TOOLS FOR INTERPLANETARY MISSION ANALYSIS

F Bonneau, J Bernard & J Foliard

Centre National d'Etudes Spatiales
Toulouse - France

ABSTRACT

In this paper, we present elementary tools for interplanetary mission Analysis : Trajectories computation, Trajectories optimisation, Trajectories description for any multiple fly-by trajectories (including swing-by). Most of these programs have been implemented on personal computers.

Already applied to some interplanetary projects (Vesta, Ariane V,ΔVega) they give good and quick results for mission analysis in phase 0 or phase A.

Keywords : "Patched conics", Interplanetary trajectories, fly-by trajectories, Interplanetary trajectories optimisation, Swing-by, Lambert's Problem delta-vega procedure.

1. INTRODUCTION

In the past, the CNES has had to evolve some tools for interplanetary projects (VENERA, Vega, GIOTTO ...). In the actual form of the French-Soviet project VESTA, CNES has the entire responsability of the realisation of the "small bodies" mission (asteroïds, comets). We also think about interplanetary mission for the technological launch of Ariane V.

It is to answer these different needs that evaluation tools have been developped for feasability and cost of the proposed missions.

The requirement of quick answers to different classes of problems leads us to construct flexible programs. Most of these programs have been implanted in a chaining structure on personnal computers.

The aim of this paper is to present the methods used, and the programs associated with them.

NOMENCLATURE

$(P_i)_{i=1,N}$	: Fly-by celestial bodies
N	: Number of bodies in the trajectories
$(\vec{X_i}, \vec{w_i})$	: Positions and velocity of P_i at time T_i
(T_i)	: Dates of fly-by
$\vec{V_i}^+$	: Absolute velocity of departure of the Spacecraft at P_i
$\vec{V_i}^-$	: Absolute velocity of arrival of the Spacecraft at P_i
$\vec{v_i}^+$	: Relative velocity of departure of the Spacecraft at P_i
$\vec{v_i}^-$	: Relative velocity of arrival of the Spacecraft at P_i
(μ_i)	: Gravitationnal constant of P_i
μ	: Gravitationnal constant of the Sun
$\vec{\Delta V_i}$	: Manoeuver at P_i
r_{im}	: Minimum pericenter radius for the seveny-by of P_i
r_i	: Pericenter radius for the swing by of P_i
$\langle , \rangle$	: Scalar product
J	: Cost function $J = \sum_{i=1}^{n-1} \|\vec{\Delta V_i}\|$

2. TRAJECTORIES COMPUTATIONS

(a) Formalism.

We use "Patched conics" Method. The trajectory is a succession of heliocentric arcs, connecting center to center, and hyperbolic arcs in the case of swing-by. Both arcs are matched together by an impulsive manoeuver, assimilating, in the case of hyperbolic arcs, the asymptotic velocities by the relative velocities of heliocentric arcs (cf. fig. 1). The spheres of influence of the planets are assimilated to the infinity of the planet, and we don't

Proceedings of the Second International Symposium on Spacecraft Flight Dynamics, Darmstadt, FR Germany, 20–23 October 1986 (ESA SP-255, Dec. 1986)

consider the time of travel in this sphere.

In this modelisation, the trajectory is completly described by the dates of fly-by (see [1], [6]).

(b) Expression of the matching Manoeuvers

(bl) Case of an Asteroïd (or comet).

In this case, we have :

$$\overrightarrow{\Delta v_i} = \overrightarrow{v_i}^{+} - \overrightarrow{v_i}^{-} = \overrightarrow{V_i}^{+} - \overrightarrow{V_i}^{-} \quad (1)$$

(b2) Swing-by.

We don't consider the small cost of the velocity increment needed for adjusting the impact point. The hypothesis is that the matching manoeuver is given at the infinity of the planet. We take analytically into account the constraint.

$$r_{i,m} \leqslant r_i$$

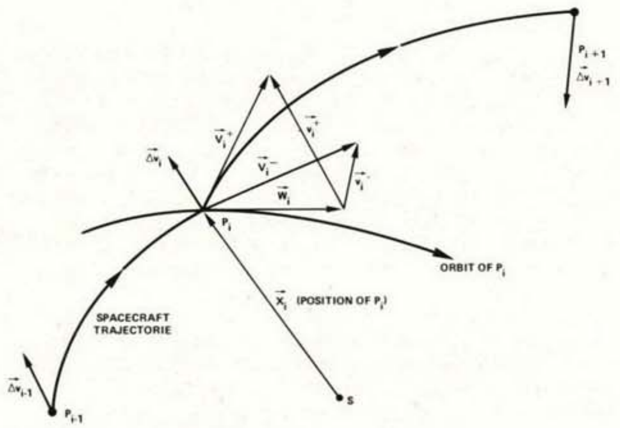


Figure 1. Spacecraft's orbit and variables used

We have two different possibilities to implement this manoeuver :
- before swing-by,
- after swing-by,

To optimize it, one can verify that "it must be done at the side of the biggest velocity"
Let us define :

$$\cos(\theta_i) = \frac{\langle \overrightarrow{v_i^+} \mid \overrightarrow{v_i^-} \rangle}{v_i^+ \times v_i^-}$$

$$\sin\left(\frac{\theta_{iM}}{2}\right) = \frac{1}{1 + \dfrac{r_{mi}\, v^2}{\mu_i}}$$

where $v = \text{Min}\,(v_i^+, v_i^-)$

θi is the needed angular deviation
θni is the maximum angular deviation given the planet attraction (see [1], [6]).
We must distinguish two cases :

If $\theta_i \leqslant \theta_{iM}$ then $\Delta v_i = \left| \, \| \overrightarrow{v_i^+} \| - \| \overrightarrow{v_i^-} \| \, \right|$ (2) (3)

If $\theta_i > \theta_{iM}$ then $\Delta v_i = \sqrt{(v_i^+)^2 + (v_i^-)^2 - 2\, v_i^+ v_i^- \cos(\theta_i - \theta_{Mi})}$

(see fig. 2-a and 2-b).

$$\| \overrightarrow{v_i^+} \| < \| \overrightarrow{v_i^-} \|$$
$$\theta_{iM} < \theta_i$$

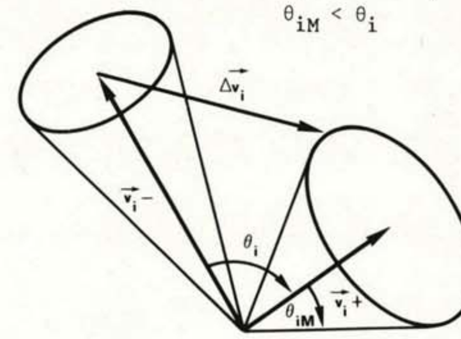


Figure 2-a. Manoeuver before swing-by

$$\| \overrightarrow{v_i^-} \| < \| \overrightarrow{v_i^+} \|$$
$$\theta_{iM} < \theta_i$$

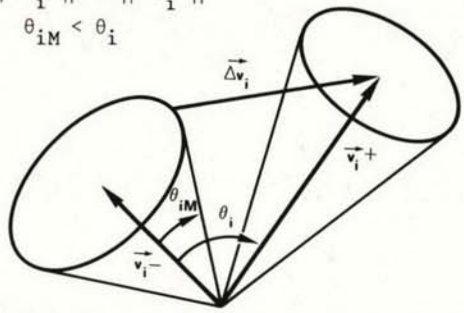


Figure 2-b. Manoeuver after swing-by

(c) Ephemerides.

Planets : The major planets orbital elements affected by their secular variations are described by polynominal developpement of 3 degrees. For Mercur, Venus and Earth, the Newcomb elements, are used. For Mars it is Newcomb corrected by Ross and for the upper planets the Gaillot's elements are used (cf. Ref. 4).

Asteroids : The asteroïd ephemerides are the TRIAD 85 catalogue (osculating parameters at 01/01/1985) from university of ARIZONA. They take into account the perturbations due to planets (Venus, Earth, Mars, Jupiter). We used a extrapolation model developped by the "Bureau des longitudes". This software modelizes the osculating orbit elements by Tchebycheff polynoms. These parameters are numericaly integrated with Lagrange equations.

A comparaison with a model using numerical integration with cowell's method has given an error less than 1000 km for Tchebycheff polynom of 6th degres extrapolated on 100 days.

With this method we have an ephemeris file precise enought for mission analysis we have to achieve.

This file is used in "Asterex" software (see [2]) which elaborates trajectory with multiple asteroïd fly-by.

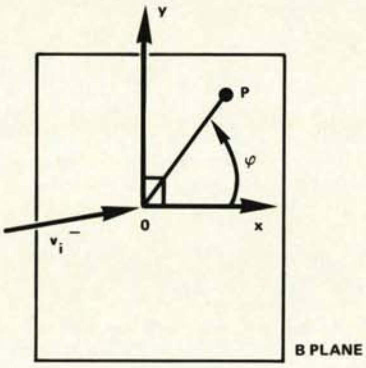
The processing on micro-computer, in order to minimize room required for file ephemerides, used two files for asteroïds osculating parameters one dated on 01/01/1986 or the other on 01/01/1999, depending on dates of fly-by given by Asterex for Vesta mission. We established a discrepency less than 100 000 Km compared with complete extrapolation program.

Comets. We used the ephemerides from triad file which gives the comets orbital parameter at perihelion.

(d) Altitude adjustement for the asteroïds.

At the end of the program TRAJEC which calculates the trajectory as indicated before, we have a trajectory in which the spacecraft goes exactly right into the center of the asteroïd. The problem is now to modify it, to get the desired impact point.

Consider th B-plane defined by the asteroïd P_i at time T_i : Centered to the asteroïd, it's orthogonal to the relative velocity $\overrightarrow{v_i^-}$, and the x-axis is in the ecliptic plane (see fig. 3).



Given P in this plane, we want to modify the trajectory, by a manoeuver $\overrightarrow{\Delta w_i}$ at time T_{mi} < Ti, to make sure that spacecraft will be at relative position P at time T_i.
$\overrightarrow{\Delta w_i}$ is calculated analytically using the transition Matrix ϕ of the orbit ϕ between T_{mi} an T_i.

$$\phi\left[T_i \; T_{mi}\right] = \begin{pmatrix} \phi_{11} & \phi_{12} \\ \phi_{21} & \phi_{22} \end{pmatrix}$$

Then we have

$$\overrightarrow{\Delta w_i} = (\phi_{12})^{-1}\,\overrightarrow{OP}$$

at first order, this will not change the time of closest approach.

3. OPTIMISATION

We want to minimize the function

$$J = \sum_{i=1}^{n-1} \|\overrightarrow{\Delta v_i}\|$$

corresponding to a trajectory determined as in TRAJEC.
The optimisation variables are the dates of fly-by $(T_i)_{i=1,n}$.

The constraints are :

$$r_{im} \leqslant r_i \text{ if } P_i \text{ is a planet}$$

These constraints are taken into account as shown in 2.b.1.

The number n of variables is limited to 10.
One can put constraints on fly-by speeds. Such constraints will be treated as penality functions.

The first derivatives are computed analytically using the transition matrix-s as in [5].

The algorithm used is a Newton-Raphson algorithm developped by CNES : it approximates the Hessian Matrix.

This algorithm is implanted on a PC. It converges quickly.

4. ASTEREX SOFTWARE

The objects of this software is to determine the possibles asteroïds fly-by sequences (from 2 to 5 asteroïds) issued from a given initial trajectory.

Asterex processes in two steps :
- Preselection level,
- Selection level.

In the preselection level, the possible asteroïds for fly-by are selected. The distances from the trajectory is the criteria for preselection. For this phase the exploration Step is 10 days along the trajectory in order to obtain non empty volume intersections at each step. The volume shape used at each exploration date is a cylinder. This allows a dichotomic exploration in order to preselect the asteroïds. This selection eleminate 90 % of the asteroïds.

In the selection step a tree-like research algorithm is used (see fig. 14). The inputs are the preselected asteroïds. The valid trajectories are those wich velocity increment, obtained after optimisation, is less than a given value.

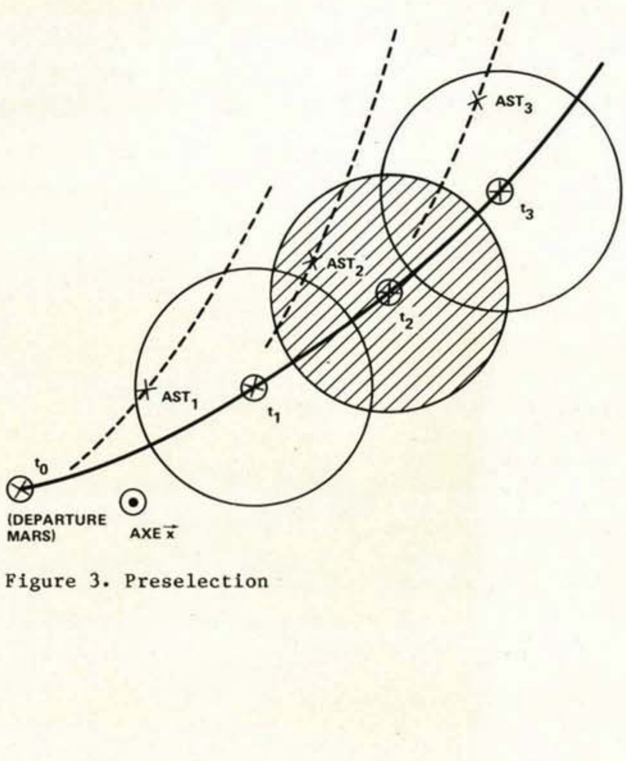


Figure 3. Preselection

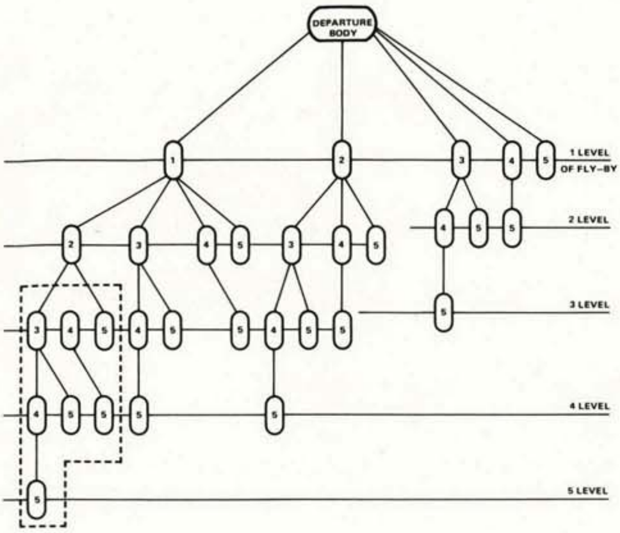


Figure 4. Selection

If the sequence TERRE → 1 → 2 is not valid

The upper levels are not taken into account for exemple level N°

3 : T → 1 → 2 → 3, T → 1 → 2 → 4, T → 1 → 2 → 5

4 : T → 1 → 2 → 3 → 4, T → 1 → 2 → 3 → 5,
T → 1 → 2 → 4 → 5

5 : T → 1 → 2 → 3 → 4 → 5

5. STRUCTURE OF THE PROGRAMS

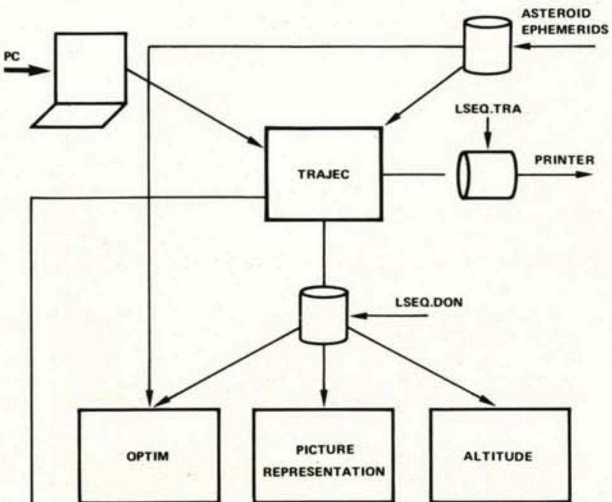


Figure 5.

All programs developped belongs to an informatic structure. They create files of results that can be used by other programs if necessary. For example, TRAJEC creates a file named lseq. DON where "lseq" is the name of the trajectory.
The optimisation program OPTIM uses this file, and the results are put in a file named lseq. OPT. Then TRAJEC can used this file to make an output description of the trajectory.

6. APPLICATIONS

(a) Vesta. Vesta is a french-soviet project. The French spacecrafts must visit 3 small bodies (asteroîds or comet) after flying over Mars.
The programs described were used to make a research of trajectories satisfaying the following balistic constraints :
departure in 1994
- V_∞ departure $\leqslant$ 3,87 km/s
equatorial declination δ_∞
- 31.5 deg $\leqslant$ δ_∞ $\leqslant$ 51.5 deg.
fly-by of Mars
$V_\infty \leqslant 5.2$ km/s
Altitude $\geqslant$ 150 kms
- Asteroîdes fly-by
at least 3 asteroîds in the sequence.
From one of them : Radius $\geqslant$ 150 km. Fly-by speed $\leqslant$ 4.2 km/s. (for penetrator experiments).
$-\sum \Delta V \leqslant 1.2$ km/s
- Total time of Mission $\leqslant$ 5,5 years.
OPTIM was used to determine first the possible target for the penetrator (named BA, as Big Asteroîds).
It shows the impossibility to get trajectories T.M.BA. So, we were looking after trajectories T.M.A.M.BA, where beetween the two fly-by of Mars, the spacecraft has an orbit of the same period as Mars, and fly-by one asteroîd "Apollo-Amor".
Then ASTEREX was used to complete such trajectories.
Finally, we found 31 trajectories for this mission, with 7 different targets for the penetrater.
For example :
CERES N° 1 Radius 511 fly-by speed 4
VESTA N° 4 Radius 288 fly-by speed 2,5
(cf. ref. [3])(see fig. 6 et 7)

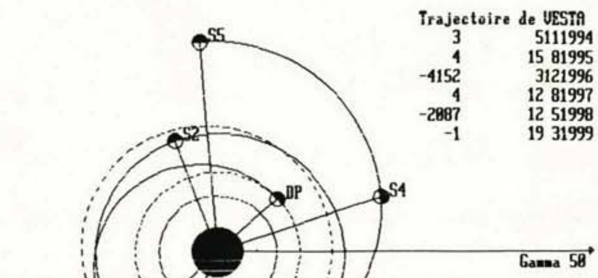


Figure 6.

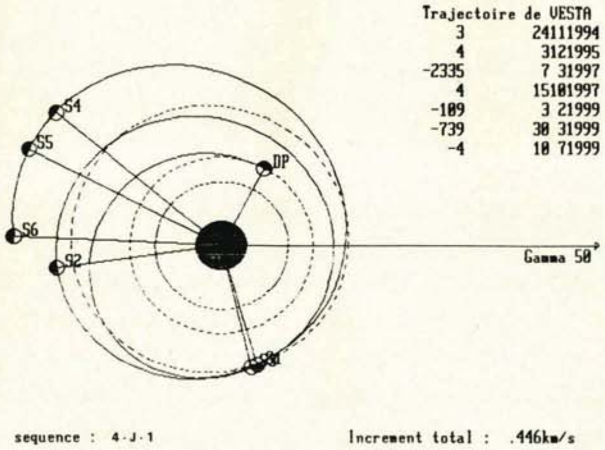


Figure 7.

(b) In the case of the technological flight of Ariane V, we studied the possibility of a meeting with Jupiter, by using the procedure ΔVEGA, possibly matched with a swing-by for a mission towards Saturne. This procedure consists in implementing an intermediate manoeuver in deep space in order to use the gravitationnal help of the earth to lead for the target planet. In the case of mission to Jupiter, the trajectory of the meeting with the earth is a trajectory of about 2 years' period. Therefore, we tried to optimize the sequence Earth - manoeuver - Earth - Jupiter by optimize the total cost in velocity increment total $\sum |\Delta V|$, together with a meeting with saturne (jupiter 2).

The final results (to be compared with the velocities of Hohman to the planets J & S rapidly equal to 8.85 and 10.4 these) are the following.

Earth departure	= 11/03/1995
V_∞ = Velocity at the infinity of departure body	= 5.23 km/s (C3 = 27.3)
Equatorial declinaison of V_∞	= - 23°
Earth rendez-vous	= 21/05/1996
Heliocentric orbital period	= 2,07 ans
Velocity increment for rendez-vous	= 600 m/sec
Earth Swing-by manoeuver	= 01/05/1997
Velocity increment for jupiter rendez-vous	= OM/S
Jupiter rendez-vous	= 30/06/1999
V_∞ at jupiter arrival	= 6,33 km/s
Saturne rendez-vous	= 22/05/2002

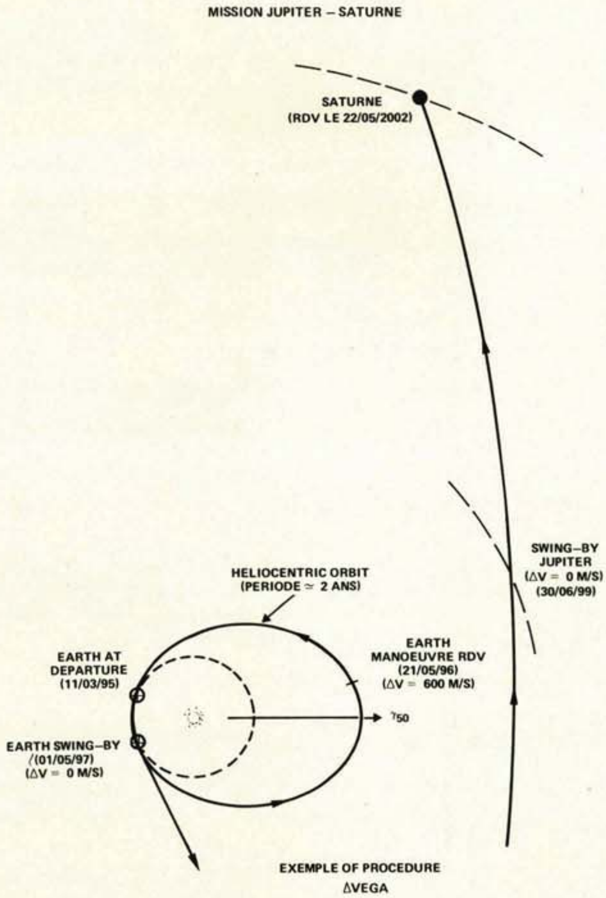


Figure 8. Example of ΔVEGA procedure

(c) We carried out a study on the possibility of a fly-by of the probe VEGA with an asteroïd of the belt Apollo. It seemed possible to fly-by the asteroïd adonis at a distance of about 5 M kms regarding the increment velocity 200 m/s.

REFERENCES

(1) BERNARD "Le mouvement du Satellite cours 83" Cepadues Edition pg 671-684)

(2) BERNARD - FORCIOLI - PERRET "Dictionnaire des Visites d'Asteroïdes"

(CNES) CT/DTI/MS/012

(3) BONNEAU "Vesta : Trajectories Completes du Créneau 1994"

(CNES) CT/DTI/MS/MN/113

(4) DANJON "Astronomie Générale"

(5) GOOGYEAR "A General Method for the computation of cartesien coordinates and partial derivatives of 2 - body problem)

NASA CR 522

(6) PERRET "CNES Cours 80 : le Document du Véhicule Spatial en orbite" Edition Cepadues pg 859-896