RE-ENTRY TRAJECTORY SIMULATION OF A SMALL BALLISTIC RECOVERABLE SATELLITE

Walkiria SCHULZ
Paulo MORAES JR.

Centro Técnico Aeroespacial, Instituto de Aeronáutica e Espaço, Space Systems Division
12228-904 São José dos Campos – SP, Brazil
wschulz@iae.cta.br

ABSTRACT *– With the purpose of recovering a small scientific satellite (named SARA), a study has been undertaken to identify, analyse and optimise the mean parameters of such a mission. The study comprises the choice of optimal mission schemes and includes an analysis of the ballistic re-entry in the Earth atmosphere. It considers determination of the re-entry corridor with optimisation of the descent trajectory and de-boost manoeuvres. It also includes a determination of landing point dispersion based on a set of disturbances acting on the spacecraft during its re-entry. All presented results are necessary for ballistic design of re-entry task and choice of nominal mission scheme.*

KEYWORDS: reusable satellite, re-entry dynamics, landing dispersion.

INTRODUCTION

Nowadays, there is an increasing demand for the realization of scientific and technological experiments under low gravity conditions. The gravity reduction turns possible more homogeneous crystal production and, consequently, new metal leagues, electronic chips, agronomic and medicinal products, etc. To perform these experiments a recoverable orbital system is needed.

The reentering trajectory of a space vehicle should be continuously under control to guarantee that it will not escape from the atmosphere, or exceed the heating and landing point limits. It can not be supposed that the vehicle will land at a desired site knowing only its initial conditions before entering the atmosphere. Atmospheric density variations, mass, aerodynamic coefficients, physic parameters and initial conditions are the main causes of trajectories deviations. So, it is important to carry out a detailed study of each reentering mission.

A study has been undertaken to identify, analyse and optimise the mean parameters of such missions. This study also considers proposals for the choice of the most adequate aerodynamic shape for a ballistic re-entry vehicle, its orientation during descents into the atmosphere, and later, landing. Included in the analysis is a determination of parametric errors and dispersion based on a set of disturbances acting on the spacecraft during its re-entry into the atmosphere.

In this study an analysis was carried out for the retrieval of the small recoverable scientific satellite SARA. This vehicle is intended to perform scientific experiments in a micro-gravity environment. It will be placed at a circular orbit with altitude of 300 km, and be later ballistically returned to Earth for reusing.

The analysis and simulations have been carried out with a Re-entry Simulation Program developed by the authors for the vehicle concept identified by SARA [1] and illustrated in Fig. 1.

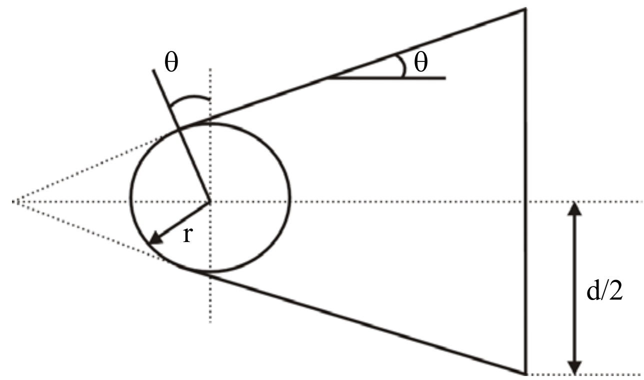

Fig. 1. SARA Concept

The concept definition of the vehicle considers: a satellite of small dimensions (micro-satellite), operating in low earth orbit, with a capability to carry small scientific and technological experiments, remaining in orbit up to 10 days, being later returned to earth, recovered at ground, and re-utilized without necessity of structural repair.

This concept, established with the aim to guide the activities concerning a preliminary design, indicates the need of undertaking studies and development work in the design of a re-entry trajectory for minimal static and thermal loads and accuracy of ground impact point.

OPTIMAL MISSION SCHEMES

The purpose of this analysis is to understand and refine the dynamic behavior of the SARA vehicle to ensure that the instruments and experiments it carries will survive re-entry. Modeling vehicle motion during re-entry requires a lot of estimates of input characteristics. A simulation then uses these inputs and generates the vehicle dynamic motion prior to deployment of the parachute system. Some of the parameters important to this simulation are the vehicle shape, the re-entry corridor and the optimal de-boost manoeuvre.

Aerodynamic Shape

The design of the SARA vehicle is intended for an orbiting microgravity laboratory that will be recovery at ground after some days in space. This laboratory provides the essential services to support experiments in a closed environment. The frustum of a cone basic configuration was elected between the proposals for the choice of the most adequate aerodynamic shape for a ballistic re-entry vehicle (Fig.1).

An axially symmetric vehicle with center of mass at the symmetry axis is suitable for ballistic re-entry in the Earth atmosphere. The center of aerodynamic pressure is behind the center of mass. Thus the vehicle is statically stable and moves into the atmosphere with zero angle of attack. Any angular disturbance when angle of attack arises (for example, turbulence, vertical wind gust, etc.) is damped due to static stability of the vehicle.

The main requirement for the aerodynamic shape is a big value of the ballistic coefficient ($\sigma_D = C_D S / m$) that allows decreasing convective heat flux and mass of heat protection. The velocity at the end of the aerodynamic deceleration phase (the region where parachute system starts operation) also depends on the ballistic coefficient value.

The frustum of a cone is a suitable aerodynamic shape for the ballistic re-entry vehicle. It provides a big volume for experiments and instruments. The natural displacement of the center of mass to the base of cone provides a good equipment arrangement and static stability at hypersonic velocity.

Re-entry Corridor

During its re-entry into the atmosphere, the space vehicle must evolve in a domain called the "re-entry corridor" or the "re-entry window". This sets the range of altitudes between which it can move at each instant, taking into account the various constraints that it can endure. Since the parameter "time" is not very significant from the mechanical or energy point of view, it is preferable to reason in terms of velocity or height. Thus, the re-entry window will be defined in general considering aspects like thermal and load factor limit.

Let us suppose that the vehicle is on a circular orbit and a de-boost impulse of velocity Δv is applied in the direction opposite to orbital motion. Such manoeuvre is optimal for real de-orbit conditions and it provides a maximal value of re-entry angle θ_{en} (flight path angle at re-entry point) for available propellant consumption. If we consider a decreasing set of de-boost impulses in assumption of ballistic re-entry, we can find the minimal value $\Delta v_{\min}$ when the atmosphere captures the vehicle, i.e. re-entry is possible. Under a small decrease of the boost impulse in comparison with $\Delta v_{\min}$ the vehicle escapes the atmosphere. The re-entry trajectory with minimal value of de-boost impulse determines the upper boundary of re-entry corridor in the atmosphere. For SARA vehicle, the minimal value of the flight path angle at re-entry point is $\left|1.292^\circ\right|$. Otherwise the atmosphere does not capture the vehicle.

Now, let us consider an increasing set of de-boost impulses and corresponding set of ballistic re-entry trajectories into a standard atmosphere of the Earth. For each trajectory we can determine a maximal value of the load factor. The trajectory for which the maximal load factor is equal to the admissible one determines the lower boundary of the re-entry corridor in the atmosphere.

To find the bounds of the re-entry window from the thermal point of view, a maximum value of the reference flux is usually used, i.e. the flux which a sphere whose radius is equal to the radius of curvature of the nose of the vehicle would experience. From general physical consideration we know the existence of two types of optimal re-entry trajectory with minimal total heat flux: when descent time is short, i.e. the trajectory is very steep; and when total heat per second is small, i.e. the trajectory is very long. We can not use very long trajectory with a small re-entry angle due to a large dispersion of landing point and possible violation of capture conditions. Thus for ballistic re-entry it is appropriate to use the steep trajectory (with taking into account limitations on the admissible load factor) to minimize the total heat flux during descent into the atmosphere.

Optimal De-Boost Manoeuvre

For the SARA vehicle de-boost manoeuvre the nominal orbit is circular and all parameters are known. For a given value of the de-boost impulse it is necessary to determine its optimal direction that provides the maximal value of re-entry angle in the atmosphere. The re-entry angle is a good criterion of optimality. It determines the total heat flux, maximal temperature, maximal load factor, dispersion of landing point, etc.

The altitude for the SARA de-orbit manoeuvre is approximately 300 km, and the estimate impulse will be something around 250 m/s. Taking these values into account the optimal orientation of de-boost impulse is against to the direction of the motion [2].

The minimal required de-boost impulse that provides the required re-entry angle θ_{en}^* in such a case is:

$$\Delta v = v_{cir}\left[1-\sqrt{\frac{2r_{at}\left(r_{cir}-r_{at}\right)}{\left(r_{cir}\sec\theta_{en}^*\right)^2-r_{at}^2}}\right] \tag{2.1}$$

where r_{cir} and v_{cir} are radius and velocity at the circular orbit, and r_{at} is the radius of the conditional boundary of the Earth atmosphere.

PARAMETRIC ERRORS AND DISPERSION

The difficulties encountered in any practical study of the dynamics of re-entry result from the uncertain knowledge of many of the important parameters that influence the trajectory. Atmospheric properties, particularly the densities existing at higher altitudes, are subject to much uncertainty. The altitude at which the planetary atmosphere is important in vehicle guidance depends strongly on flight path angle, lift, drag, and density characteristics of the re-entry vehicle. The heating and deceleration loads, which accompany high-velocity re-entry into the atmosphere, are strong functions of the initial penetration angle and vehicle design characteristics.

In the process of choosing the nominal re-entry trajectory, it is very important a correct estimation of its sensitivity to disturbing factors. An analysis of derivatives of the re-entry parameters or landing point location with respect to errors, allows to estimate the sensitivity of the trajectory with respect to disturbances. Then we should recognize the most significant factors and take measures for the minimization of their effects.

One of the most significant disturbing factors are errors of de-boost impulse realization on time of execution, value of the de-boost impulse, and in-plane orientation. Another important disturbing factor is a difference between the real atmosphere and the standard one. Other perturbing factor is the non-nominal aerodynamic characteristics of re-entry vehicle. They are due to two reasons: non-correct determination of the characteristics; and change of the aerodynamic shape during re-entry.

The last considered disturbing factor is a displacement of vehicle's center of mass from the symmetry axis. This displacement may be due to: error at determination of the center of mass position; movement of the center of mass after expenditure of propellant; and asymmetric change of the aerodynamic shape in flight.

Errors of the De-Boost Impulse

There are different reasons for errors at de-boost impulse realization. As a result, the extra-atmospheric trajectory may differ from the nominal one in such a way that the re-entry point or the flight time may be displaced with respect to the nominal ones. De-boost impulse error may also change the re-entry angle and the re-entry velocity. The de-boost errors can be divided on three main components.

Error of de-boost impulse execution time

This may occur as a result of an incorrect determination of the engine switch-on and switch-off times. Another reason may be an execution error of these commands.

This error only shifts the re-entry trajectory, since the initial orbit is circular. The consequence is that the landing point shifts also in the plane of descent trajectory by a downrange value of [3]:

$$\delta L = \frac{v_{cir}}{r_{cir}} r_E \delta t_{db} \qquad (3.1)$$

where r_E is the average radius of the Earth, and δt_{db} is the error of de-boost impulse execution time. Fig. 2 illustrates the derivative of downrange with respect to an error of de-boost impulse execution time.

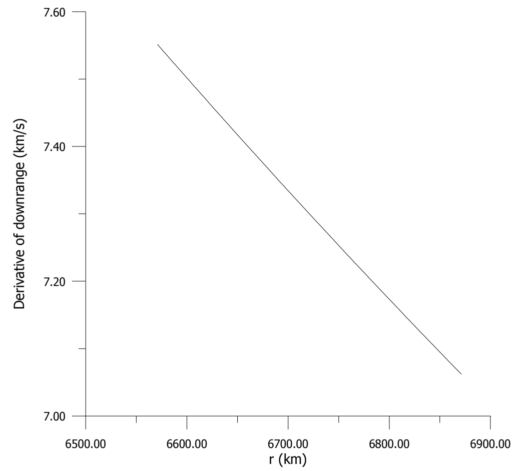

Fig. 2 Derivative of downrange with respect to de-boost time error

Error of de-boost impulse value

This may appear as a result of an incorrect determination of this value, or an execution error. Another reason is a dispersion of the engine impulse during the process of switch-off.

This error influences the initial conditions of re-entry, as re-entry velocity v_{en}, and re-entry angle θ_{en}. Besides, the error changes an angular range of extra-atmospheric trajectory Φ_{en} (from de-boost point to re-entry point). As a result, the latitude φ_{en}, and longitude λ_{en}, of the re-entry point are changed.

Fig. 3 illustrates re-entry velocity changes with respect to the value of de-boost impulse error.

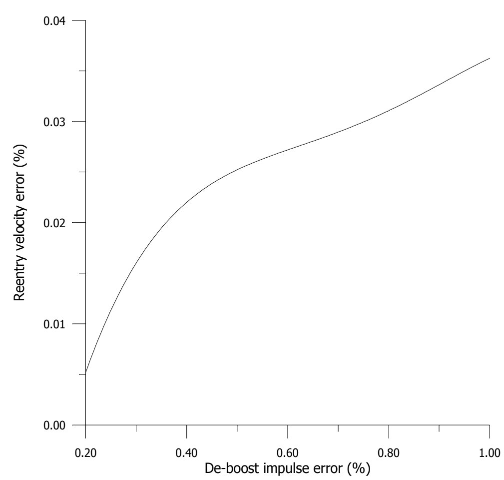

Fig. 3 Re-entry velocity changes related to value of de-boost impulse error

Fig. 4 illustrates re-entry angle changes with respect to the value of de-boost impulse error.

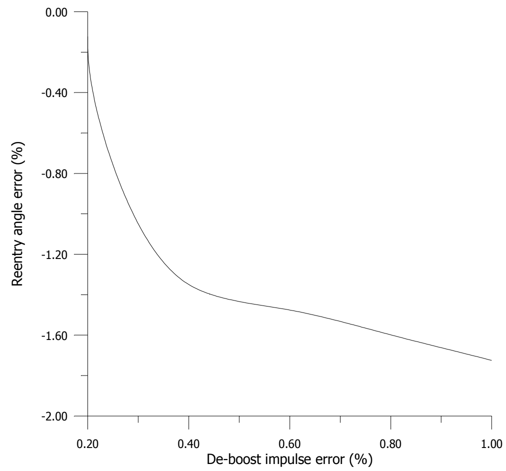

Fig. 4 Re-entry angle changes related to value of de-boost impulse error

Fig. 5 illustrates extra-atmospheric range changes with respect to the value of de-boost impulse error.

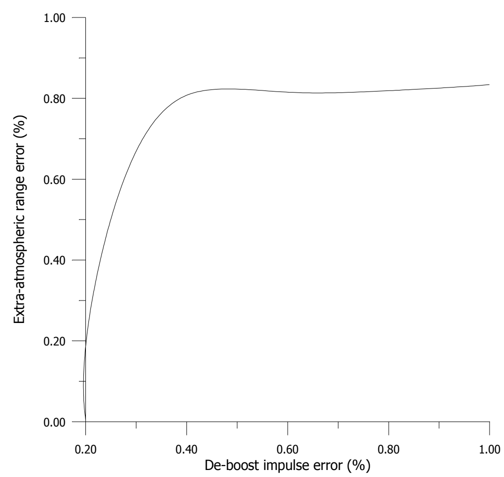

Fig. 5 Extra-atmospheric range changes related to value of de-boost impulse error

Error of de-boost impulse orientation in the motion plane

This arises due to an improper determination of the local vertical, and thus it is an instrumental error. Another reason is connected with the execution of command on attitude orientation before the de-boost manoeuvre.

When the de-boost impulse is directed against the motion, the simulations showed that the value of re-entry angle, the re-entry velocity and the angular range of extra-atmospheric trajectory do not depend, in linear approximation, on small errors of de-boost impulse orientation in the motion plane.

Variation on Atmospheric Parameters

To analyse the effects of the aerodynamic forces acting on a vehicle in flight, it is necessary to model the planetary atmosphere in which the flight takes place. The aerodynamic forces are most effective near the planet's surface. So only a very thin layer in the lower reaches of the atmosphere needs to be considered.

Many of the more complicated aspects of planetary atmospheres are of no consequence in aerodynamic calculations. For instance, though the atmosphere is composed of a mixture of gases, it may be treated as a uniform gas of unvarying composition throughout the aerodynamically important altitudes. In fact, the overriding feature of the atmosphere, as far as its effect on the vehicle is concerned, is the density. The particular composition of the atmosphere can only have an important influence on the aerodynamic heating of the vehicle. Hence, for performance analysis, the concern in modelling the atmosphere will be to conveniently and accurately represent its density. From this, other physical properties of interest will follow.

The variation on atmospheric density includes season-latitude, diurnal and random components. Season-latitude and diurnal variations are systematic and describe a mean or expected state of atmosphere as function of altitude, latitude, month and local time. The random component determines a difference between actual state of atmosphere and systematic components. Creating an exact model of disturbed atmosphere is a very complicate task due to the limited experimental data available. Thus, it is necessary to use some reasonable hypothesis that does not contradict with observed processes in the atmosphere.

Figs. 6 and 7 illustrate the error on landing point coordinates (latitude and longitude) due to a theoretical error in density determination. The landing position is the point where the parachute system starts to operate. Its altitude is 10 km. For the simulations the re-entry angle was chosen equal to -3^{o}, the re-entry velocity was 7722 m/s and the ballistic coefficient was 0.002 m^2/kg.

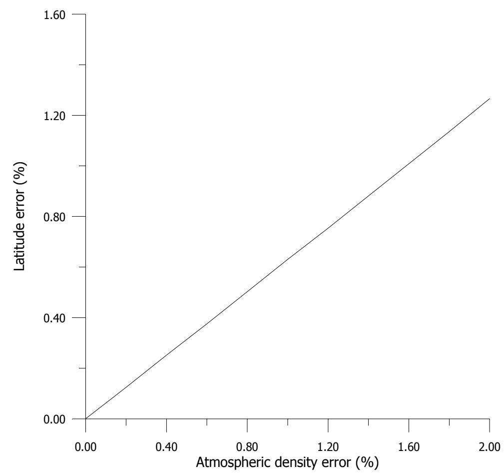

Fig. 6 Latitude disturbance related to atmospheric density error

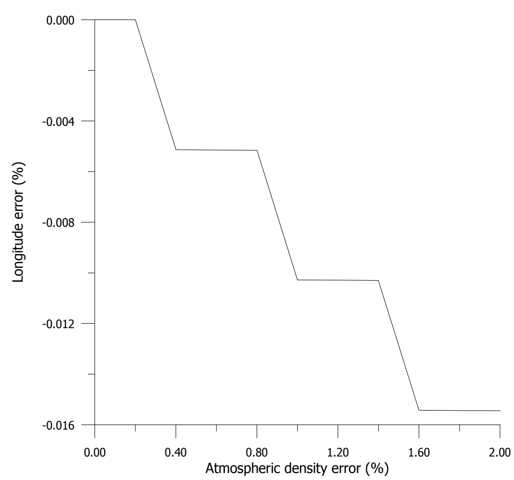

Fig. 7 Longitude disturbance related to atmospheric density error

Non-Nominal Aerodynamic Characteristics

Any variation of an aerodynamic characteristic from the nominal value is a significant disturbing factor. The aerodynamic force is proportional to the drag coefficient that depends on Mach number, altitude of flight and angle of attack. For a ballistic re-entry trajectory the nominal angle of attack is zero. Therefore, a non-zero angle of attack is considered as a disturbing factor.

We can determine the aerodynamic coefficient of re-entry vehicle by calculation, wind tunnel test and flight test. The choice between the three methods depends on the complexity of the vehicle's aerodynamic shape and allowable resources. The most accessible way is the calculation of aerodynamic characteristics. We can determine aerodynamic coefficients with accuracy of 5 to 10% taking into account the accuracy of atmospheric parameters [3].

Figs. 8 and 9 illustrate the error on landing point coordinates due to a theoretical error in drag coefficient determination considering the region of 10% to 20%.

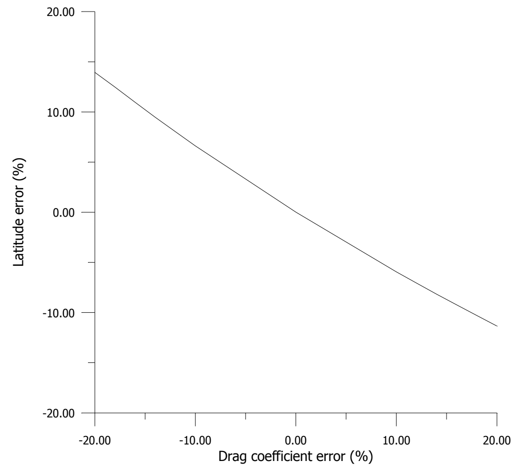

Fig. 8 Latitude disturbance related to drag coefficient error

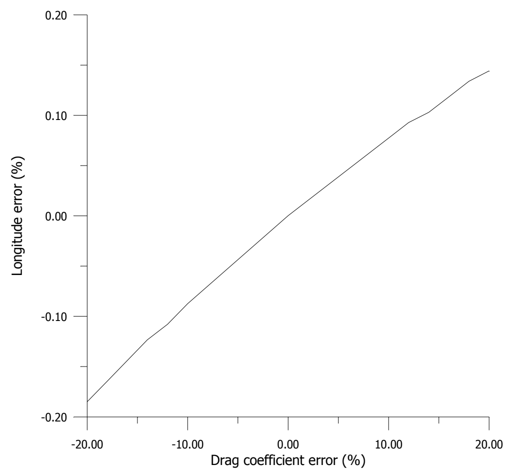

Fig. 9 Longitude disturbance related to drag coefficient error

It is necessary to note that the error of aerodynamic characteristics determination is the main source of error for reusable re-entry vehicle that should preserve its aerodynamic shape from flight to flight.

Displacement of the Center of Mass

In a ballistic re-entry vehicle any displacement of center of mass (c.m.) from the symmetry axis is one of the most significant disturbing factors. It violates the axial symmetry of vehicle mass distribution while the aerodynamic shape retains the axial symmetry. As a result, a trim angle of attack arises that is almost constant during flight time. The angle of attack produces a lift force that produces much more dispersion of the landing point than a disturbed atmosphere, or errors of de-boost impulse.

Figs. 10 and 11 illustrate the error on landing point coordinates due to a lift force appearance as a consequence of the displacement of the center of mass. This displacement is represented by the lift-to-drag ratio value. For SARA type re-entry vehicle, if the c.m. displacement is of 0.2 to 1.0 mm, the lift-to-drag ratio is 0.01 to 0.05 [3].

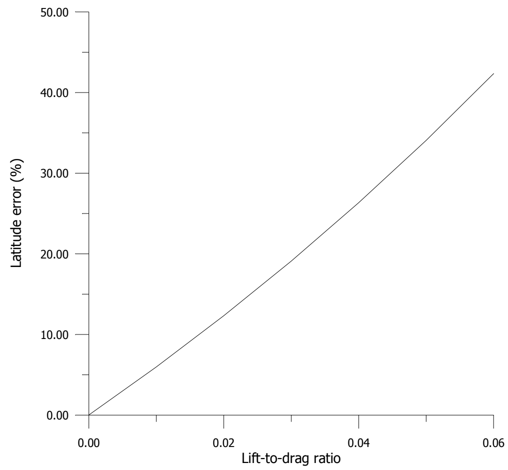

Fig. 10 Latitude disturbance related to lift-to-drag ratio

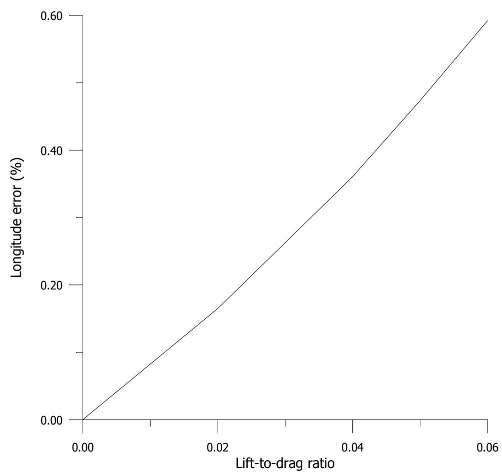

Fig. 11 Longitude disturbance related to lift-to-drag ratio

CONCLUSIONS

We carried out a short analysis of the re-entry corridor conditions. This allows us to conclude that the re-entry vehicle should have sufficiently big ballistic coefficient and the re-entry angle should be as big as possible to reduce the total heat flux.

It is shown that the most significant disturbing factors are execution errors of de-boost impulse and variation of atmospheric density with respect to standard values. Non-nominal aerodynamic characteristics and displacement of vehicle centre of mass from symmetry axis are investigated disturbing factors.

Some errors are independent and we can suppose that they have standard distribution. Then it is possible to sum them under a square root. Some errors have correlation that we should take into account. Concrete values of errors are given in passport of engine and control system equipment.

Considering the error of de-boost impulse execution time, for initial circular orbit with altitude of 300 km (r_{cir} = 6671 km), the landing point downrange position is shifted by 7.38 km for each second of error (Fig.2). It means that the landing point should be significantly affected by such an error.

The error on the value of de-boost impulse has insignificant influence on the re-entry velocity (Fig.3), but generates an error of approximately 1% on re-entry angle (Fig.4). Considering a de-boost impulse error of 1 m/s, the error of re-entry point angular range will be of 0.8% (Fig. 5), and the landing point error will be approximately 15 km.

Extra-atmospheric trajectory and, consequently, the trajectory inside the atmosphere are both insensitive to small errors of de-boost impulse orientation in the motion plane. This result allows us to reduce landing point dispersion.

The influence of an error in the atmospheric density determination is very significant over the latitude of the landing point (Fig. 6). But it has almost no influence over the longitude (Fig. 7).

It should be noted that a negative variation of the drag coefficient produces overshoot (landing point displacement is positive) while positive variation produces undershoot (Fig. 8). A change of the drag coefficient in 1% results in a landing point displacement of 1.2 km approximately.

For SARA re-entry vehicle, 1mm displacement of c.m. produces a lift-to-drag ratio of 0.052. As a result, a significant dispersion of landing point arises. It should be noted that an accuracy of 1mm for c.m. position is a very complicated technical task. The results show that this displacement can provide a landing point dispersion of almost 60 km. To neutralize the action of the lift force it is necessary to twist the vehicle around the symmetry axis with angular velocity of 10 degrees/s or more before re-entry. Due to the rotation of vehicle, the direction of side force changes continuously and resulting effect is near zero.

We should note that the obtained accuracy of the landing point depends on accepted assumptions about accuracy of de-orbit manoeuvre and parameters of the vehicle, disturbed atmosphere, etc. This accuracy should be optimistic, but it illustrates an order of the expected landing accuracy. We should consider these obtained values as preliminary ones and update them in the process of SARA development design.

ACKNOWLEDGMENTS

The authors wish to express their appreciation for the support provided by FAPESP (Foundation to Support Research in São Paulo State).

REFERENCES

[1] P. Moraes Jr., "Design Aspects of the Recoverable Orbital Platform SARA," *8^0 Congreso Chileno de Ingenieria Mecánica,* Concepción, Chile, 1998.

[2] Y.G. Sikharulidze, P. Moraes Jr., A.N. Korchagin, "Analysis of Accuracy at Ballistic Re-Entry in the Earth Atmosphere," *14th International Symposium on Space Flight Dynamics*, Foz do Iguaçu, Brazil, February 1999.

[3] Y. G. Sikharulidze, "Aspects of the Re-entry Dynamics of Space Vehicles - Part II," *Curse notes*, São José dos Campos, Centro Técnico Aeroespacial, May 2001.