AERO-GRAVITY ASSIST MANOEUVRES WITHIN PRELIMINARY INTERPLANETARY MISSION DESIGN: A MULTI-OBJECTIVE EVOLUTIVE ALGORITHM APPROACH

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ABSTRACT

The paper presents a new approach to deal with the preliminary space mission analysis design of particularly complex trajectories focused on interplanetary targets. According to an optimisation approach, a multi-objective strategy is selected on a mixed continuous and discrete state variables domain in order to deal with possible multi-gravity assist manoeuvres (GAM) as further degrees of freedom of the problem, in terms of both number and planets sequence selection to minimize both the Δv expense and the time trip time span. A further added value to the proposed algorithm stays in that, according to planets having an atmosphere, aero-gravity assist manoeuvres (AGAM) are considered too within the overall mission design optimisation, and the consequent optimal control problem related to the aerodynamic angles history, is solved. According to the target planet different capture strategies are managed by the algorithm, the aerocapture manoeuvre too, whenever possible (e.g. Venus, Mars target planets). In order not to be trapped in local solution the Evolutionary Algorithms (EAs) have been selected to solve such a complex problem. Simulations and comparison with already designed space missions showed the ability of the proposed architecture in correctly selecting both the sequences and the planets type of either GAMs or AGAMs to optimise the selected criteria vector, in a multidisciplinary environment, switching on the optimal control problem whenever the atmospheric interaction is involved in the optimisation by the search process.

Symbols

δ	= semi-angular deviation for GAM between the v_∞^-, v_∞^+ in\outcoming vectors [rad]
ϕ	= Angular deviation for AGAM between the v_∞^-, v_∞^+ in\outcoming vectors [rad]
ρ	= Atmospheric density [kgm^{-3}]
γ	= Flight path angle [rad]
μ	= Bank angle [rad]
$\delta\Delta t_{transf\ j}$	= j-th heliocentric transfer time variation with respect to the linked conics solution
$\Delta\lvert v_\infty\rvert$	= Relative velocity losses because of drag [ms^{-1}]
ω_I	= i-th planetary passage orbital plane inclination according to the reference [rad]
A	= Surface [m^2]
k_{planet}	= Planetary constant [m^3s^{-2}]
N	= No. of flybys apart from the departure and target planets
Q	= Heat load [J/m^2]
$\underline{r}$	= Object position vector according to the primary attractor
r_{interf}	= Planetary atmosphere limit [m]
$\underline{S}$	= (1xN) Planet sequence vector
v_∞=	= Incoming s\c velocity vector relative to the planet[ms^{-1}]
V=	Velocity vector modulus
v_c	= Relative velocity vector on circular orbit at $\lvert r\rvert$ equal to the atmospheric path [ms^{-1}]
X	= Distance from the stagnation point [m]

1. INTRODUCTION

The interplanetary mission design is a challenging task whenever optimal solutions are asked for in terms of fuel mass savings. A well-known strategy involves possible planetary flybys to obtain a gravitational help. Such a technique has been largely applied starting from the Mariner 10 up to the most recent Cassini-Huygens and Rosetta missions. Nowadays space missions keep being more and more demanding in terms of scientific, operative payloads mass requirements: different techniques are items of current space research topics, such as better performing propulsion units and energy conversion. A research branch involves possible atmospheric manoeuvres in order to increase the momentum exchange at the planetary flybys. The aeroassisted manoeuvres (AGAM) have never been applied in practice because of technological issues related to the high aerodynamics efficiency (up to 10) required to be effective, the enormous heat loads suffered by the probe during the passage and, last but not least, the fine precision the GNC system must assure. However the problem has been quite studied: starting from the sixties the advantage of AGAM whenever large plane changes are asked has been highlighted [1]. Thanks to the studies related to the definition of very high efficiency shapes in a hypersonic environment the AGAM applicability became realer [2]. Based on those results, McRonald and Randolph proposed an AGAM solution for very demanding missions towards the Sun and Pluto, demonstrating that, by applying a $Mars_{AGAM}$, the C3 and the transfer time are significantly reduced and the radiation problem related to a Jupiter GAM (representing the default strategy) is avoided [3][4]. The authors propose a constant height maintenance during the atmospheric passage, constraining the planetary trajectory to be planar. Lohar & al. by deepening the former studies focusing on the heat load evaluation, concluded that those manoeuvres keep being unreal because of lack of technologies [5]. Bonfiglio & als. highlighted the benefits the AGAMs manoeuvres insertion have in terms of the launch window set enlargement [6]. Johnson, in a recent study, showed that the best fuel saving AGAM does not correspond to the constant height manoeuvre, but a varying height is preferable to reduce the drag losses [7]. The current work, starting from that last work, considers the AGAM as a further degree of freedom to be inserted in an interplanetary trajectory preliminary optimisation scenario. An algorithm architecture has been implemented to manage the number and sequence of possible AGAM and GAM as control variables to minimize both the on-board fuel demand and the transfer time. The atmospheric manoeuvres are modelled removing the McRonald constraint and controlling the s\c in bank angle. The paper firstly presents the problem modelling, then the multiobjective optimization selected approach and finally some of the obtained results.

2. THE PROBLEM

The work here presented is limited to the impulsive manoeuvre class, hence a natural objective function for the mission design optimisation stays in the minimization of the global $|\Delta \underline{v}|$ asked to the propulsion module. On the other hands, the transfer time has to be limited because of on-board device aging. Therefore, a possible vector $\underline{G}$ of the objective functions is naturally defined for an interplanetary chemical-propelled trajectory:

$\underline{G}=[\Sigma_i \Delta v_i \; \Delta t]$; i=1,…,n; n=no. of propelled manoeuvres

However, it has to be noted that, whenever atmospheric manoeuvres are part of the interplanetary trajectory either the heat or the heat flux peak on the probe could be asked to be optimised, according to a multidisciplinary point of view. The heat minimization involves, in fact, the structural, the thermal, and the attitude control spacecraft design. The $\underline{G}_{atm}$ objective function vector is then defined as:

$$\underline{G}_{atm}=[\Sigma_i \Delta v_i \; Q]$$

The criteria vectors definition opens the problem of the analytical model to be selected to deal with it and, consequently, the free variable $\underline{X}$ and parameter vector $\underline{P}$ definition. In the following paragraph the models here adopted are briefly given.

3. THE PROBLEM MODELIZATION

The orbital mechanics is here modelled according to a keplerian approach; hence the spacecraft dynamics answers the following vector second-order differential equation:

$$\frac{d^2 \underline{r}}{dt^2} = -\frac{k_{primary-body}}{|\underline{r}|^3}\underline{r} \qquad (1)$$

The object motion is completely known by the six keplerian parameters identification, easily done by applying the three invariants of the motion, the angular momentum $\underline{h}$, the eccentricity $\underline{e}$, the energy E [8].

From the energy equation the absolute value of the velocity as a function of the position on the conic can be obtained [8]. Hence, the global $|\Delta \underline{v}|$ momentum variation given by an impulsive manoeuvre for a ballistic transfer between two co-focal non intersecting orbits needs knowing the six keplerian parameters according to the departure, the target orbits and the transfer between the two conics. However, whenever the heliocentric transfer occurs between two planets the actual $|\Delta \underline{v}|$ to be given by the propulsion module is strictly connected to the gravitational planetary field escape\capture. In other words to correctly compute the energy jump eq.1 must be applied by assuming the planet as the main attractor as far as an $\underline{r}_\infty$ position from the planet is gained by the s\c; from that position on the main attractor is turned on the Sun, giving rise to a reference frame change [8][9]. Moreover, by dealing with possible GA manoeuvres focused on saving fuel mass, such an approach is definitely necessary, as the propelled $|\Delta \underline{v}|$ is lowered thanks to the planetary flyby effects on the value and direction of the incoming and outcoming heliocentric s\c velocity vectors. As known, such a variation on the heliocentric velocity vector depends on the minimum distance from the planetary surface r_p, the relative s\c incoming velocity vector $\underline{v}_\infty$, the hyperbolic orbit plane inclination i, the planetary heliocentric velocity vector $\underline{V}_p$. In order to enlighten the computational effort, a nested architecture has been here implemented by considering firstly the interplanetary trajectory definition from the sole heliocentric point of view, assuming a *linked conics* approach; whenever optimal zones are detected in the solution space, a finer search starts taking into account the attractor change whenever a planetary sphere of influence is entered, according to the *patched conics* approach. The models adopted for the two nested modules of the overall architecture are given in the followings.

Linked conics models

The *linked conics* module assumes, always, the Sun as the main attractor. Heliocentric conics arcs connecting at least two planetary orbits are computed by solving the two-boundary problem of eq.1 with $\underline{r}_{in}(t)$ and $\underline{r}_{fin}(t+\Delta t)$ being the solutions of eq.1 according to the departure and target planet motion respectively. The Lambert's problem solution has been here applied, in order to find the possible conic connecting the two given position vectors (starting-final planet positions) and the interval of time Δt_{trans} to go through such a path. By knowing the departure and target planetary orbits from ephemeris and the transfer orbit, the $|\Delta \underline{v}|$ needed for the interplanetary transfer can be obtained. Hence, the optimisation problem here proposed has, at least, the following free variables and parameters sets:

$\underline{X}= [t_{in}\ \Delta t_{transf}]$;

$\underline{P}=[a_{in}, e_{in}, i_{in}, \Omega_{in}, \omega_{in}; a_{fin}, e_{fin}, i_{fin}, \Omega_{fin}, \omega_{fin}]$

in=departure planet; fin=target planet

Such an approach can be extended to consider the GAM as further degrees of freedom to enlarge the search space for a better optimum for the $\underline{G}$ vector. Gravity assist manoeuvres, in fact, aim obtaining a s\c momentum change with no fuel mass expense, just exploiting the planetary mass gravitational effect. Sequential Lambert's problems can be solved by pairs of consecutive selected planets to connect different conics arcs with a velocity vector discontinuity at the j-th planet encounter. To this end, how many and which planets for possible encounter must be selected in order to define the $\underline{r}_i(t_i)$ vectors needed as input by each Lambert arc. The work here presented assumes those quantities as further variables for the optimization problem, making the $\underline{X}$ vector larger:

$\underline{X}= [N, \underline{S}, t_{in}, \Delta t_{transf\text{-}1},\ldots, \Delta t_{transf\text{-}n}]$

Obviously, the $\underline{P}$ vector is enlarged too, according to the number and type of planets selected by the current solution, up to a ((N+2)x6) and ((N+2)x1) dimension respectively. The GAMs, the AGAMs and the target planet capture are taken into account within the *linked conics* as boundary conditions on the position vector $\underline{r}_{s\backslash c}$ ($\underline{r}_{s\backslash c}(t_i)=\underline{r}_{planet}(t_i)$) to solve the N Lambert's problems; the global heliocentric $|\Delta \underline{v}|_{glob}$ is computed as the sum of the single $|\Delta \underline{v}|_i$ to be supplied at each i-th trajectory discontinuity nearby a planetary pass.

Thanks to the momentum exchange with the planet, however, part of each computed $|\Delta \underline{v}|_i$ is supplied by the planet itself, and it does not enter the computation of the propelled $|\Delta \underline{v}|_{fuel\text{-}i}$ to be minimized:

$$\left|\Delta \underline{v}\right|_{fuel-i} = \left|\, \Delta \underline{v}_i - \Delta \underline{v}_{planet-i} \,\right| \qquad i=1,\ldots,N+2 \qquad (2)$$

The $|\Delta \underline{v}|_{planet\text{-}i}$ momentum exchange amount because of the flybys and possible atmospheric manoeuvres are approximated assuming the maximum incoming relative velocity rotation for GAMs, the dynamic vertical equilibrium for the AGAMs [3][4][9]. The planetary capture is supposed to be completely propelled by assuming $|\Delta \underline{v}|_{fuel\text{-}capture}=|\underline{v}_{\infty,s\backslash c\text{-}target}|=|\underline{v}_{helio\text{-}s\backslash c\ at\ target}-\underline{v}_{helio\text{-}target}|$. In particular, the heliocentric $|\Delta \underline{v}|$ amount because of the gravitational planetary effect is computed as:

$$\begin{cases} \left|\Delta \underline{v}\right|_{GA-\max} = 2 v_\infty \sin 2\delta \\ \delta = \arcsin \dfrac{k_{primary-body}}{v_\infty^2 r_{interf} + k_{primary-body}} \end{cases} \qquad (3)$$

The heliocentric $|\Delta \underline{v}|_{AGAM}$ amount because of the aero-gravity assisted planetary effect assumes, as always obtainable, the $\underline{v}_\infty$ vector rotation to gain the heliocentric outcoming velocity versor asked by the Lambert's arc computation. According to a constant height manoeuvre, the energy loosing because of atmospheric drag effects can be modelled as [3][4]:

$$\frac{\Delta\left|\underline{v}_\infty\right|}{\left|\underline{v}_\infty\right|} = -\frac{\phi}{c_l/c_d}\left[1+\left(\frac{v_c}{v_\infty}\right)^2\right] \qquad (4a)$$

The present work removes the constant height hypothesis. Comparisons on a $|\Delta \underline{v}|_{fuel}$ minimisation scenario for the atmospheric manoeuvre by using a constant height and a constraint-free 3D motion models respectively lead to the definition of a correction factor of eq.4a equal to two:

$$\frac{\Delta\left|\underline{v}_\infty\right|}{\left|\underline{v}_\infty\right|} = -2\frac{\phi}{c_l/c_d}\left[1+\left(\frac{v_c}{v_\infty}\right)^2\right] \qquad (4b)$$

Patched conics models

Differently from the *linked conics*, the *patched conics* approach enters the planetary passage\capture details both in terms of $|\Delta \underline{v}|_{planet\text{-}i}$ and Δt_i computation. This more complicated approach is necessary in order to correctly describe the aero-assisted manoeuvre in terms of heat load and guidance law associated, while it would not be necessary for ballistic manoeuvres.

For the simple gravitational mechanics, as already pointed out, six quantities have to be defined according to the two-bodies model to have the relative s\c motion around the planet completely defined. A GAM is fully described introducing the following $\underline{X}$ vector

$\underline{X}_{GAM}= [\delta\Delta t_{transf\text{-}1},\ldots, \delta\Delta t_{transf\text{-}n}, r_{p1}, \ldots, r_{pn}, \omega_1, \ldots,\omega_n]$;

Moreover, the possibility to insert a further degree of freedom in terms of aerocapture manoeuvre at the target planet, asks for dedicated problem formalization.

To this end the $\underline{X}$ vector is changed as follows:

$\underline{X}_{GAM}= [\delta\Delta t_{transf\text{-}1},\ldots, \delta\Delta t_{transf\text{-}n}, r_{p1}, \ldots, r_{pn}, \omega_1, \ldots,\omega_n]$

an AGAM asks for a different set of dynamics equations because of the aerodynamics loads. Within the present work the fixed height approach is overcome and the whole set of equation governing the motion of the centre of mass is applied with no constraints but $\underline{r}_{s\backslash c}>R_{planet\text{-}i}$. The differential system governing the atmospheric motion is characterised by two free dynamics: the bank angle (μ) and the angle of attack. The former angles are here treated as a parameter and as a variable vector respectively. Hence, a trimmed flight history is imposed, while an optimal lateral control law is looked for. Moreover, some configuration quantities are assumed as parameters leaving as a free variable the reference surface for the aerodynamics effects. The boundaries on A are defined according to the admissible range for the ballistic coefficient of the waveriders found in literature.

The $\underline{X}$ and $\underline{P}$ vectors are changed as follows:

$\underline{X}_{AGAM}= [\underline{X}_{GAM}, \mu_1,\ldots, \mu_w, A]$

$\underline{P}_{AGAM}=[cl,E, m, N,\underline{S}]$

The $|\Delta \underline{v}|_{planet-i}$ is now computed according to trajectory obtained from the current $\underline{X}$ free variable vector. It has to be noted that N and $\underline{S}$ disappeared from the variable vectors as they are assumed as parameters within the *patched conics* optimisation module defined by the former *linked conics* optimisation module. The capture manoeuvre dynamics is ruled either by eq.1 or atmospheric motion equations depending on the pericentre altitude. The $|\Delta \underline{v}|_{fuel,\ target\ capture}$ computation asks for the inbound hyperbolic path and the desired final planetary orbit complete knowledge. The heat computation is here obtained by considering the stagnation point load. A further development would invoke a CFD module to a finer multidisciplinary analysis. The heat flux at the stagnation point is obtained thanks to the Reynolds analogy between viscous stress and heat flux [13]. Its integration in time and area gives the atmospheric passage heat load Q.

4. THE OPTIMIZATION TECHNIQUE

The optimization problem here analysed highlights different items to deal with: costs are no more scalar but vectors; free variable domains are both discrete and continuous; cost functions to be optimized are multimodal. Hence, a global multiobjective optimisation tool that does not ask for gradient and Hessian computation is aimed. Moreover, according to the application, it could be definitely useful to acquire a set of possible optimal solution among which to select depending on the space system design demand: as the trajectory and the system design are highly interdependent the possibility to change the flight path to answer a particular engineering constraint just picking up a different optimal solution would save a time and possibly optimize the space system design too. That is why a genetic algorithm technique has been here selected: different solutions can be analyzed and kept alive simultaneously; to be trapped in a local minimum is then avoided and a global optimum can be easier captured. No C^j membership is asked to the $\underline{G}$ elements as neither gradient or Hessian is computed; any kind of variable domain can be managed. On the other end, some items must be solved in dealing with the GAs: problem coding and operator selection, convergence criterion definition, constraint management, and the genetic drift. Within the current work a real coding has been applied to speed up the convergence, while a specific convergence criterion has been implemented. Constraints have been simply treated by applying penalties [12]; for the genetic drift management a hybrid elitism together with the interference severity techniques turned out to be the best choice to maintain sparsity and completeness in the final solution set. The elitism speeds up the process as the active population dimension is contained, while preserving the best solutions in the elite. The interference severity prevents from niches, maintains the search in the solution space well spread [13]. A non-dominance criterion according to Pareto has been applied to turn the $\underline{G}$ vector to a single element dimension and for the fitness computation [14]. In particular, specifically for the *linked conics* module, the ranking is based on the following fitness:

$$Fitness(i)=[\Sigma_j T_{ij}, ND_i] \qquad (5)$$

T_{ij}= counter for the i-th chromosome invasion of the interference zone of the j-th chromosome:

$$x_i \in \tau_j \rightarrow T_{ij}=1;\ x_i \notin \tau_j \rightarrow T_{ij}=0$$

ND_i=no. of chromosomes that dominate the i-th individuals, according to the $\underline{G}$ vector

5. VALIDATION & RESULTS

Several validation sessions have been run in order to check for the convergence and sparsity properties of the implemented GA tool on a multiobjective optimization environment. Results, here omitted for lack of space, highlighted the ability of the algorithm in catching several complex Pareto fronts discontinuous, concave and convex with a good distribution on the front. Tests functions came from literature and the comparison with different proposed methods showed that the proposed GA performances are definitely comparable with the most performing approaches [15].

Results from the *linked-patched conics* modules are given for a possible mission to Titan in order to highlight the algorithm performance in dealing with a mixed discrete-continuous domain and forecasting good niches of $\underline{S}$, for the *patched conics* analysis. A possible AGAM is then discussed in detail. The linked module analyses the interplanetary transfer to Saturn; at first trajectories with GAMs only are presented (fig.1), then this constraint is removed (fig.2). The bounds of N can be settled by the user, with a default range of [1 4] for GAMs only trajectories and [1 2] for GAM+AGAM paths. Thanks to the interference severity technique, sparsity is maintained in terms of number of flybys and $\underline{S}$ sequence vectors. For all the paretian solutions, the algorithm has lead to trajectories for which the intermediate propelled Δv is virtually zero, i.e. Δv required is provided by the planetary flyby. For GAM only trajectories, the best solution in terms of Δv is given by a [Ma J] sequence, path which is also present in the knee region of the front.

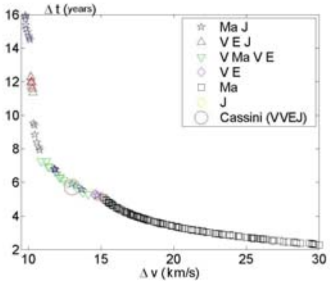

Fig.1: E→S GAM only trajectories: linked conics

Very good compromise solutions can be obtained by following the [V Ma V E] and [V E] trajectories. In order to give evidence of the effectiveness of the algorithm, it is important to notice that cost functions associated with the Cassini mission, studied by NASA, lie in the detected front ; the actual mission sequence [V V E J] has not been found, probably due to a different launch window because of a Cassini deep space manoeuvre (not taken into account here) after the first venusian flyby. A single martian flyby gives the best solutions in terms of Δt, not equally effective from an energetic point of view.

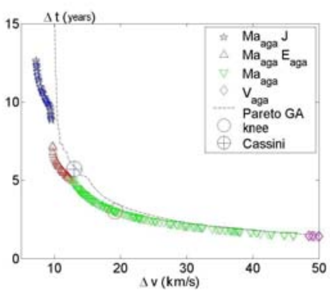

Fig.2: E→S GAM+AGAM trajectories: linked conics

Fig.2 reports the results for GAM+AGAM trajectories, according to eq.4b for the energy variation computation in atmospheric manoeuvres; eq.4a utilisation leads to very similar results in terms of overall shapes of the Pareto fronts, paretian $\underline{S}$ and $|\Delta \underline{v}|_{fuel.}$ Hence the analyses here given having applied eq.4b are definitely valid whenever eq.4a is used. The best Δv solution is obtained with a [Ma J] sequence too: the AGAM instead of a GAM on Mars allows a ~2.5kms^{-1} saving; a ~6.5kms^{-1} is gained according to a direct transfer to the planet (~13.9kms^{-1}). A solution comparison according to the same energy demand, shows a transfer time reduction gain: according to the minimum $|\Delta \underline{v}|_{fuel\text{-}GAM}$ (~9.8kms^{-1}) the transfer duration is more than halved. A Mars and Earth AGAM coupling turns out to be a good sequence too, according to Δv_{fuel} . The best compromise solutions are anyway obtained with a single AGAM on Mars: these trajectories give strong improvements in the knee region of the Pareto front, compared with GAM only trajectories, as table 1 shows. Fig. 4 shows the Pareto front according to the $\underline{G}_{AGAM}$ cost vector: the knee solution ([E Ma S], Δv=19.21km/s, Δt=1099days), sketched in fig.3, has been selected as interplanetary transfer to input in the $\underline{P}_{AGAM}$ within the study of the complete mission to Titan. The Δv_{fuel} is here computed from LEO orbit (h=300km) to a parking orbit around Titan.

Table 1: GAM-AGAM comparison

Solution	**GAM only**	**GAM+AGAM**
min dv	Δv=9.77 km/s	Δv=7.25 km/s
Δv=15km/s	Δt=5.15 years	Δt=3.91 years
Δt=5 years	Δv=15.23 km/s	Δv=12.55 km/s

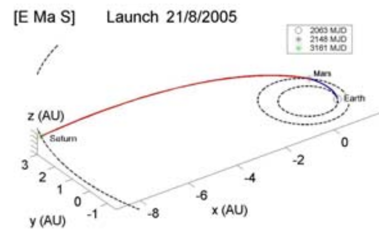

Fig.3: knee trajectory

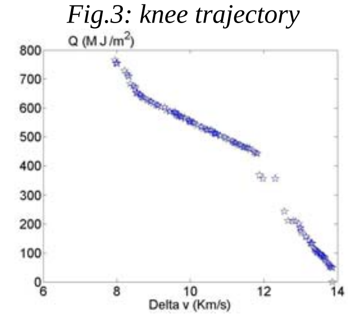

Fig.4: Δv-Q Pareto front: patched conics

The heat loads are definitely high (O (10^{2}MJm^{-2})) asking for devoted high-performing radiative protections. Fig.5 highlights detailed results of the AGAM on Mars. In particular, the tool, trying to maximise the $|\Delta \underline{v}|_{planet\text{-}AGAM}$ to answer the $\underline{G}_{AGAM}$ minimisation, turns out the height profile reported in fig.5b: the lower the height the higher the lift, hence the vehicle manoeuvrability. A 40Km minimum height (acceptable for Mars topography) is required. On the other hand, the heat load and the drag effects increase rapidly, that is why the atmospheric permanence is definitely low: 80s instead of 480s proposed by results for a constant height atmospheric manoeuvre [3][4].

Results showed the proposed atmospheric manoeuvre gain a 90% of the $|\Delta \underline{v}|_{AGAM}$ attainable with the McRonald technique because of a doubled energy losses. However, an out-of hyperbolic passage plane component can be produced in the $\Delta \underline{v}_{AGAM}$ by applying the proposed manoeuvre, definitely useful from the overall heliocentric point of view; a 0.79$|\underline{v}|_{\infty}$ normal component for the energy variation vector is attainable. On the contrary, the McRonald's is a planar trajectory as, to completely counterbalance the centrifugal effects the whole possible lift load is exploited. The optimum bank history is given in fig.5a: the bank angle stays within –90° and 90° most of time, assuring a positive lift vector. Because of a simple linear interpolation, discontinuities are present in the graph. The flight path angle has a critical trend: a $\dot{\gamma} = 2°s^{-1}$ is asked at the lowest height. From a multidisciplinary point of view, such a pull up manoeuvre is highly demanding in terms of inertial loads on the structure: by constraining the flight path angle derivative the inertial loads decrease, while increasing the $|\Delta \underline{v}|_{fluel-glob}$.

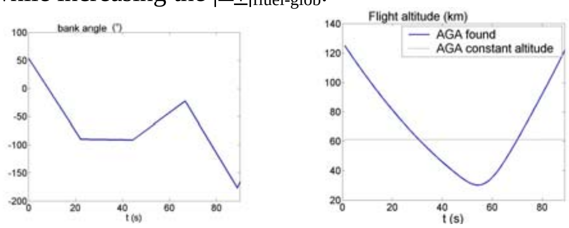

Fig.5a-b: Mars AGAM-details

A good compromise is offered by the $\dot{\gamma} = 1°s^{-1}$ solution, as given in table 3: the price to be paid is in terms of Q loads, increased by the 15%.

Table3: inertial loads vs. flight path angle derivative

$\dot{\gamma}_{max}$ **[°s^{-1}]**	**Acc_{max}[ms-^{2}]**	**Δv_{min} [Km/s]**	**Q_{max}[MJm^{-2}]**
1	261	8.02	894

The ballistic coefficient (β_l=m/A*C_l) bounds are fixed according to previous studies on the waveriders ([30-50]): Tab. 4 gives the adopted mass and aerodynamics parameter values.

Table4: Configuration parameters

Aerodynamic efficiency	10
CL	0.1
mass	1000Kg

6. CONCLUSIONS

An algorithm architecture is here proposed to deal with the interplanetary mission preliminary design optimisation with possible atmospheric\gravitational manoeuvres to reduce the on-board fuel demand and the transfer time. An atmospheric dynamics less constrained than the Mc Ronald studies, has been implemented. Such an approach showed the advantage of obtaining a non-planar planetary trajectory, at the flyby, enhancing the energetic help attainable by the encountered planet. A two-level architecture is proposed to maintain the number and sequence of encountered planets as a further degree of freedom for the optimal solution detection: thanks to the particular genetic algorithm a well spread Pareto front is detected and a set of solutions well distributed in the search space are given to the system designer. The multiobjective approach balances the final solution set according to multidisciplinary aspects to be further developed by adding more detailed modules. Solutions showed that the insertion of mixed GAM-AGAM sequences could definitely lower the on board fuel mass while reducing the transfer times. As a drawback a quite demanding manoeuvre is identified for the atmospheric passage, particularly focusing on the inertial and heat loads.

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