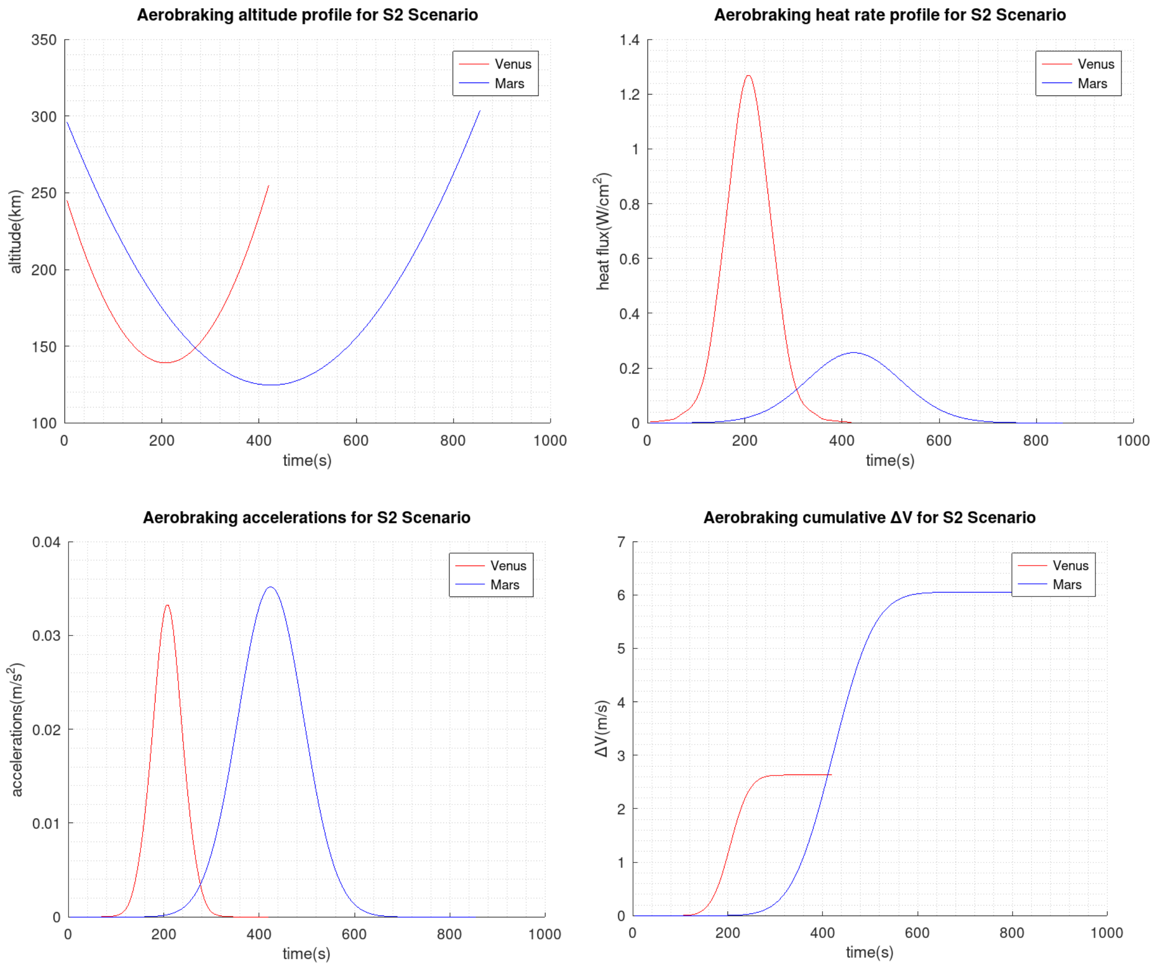


Figure 6: Nominal altitude, heating rates, accelerations and cumulative DV for a single atmospheric pass in the S2 aerobraking campaign.

3.3 Lift Modulation-based Aerocapture + Aerobraking (S3)

In the third scenario, the main spacecraft performs aerocapture using a similar type of vehicle as in the case of S2, but which has an inflatable aerodynamic control surfaces which initially produce a small positive lift to the vehicle. A single event at some point in the atmospheric pass (a time which is determined by the onboard computer) reverses the lift vector in order to shorten or lengthen the period that the vehicle is kept inside the atmosphere, so as to enter the pre-defined initial planetary orbit.

A subsequent (short) aerobraking phase is used to bring the spacecraft to its' final scientific orbit.

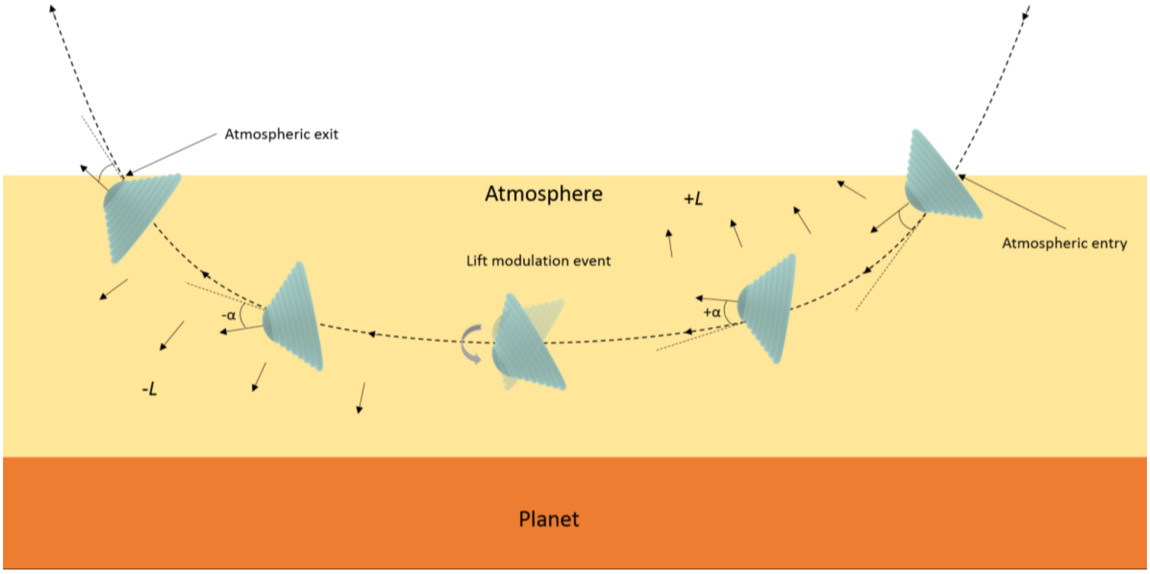


Figure 7: Aerocapture using lift-modulation scheme. The exact location of the modulation event is calculated according to the measured atmospheric conditions shortly after entry.

In the present study we have concluded that lift modulation is a very efficient means of performing aerocapture. In fact, and as shown in Figure 8, using the Total Corridor Width (TCW), peak drag and peak heat flux as key performance indicators, a lift modulation-based device with a modest lift-to-drag ratio of 0.2 produces lower decelerations and lower peak fluxes, as well as similar TCWs, as a drag-modulation device with a 20:1 area ratio between initial and post-separation event – a number which has proven infeasible to produce in our activity, given the constraints on mass (larger area) and stability requirements (smaller area) which limit the vehicle area at both ends.

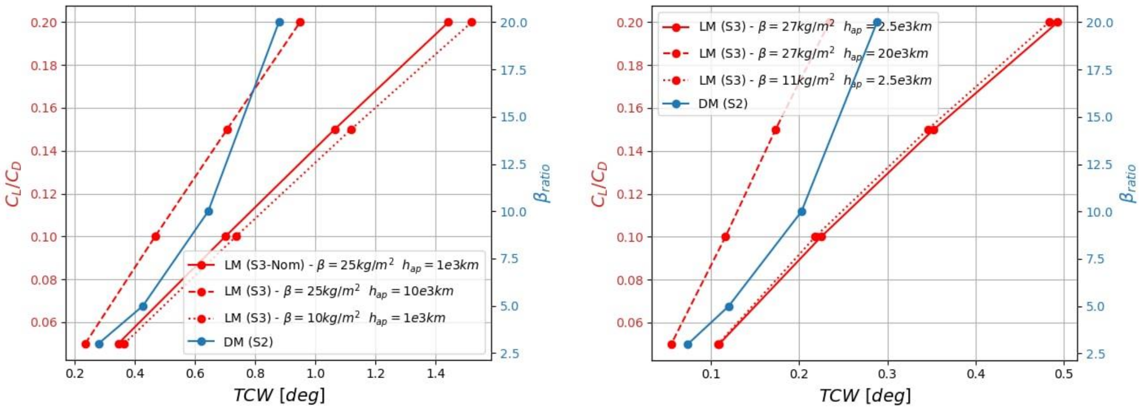


Figure 8: Comparison of the TCW between the drag and lift modulation strategies for Mars (left) and Venus (right)

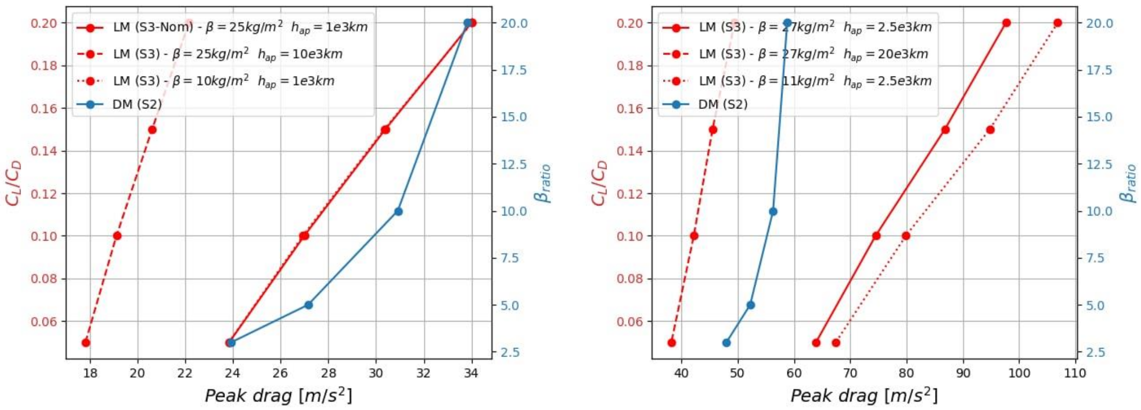


Figure 9: Comparison of the peak drag between the drag and lift modulation strategies for Mars and Venus.

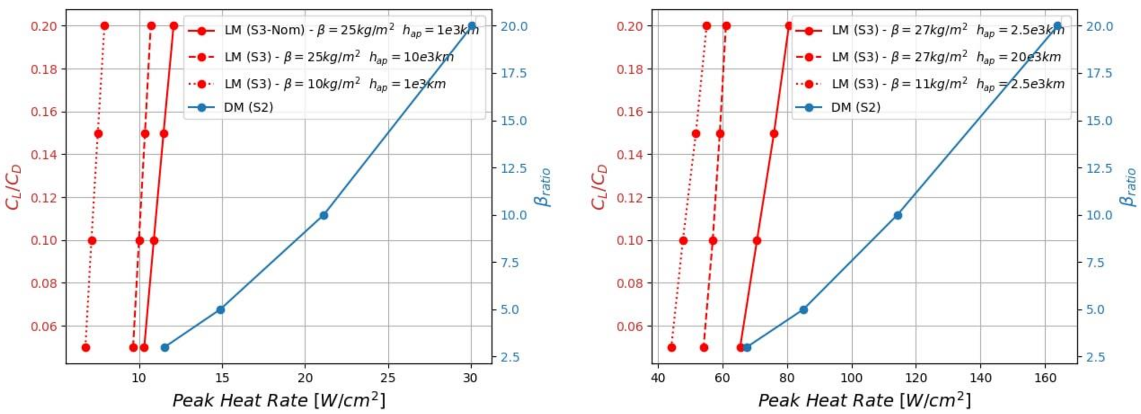


Figure 10: Comparison of the peak heat rate between the drag and lift modulation strategies for Mars and Venus.

Although a lift-modulation device poses design challenges, the lift modulation configuration (scenario S3) was deemed a more feasible solution for aerocapture than drag modulation.

The S3 scenario aerocapture takes slightly more than in S2 (about 400s at both Mars and Venus) for a similar Delta-V (1.6-1.7km/s). Heat rates are again higher for Venus (>40W/cm^2, still lower than the 75W/cm2 constraint) than for Mars (just over 7W/cm^2).

For the lit modulation scenario, we have chosen a lift-up attitude initially and only then a lift-down one such that the atmospheric pass is longer and that there are less pronounced acceleration peaks than in the alternative case (lift-down, then lift-up).

The steeper entry trajectory for the S3 case also results in higher and earlier peak heat fluxes as compared to the S2 scenario.

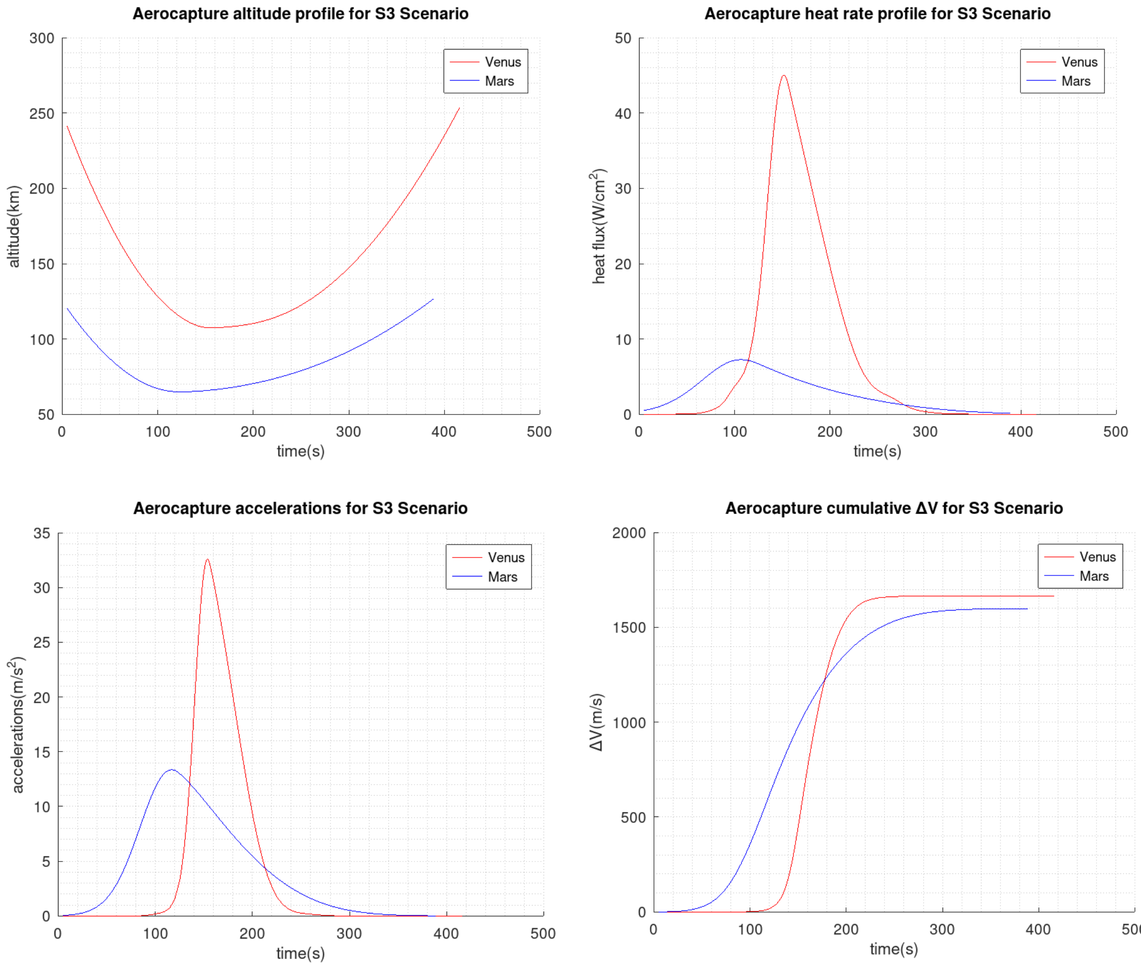


Figure 11: Nominal altitude, heating rates, accelerations and cumulative DV for the S3 aerocapture scenario.

The subsequent orbit reduction campaign using aerobraking is equivalent to the S2 case, given that the same configuration (blunted sphere-cone) and aerodynamic reference area (140m^2) is used. Therefore there is no need to reproduce the same outputs here.

4 VEHICLE CONFIGURATIONS

4.1 TRAILING BALLUTE

The trailing ballute concept is the simpler of the two concepts and is most suited to an accelerated aerobraking mission. It is meant to use the lightest possible material that can accommodate the heating conditions during an atmospheric pass, and which can still become rigid once deployed (to facilitate attitude control of the composite during exo-atmospheric phases). It has been sized to meet similar dynamic pressures as those in past missions, about 0.3N/m^2 (so that even if the concept fails/detaches at any given point, the spacecraft still has a high probability of surviving the subsequent atmospheric conditions).

A container is placed at the back of the host spacecraft for the interplanetary transfer to Venus or Mars until after orbit insertion (and possibly an orbit reduction manoeuvre), after which the device is deployed. The main components are the container itself, the inflation system containing the gas that is meant to fill the inflatable structures, the inflatable structure itself, the thermal protection system which is a coating in this case, and the sail-like structure that extends to cover about 185m2 (for the Venus case) and 160m2 (for Mars).

This concept as presented results in an inflatable mass which is less than 200kg in both cases (190kg for the Venus design, and 177kg for the Mars design). The design corresponds to reference areas which were calculated to compress any aerobraking campaign to less than 100 days at Venus starting from a orbit of a 24hr period, and to less than 40 days at Mars starting from an orbit with a similar 24hr period.

If a quicker aerobraking would be required, the system can also be resized. The mass of the system will then grow approximately quadratically with a geometrically larger area.

As a clarification, this design has not been adopted for the scenarios covering an aerocapture followed by an aerobraking period. In those cases, the inflatable system that completed the aerocapture is then used later on for aerobraking. It is noted that because the initial altitude will be much lower than for this particular scenario, aerobraking durations will also be much shorter

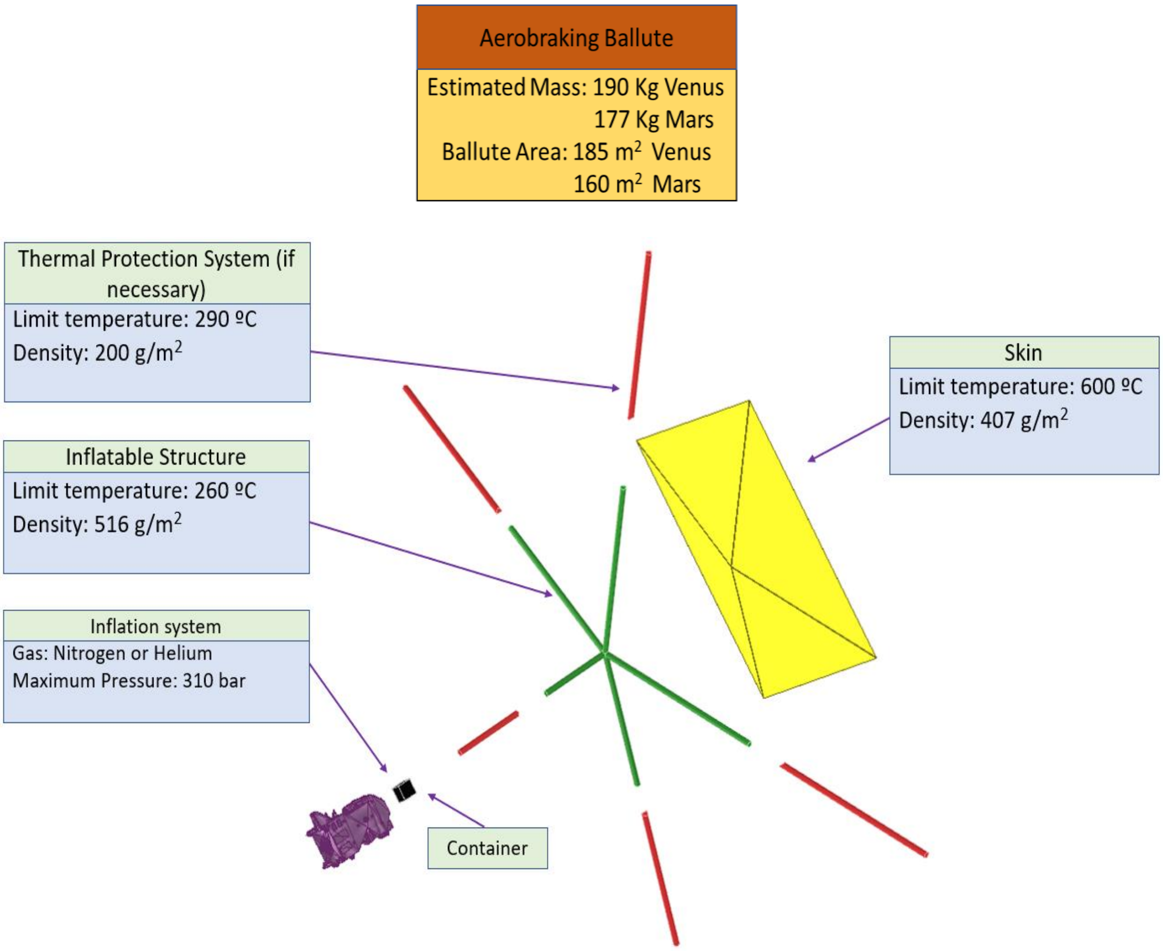


Figure 12: Aerobraking concept developed for Mars and Venus Accelerated Aerobraking.

4.2 Blunted Sphere-Cone

The blunted sphere-cone configuration is meant to address aerocapture scenarios at Mars and Venus. Given the limited control capabilities that result from having a single separation event to control the post-aerocapture orbit, and in order to ensure sufficient margin, this altitude was set to approximately 10 000km.

The system is significantly more complex than the one proposed for aerobraking, and is placed around the main spacecraft instead of behind it in order to protect it from the heat fluxes generated around the vehicle during the atmospheric pass. It is composed of a rigid nose section, a large thermal protection system covering it, an inflation system, an inflatable structure consisting of a stacked toroid, an attachment interface between the inflatable structure and the TPS surface, and finally a release mechanism which connects it to the main spacecraft.

Although the initial ballute area is similar for Venus and Mars missions (300m^2 initially and 140m^2 after the ejection event, when performing a drag-modulation based aerocapture), the complete system weighs 1140kg for Venus and 753kg for Mars (note that these are the numbers for the lift-modulation device, which carries significantly less thermal protection system than the drag modulation device). The difference between the designs for Venus and Mars is due to the different heating rates during the atmospheric pass when arriving from a hyperbolic trajectory and targeting a similar altitude at each planet (the Venus gravity field is deeper, which means a larger deceleration is required at Venus when compared to Mars to arrive at an orbit with the same altitude; this in turn means a longer and deeper atmospheric pass is required at Venus when compared to Mars,

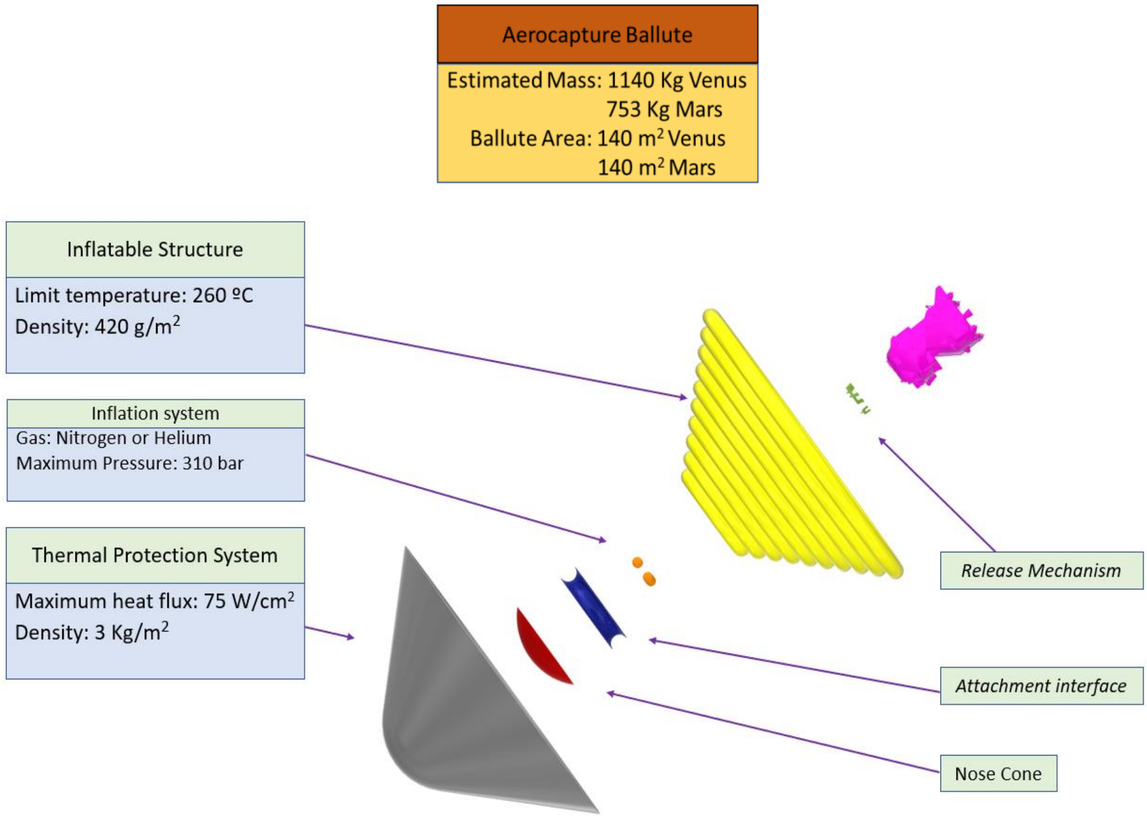


Figure 13: Spherical nose-cone with stacked toroid concept proposed for Venus and Mars aerocapture.

which when added to the higher entry velocity leads to significantly higher thermal fluxes and decelerations).

The inflation system and the materials used in the inflatable structure are similar to those used in the aerobraking concept. However, the Thermal Protection System is both far denser as well as much more heat resistant.

5 INTEGRATED RESULTS

The results obtained as performance indices for the converged aerobraking and aerocapture designs are summarized in Table 3 and Table 4, taking into account each of the modules above.

The S2X design corresponds to an alternative configuration where the drag modulation event deflates a fraction of the inflatable but all the mass is kept, whereas the S2Y design corresponds to an alternative configuration where the drag modulation event results on the ejection a fraction of the inflatable.

Table 3: Summary of aerobraking scenarios

Aerobraking parameters	Mars				Venus			
	S1	S2X	S2Y	S3	S1	S2X	S2Y	S3
Vehicle mass [kg]	1850				1650			
Inflatable mass [kg]	177	1520	785	753	190	2363	1219	1140
Reference area [m^2]	160	140	140	140	185	140	140	140
Ballistic coefficient [kg/m^2]	5.76	10.94	8.56	8.45	4.52	13.03	9.31	9.06
Initial apocenter altitude [km]	30610	10000			66555	20000		
Mission duration [days]	28.00	18.20	14.24	14.08	89.80	95.36	68.09	66.18

- **Analysis of Aerobraking Results**

The results from the tables above can be compared with the nominal mission sequences for both a Mars and a Venus mission, where >300 days and ~550 days of an aerobraking campaign after orbit insertion are required to arrive at the respective final operational orbits. A trailing ballute weighing 177kg for Mars and 190kg for Venus and with an area of 160 and 190m^2 respectively (when fully unfurled) would be required to compress the timeline to 28 and 89 days respectively, a reduction to 1/10th and 1/6th of the duration of an aerobraking campaign where no inflatables are used (the same initial altitude is considered, corresponding to a 24hr period).

The duration of aerobraking campaigns for the aerocapture cases have also been studied. It is clear that the weight of the inflatables in both Venus scenarios (S2 and S3) is excessive, something which is further reinforced by the attitude control sizing results shown in section 3.3.3. For the Mars case, the S2Y and S3 scenarios appear more feasible, with aerobraking campaigns lasting 14-18 days beyond the initial capture, leading to a very quick arrival at the final operational orbit.

The ballistic coefficients are nevertheless much higher for the aerocapture than the aerobraking case due to the additional TPS that needs to be carried into orbit to survive the manoeuvre; this contributes to a much smaller delta-V per atmospheric pass in scenarios S2/S3 than in scenario S1 (2.6m/s vs. 6m/s), which is not especially relevant given the short durations involved.

Table 4: Summary of aerocapture scenarios

Aerocapture parameters	Mars			Venus		
	S2X	S2Y	S3	S2X	S2Y	S3
Vehicle mass [kg]	1850			1650		
Inflatable mass (mod) [kg]	1520	1520 (785)	753	2363	2363 (1219)	1140
Reference area (mod) $[\mathrm{m}^2]$	300 (140)	300 (140)	140	300 (140)	300 (140)	140
Ballistic coefficient (mod) $[\mathrm{kg/m}^2]$	11.46 (24.56)	11.46 (19.21)	18.97	13.93 (29.86)	13.93 (21.35)	20.76
C_L/C_D (mod)	0.0	0.0	0.2 (-0.2)	0.0	0.0	0.2 (-0.2)
Flight-path angle [º]	-8.49	-8.44	-8.91	-9.14	-9.13	9.20
Entry velocity [m/s]	6.0			10.8		
Peak heat rate [W/m^2]	5.95	5.85	7.26	41.01	39.65	45.00

- **<u>Analysis of Aerocapture Results</u>**

The results obtained for the aerocapture cases are shown in Table 4 above. Peak decelerations and heating are higher for the lift-modulation scenario than for the drag-modulation one, something which is clearly due to the steeper entry flight-path angles involved (0.4° steeper for Mars, 0.1° steeper for Venus). Meanwhile, it is clear that the values for the Venus case are infeasible (the blunted sphere-cone alone is heavier than the spacecraft), which appears to be essentially due to the TPS thickness required to handle the heating environment during the atmospheric flight. Indeed, even for one of the Mars cases (S2 scenario), the mass fraction for the inflatable is 45%, which is as much as twice the mass fraction of the aeroshell used in past Mars missions (21-23%).

Still, given the very low peak heat rate involved in the nominal aerocapture trajectory, it is likely that an inflatable with a 1/3 to ¼ of the aerodynamic surface studied here (and consequently with a much lower mass) would still be subject to a heat rate well below the 75W/cm^2 limit. We note however that the smallest area that still results in a stable atmospheric flight configuration is 140m^2. Therefore, the only way to make the mass-optimal design feasible would be to change the design of the main spacecraft such that the center of mass of the composite vehicle (spacecraft + inflatable device) was moved further towards the nose of the inflatable.

- **Main Study Findings**

We can summarize the conclusions drawn from this study in four key findings:

- The accelerated aerobraking scenario (S1, which accelerates aerobraking by as much as 6-10x using a square-shaped trailing ballute) is feasible at Venus and Mars using small inflatable devices with a mass between 177-190kg
- Within the aerocapture scenarios, only the lift-modulated aerocapture at Mars (S3) is competitive with the reference missions (chemical orbit insertion + aerobraking)
- Severe thermal environment for aerocaptures at Venus (as well as stability requirements applicable to the aerocapture configuration) are the main obstacles precluding lower mass solutions
- The Mars aerocapture design could be further mass-optimized, but only if the spacecraft shape is modified to improve stability when enclosed by the blunted sphere-cone device.