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A branching method for ballistic trajectories and its application to JUICE mission

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Abstract

In any interplanetary mission it is important to grant the feasibility of flying by secondary bodies, in order both to achieve the scientific targets and to maximize payload, by reducing propellant consumption and shielding mass. JUICE mission focuses on Jupiter major moons, in particular Ganymede, Callisto, and Europa, and on the space environment driven by the planet's magnetosphere. Thus both goals and constraints of the mission must be considered.

This paper presents a procedure for the design of a gravity assisted mission, which considers only ballistic arcs; future developments foresee the inclusion of thrust manoeuvres. Encounters are thought as punctual, like in a patched conic model; no simplifying assumptions have been made for the satellites orbits, although a preliminary design could allow for them. The procedure is not based on the resolution of the Lambert problem for phasing, but takes the maximum flyby bending angle into account: this provides the automatic pruning of the unfeasible arcs, that often result from the Lambert problem solution, and an easy extension to more complete gravitational models. The method has been applied to the reference JUICE orbiter trajectory, starting from either G2 or G3 flybys, in order to reach Europa quickly and reduce the number of perijoves.

1. Introduction

Jupiter is surrounded by the biggest moons in Solar System, perfect for shaping the spacecraft trajectory with their gravity assists, avoiding main engine maneuvers, usually exploited for leaving the Earth or for planetary capture. Nevertheless, one must look out for radiations induced by Jupiter belts (5-15 R_J) and remember that Europa (9.5 R_J) is embedded in them, while Ganymede (15 R_J) and Callisto (26 R_J) are quite outside. The latter satellites are an effective choice to perform several flybys, also because they are the most massive among Galilean moons. In particular, Ganymede is preferred for its greater velocity and mass. After main engine maneuvers, which lead the spacecraft to enter in orbit around Jupiter, a sequence of Ganymede and Callisto flybys is almost mandatory to reduce apocentre and inclination (the orbits of Galilean moons are almost equatorial), finally allowing Europa flybys.

2. Considerations about design

According to previous observations, reaching Europa while keeping the total ionizing dose low is one of the most puzzling goals of the mission. Current mission design includes two Europa flybys, after 5 Ganymede and 3 Callisto flybys, with 9 perijoves passages. A quick gaze at Tisserand diagram suggests the possibility of reaching Europa with a lower number of flybys wrt nominal mission. A first option is to achieve this result only with Ganymede gravity assists, a second option inserts Callisto flybys in the sequence.

3. Search structure

The basic idea is to divide the trajectory into ballistic arcs; each one connects a flyby to another one. Ballistic arcs are shaped by the gravity assist performed at the beginning of the arc, which provides the direction the outgoing V_{inf} vector, by rotating the incoming one. The flyby geometry depends on the bending angle and the angle θ between Jupiter equatorial plane and the B-plane (i.e. the flyby plane). Whereas the latter angle can be considered as a free parameter, the former is constrained by the minimum permissible altitude of the hyperbola pericenter, according to equation (1):

$$\sin\left(\frac{\delta_{MAX}}{2}\right)=\frac{\mu_{sat}}{\mu_{sat}+V_{\inf}^{2}(R_{sat}+h_{\min})} \qquad (1)$$

Dealing with JUICE mission, in particular with the capture phase, assuming V_{inf} of about 6 km/s, and 200 km minimum altitude, δ can be at most 8° or 10° (respectively for Callisto and Ganymede); consecutive flybys of the same satellite are required.

A second constraint concerns the phasing between the spacecraft and the satellite to be encountered. The equations to be satisfied are the equalities of the three components of the positions of spacecraft and satellite at the end of the ballistic arc (error function). If a central gravity field is assumed, a further parameter, namely the increment of the spacecraft mean anomaly ΔM, defines the spacecraft position and the epoch of the encounter, which, in turn, provides the satellite position. Anyway, when further phases of the design require more complete gravity models, the epoch of the encounter replaces ΔM as unknown parameter, and the spacecraft position is calculated by integration.

An automatic and efficient selection among all allowable parameter triplets (δ, θ, ΔM) is mandatory, in order to explore the great number of possible branches in a multi-flyby mission. The search is carried out in three steps. The first step is a rough scan among all permissible values of the triplets. For each θ, ranging from 0 to 2π, δ is from 0 to δ_{MAX}, provided by equation (1), while ΔM_{max} is set as a compromise to grant a sufficient number of solutions while keeping the number of perijoves low. Within these boundaries, error function is evaluated at the end of the arc. It has been found that in a (δ, ΔM) diagram for an assigned θ, couples of suitable solutions are contained in small bands of ΔMs. In the second step, by using finite difference comparisons, bands are selected, separated, and then evaluated again with larger resolution; this process provides, after a new selection, the initial guess at several suitable triplets. The third step finds a solution vector by solving numerically the error function equations for each one of the initial triplets acquired from the previous step, setting 10 km as maximum tolerance in the error function norm.

Figure 1 summarizes these steps, which are sequentially applied to all the arcs in a flyby sequence prefixed by the user, starting from an initial flyby in assigned position. The procedure generates a growing number of branches, which are pruned if the extension towards the following satellite results to be unfeasible. All branches found for each arc are followed in order to guarantee the achievement of several trajectories, which connect all satellites in the desired flyby sequence; the preferable solution is selected according to other mission requirements.

4. Summary and Conclusions

Several preliminary trajectories for JUICE mission have been found by means of a procedure suitable to analyze a sequence of gravity assist maneuvers. The spacecraft state immediately before G2 or G3 flyby defines the incoming V_{inf} vector and epoch, which are the only required data to start the procedure. Fast trajectories (for example, a Ga-Ga-Ca-Eu with 5 perijoves) have been found. Thrust maneuvers will be introduced in an improved optimization procedure, which is under study.

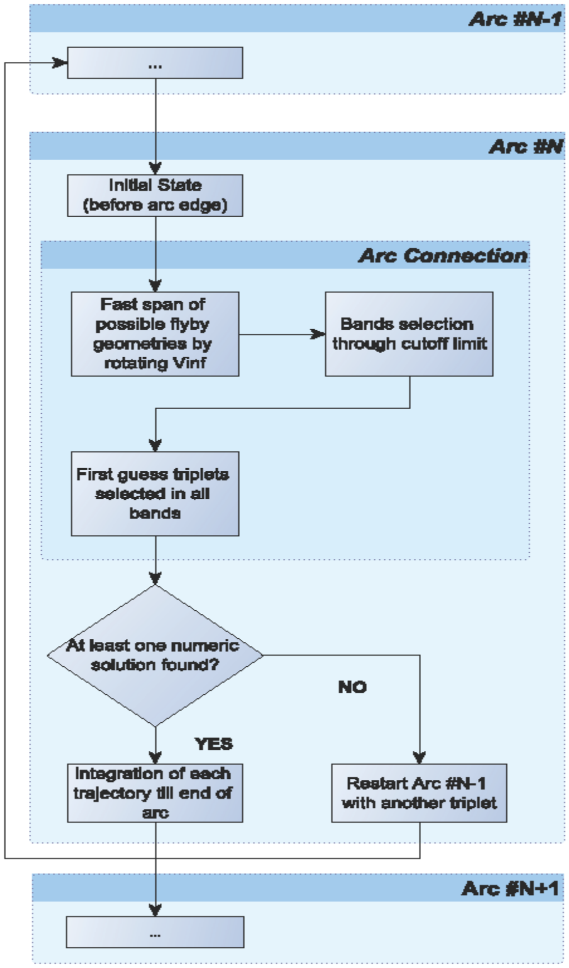

Figure 1 General scheme for branch exploration

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