GUIDANCE TRADE-OFF FOR AEROCAPTURE MISSION

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ABSTRACT

In the very late 90's, EADS-ST began home funded studies on aerocapture problems. The objectives of these studies were at that time to prepare a possible cooperation within the NASA/Cnes MSR-Orbiter program by investigating this new orbital insertion technique studying different algorithmic solutions from a guidance point of view. According to these preliminary studies, EADS-ST was retained in 2002 by ESA to study insertion techniques such as aerocapture, aero-gravity assist or aerobraking techniques within the frame of Technological Research Program able to bring solutions to Aurora program. In the frame of the ATPE (Aeroassist Technologies for Planetary Exploration) TRP program, EADS-ST, led by Astrium-Gmbh (now part of EADS-ST), developed and implemented an efficient and simple guidance scheme able to cope with mission requirements for aerocapture on Mars, Venus or the Earth: the Feedback Trajectory Control, or FTC. The development of this guidance scheme was made according to a preliminary trade-off analysis using different guidance schemes. Among those ones was an original predictor-corrector guidance scheme, already analyzed within the frame of the MSR-O mission. But, the FTC algoritm was prefered because of its good results and high simplicity.

This paper presents an upgrade of the original Apoapsis Predictor, or AP, with the improvement of its robustness woth respect to off-nomonal flight conditions and its process simplification. A new trade-off analysis is then detailed on a Mars Sample return mission.

INTRODUCTION

EADS-ST (Flight Control team) has developed different guidance schemes[5,6] able to cope with aerocapture mission requirements: arriving on a hyperbolic obit, the insertion of a robotic or manned spacecraft on an elliptic (or circular) orbit around the targeted planet is achieved using a single and short (only a few minutes) atmospheric path. The energy dissipation required to exit on an elliptic orbit is then made via the management of the aerodynamic forces on the vehicle. After the aerocapture manoeuvre, a limited propulsive manoeuvre may be required to reach a given parking orbit from the exit conditions. The mission analysis optimising the re-entry conditions in order to minimise these ΔV correction cost with respect to the predefined parking orbit, such insertion technique is quite propulsion free.

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Among the different guidance scheme studied by EADS-ST, the Feedback Trajectory Control[6] yielded the best performances for a MSR mission[5]. It was then retained to perform all the set of ATPE[7] aerocapture manoeuvres. Moreover, considering a limited adaptation, it can also be used to perform an aero-gravity assist manoeuvre with good accuracy. The FTC scheme is built using a virtual reference trajectory related only to the apoapsis control on which it performs a PID-like tracking and a decoupling between in-plane and out-of-plane motions, respectively for apoapsis and inclination control. This reference trajectory is built prior to the flight, and, if large re-entry offsets are observed due for example to navigation errors or orbital manoeuvres failure, it might not be adapted to the mission anymore. In that meaning, this guidance scheme could be not robust to important deviations prior to the atmospheric path. On the contrary, a guidance scheme relying on only targeted parameters and on a predictor-corrector technique[2,3] could present some advantages, its main drawback being the computation burden in the case of a fully numerical scheme. Such a guidance scheme has, in a recent past, been investigated by EADS-ST[5], but with only poor performances due to a too high sensitivity to off-nominal flight conditions. The aim of this paper being to present a new trade-off analysis between these two kinds of guidance scheme, the first task to do is to refurbish the original Apoapsis Predictor guidance scheme according to different improvement ways, and then to assess it on a reference mission for which the FTC scheme already yields good performances.
In the first part of this paper, one makes a brief recall of the FTC and original AP schemes. Then, one presents the possible improvements that could increase the final accuracy and decrease the computation burden. The improvements yielding the best compromise between final accuracy and CPU load are then retained for an updated trade-off analysis. This trade-off analysis based on Monte-Carlo simulations is performed on the robotic MSR mission of the ATPE program and it is extended to an extra MSR mission using an AFE-like vehicle[1].

ATPE MSR MISSION

The robotic Mars Sample Return mission[7] is characterised by an aerocapture at the arrival on Mars, fig. n°1, and then for the back trip to Earth, another aerocapture manoeuvre when reaching the Earth (not considered here).

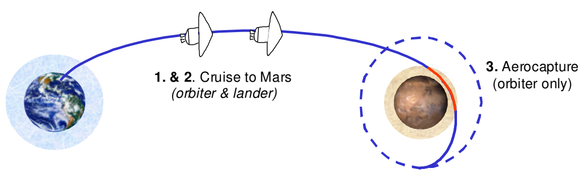

Fig n° 1

The nominal entry conditions on Mars (at 120 km altitude) of the inflatable capsule, or ITV for Inflatable Technology Vehicle, fig. n°2, are such as follows:

relative velocity	5687	m/s
flight path angle	-10.24	deg
heading angle	38.04	deg

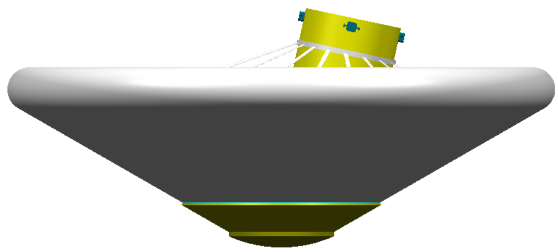

Fig n° 2

According to these entry conditions and a circular 500 km parking orbit, the orbital parameters at atmosphere's exit are:

apoapsis	500	km
periapsis	11	km
inclination	50	deg

that yields a nominal ΔV correction cost of 113 m/s.

FEEDBACK TRAJECTORY CONTROL

The FTC scheme uses a decoupling between in-plane and out-of-plane motion for respectively apoapsis and inclination control, fig.n°3.

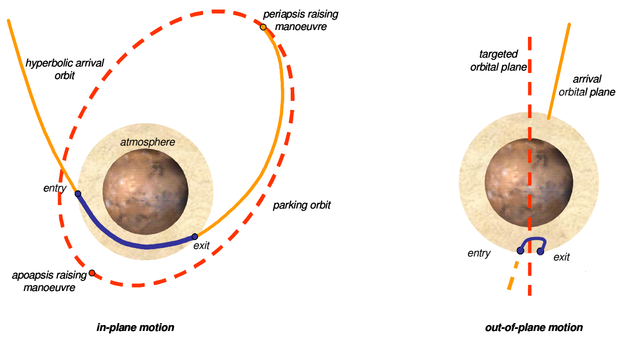

Fig n° 3

The in-plane control, which may be undesrtood as an extension to the whole atmospheric path of the Cerimele-Gamble scheme[1], performs tracking of a virtual reference trajectory that is defined by a constant bank angle profile yielding to the targeted apoapsis without inclination control. That reference trajectory gives the evolution of the tracking parameters (i.e. cosine of the bank angle, vertical velocity and dynamic pressure) with respect to the orbital energy. It has to be noted that it would also be possible to consider a piecewise constant bank angle profile. Using this, the absolute value of the commanded bank angle is given via its cosine by:

$$\cos\mu_{com} = \cos\mu_{ref} + G_{\dot{h}}\frac{\dot{h} - \dot{h}_{ref}}{q} + G_q\frac{q - q_{ref}}{q}$$

Of course, the computation of the commanded bank angle is possible only if its cosine is lower than 1. If not, the commanded bank angle is set to 0 deg or 180 deg according to the sign of the previous equation.

The out-of-plane control uses directly the well known roll reversal technique and the Cerimele-Gamble[1] logic: a roll reversal is triggered each time the current inclination offset overshoots a predefined inclination corridor defined with respect to the velocity, fig. n°4.

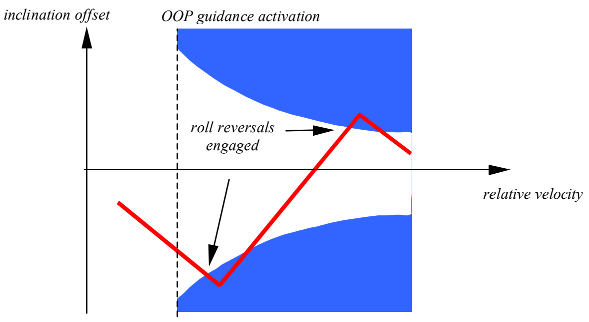

Fig n° 4

In all the cases, a roll reversal is always performed passing through 0 deg.

Finally, roll rate saturation is considered such that the commanded bank angle offset between two guidance calls is achievable with the roll rate limitation.

APOAPSIS PREDICTOR SCHEME

The AP predictor-corrector technique developed by EADS-ST is simply based on both the physical understanding of the aerocapture phenomenon and a very light adaptation of a Γ-guidance scheme as the one developed for the Ariane 5 launcher exoatmospheric flight. Indeed, in order to raise (resp. lower) the reached apoapsis, the best to do is to command a full lift-up (resp. full lift down) bank angle.

Starting from this consideration, and using a decoupling between in-plane and out-of-plane motions as for the FTC (same lateral logic), the in-plane AP logic uses a two steps process, fig. n°5.

The first one is a forward propagation process that realizes the prediction of the reached apoapsis according to 3 constant bank angle profiles trajectories, from the current time till the atmosphere's exit (or a crash if so) using a numerical integration (4th order Runge-Kutta method). This bank angle set is compound of the previous commanded bank angle μ^{k-1}_{com} and lift-up μ^k_+ and lift-down μ^k_- bank angles. Because of the roll rate limitation, $\dot{\mu}_{max}$, it is not possible from one guidance step to the other to perform a full lift-up or lift-down bank angle from the current value. Thus, the retained lift-up and lift-down bank angles are defined from the previous commanded bank angle by a positive or negative angular course limited by the roll rate limitation on a guidance step Δt_{AP} :

$$\begin{cases} \mu^k_+ = \mu^{k-1}_{com} + \dot{\mu}_{max}\cdot\Delta t_{AP} \\ \mu^k_- = \mu^{k-1}_{com} - \dot{\mu}_{max}\cdot\Delta t_{AP} \end{cases}$$

The second step uses then the set of reached apoapsis to determine the commanded bank angle by a simple linear interpolation with respect to the targeted one.

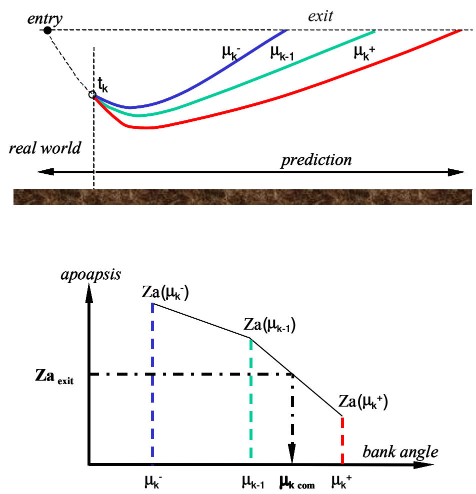

Fig n° 5

Finally, because the performances of the in-plane logic may be degraded by the inclination control, some specific management were retained for the original AP scheme. IP and OOP logics are triggered on different energy criteria (the first roll reversal is supposed to be performed short before the skip manoeuvre), and, when a roll reversal is engaged, the in-plane guidance is deactivated for the roll duration, see fig. n°6.

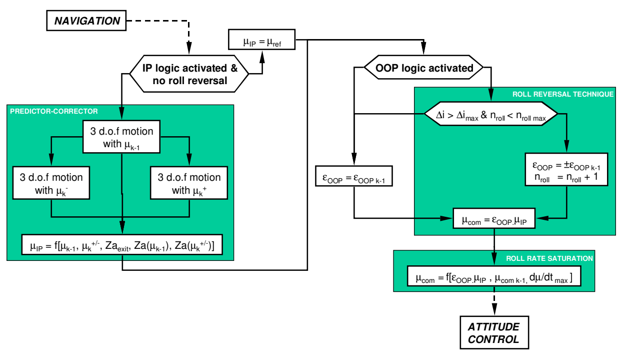

Fig n° 6

The two next figures illustrate the AP scheme process for the nominal aerocapture entry conditions case. Fig. n°7 presents a 0.01 Hz sampling of the predicted trajectories while fig. n°8 shows the evolution of the predicted apoapsis according to μ^k_+ and μ^k_- bank angle commands.

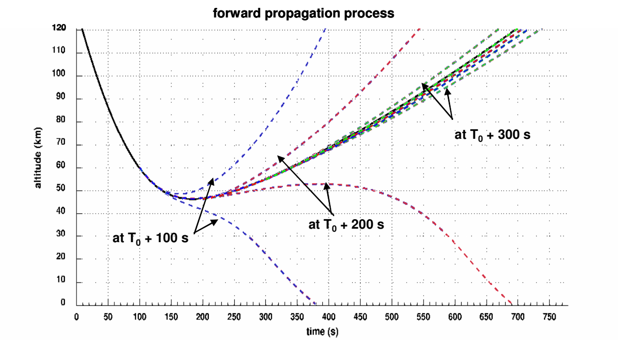

Fig n° 7

One may easily notice that the extreme trajectories converge (even with crashes on Mars ground for some of them) but quite slowly towards the reference trajectory.

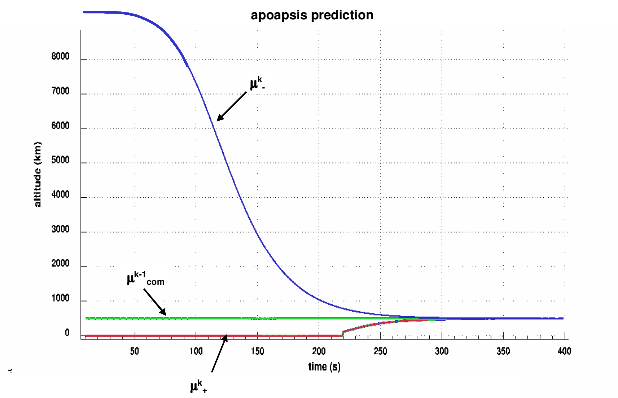

Fig n° 8

IMPROVEMENT WAYS

The main drawback of the AP scheme is that, first, the computation time is quite long, and then, the final accuracy is not good enough to meet the mission requirements. To illustrate this purpose, fig. n°9 presents a sampling of the aerocapture trajectories provided by a 1000 runs Monte-Carlo simulation for the Martian aerocapture of the MSR mission.

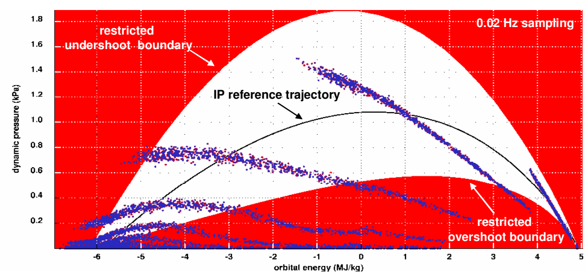

Fig n° 9

One can easily notice that most of trajectories are out of the restricted aerocapture corridor[5]. Considering a 170 m/s ΔV requirement, only 21 % of the simulated cases meet this performance index, while around 7 % others yield hyperbolic exits. Such results are insufficient.

But, some improvements from different kinds may be implemented.

The first of these possible improvements concerns the computational burden via a simplification of the prediction process. Namely, the AP scheme uses a set of three predicted trajectories. But, only two of them are useful. According to the sign of the predicted reached apoapsis offset using the previous commanded bank angle profile, one knows if the next commanded bank angle will have to be lower or higher than the previous one, i.e. μ^k_- if $\Delta Za(\mu^{k-1}_{com}) < 0$, or μ^k_+ if $\Delta Za(\mu^{k-1}_{com}) > 0$. Thus, only 2 trajectories have to be in-flight predicted, what naturally cuts down by one third the computational burden.

The second improvement way concerns more the mission analysis side. Indeed, as for the FTC scheme, considering entry conditions leading to a reference trajectory that is centred within the aerocapture corridor with respect to the flight path angle (and no more to the bank angle) improves naturally the results[6]. For example, for the FTC scheme, the best reference trajectory corresponds to a –10.81 deg flight path angle. With such a design, the reference trajectory dives more quickly into the dense layers of the atmosphere (see fig. n°10) what increases naturally the guidance robustness.

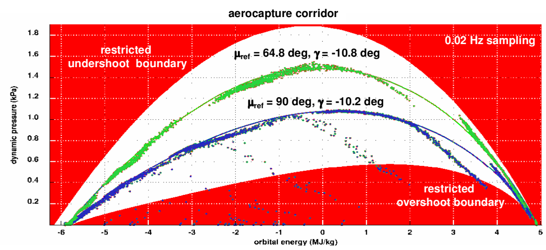

Fig n° 10

The previous FTC results having been provided using a 90 deg reference trajectory, the results linked to such improvement way will not be presented here.

Because the forward propagation process of the AP scheme relies on a numerical integration of motion, a natural way to increase the performances is to improve the on-board knowledge of both atmospheric and aerodynamic models[3]. The ATPE baseline[7] considering only drag measurements, it is not possible to get an accurate estimation of both C_D and C_L coefficients. Thus, such method is removed from the set of possible solutions.

Concerning the atmospheric density profile, one considers a first order filtering[1]:

$$\rho_i = k \cdot \rho_{ref} \quad \text{with} \quad k = (1-\lambda)k + \lambda \frac{1}{\rho_{ref}} \frac{2m\Gamma_D}{SC_D V^2}$$

added by a moving median filtering based on the n previous drag measurements as follows:

$$\rho = \frac{1}{n} \cdot \sum_{i=1,n} \rho_i$$

Such filtering process being able to cope with high or low frequencies atmospheric dispersions as investigated by Powell[3]. Being ineffective when assessed on the MSR-O mission, the first order filtering that was considered by Cerimele-Gamble[1] was not taken into account by the original AP baseline.

The improvement of the inclination accuracy tends to deteriorate the apoapsis one, so the two last improvement ways are linked to the roll reversal strategy.

The first possibility is simply to modify the rolling logic. Instead of implementing a complex roll strategy[4] whose tuning would not be simple to do, the three following options will be assessed when a roll manoeuvre will be triggered: always by a full lift-up bank angle (original AP and FTC baseline, case 1), a full lift down bank angle (in order to avoid as much as possible high energetic exit conditions), or through the shortest angular way (case 2, fig n° 11) .

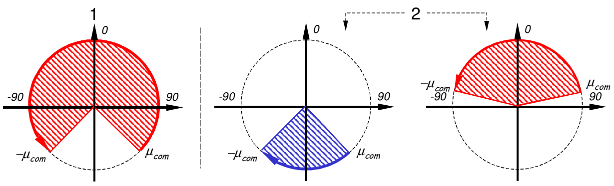

Fig n° 11

Considering roll reversal performed only through a full lift down bank angle in order to avoid as much as possible high energetic exit conditions has to be withdrawn due to too poor performances leading in some cases to a crash on the planet.

The second solution which is the most complex to implement is to integrate the lateral logic within the forward propagation process to get the absolute value of the commanded bank angle, while keeping out of the in-plane logic loop the same lateral logic to get the sign of the commanded bank angle, see fig. n° 12.

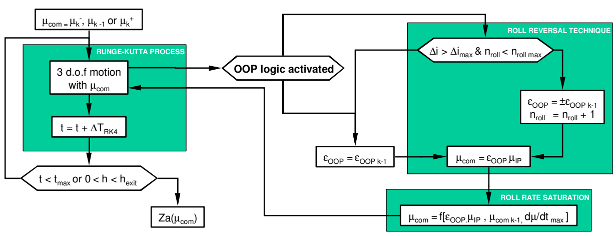

Fig n° 12

The main drawback of this last solution is to naturally degrade the on-board computation burden, the numerical integration frequency having to be increased to be representative enough of the impact of the roll manoeuvres on the reached apoapsis.

PERFORMANCES ASSESSMENT

The performances assessment is made with 1000 runs Monte-Carlo simulations using a dedicated simulation tool, see fig. n°13.

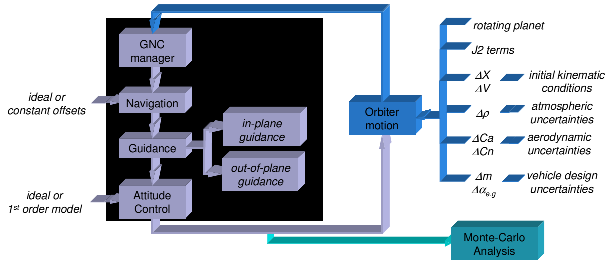

Fig n° 13

Each improvement is tested separately. If we except the modification of the reference trajectory and the natural simplification of the forward propagation process (only two predicted trajectories are computed), the best solution to retain is, see fig.n°14 for its implementation:

- atmospheric density estimator with both first order and sliding median filtering;
- roll reversal through the shortest way
- full decoupling between in-plane and out-of-plane logic (i.e. no integration of the roll strategy within the forward propagation process of the in-plane logic).

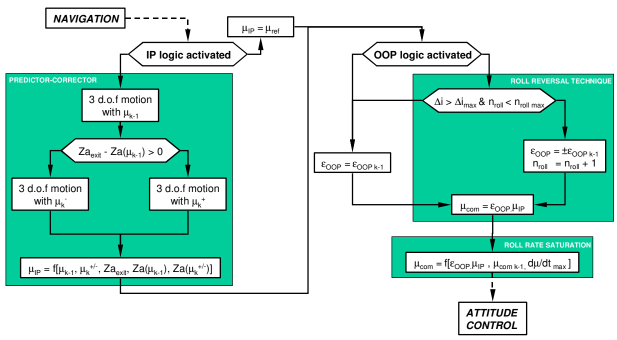

Fig n° 14

Doing so, one gets the following statistical results provided by a 1000 runs Monte-Carlo simulation (see fig. n°15 presenting a 0.02 Hz sampling of the trajectories within the aerocapture corridor):

parameter	mean value	standard deviation
ΔZa	366.5 km	4122 km
ΔZp	184.4 km	2062 km
Δi	-0.03 deg	0.36 deg
ΔV	148.8 m/s	114.3 m/s

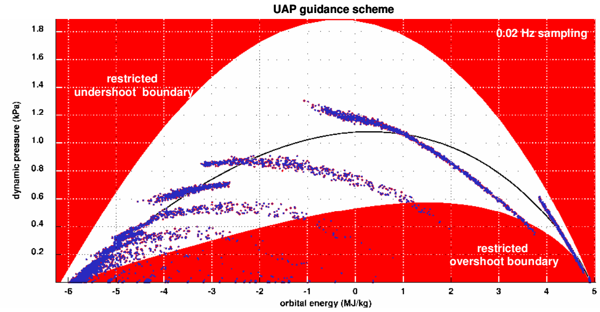

Fig n° 15

As for FTC scheme, the high energetic exit conditions are mainly due to too large atmospheric dispersions (beyond -70 % of the dispersion profile) that are linked to important L/D dispersions (beyond -5 %), see fig. n°16.

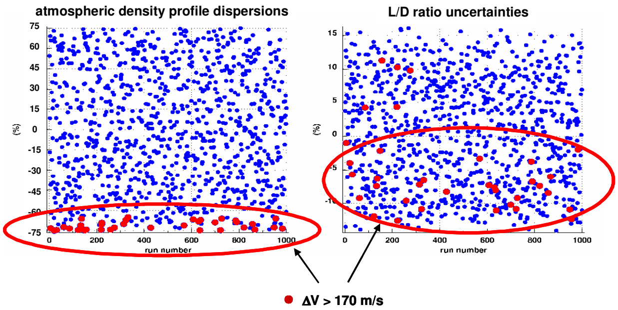

Fig n° 16

Concerning the design constraints, even if they are not taken into account by the in-plane logic (it could be with only light modifications), heat flux and g-load requirements (resp. 680 kW/m^2 and 10 g for the robotic mission) are met with important margins, see next table and fig. n°17.

parameter	mean value	standard deviation
g load	1.87 g	0.17 g
heat flux	149 kW/m^2	7.8 kW/m^2
heat load	23.9 MJ/m^2	0.95 MJ/m^2

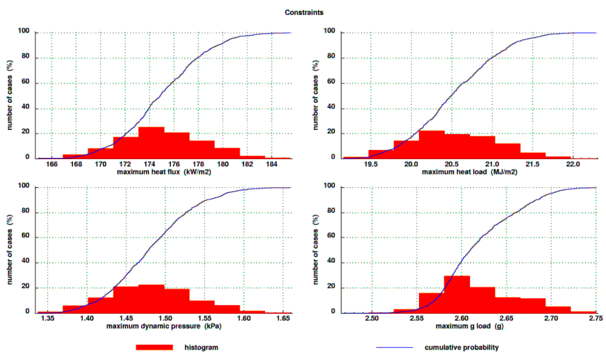

Fig n° 17

Compared to previous results, the Upgraded Apoapsis Predictor guidance scheme yields very good results that are now similar to FTC performances.

FTC/UAP TRADE-OFF ANALYSIS

The trade-off analysis is performed using performance index such as fulfilment of the mission requirements (with respect to final accuracy, or ΔV correction cost, and to the vehicle design constraints), the code complexity and the computational burden.

If one considers the ΔV correction cost performance index, one notices that both guidance schemes yield very similar performances, see fig. n°18. The FTC scheme appears to be more robust for atmospheric dispersions beyond -60 %, but it is counterbalanced by a 3 m/s higher mean ΔV cost below. And concerning the design constraints, one gets also very similar results. Thus, the ΔV correction cost performance index appears to be not very discriminating.

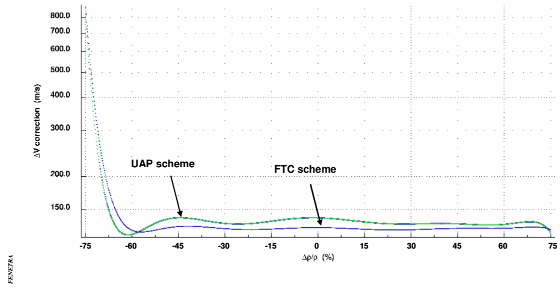

Fig n° 18

From a complexity point of view, UAP scheme requires more encoding due to its numerical prediction process, and also more internal and mission data. But, contrary to FTC, it needs less on-board memory for mission data, only the atmospheric density nominal profile having to be tabulated with respect to the altitude. There too, UAP advantages are counterbalanced by its relative drawbacks.

Finally, the most discriminating parameter is given by the CPU load estimation. Fig. n°19 presents the evolution versus time of the CPU time needed at each guidance step for both guidance schemes and using a Sun Ultra 60 workstation with a Specfp 2000 index of 166. Even with a not optimised FTC baseline (i.e. the look-up-table scrutations are always performed starting from the top of the files) and an optimised UAP prediction process (the integration frequency is set at 0.1 Hz that appears to be a limit to get accurate results), there is an important gap between both schemes. For UAP scheme, the CPU time varies between 10 ms, at the beginning of the aerocapture manoeuvre, and 0.3 ms when exiting the atmosphere, while it does not exceed 0.4 ms for FTC scheme (even 0.1 ms when considering an upgraded searching process of the reference parameters in the different look-up-tables).

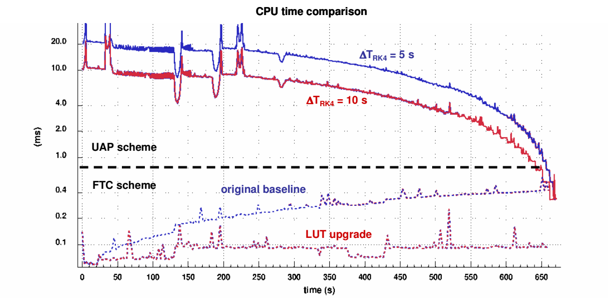

Fig n° 19

EXTENDED FTC/UAP TRADE-OFF

Previous results show that both guidance schemes yield very similar performances, but with an important drawback for the UAP scheme due to its computational burden.

In order to be sure that those conclusions are not linked to the mission and/or to the aerocapture vehicle, one has considered an extra MSR mission built using an AFE-like vehicle, see fig. n°20 that presents (only for illustration purpose) an AFE capsule design using an Apollo-like back-cover and an AFE-shape heat shield.

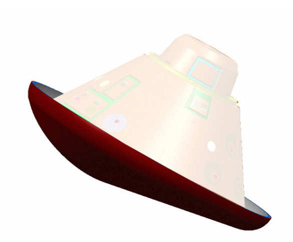

Fig n° 19

This kind of capsule was the baseline capsule for the first aerocapture demo-flight with the Shuttle[1], and also for the MSR-O mission[4].
The retained mission scenario corresponds to the following entry conditions:

relative velocity	5762	m/s
flight path angle	-10.88	deg
heading angle	80.44	deg

According to these entry conditions and to an elliptic 1400 km/200 km parking orbit, the orbital parameters at atmosphere's exit are:

apoapsis	1400	km
periapsis	31	km
inclination	9.52	deg

that yields a nominal ΔV correction cost of 38 m/s.

Keeping the same process baseline for the roll strategies (always through full lift-up bank angle for FTC, and through the shortest angular way for UAP), and using 1000 runs Monte-Carlo simulations, one gets no crash on Mars ground, and some hyperbolic (around 0.016 % for FTC and 0.014 % for UAP) and high energetic exit cases (around 4.1 % for FTC and 4.8 % for UAP over the ATPE 170 m/s requirement), see fig. n°22 (FTC scheme) and n°23 (UAP scheme).

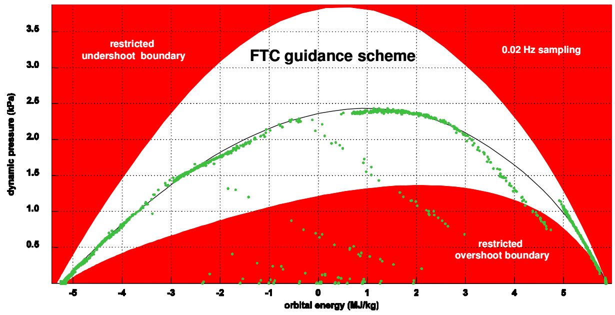

Fig n° 22

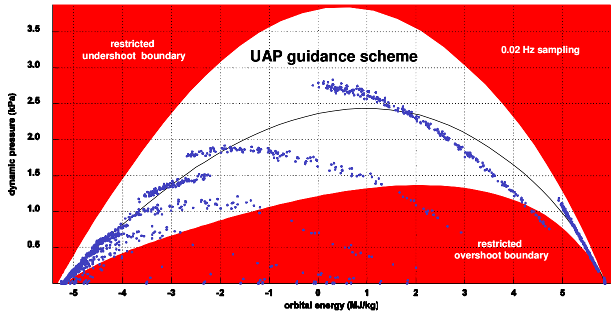

Fig n° 23

As for previous mission and vehicle, these cases are still due to overshoot or near oveshoot conditions induced by important atmospheric density dispersions (beyond -60 % dispersions on $\Delta\rho/\rho$) and, for some of those cases, by L/D dispersions (beyond -5 %).

Fig. n°24 summarizes those results with respect to the ΔV performance index, while next table presents the 95 % value on the design constraints.

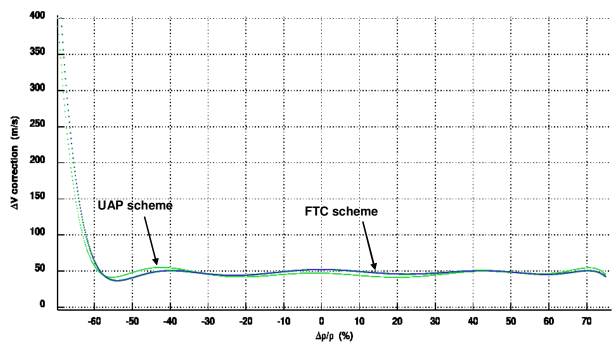

Fig n° 21

95 % value	FTC scheme	UAP scheme
g load	2.1 g	2.3 g
heat flux	238 kW/m^2	247 kW/m^2
heat load	39.2 MJ/m^2	35.5 MJ/m^2

One notices the same behaviour as previously shown: performances are very similar, both guidance schemes yielding results within less than 1 m/s offset as long as the atmospheric density dispersion is below -60 %, with a mean ΔV correction cost just below 60 m/s. And as previously mentionned, increasing the performance level, mainly towards the guidance robustness, may be performed considering a lower reference bank angle trajectory in order to dive deeper into Mars atmosphere what improves naturally the management of the aerodynamic forces.

CONCLUSION

Within the 2002 preparatory phase of the ESA ATPE technological research project, EADS-ST applied results of previous internal studies on guidance scheme design to perform aeroassist manoeuvres such as aerocapture, aerogravity assist and also aerobraking on Mars, Venus or the Earth while meeting path (g-load, heat flux and heat load) and final constraints (mainly ΔV correction cost needed to reach the parking orbit).
According to a study extension still sponsored by ESA, EADS-ST brought some upgrades to a numerical predictor-corrector guidance scheme that was formely developed in the frame of the MSR-O project but was rejected due to too poor performances. Using only light modifications concerning mainly the atmospheric density profile estimation and the roll strategy, this upgraded Apoapsis Predictor yields similar performances in terms of final accuracy and design constraints fulfilment than the Feedback Trajectory Control guidance scheme that is up to now the ATPE baseline for aerocapture manoeuvres. But being built around a numerical process, this new guidance scheme whose original design yields a natural higher robustness in case of important changes of the parking orbit (no predefined look-up-tables are needed) is by far more time consuming than the FTC scheme. Its on-board implementation would then require specific soft/hardware developments to be as reactive as the FTC scheme mixing analytical and numerical prediction phases.

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ACRONYMS AND SYMBOLS

AFE	Aeroassist Flight Experiment
AP	Apoapsis Control
FTC	Feedback Trajectory Control
IP	In-Plane
ITV	Inflatable Technology Vehicle
MSR	Mars Sample Return
MSR-O	Mars Sample Return Orbiter
OOP	Out-Of-Plane
UAP	Upgraded Apoapsis Control
ΔV	propulsive correction cost
Za	apoapsis altitude
i	inclination
Δi	inclination offset
V	relative velocity
μ	bank angle