Aerocapture Guidance Design for the AERODEM Mission

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ABSTRACT

Since early developments in the 80's the aerocapture has always been a promising insertion technique to place a spacecraft on a parking orbit after an interplanetary cruise. However it has never been in-flight demonstrated, defining an aerocapture mission around Earth yielding numerous safety issues in addition to requiring highly energetic conditions at entry interface. It is clearly less the case for an exploration mission. In order to deplete the energy of the spacecraft along its atmospheric path new aerocapture principles emerged in the recent years by replacing the classic lift modulation by a single or multiple-event drag modulation. As for any aerocapture mission, propulsive corrections will have to be performed after atmospheric exit in order to raise the periapsis and then to adjust the apoapsis to the targeted value and, if really needed, to correct the inclination. But the main advantage of such new technique is to ease the design of the spacecraft that does not require a dedicated RCS to control the attitude of the vehicle during its atmospheric path but only a mechanical deployment /jettisoning of a rigid or inflatable heat shield, the spacecraft being thus passively stabilized at a low spinning rate.

AERODEM is an aerocapture demonstration mission at Mars studied for ESA that should rely on such insertion technique. Within the frame of past ESA, EU or even in-house funded studies, different aerocapture guidance schemes have been designed at ArianeGroup in order to reach a parking orbit using the lift modulation technique. Among those ones and after some adaptation to manage only the drag a simple and robust numerical predictor-corrector guidance scheme has been selected to perform such mission. This paper aims at presenting the retained guidance design whose preliminary performance is illustrated by Monte-Carlo simulations for two generic missions termed as standalone, for a 470 kg spacecraft, or piggy-back, for a 155 kg spacecraft.

1. INTRODUCTION

The insertion of a spacecraft around a planet surrounded by an atmosphere may be done in two different ways. On the one hand, there is the full chemical braking technique which is costly and has a direct impact on the size/weight of the payload. On the other hand, we find the aerobraking and aerocapture techniques which use directly the deceleration induced by the drag and lift aerodynamic forces to reach the targeted orbital parameters. Benefiting from the atmosphere helps de facto in increasing the size/weight of the payload. Differences between aerobraking and aerocapture are numerous. The first one is the minimum altitude experimented during the atmospheric path. For an aerobraking, the spacecraft remains at the limit of the atmosphere. The drag induced in such flight conditions is very low and reshaping the incoming interplanetary path is long to obtain requiring hundreds of orbits. For the aerocapture that may be regarded as a failed atmospheric entry, the spacecraft plunges into the atmosphere's planet and the minimum altitude may be very low accordingly to the entry conditions and to the targeted ones at exit. This longer atmospheric path enables a much shorter insertion and makes the aerocapture as a one-shot insertion technique. But the main difference between those two concepts is that until now only the aerobraking has been in-flight demonstrated: around Venus (Magellan in 1993, Venus Express in 2006), or Mars (Mars Global Surveyor in 1997, ExoMars TGO in 2017-18). Even if the first developments were made for a demo-flight around Earth (AFE experiment in the late 80's), the aerocapture has never been in-flight tested. Thus, up to now, the aerocapture remains only a hypothetic insertion technique.

From a guidance standpoint, the first studies on the aerocapture [1,…,7] considered the lift modulation to control apoapsis and inclination at exit, acting on the periapsis being not that much feasible during the atmospheric path. Since those first developments, new solutions compliant with a simpler mission/spacecraft design emerged relying on single or multiple-event drag modulation [8,…,13]: using an inflatable or deployable heatshield, the drag may be modified in-flight by jettisoning or retracting this heatshield to adapt the velocity that is needed to reach the targeted apoapsis at exit. With such control concept, there is no way to control the inclination during the atmospheric path and to avoid a costly post-exit correction manoeuver, the requirement on the inclination at exit will have to drastically relaxed. Recently, ESA began studying Mars exploration mission concepts implementing a single-event drag modulation aerocapture, studied here as AERODEM. AERODEM stands for aerocapture demonstration mission on Mars: it aims at demonstrating the feasibility of an aerocapture mission around Mars for two types of demo-missions (under the assumption of a shared Ariane 64 launch, or a dedicated Ariane 62 launch) termed as standalone, for a 500 kg-class spacecraft, and piggy-back, for a 100 kg-class spacecraft.

In the past, and within the frame of CNES/ESA [4,5] and EU [7] funded studies or even in-house funded activities [6], Ariane Group has been involved in the design of GNC solutions for lift-modulation aerocapture with guidance schemes relying either on trajectory tracking [4], numerical predictor-corrector[5,7] or even artificial neural networks [6]. The open-literature on single event drag modulation technique highlighting guidance solutions using mainly the predictor-corrector technique[10,11], it was decided to limit the analysis to this technique and to reuse and adapt what was developed in the past by Ariane Group to the aerocapture phase of AERODEM.

After a quick presentation of the AERODEM mission limited to the aerocapture maneuver, the second part of the paper aims at presenting the retained guidance scheme able to cope with the AERODEM mission requirements. Before concluding a performance assessment of the designed guidance scheme is presented considering a guidance-oriented simulation tool including a simplified navigation performance model.

2. AERODEM MISSION

The operating mode of a classic aerocapture is quite simple as illustrated on Fig. 1. After a last trajectory correction maneuver (TCM) enabling also to properly update the inertial navigation, the guidance uses the aerodynamic forces to deplete the energy provided by the interplanetary path in order to control the orbital parameters (mainly apoapsis and inclination) at atmosphere's exit.

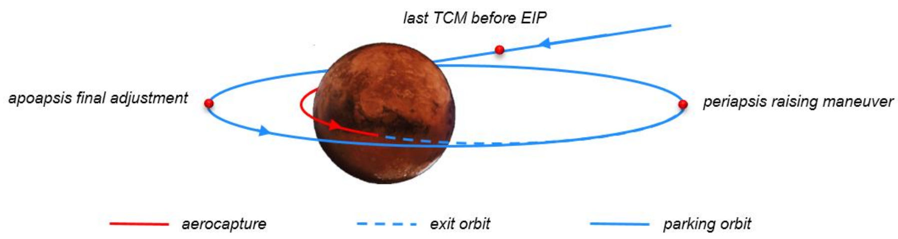

Figure 1. Aerocapture mission

After exit, some adjustments will have to be done. Firstly the periapsis will have to be raised when reaching the apoapsis (the atmospheric path has no impact on the periapsis that is mostly defined by the incoming interplanetary conditions). Then, because the guidance is not perfect and unpredicted off-nominal flight conditions after guidance switching-off may occur and affect the exit conditions the apoapsis offsets will have to be zeroed. This correction maneuver will have to be performed when reaching the raised periapsis. Eventually, and for same reasons, inclination deviations will also have to be corrected when reaching the closest node line from the apoapsis. In the end, and in addition of the mission requirements expressed straightforwardly towards the GNC chain the performance of the aerocapture GNC chain may simply be modelled by the total propulsive correction cost needed to meet the mission requirements.

For a classic lift-modulation aerocapture, the vehicle is 3-axis controlled to provide a lift acceleration in a direction enabling to reach apoapsis and inclination objectives at exit, the direction of the lift to be performed being in-flight computed at each guidance call as long as the atmosphere is dense enough to provide an efficient correction. The objective and operating mode of a single-drag event aerocapture is slightly different, see Fig. 2. Firstly, the vehicle is not 3-axis controlled but assumed to fly under a 0 deg angle-of-attack (equilibrium conditions) with a low spinning rate. Then, the objective of the guidance is only to determine the jettisoning time of the inflatable or deployable heatshield in order to reach the energy depletion level compliant with the exit conditions defined in terms of apoapsis only. In contrast to the lift modulation technique, the single drag event modulation is one-shot: once the heatshield has been jettisoned there is no more way to adjust the exit conditions. In addition, because only the in-plane motion is controlled by the on-board guidance, the mission requirement towards the inclination will need to be relaxed to avoid a too large correction cost after exit.

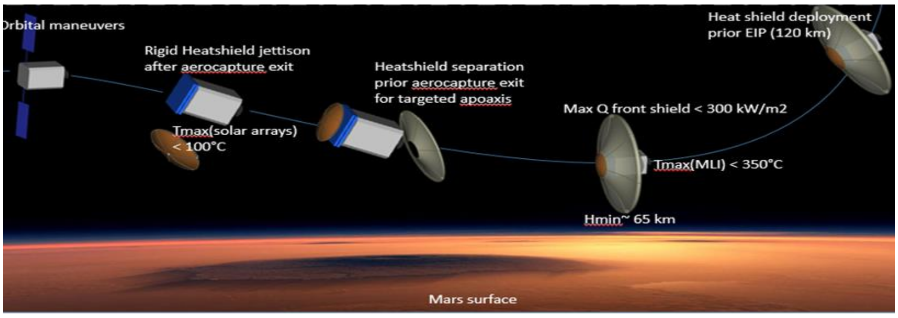

Figure 2. AERODEM aerocapture

Within the frame of the AERODEM study Ariane Group (Les Mureaux) and Airbus Defence and Space (Madrid) Mission Analysis departments analysed the whole mission scenario from take-off to the parking orbit. Considering the opportunity to fly as a passenger on a Ariane64 launch (not before 2030), this preliminary analysis highlighted 2 mission scenarii for an aerocapture on Mars with a 500 kg class (including the jettisonable heatshield) or 100 kg-class orbiter taking into account all the mission requirements as expressed by ESA. Those missions are respectively termed as standalone or piggyback. The main features of those vehicles briefly are recalled on Table 1.

Table 1. Spacecrafts main feautures

mission	**Standalone**	**Piggy-back**
mass at entry	470 kg	155 kg
heatshield mass	216 kg	97.6 kg
reference area at entry	27.7 m^2	10.2 m^2
reference area after heatshield separation	3.9 m^2	0.9 m^2
nose radius	1 m	0.3 m

Those missions aim at targeting similar exit conditions, that is to say a slightly elliptic obit with an eccentricity below 0.05, an apoapsis ranging from 500 up to 1500 km AGL for a periapsis ranging from 500 up to 1000 km AGL. Because there is no possibility to control the inclination during the atmospheric path, the mission requirement towards the inclination of the parking is drastically relaxed and can even be considered as not available. Thus, for a 90 deg incoming orbit, inclination corrections will have to be considered only if the inclination at exit is below 70 deg, which is less than probable with regards to the duration of the aerocapture.

Because correcting the exit conditions to reach the targeted ones is not free of charge, the post-aerocapture maneuvres will have to be made to limit the fuel consumption. In order to leave margins towards the mission requirements, the guidance will target an apoapsis around 1000 km AGL. Even if not perfect, the guidance accuracy should be better than 500 km. Consequently, the retained strategy is only to raise the periapsis such as reaching an elliptic orbit with an eccentricity 0.05 without modifying the apoapsis obtained at exit. If doing so the periapsis remains below 500 km AGL, the apoapsis will be adjusted to get a 500 km AGL periapsis. In the cases the apoapsis at exit would be outside the mission requirement, the apoapsis correction will be defined to reach the lower or upper limit of the mission requirement, and the periapsis correction that will be done first will be such as to fulfil the eccentricity requirement.

In addition to those mission requirements, constraints on the design of the spacecraft have to be taken into account. As for any spacecraft passing through the atmosphere, the g-load as well as the dynamic pressure peaks will have to be limited mainly to preserve the integrity of an optional multilayer insulation (MLI) cover protecting the solar panels and the scientific payload. For same reasons, the thermal fluxes on the front shield and especially at the bottom part of the payload will also have to remain as low as possible. These vehicle constraints will be managed only passively considering that reaching the targeted conditions at exit is the priority, and their fulfilments will be established only thanks to the Monte-Carlo simulations defined to assess the GNC performance.

With this set of mission requirements and vehicle design constraints, the entry conditions, defined at 120 km AGL crossing, for the standalone and piggyback missions are as presented at Table 2.

Table 2. Entry conditions for standalone and piggyback missions

mission	Standalone	Piggyback
longitude	-8.22 deg	-8.23 deg
latitude	-12.56 deg	-12.35 deg
relative velocity	6255.8 m/s	6255.6 m/s
flight path angle	-8.63 deg	-8.49 deg
heading angle	-2.25 deg	-2.25 deg

3. GUIDANCE DESIGN

From a guidance standpoint many solutions exist to manage an aerocapture using the lift or only the drag to deplete the energy. A quick survey of recent publications on the drag modulation technique [10,12] highlighted 3 different methods to perform such mission: deceleration curve-fit method initially developed for Mars Pathfinder (comparison between the measured deceleration and pre-loaded profiles depending on the entry flight path angle), a pure predictive guidance algorithm (single prediction of the exit conditions in the case the jettisoning is done at the current time of the prediction) and a classic numerical predictor-corrector (prediction of exit conditions for different jettisoning times and then correction to get the targeted exit conditions). The predictor-corrector technique yielding the most interesting results in terms of apoapsis offsets at exit but for a slightly more complex implementation and a higher computational burden, it was decided to limit the analysis to this technique and to refurbish and adapt the last developments made for AEROFAST in terms of guidance scheme (a numerical predictor-corrector) and simulation platform. Within the frame of this preliminary analysis, only the jettisoning of an inflatable heatshield is considered, but developed guidance principles could be straightforwardly used to manage the retracting of a deployable heatshield.

Considering that the jettisoning time is the only commanded term by the guidance, the guidance scheme is very simple to define and to implement.

At each guidance call period, a trajectory prediction is performed using a classic 4th order Runge-Kutta process with the last predicted jettisoning time, or $T_{jtsn,k-1}$. This first prediction yields a predicted apoapsis $Za_{k,1}$. If it is lower (resp. higher) than the targeted one, or Za_{tgt}, then the predicted jettisoning is too late (resp. premature). A second prediction is done with an update predicted jettisoning time defined by an decrease (resp. increase) of the previous one, or $T_{jtsn,NPC} = T_{jtsn,k-1} + \Delta T_{NPC.}$ This second prediction yields a new prediction of the apoapsis at exit, or $Za_{k,2}$.

Once the prediction phase is terminated, the correction phase is entered and the predicted jettisoning time is simply given by a linear interpolation over the set ($T_{jtsn,NPC}$, $Za_{k,2}$) and ($T_{jtsn,k-1}$, $Za_{k,1}$).

This prediction-correction process is then looped until the current time gets over the predicted jettisoning time.

A great advantage of such simple guidance scheme is that it does not need a large set of internal data: the RK4 sampling period or ΔT_{RK4}, the jettisoning time offset ΔT_{NPC} (fixed value or adapted once the convergence has been almost obtained) and of course an initial guess $T_{jtsn,0}$ (set at the EIP crossing time or some seconds after). Even if there is no real doubt for being compliant with a real time application (that was already the case at the time of the ATPE program from ESA), the CPU burden may already be lightened by adapting the RK4 sampling period to the current time. To make as simple as possible, only 2 values for ΔT_{RK4} may be considered: a rather large one at the beginning of the atmospheric path and a refined one to get accurate exit conditions.

But these advantages are balanced by some drawbacks. The main one which is classic for an aerocapture guidance scheme is the need to get an in-flight estimation of the atmospheric density profile as well as the drag coefficient. This can be done by filtering the accelerometer data (moving filter over a given time period) in order to get a rough estimation of the atmospheric density and drag coefficient deviations. The second one is that depending on the initial guess $T_{jtsn,0}$ a very early separation of the heatshield that will have been deployed/inflated prior entering the atmosphere will not be possible. There is then a risk for too energetic entry conditions to exit the atmosphere with large deviations. However such risk could be mitigated by entering the aerocapture guidance mode some time before crossing the entry interface point.

The next figures illustrate the behaviour of the guidance scheme on an arbitrary simulation case. For illustration purpose, this plot of Fig. 3 has been generated by predicting, at each guidance call, trajectories with the previous predicted jettisoning time, an augmented one and a reduced, the initial guess $T_{jtsn,0}$ being here set at 200 s from EIP. Even if some predictions may lead to a crash or a too energetic exit, the convergence towards the reference trajectory profile (black dashed curve) is rather quick to get. For a non-real time assessment, the prediction process has not been too refined, all trajectories being predicted from the current state till a crash or an exit. Prediction cases yielding a crash could clearly be stopped at culmination in order to save CPU time.

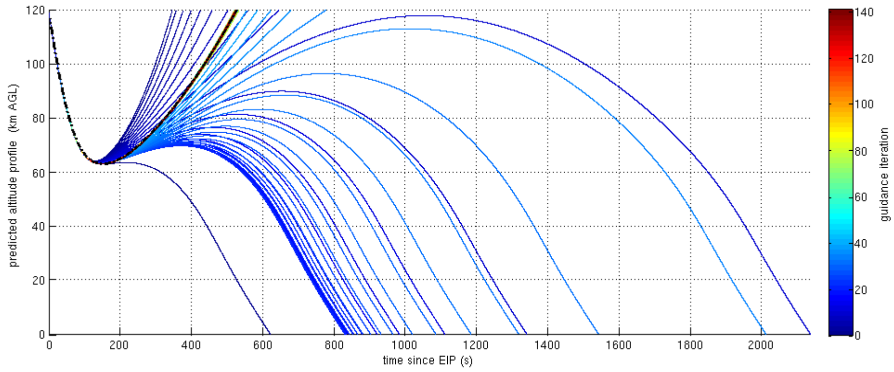

Figure 3. Predicted trajectories

Around 40 s after EIP crossing, the predicted jettisoning time is less than 3 s away from the final value which is defined for that run case at 140 s after EIP. Fig. 4 illustrates the convergence of the guidance towards the final value. The targeted apoapsis is set at 1034 km AGL. The right hand plot displays the evolution of the apoapsis for a jettisoning time increase (blue curve) or a reduced one (red curve). The green curve represents the evolution of the predicted apoapsis with the previous solution $T_{jtsn,k-1}$.

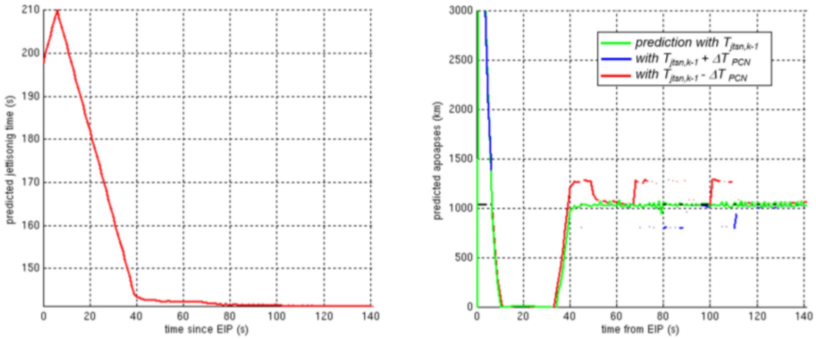

Figure 4. Predicted trajectories

Fig. 5 presents the evolution of the thermal and structural loads on the vehicle during the atmsopheric path.

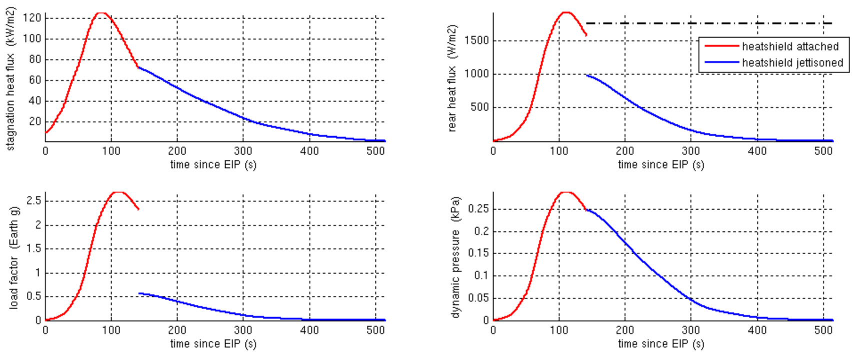

Figure 5. Thermal and structural loads profiles

We observe that the separation of the heatshield occurs for a rear thermal flux level below the requirment, set at 1750 W/m^2 (qualification thermal flux limit for the solar arrays) and also well below the black Kapton MLI limit (9140 W/m^2) that could be used to protect the payload during the atmospheric path. The atmospheric path path being performed at a rather high altitude, the rigid heatshield heat flux is also well below the limit set at 1.8 MW/m^2.

4. GUIDANCE PERFORMANCE

Once the behaviour of the proposed guidance scheme has been analysed and used to properly set all the internal data of the guidance (initial guess $T_{jtsn,0}$ set at 150 s from EIP, 1 Hz guidance call frequency, 5 s RK4 sampling period from EIP to pull-up, then 0.5 s till prediction termination), the GNC performance is established considering a 3-DOF guidance-oriented simulation tool and 300 runs Monte-Carlo (MTCL) simulations.

The retained off-nominal conditions are as follows:

- Entry conditions:

  Table 3 presents the 1σ errors on the position and velocity at EIP (assumed the same for standalone and piggyback missions). Longitude errors may appear wide but because we target a polar orbit they won’t have a too large impact on the exit conditions. Those values are obtained considering an optical navigation update at last TCM and a class 3 IMU.

Table 3. position and velocity dispersions at entry

mission	**1 σ value**
longitude	108.8 deg
latitude	0.06 deg
relative velocity	0.52 cm/s
flight path angle	0.084 deg
heading angle	0.032 deg

- Atmosphere:

  The atmospheric density model is defined here by the ExoMars 2016 reference pre-flight trajectory profile (EMCD V4.31 model for an arrival date on the 19/10/2016). The evolution of the atmospheric dispersions, derived from Mars InSight entry data, is simplified as follows (max values considering a uniform distribution): ±45 % above 80 km AGL, ±15 % below 50 km AGL and linear interpolation between 50 and 80 km AGL.

- Aerodynamic behaviour:

  Dedicated studies performed at Ariane Group derived from available AEDB developed by Ariane Group for ESA exploration programs (MarcoPolo-R, Huygens and ExoMars) yielded an aerodynamic model depending on the current flow regime: continuum hypersonic, free molecular or rarefied. Whatever is the current flow regime, a ±5 % dispersion (uniform distribution) has been considered.

- Navigation:

  The Navigation performance is simulated via a dedicated performance model obtained by covariance propagation on a reference trajectory of all contributors of the IMU (a class 3 sensor enabling a corridor width of ±0.24 deg under the assumption of an optical navigation at last TCM): non-orthogonalities, misalignments, scaling factors etc. Fig. n°6 displays the evolution of the estimated navigation errors (3 σ values) wrt the orbital energy E (with a specific expression of the orbital energy as recalled on Fig. 6).

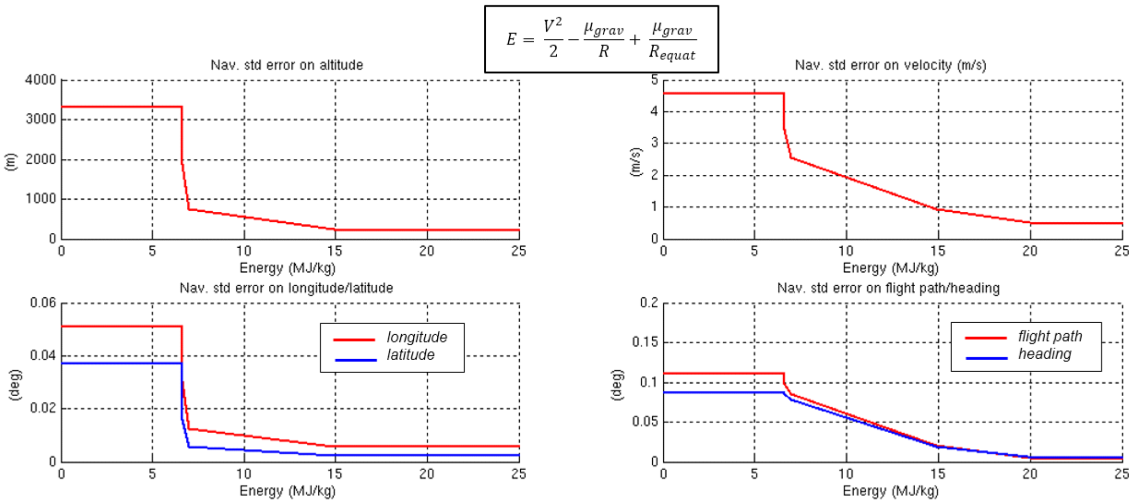

Figure 6. Navigation peformance model

- Control:

  For stabilization purpose the spacecraft will be spun at low spinning rate. Because a simple 3-DOF simulation platform is retained to assess the feasibility and the performance of the designed guidance scheme, the angular motion is not simulated and the assumption of a constant 0 deg angle-of-attack profile is retained. Additional studies will have to be carried out to assess the impact of the spinning rate on the global GNC performance.

Standalone mission

Fig. 7 illustrates the GNC performance for the standalone mission. We observe in some cases a premature jettisoning of the heatshield. These cases are mainly driven by low energetic entry conditions coupled with an estimated denser atmosphere resulting in an early separation. For totally opposite conditions we find also some cases with a late separation. Even if some rare cases are beyond the mission requirements in terms of apoapsis at exit (the guidance targets an apoapsis at 1034 km AGL), some exit conditions yield an apoapsis below 500 or over 1500 km AGL. But apart from those cases, 97 % of the simulated cases fully meet the mission requirements and reaching a parking orbit with an eccentricity below 0.05 requires a propulsive correction cost up to 300 m/s for 99.7 % of those cases.

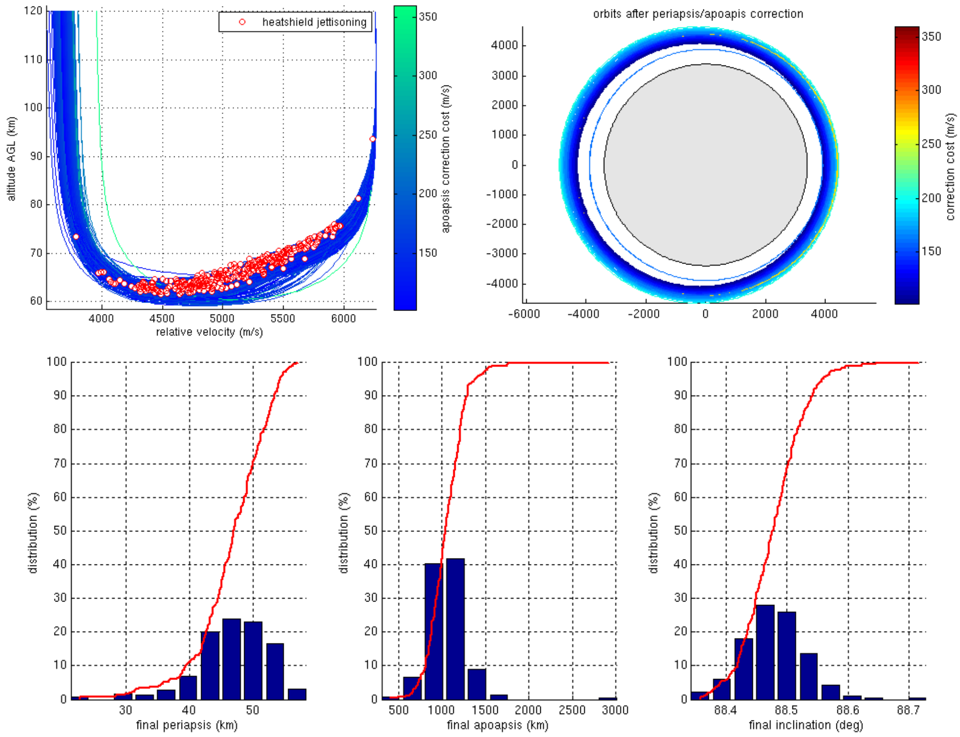

Figure 7. Standalone GNC performance

Concerning the structural and thermal loads, we get the results plotted on Fig. 8. The main point to highlight is the maximum rear heat flux peak which in most of 50 % of the simulated cases is over the qualification limit of the solar arrays meaning that the solar arrays will need a thermal protection to survive the atmospheric path, even if performed at a rather high altitude (no less than roughly 60 km AGL).

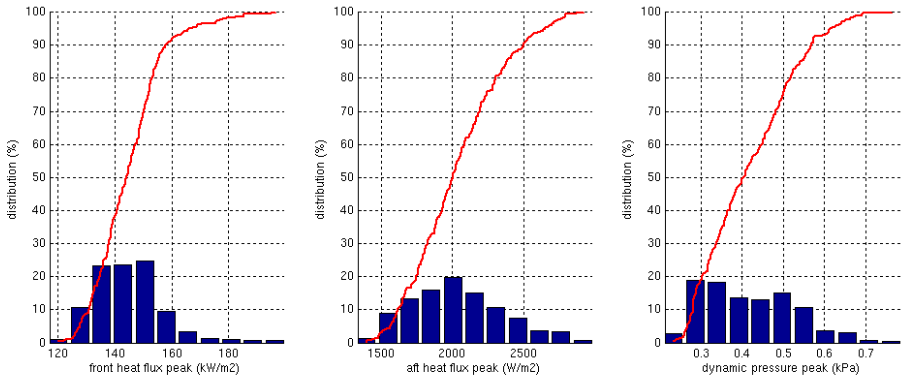

Figure 8 Structural and thermal loads

It has to be noted that in most of the MTCL cases the inflatable/deployable heatshield may be jettisoned prior reaching the rear heat flux peak, see illustration on Fig. 9.

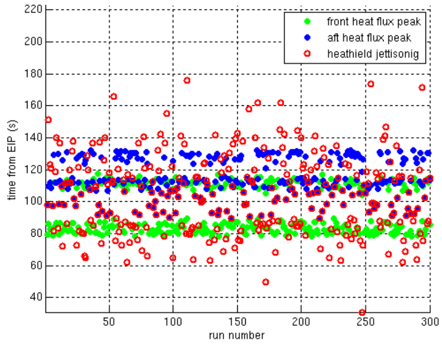

Figure 9. Jettisoning and aeroheating timeline

Piggyback mission

We get very similar results for the piggyback mission, simulations close or beyond the mission requirements being the result of same off-nominal flight conditions, see Fig. 10: no crash on Mars, no over-energetic cases. 97 % of the simulated cases meet the mission requirements, and for those cases, the correction cost needed to reach the parking orbit with an eccentricity below 0.05 does not exceed 270 m/s.

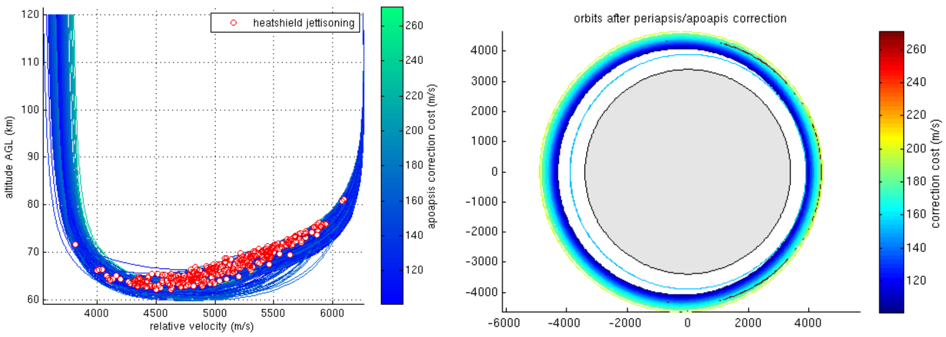

Figure 10. Piggyback performance

As for the standalone mission, the thermal loads encountered during the atmospheric path are such that the solar arrays have to remain folded and protected by a MLI cover during the aerocapture.

All those results show first that the preliminary mission analysis studies have been well done and then that, at this stage of the feasibility analysis, the guidance design is able to cope with the AERODEM mission requirements.

5. CONCLUSION

Until now the feasibility of the aerocapture as an efficient and almost free of charge aeroassisted insertion technique has been demonstrated on many cases for missions that were eventually never performed. For some time the classic lift modulation technique is being replaced by a single or multiple-event drag modulation technique. Discarding any large orbital plane deviation from the mission baseline, such aeroassisted technique appear promising at least for robotic missions (manned missions could possibly imply more stringent requirements). Targeting exit conditions minimizing the propulsive corrections to reach the final parking orbit (periapsis raising and then apoapsis adjustement) may be achieved by a simple numerical predictor-corrector guidance scheme whose objective is just to define in-flight the jettisoning or retracting time of an inflatable or deployable heatshield. The guidance principle is simple but the command being one-shot (once the heatshield is jettisoned there is no more possibility to modify the energy depletion), the guidance scheme needs to be very accurate to avoid a crash or a too energetic exit. Based on the prediction-correction technique, it needs to be fed with an accurate modelling of the aerodynamic behaviour of the vehicle as well as a rather precise in-flight estimation of the atmospheric density profile to be flown. Dedicated estimation processes are thus needed relying on the accelerometer measurements and a predicted atmosphere model. These drag measurements may also be used to get an in-flight update of the drag model used for the prediction process.

For this preliminary feasibility analysis, jettisoning delays have not been considered but a nominal separation modelling could be included to the prediction model. In addition, only a constant 0 deg angle-of-attack profile has been retained; the low spinning rate required to stabilize the vehicle through its atmospheric path will clearly need to be simulated to assess more accurately the GNC performance in more realistic flight conditions. If needed, a nominal angular motion could be also integrated to the prediction phase, different spinning conditions being then regarded as off-nominal flight conditions.

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NOTATIONS AND ABREVIATIONS

AEDB	AeroDynamic DataBase
AERODEM	AEROcapture DEMonstration
AEROFAST	AEROcapture for Future spAce tranSporTation
AGL	Above Ground Level
AFE	Aeroassist Flight Experiment
ATPE	Aeroassisted Transfer for Planetary Exploration
CPU	Computation Power Unit
DOF	Degree Of Freedom
EIP	Entry Interface Point
EMCD	European Mars Climate Database
GNC	Guidance Navigation Control
IMU	Inertial Measurement Unit
jtsn	jettisoning
MLI	Multi-layer Insulation
MSR-O	Mars Sample Return Orbiter
MTCL	MonTe-CarLo
NPC	Numerical Predictor Corrector
RK4	Runge-Kutta 4th order
TCM	Trajectory Correction Maneuver
$T_{jtsn,NPC}$	predicted jettisoning time at guidance call period
$T_{jtsn,k-1}$	predicted jettisoning time at guidance iteration #k-1
ΔT_{NPC}	offset search time for the prediction phase of the NPC

ΔT_{RK4}	RK4 sampling period for the prediction phase of the NPC
$Za_{k,i}$	predicted apoapsis at guidance iteration #k for prediction #i
Za_{tgt}	targeted apoapsis