

ORBITAL CHANGES USING ATMOSPHERIC MANEUVERS

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ABSTRACT

The study of atmospheric maneuvers for satellites is an important aspect of the exploration of planets surfaces and atmospheres. To take more advantage of the gains due to atmospheric maneuvers, we need to develop an optimal control law to maneuver the satellite. This control law should minimize the fuel consumption required by the velocity variation due to engines on board the satellite. With this in mind, the aim of the present work is to establish what is the performance gain that can be achieved using aerodynamic forces combined with propulsive ones, with the objective of changing a satellite orbital plane around the Earth. Results of several simulations are presented.

1 - INTRODUCTION

To enable low cost missions to make orbit transfers, for maneuvers between long distance targets in the Solar System, and for the space vehicles that have to be captured for reutilization, it is required to find alternatives to reduce fuel expenditure. The current capacity is very limited by the excessive fuel needed to launch and transport heavy loads into space. This situation motivated the specific technical development of orbital maneuvers using natural forces, replacing, at least in part, propulsive forces.

Several control methods for vehicles crossing the atmosphere have been studied to guarantee that the acceleration and the heating stay between the predefined boundaries. The maneuvers that use the atmosphere to modify a spatial vehicle velocity are referred to as “aeroassisted maneuvers”. In this kind of maneuver, the atmosphere has the function of reducing the vehicle velocity causing an orbital transfer that can be coplanar or not.

Since the first works in the beginning of the 60's, it has been established that a substantial performance gain could be reached using aerodynamical forces together with the propulsive ones, with the objective of causing an orbital plane change around the Earth. This kind of maneuver, that can be carried out in the vicinity of any atmospheric planet, was called “synergetic plane change” and is part of the aeroassisted orbital transfers.

Application examples for flight concepts related with aeroassisted maneuvers include ballistic missiles, spatial probes (e.g. Gemini), lunar missions returned vehicles (e.g. Apollo) and the Space Shuttle.

The main goal of an aeroassisted maneuver on an orbital transfer is to cause an energy decrease that results in the desired orbital change. One or more propulsive maneuvers can be applied to reach the final objective, but the advantage of using the atmosphere is the fuel savings when compared with the equivalent exclusive propulsive maneuver. As an example, according to Miele (1996), the fuel saving for a planar or quasi-planar aeroassisted transfer between a geostationary orbit and a LEO (low Earth orbit), can reach 60% of the fuel needed by a Hohmann equivalent transfer. Atmosphere density variations, vehicle mass, aerodynamics coefficients, physical parameters and initial conditions are the main causes of the deviations in the trajectory in vehicles entering the atmosphere.

Historically, the study of atmospheric maneuvers began in the mid-sixties, when NASA started to think more seriously about a manned mission to Mars as the next step to the Apollo program. The Mars vehicle mass minimization was one of the project main goals. Therefore, the aerodynamic drag utilization, as the velocity reducer to provide the vehicle capture by the red planet, was broadly studied and demonstrated a significant fuel economy that became essential to the project.

Wingrove (1963) investigated several control methods (developed until then) for atmosphere crossing vehicles, and grouped them in three general classes (reference, prediction and closed form), in accordance with their advantages/disadvantages related with the initial conditions manipulation ability.

Walberg (1985) compiled a survey of 33 other papers and technical notes about plane changes using aerodynamic and propulsive forces. By the end of the 80's, Mease (1988) presented the state of art of the aeroassisted orbital transfer's optimization problem, emphasizing the fundamental principles that increase the knowledge with regard to this subject.

More recently, Calise (1988), Hull et al. (1988a,b), Mease et al. (1988), Miele et al. (1988), Cochran et al. (1994), Ma (1996) and Mishne et al. (1997) started to study several different approaches of the optimal plane change transfer problem using the atmosphere with closed-form and quasi-closed-form solution methods.

The U.S. Standard Atmosphere 1976 is used as the atmospheric model. In this model, the atmospheric densities and temperatures, and others parameters are represented up to an altitude of 1000 km, based on satellite and rocket data and on the perfect gas theory. It is also supposed that the terrestrial atmosphere rotates with the same velocity as the Earth rotation movement.

2 - TRANSFER ORBIT DESCRIPTION

The basic problem discussed in this work is concerned with orbit transfer maneuvers. In the special case considered here, an initial and a final orbit around the Earth are completely specified. The problem is to find how to transfer the spacecraft between those two orbits in such a way that the fuel consumed is minimum. There is no time restriction involved here, and the spacecraft can leave and arrive at any point in the given initial and final orbits. The maneuver is performed using an engine that is able to deliver a thrust with constant magnitude and variable direction and with the use of the atmosphere to make a plane change. The mechanism, time and fuel consumption to change the

direction of the thrust are not considered in this work. An impulsive engine maneuver is used for comparison with the strategy described above.

As the maneuver goes on, the trajectory followed by the satellite can be divided into two parts: outside the atmosphere the spacecraft is supposed to follow a Keplerian motion controlled only by the thrusts (whenever they are active); inside the atmosphere, thrusts are not firing and motion is governed by two forces: Earth's gravity field and atmosphere drag force.

For propulsive maneuvers purposes, thrusts are assumed to have the following characteristics:

- i) Fixed magnitude: The force generated by them is always of constant magnitude during the maneuver. The value of this constant is a free parameter (an input for the algorithm developed here) that can be high or low;
- ii) Constant ejection velocity: Meaning that the velocity of the gases ejected from the thrusts is constant. The importance of this fact can be better understood by examining Prado (1989);
- iii) Free angular motion: This means that the direction of the force given by the thrusts can be modified during the transfer. This direction can be specified by angles called pitch (the angle between the direction of the thrust and the perpendicular to the line Earth-spacecraft) and yaw (the angle with the orbital plane). The variation of these angles is free;
- iv) Operation in on-off mode: It means that intermediate states are not allowed. The thrusts are either at zero or maximum level.

The solution is given in terms of the time-histories of the thrusts (pitch and yaw angles) and fuel consumed. For the propulsive part of the mission, any number of "thrusting arcs" (arcs with the thrusts active) can be used for each maneuver. Instead of time, the "range angle" (angle between the radius vector of the spacecraft and an arbitrary reference line in the orbital plane) is used as the independent variable.

3 - EQUATIONS OF MOTION

The motion of a space vehicle with variable mass in a gravitational field, subject to the aerodynamic and thrust forces, is given by the equations (Vinh, 1981):

$$\frac{d\vec{r}}{dt} = \vec{v} \tag{1}$$

$$\frac{d\vec{v}}{dt} = \frac{1}{m}(\vec{T} + \vec{A}) + \vec{g}(\vec{r}, t) \tag{2}$$

$$\frac{dm}{dt} = -\frac{c}{g_0} T \tag{3}$$

There, \vec{r} is the position vector, \vec{v} is the vehicle velocity vector in relation to the atmosphere, m is the mass, \vec{T} is the thrust vector, \vec{A} is the aerodynamic force, \vec{g} is the acceleration due to gravity and c

the specific fuel consumption. In the Equation (3), g_0 is a constant related with the value of the acceleration of the gravity in a reference level (usually sea level).

The aerodynamic force can be decomposed (as it is done conventionally) in drag force \vec{F}_D , opposed to the vector speed, and lift force \vec{F}_L perpendicular to the other (see Figure 1).

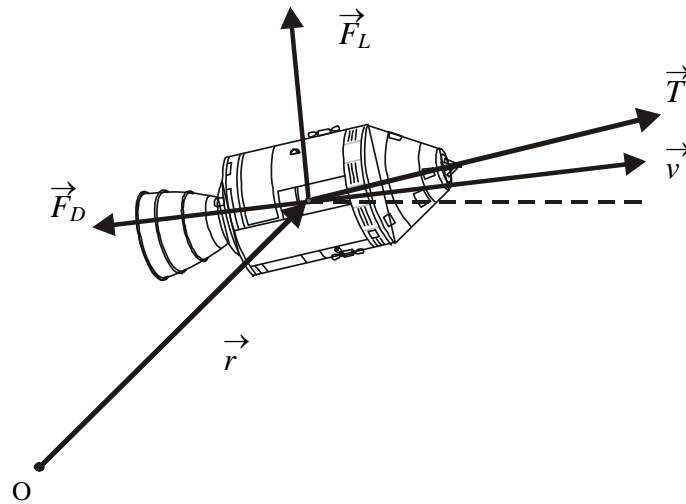


Fig. 1 - State variables, aerodynamic and thrust forces.

The magnitude of these forces is given by well known relationships (Vinh, 1981).

$$F_D = \frac{1}{2} \rho S v^2 C_D \tag{4}$$

$$F_L = \frac{1}{2} \rho S v^2 C_L \tag{5}$$

The Atmospheric Model supplies the atmosphere density ρ . The coefficients C_D and C_L are, respectively, drag and lift coefficients relative to the shock surface area S .

Besides decomposing the aerodynamic force in drag and lift force, it is convenient to decompose the latter in "altitude lift" \vec{F}_A and "lateral lift" \vec{F}_B (see Figure 2). The directions and magnitudes of these forces are calculated through the following relationships (Guedes, 1997):

$$\vec{F}_D = -\frac{1}{2} \rho S v^2 C_D \hat{v} \tag{6}$$

$$\vec{F}_A = \frac{1}{2} \rho S v^2 C_A \hat{S} \quad (7)$$

$$\vec{F}_B = \frac{1}{2} \rho S v^2 C_B \hat{H} \quad (8)$$

$$\hat{v} = \frac{\vec{v}}{|\vec{v}|}, \quad \hat{H} = \frac{\vec{H}}{|\vec{H}|}, \quad \vec{H} = \vec{r} \times \vec{v}, \quad \hat{S} = \frac{\vec{S}}{|\vec{S}|}, \quad \vec{S} = \vec{v} \times \vec{H}$$

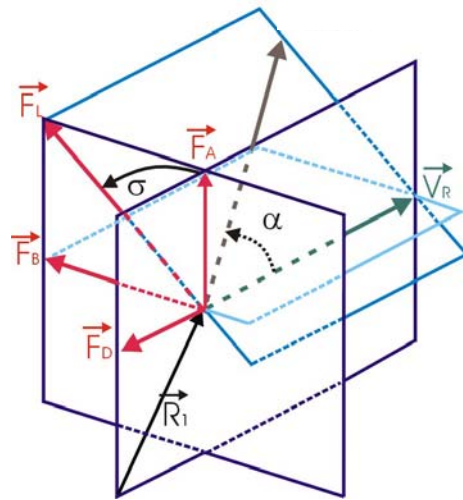


Fig. 2 - Components of the aerodynamic force, angle of attack α the and bank angle σ .

The lift altitude and lateral coefficients are calculated with the following functions of the bank angle:

$$C_A = C_L \cos(\sigma) \quad (9)$$

$$C_B = C_L \sin(\sigma) \quad (10)$$

The drag and lift coefficients are functions of several factors, among them the geometry of the vehicle and the angle of attack. Some authors presented expansions in series for the determination of these coefficients as function of the atmospheric density. However, Regan and Anandakrishnan (1993) and Guedes (1997) considered that C_D and C_L can be calculated through relationships with the angle of attack α :

$$C_D = K_1 + K_2 \sin^2(\alpha) \quad (11)$$

$$C_L = K_3 \sin(2\alpha) \quad (12)$$

The values of K_1 , K_2 and K_3 are strongly dependent of the vehicle format. They were chosen such that the atmospheric effects on inclination were greater.

A single-impulsive maneuver with the impulse applied at the intersection plane between the initial and final orbits is used for comparison. The velocity variation on this case was found using (Chobotov, 1991):

$$\Delta V = 2 V_{C1} \operatorname{sen}\left(\frac{\theta}{2}\right) \quad (13)$$

Where, V_{C1} is the satellite velocity in a circular orbit, at the impulse application moment, and θ is the inclination variation.

The fuel consumption was calculated using:

$$m_f = m_i \exp\left(-\frac{\Delta V}{g_0 I_{SP}}\right) \quad (14)$$

The specific impulse I_{SP} is a parameter of propellant quality and is equal to 345 s in the examples studied on this work.

4 - RESULTS

Several simulations were carried out with the objective of obtaining the inclination variation due to the passage of the vehicle in the atmosphere. The maneuver with plane change was chosen due to its high cost in comparison with orbital maneuvers that change other orbital parameters.

The comparisons were done with totally propulsive maneuvers with impulsive jets, and partly propulsive with continuous jets and partly atmospheric maneuvers. In the latter, the propulsive maneuvers with continuous jets were used to, initially, inject the vehicle in an orbit through the terrestrial atmosphere and, after the accomplishment of the necessary atmospheric maneuver, remove it of its atmospheric orbit and take it to the target final orbit. The impulsive maneuvers were chosen for the totally non-atmospheric part of the study, because it is easier and less expensive to make a plane change with an impulse applied on the node, than to make this change continuously around the node. This maneuver is optimal in the sense that the inclination variations treated here are small when compared to the ones required for a three-impulse plane change maneuver (Chobotov, 1991).

Among the several simulations performed for this paper, we selected a case that demonstrates how advantageous it can be to use an atmospheric maneuver for an orbital plane change. In this case, the vehicle is initially in a circular and equatorial orbit with approximately 2420 km of altitude, and it is required to accomplish a change of plane of about 14° of positive inclination, with an allowed error of 0.5° .

The propulsive maneuvers are realized with the use of a continuous thrust with magnitude 1000 N. An optimization procedure (Biggs, 1978; Biggs, 1979; Prado, 1989) is applied to find the direction of the thrust in every instant of time. We refer the reader to the references above for complete details of this procedure.

For the second study, a maneuver with continuous jets was accomplished to place this vehicle in an eccentric orbit with perigee inside the atmosphere ($a = 7640$ km and $e = 0.15$). This passage inside the

atmosphere may provoke different orbital changes depending on the chosen attack and bank angles for the vehicle entrance. With the objective of maximizing the change in inclination reached in this passage, these angles were selected so that the orbit suffered a variation in inclination close to 8° in the first passage by the perigee.

Then, a new passage by the atmosphere was necessary so that the orbital inclination reached the value close to 14° , as required. After that, an additional maneuver with jets was performed to remove the vehicle from the atmospheric orbit and take it to the final circular orbit previously established. The values of the elements of the initial, final and intermediate orbits are shown in the Table 1.

TABLE 1 – ORBITAL ELEMENTS OF THE VEHICLE

Orbital Elements	Initial Orbit	1 st Transfer Orbit	2 nd Transfer Orbit	3 rd Transfer Orbit	Final Orbit
Semi-major axis	8800.000	7640.000	7243.837	6993.947	8800.000
Eccentricity	0.0	0.1518	0.105	0.073	0.006
Inclination	0.1	0.1	7.76	13.85	13.86
Argument of Periapse	0.0	0.0	-172.814	3.534	3.543
Ascending Node	0.0	0.0	186.619	11.618	301.472

In this table, the initial and final orbits are specified as circular orbits with semi-major axis of 8800 km. The first transfer orbit is the one achieved after the application of propulsion, to cause a perigee passage inside the atmosphere. Figure 3 shows the optimal control history for this maneuver. The yaw angle is always zero, because this is a planar maneuver. This maneuver is performed using only one burning arc, because the initial and first transfer orbit has an intersection at the apogee of the first transfer orbit.

The second transfer orbit is the one obtained after the first passage in the atmosphere. It can be seen that the inclination was changed by about 8 degrees and the semi-major axis decreased nearly 300 km. These variations are very sensitive to the chosen values of the initial conditions, spacecraft size and orientation, and any change in these parameters can yield results completely different.

Then, the spacecraft stays in a trajectory that crosses the atmosphere one more time, until the third transfer orbit is achieved, with an inclination that satisfies the required constraints ($\Delta i = 14^\circ \pm 0.5^\circ$). This third transfer orbit is the result of two passages in the atmosphere, thus the resulting energy loss

is very high. At this point, the propulsive system is turned on again and the eccentricity and semi-major axis are adjusted to reach the final orbit. Figure 4 shows the optimal control history for this maneuver. The propulsion is applied in two arcs, the first one at the apogee of the third transfer orbit and the second one close to 180° apart from the first arc.

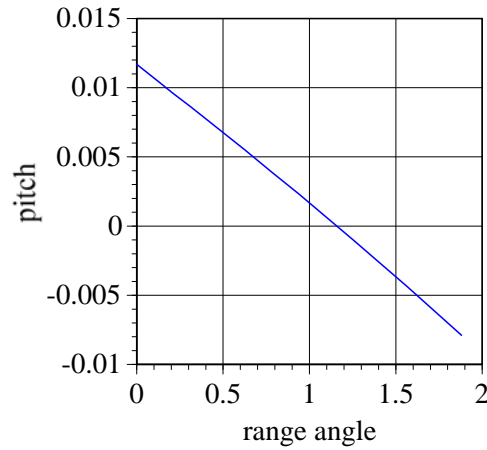


Fig. 3 - Optimal control history for the maneuver that uses the atmosphere - Departure.

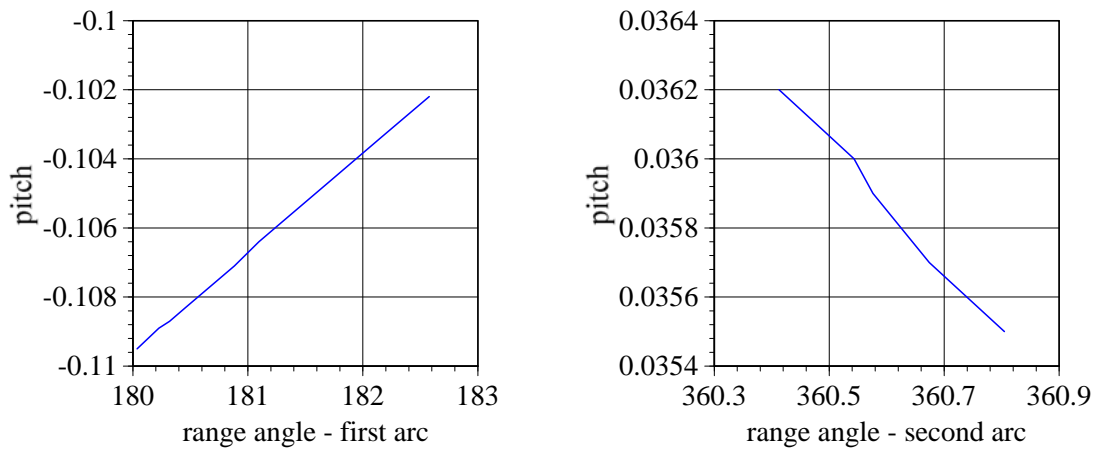


Fig. 4 - Optimal control history for the maneuver that uses the atmosphere - Return.

Using this procedure, an inclination impulsive maneuver is replaced by two maneuvers that yield a lower cost: one maneuver to transfer the spacecraft to an orbit that crosses the atmosphere and one maneuver that removes it from the atmosphere.

The values found for the fuel consumptions are presented in the Table 2. The fuel consumption for the maneuver with atmosphere is divided in two parts: maneuvers with jets to place the vehicle in an

eccentric orbit with perigee in the atmosphere (DEPARTURE) and, later, bring it for the final orbit (RETURN).

TABLE 2 – FUEL CONSUMPTION

	No Atmosphere Maneuver	Atmospheric Maneuver	
	(Impulsive Thrust)	(Continuous Thrust)	
Consumption		DEPARTURE	RETURN
		7.1 kg	10.8 kg
Total consumption	33.1 kg	17.9 kg	

It can be noticed that, in this case, it was found a fuel economy of approximately 50% bringing the vehicle to the atmosphere and leave it to make naturally the plan change required.

This example, chosen among the accomplished simulations, demonstrates the advantages of using atmospheric maneuvers. Other cases can be found that show that, for small desired variations in inclination, the use of the atmosphere for plane change may not be advisable.

For different pairs of angle of attack (ALPHA) and bank angle (SIGMA), different disturbances act on the vehicle provoking different orbit changes. For each pair, a variation in each orbital element can be visualized in a graph of the type "level curves". The Figures 5 shows the variations in semi-major axis, eccentricity and inclination suffered by the vehicle when passing inside the terrestrial atmosphere. In these plots the attack and bank angles are in radians, the variation in semi-major axis is in kilometers and the variation in inclination in degrees. The example chosen to illustrate how these plots work is not the last one, because for certain angle of attack and bank angle pairs, in such case, the atmospheric maneuver becomes a reentry. We chose a maneuver with a perigee higher to avoid a reentry.

This type of illustration shows the magnitude of the variation on the orbital elements that the vehicle can suffer when crossing the terrestrial atmosphere with certain aerodynamic characteristics. This could be used to generate appropriate forecasts to each case, and predict the appropriate choice of these characteristics as function of the desired result.

In a fast analysis of this figure, some interesting results can be noted. In the Figure 5.a, for instance, it is noticed that the bank angle provokes very small alterations on the semi-major axis. Following a vertical line (alpha constant) it is possible to view a small increase in the semi-major axis decay. There is a similar behavior in the others elements: eccentricity and inclination (b) and (c), in particular for small values of the angle of attack. Figure 5 also shows a property close to a anti-symmetry in relation to the vertical line $\alpha = 0^\circ$, with means that values of α and $-\alpha$ have the opposite effects in the inclination variation. This means that the angle of attack dominates the behavior of this maneuver for those Keplerian elements.

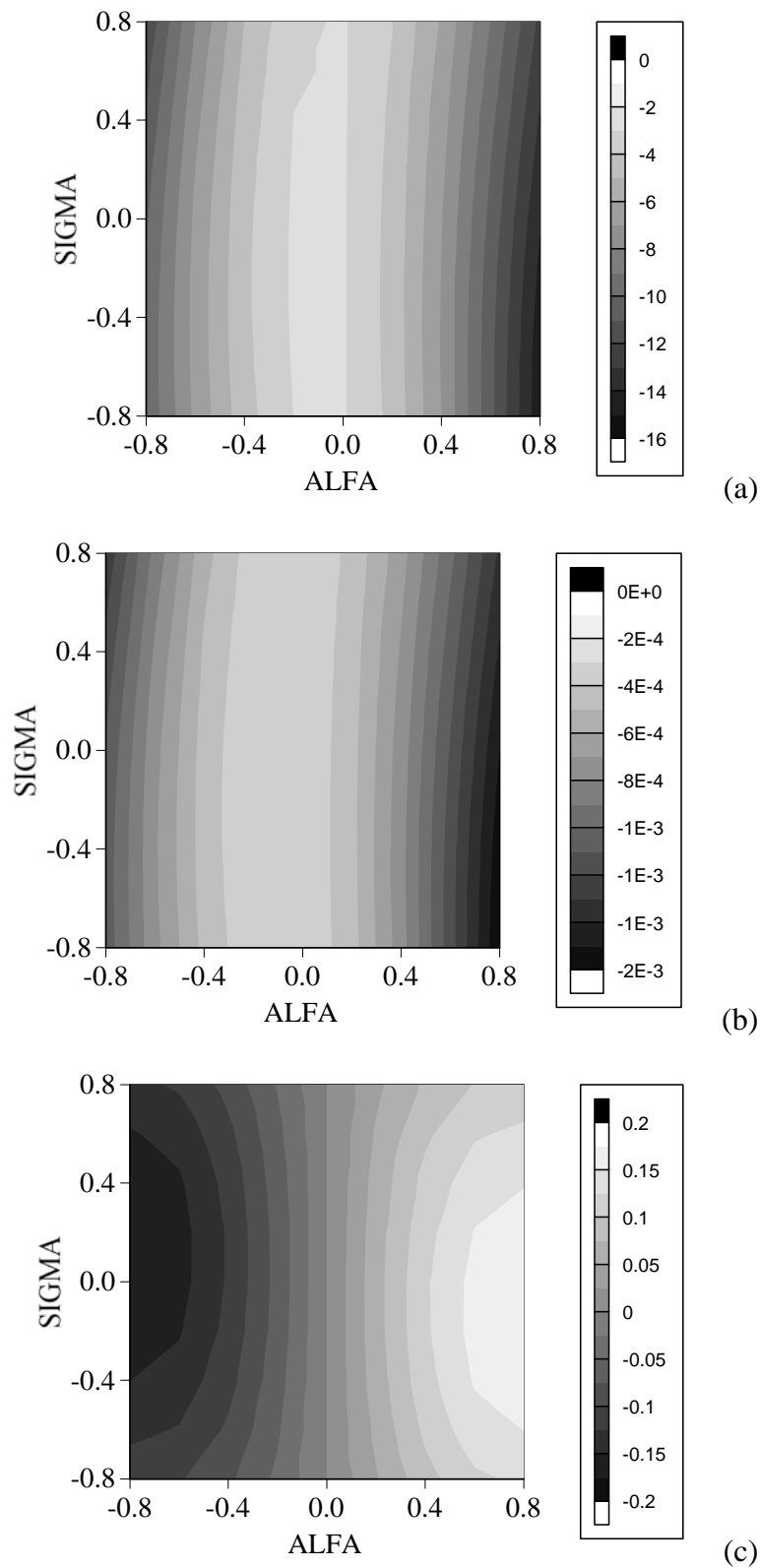


Fig. 5 – Variation on semi-major axis (a), eccentricity (b) and inclination (c) caused by the atmosphere crossing of a satellite for different values of angle of attack (ALFA) and bank angle (SIGMA)

5 - CONCLUSIONS

Based on the previous discussion, it is possible to conclude that aeroassisted maneuvers represent an extensively applicable technology. The related literature presents several and very convincing demonstrations of the gains reached with the use of the atmosphere. A special remark can be done on the fact that current missions use this technology.

The expected advantage for the atmospheric maneuvers procedure leans on the fact that, depending on the aerodynamic characteristics of the vehicle (bank and attack angles), the atmosphere would take charge of the target plane change, saving a significant portion of the necessary fuel for the accomplishment of the complete orbital change. This expectation is valid, because the aerodynamic characteristics can be found and chosen before the entrance of the vehicle in the atmosphere.

However, our simulations show that this problem is highly dependent of such initial conditions as mass of the vehicle and orbital elements of the initial and final orbits. Thus, it can be advantageous to accomplish a descent to the terrestrial atmosphere in certain cases and completely disadvantageous in others. It is also necessary to take in consideration the fact that a vehicle, that will face the current heating conditions of one or more passages by the atmosphere, should be appropriately prepared with coatings or other protection systems. This adaptation can mean more mass due to the increment of insulating material and, consequently, a smaller quota of available mass on board for the storage of fuel. Thus, resulting in aeroassisted maneuvers which do not imply significant fuel savings.

6 - ACKNOWLEDGMENTS

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