MINISTÉRIO DA CIÊNCIA E TECNOLOGIA
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

INPE-8062-PRE/3878

DELTA-V ESTIMATE FOR JUPITER SWING-BY TRAJECTORIES

Antonio Fernando Bertachini de Almeida Prado

Paper presented at the 6th Pan-American Congress of Applied Mechanics and 8th International conference on Dynamic Problems in Mechanics,
Rio de Janeiro, Brazil, January, 04 -08, 1999.

INPE
São José dos Campos
2001

DELTA-V ESTIMATE FOR JUPITER SWING-BY TRAJECTORIES

Antonio Fernando Bertachini de Almeida Prado
Instituto Nacional de Pesquisas Espaciais - INPE - Brazil
São José dos Campos - SP - 12227-010 - Brazil
E-mail: PRADO@DEM.INPE.BR

ABSTRACT

In this paper the Swing-By maneuvers that use the planet Jupiter as the body for the close approach are studied. The goal is to simulate a large variety of initial conditions for these orbits and study them according to the effects caused by the close approach in the orbit of the spacecraft. The well-known regularized (Lamaître regularization) planar-restricted-circular-three-body problem is used as a model. It is emphasized the calculation of the change in the velocity required to perform those maneuvers and the initial flight path angle of these maneuvers, both calculated when the spacecraft is at the Earth. This is important, because it represents the cost of each possible trajectory. Plots are made to show the regions of minimum impulse required. In that way, the results shown in this paper can be used to find trajectories that requires minimum cost to accomplish the goal of making a close approach with Jupiter, and it represents a technique to make the optimization of interplanetary trajectories.

INTRODUCTION

The importance of the Swing-By trajectories can be very well understood by the number of missions that flew or are scheduled to fly using this technique. A very successful example is the Voyager mission that flew to the outer planets of the Solar System with the use of successive Swing-By in the planets visited to gain energy (Flandro, 1966). The Swing-By trajectories have a very wide range of applications, as shown in the literature (Hollister & Prussing, 1966; Carvell, 1985; Weinstein, 1992; Swenson, 1992; Farquhar & Dunham, 1981; D'Amario et all, 1982; Farquhar et all, 1985). The goal of this paper is to continue the research made in Broucke (1988) and Broucke & Prado (1993a and 1993b), where a large variety of initial conditions for these orbits were classified according to the effects caused by the close approach with Jupiter in the orbit of the spacecraft. The well-known planar restricted circular three-body problem is used as the model for the dynamics, in the same way it was used in Broucke & Prado (1993a and 1993b). The equations are regularized (using Lamaître's regularization), so it is possible to avoid the numerical problems that come from the close approach with Jupiter.

Among the several sets of initial conditions that can be used to identify uniquely one trajectory, the same one used in Broucke & Prado (1993a and 1993b) is used here, with the variables: 1) J, the Jacobian constant; 2) The angle ψ, that is defined as the angle between the line m_1-m_2 (Sun-Jupiter) and the direction of the perigee of the trajectory of the spacecraft around Jupiter; 3) R_p, the distance from the spacecraft to the center of Jupiter in the moment of the closest approach to Jupiter (perigee distance). For a large number of values of these three variables, the equations of motion are numerically integrated forward and backward in time, until the spacecraft is at a distance that can be considered far enough from Jupiter. At these two points the two-body celestial mechanics formulas can be used to compute the energy and the angular momentum before and after the close approach. Those quantities are used to identify up to sixteen classes of orbits, accordingly to the changes in the energy and angular momentum caused by the close encounter. They are named with the first sixteen letters of the alphabet (Broucke & Prado, 1993b). The results of the present extension of this research are shown in plots, where the velocity increment and the flight path angle is plotted in a two-dimensional graph that has in the horizontal axis the angle ψ (the angle between the perigee vector and the Sun-Jupiter line) and in the vertical axis the Jacobian constant of the spacecraft. One set of plots is made for each value of the parameter R_p. The present paper has to be considered as a continuation of Broucke & Prado (1993b). The new aspect in the present paper is that the velocity increment and the flight path angle required for the maneuver are calculated.

DEFINITION OF THE PROBLEM AND MATHEMATICAL MODEL

To solve this problem, it is assumed three bodies: the Sun, the planet Jupiter and a third particle of negligible mass (the spacecraft). It is also assumed that the total system (Sun + Jupiter + spacecraft) satisfies the hypothesis of the planar restricted circular three-body problem: all the bodies are point of masses, the Sun and Jupiter are in circular orbits around their mutual center of mass. With these assumptions, the problem consists in studying the motion of the spacecraft near the close encounter with the planet Jupiter. In particular, the energy and the angular momentum of the spacecraft before and after this close encounter are calculated, to detect the orbit change during the close approach.

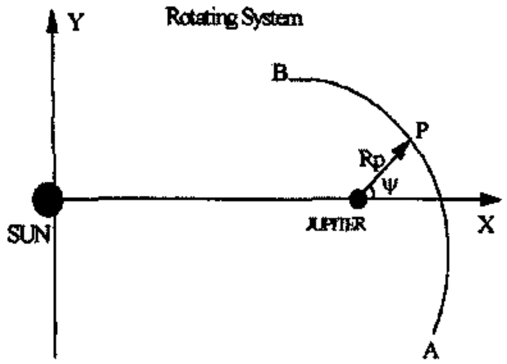

Fig. 1 explains the geometry involved in the close encounter. The spacecraft leaves the point A, crosses the horizontal axis (the line between the Sun and the planet Jupiter), passes by the point P (the periapsis of the trajectory of the spacecraft around Jupiter) and goes to the point B. The points A and B are choosen in a such way that the influence of Jupiter can be neglected at those points.

Fig. 1 Geometry of the Close Encounter

Under those assumptions, the procedure involved to solve this problem is: i) To specify arbitrary values for the Jacobian constant, the perigee distance (R_p) and the angle ψ; ii) Starting with the spacecraft in the perigee (P), to integrate numerically its orbit forward in time until it reaches the point B; iii) Starting again in the perigee (P), to integrate its orbit backward in time until the spacecraft reaches the point A; iv) At the points A and B the energy and the angular momentum of the spacecraft are calculated, and it is possible to classify both segments; v) The numerical integration is extended beyond the points A and B to verify if the spacecraft has none, one or two possible close encounters with the Earth, and at those points the increment in velocity and the flight path angle are calculated. The equations of motion for the spacecraft are assumed to be the ones valid for the well-known planar restricted circular three-body problem, writing in the rotating reference system and using the standard canonical system of units (Szebehely, 1967). Based in those conventions, the equations of motion of the spacecraft are:

$$\ddot{x} - 2\dot{y} = x - \frac{\partial V}{\partial x} = \frac{\partial \Omega}{\partial x} \qquad \ddot{y} + 2\dot{x} = y - \frac{\partial V}{\partial y} = \frac{\partial \Omega}{\partial y} \tag{1}$$

where Ω is the pseudo-potential given by:

$$\Omega = \frac{1}{2}\left(x^2 + y^2\right) + \frac{(1-\mu)}{r_1} + \frac{\mu}{r_2} \tag{2}$$

RESULTS

The main results of this paper are the magnitudes of the impulses (ΔV) required to start the outbound trajectories at the Earth (to go to Jupiter), or to stop the inbound trajectories at the Earth (coming from Jupiter). It is assumed that the impulse required is the difference between the inertial velocities of the Earth and the spacecraft. It means that the spacecraft is assumed to be traveling attached to the Earth (they both have the same position and velocity at a given time), but it is free of the attraction of the Earth's gravity field. In other words, the impulse required to escape the Earth is not included in the results shown here. Another quantity calculated is the flight path angle at the Earth, that is defined as the angle between the inertial velocities of the spacecraft and the Earth at the point that their orbits intersect. Figs. 2 and show the results. All the plots have the angle of approach ψ (in degrees) in the horizontal axis and the Jacobi Energy in the vertical axis. The values shown are: i) The flight path angle (in degrees) for the outbound trajectories in figures named "a"; ii) The ΔV (in canonical units) to start the outbound trajectories in figures named "b"; iii) The flight path angle (in degrees) for the inbound trajectories in figures named "c"; iv) The ΔV (in canonical units) to stop the inbound trajectories in figures named "d"; v) The total ΔV, given by the addiction of the two ΔV shown in "b" and "d", also in canonical units, in figures named "e".

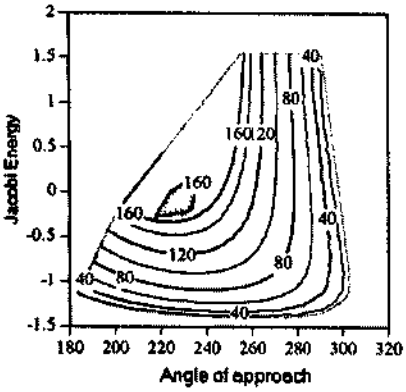

Fig. 2a - Flight Path Angle for Outbound Trajectories

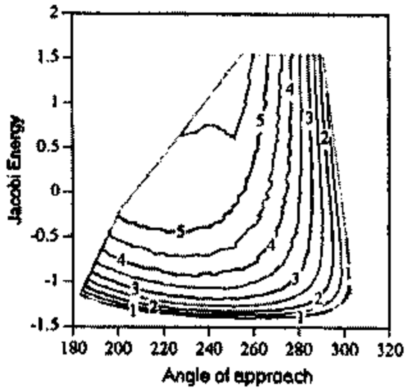

Fig. 2b - ΔV for Outbound Trajectories

Fig. 2 - Flight Path Angle and ΔV for Outbound Trajectories ($R_p = 2.0\ R_J$).

From those figures it is easy to find the regions with minimum ΔV. It corresponds, as expected, to the regions with flight path angle close to zero.

CONCLUSIONS

A numerical algorithm to calculate the effects of a close approach with Jupiter in the trajectory of a spacecraft is developed. A classification of a large number of trajectories were made and some of them were shown in detail. It was also showed which ones of those trajectories have a potential use for missions involving departures and/or arrivals in the planet Earth. The impulses (ΔV) involved in those transfers are calculated, as well as the flight path angles at the point where the orbits of the spacecraft and the Earth intersect. Those results are sufficient to identify regions of minimum ΔV for practical maneuvers. It is a new technique to study optimization of interplanetary trajectories.

REFERENCES

BROUCKE, R.A.: "The Celestial Mechanics of Gravity Assist". AIAA paper 88-4220. In: AIAA/AAS Astrodynamics Conference, Minneapolis, MN, 15-17 Aug. 1988.

BROUCKE, R.A.: and PRADO, A.F.B.A.: "On the Scattering of Comets by a Planet". In: 181st Meeting of the AAS, Phoenix, AZ, 3-7 Jan. 1993.

BROUCKE, R.A. & PRADO, A.F.B.A.: "Jupiter Swing-By Trajectories Passing Near the Earth". Advances in the Astronautical Sciences, Vol. 82, No. II, pp. 1159-1176.

CARVELL, R.: "Ulysses-The Sun From Above and Below". *Space*, Vol. 1, pp. 18-55, Dec. 85-Feb. 86.

D'AMARIO, L.A.; BYRNES, D.V.; STANFORD, R.H.: "Interplanetary Trajectory Optimization with Application to Galileo". *Journal of Guidance, Control, and Dynamics*, Vol. 5, No. 5, pp. 465-471, Sept.-Oct. 1982.

FARQUHAR, R.W.: and DUNHAM, D.W.: "A New Trajectory Concept for Exploring the Earth's Geomagnetic Tail". *Journal of Guidance and Control*, Vol. 4, No. 2, pp. 192-196, 1981.

FARQUHAR, R.; MUHONEN, D.; CHURCH, L.C.: "Trajectories ond Orbital Maneuvers for the ISEE-3/ICE Comet Mission". *Journal of Astronautical Sciences*, Vol. 33, No. 3, pp. 235-254, July-Sept. 1985.

FLANDRO, G.: "Fast Reconnaissance Missions to the Outer Solar System Utilizing Energy Derived from the Gravitational Field of Jupiter". *Astronautical Acta*, Vol. 12, No. 4, 1966.

HOLLISTER, W.M.; PRUSSING, J.E.: "Optimum Transfer to Mars Via Venus". *Astronautica Acta*, Vol. 12, No. 2, pp. 169-179, 1966.

PRADO, A.F.B.A. & BROUCKE, R.A.: "A Classification of Swing-By Trajectories using The Moon". *Applied Mechanics Reviews*, Vol. 48, No. 11, Part 2, November 1995, pp. 138-142.

SWENSON, B.L.: "Neptune Atmospheric Probe Mission". AIAA paper 92-4371. In: AIAA/AAS Astrodynamics Conference, Hilton Head, SC, Aug. 10-12, 1992.

SZEBEHELY, V.G. *Theory of Orbits*, Academic Press, New York, 1967.

WEINSTEIN, S.S.: "Pluto Flyby Mission Design Concepts for Very Small and Moderate Spacecraft". AIAA paper 92-4372. In: AIAA/AAS Astrodynamics Conference, Hilton Head, SC, Aug. 10-12, 1992.

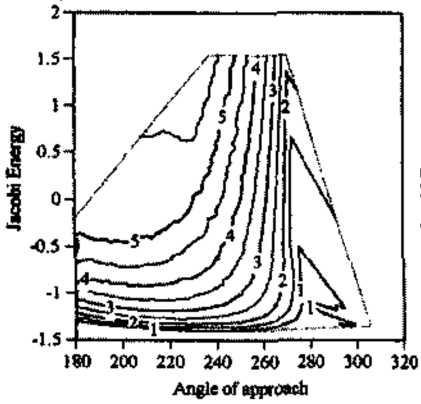

Fig. 3a – Flight Path Angle-Outbound Trajectories

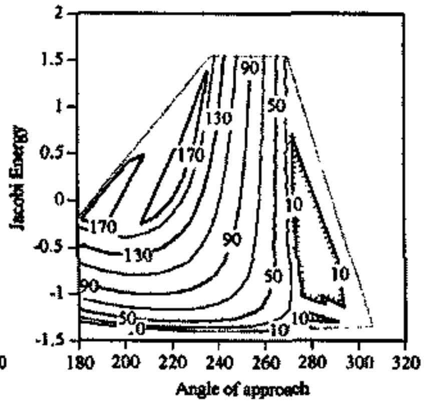

Fig. 3b - ΔV for Outbound Trajectories

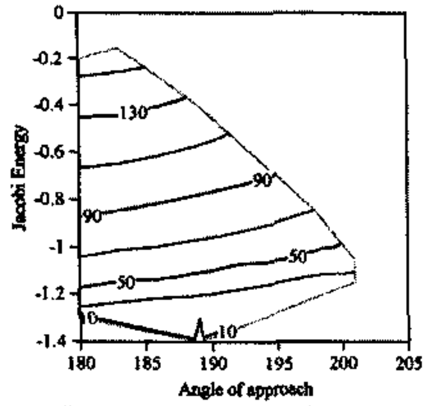

Fig. 3c - Flight Path Angle - Inbound Trajectories

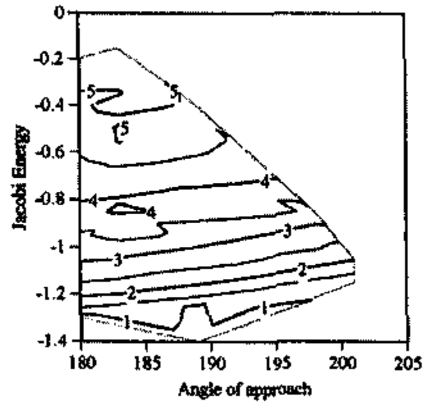

Fig. 3d - ΔV for Inbound Trajectories

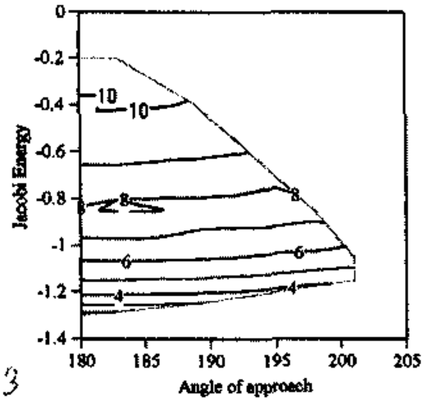

Fig. 3e - Total ΔV (Inbound + Outbound) Trajectories

Fig. 3-Flight Path Angle and ΔV for Outbound/Inbound Trajectories ($R_p = 10.0\ R_J$).

MINISTÉRIO DA CIÊNCIA E TECNOLOGIA
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

AUTORIZAÇÃO PARA PUBLICAÇÃO

Número: ETE-0011/2000

TÍTULO

Delta-V Estimate for Jupiter Swing-By Trajectories

AUTOR

Antonio Fernando Bertachini de Almeida Prado

TRADUTOR

EDITOR

ORIGEM	PROJETO	SÉRIE	No. DE PÁGINAS	No. DE FOTOS	No. DE MAPAS
DMC		- 780			

TIPO

○ RPQ ◉ PRE ○ NTC ○ PRP ○ MAN ○ PUD ○ TAE ○

DIVULGAÇÃO

◉ EXTERNA ○ INTERNA ○ RESERVADA ○ LISTA DE DISTRIBUIÇÃO ANEXA

PERIÓDICO / EVENTO

Apresentado no Sixth Pan-American Congress of Applied Mechanics and Eighth International Conference on Dynamic Problems in Mechanics

CONVÊNIO

AUTORIZAÇÃO PRELIMINAR

__/__/__ DATA

Hélio Koiti Kuga
Chefe da Divisão de Mecânica Espacial e Controle - DMC
Carimbo e Assinatura Titular da Unidade

REVISÃO TÉCNICA

☐ SOLICITADA ☒ DISPENSADA

Carlos E. Santana
Coordenador Geral
Engenharia e Tecnologia Espacial
Carimbo e Assinatura Titular de Nível "A"

RECEBIDA __/__/__ DEVOLVIDA __/__/__

Assinatura do Revisor

REVISÃO DE LINGUAGEM

☐ SOLICITADA ☒ DISPENSADA

Carlos E. Santana
Coordenador Geral
Engenharia e Tecnologia Espacial
Carimbo e Assinatura Titular de Nível "A"

RECEBIDA __/__/__ DEVOLVIDA __/__/__

Assinatura do Revisor

AUTORIZAÇÃO FINAL

18/12/00 DATA

Carlos E. Santana
Coordenador Geral
Engenharia e Tecnologia Espacial
Carimbo e Assinatura Titular de Nível "A"

PALAVRAS-CHAVE

Astrodinâmica, Trajetórias Espaciais, Mecânica Celeste, Manobras Orbitais

(continua na folha 2/2)

MINISTÉRIO DA CIÊNCIA E TECNOLOGIA
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

AUTORIZAÇÃO PARA PUBLICAÇÃO

Folha 2/2

SECRETARIA

__/__/__ DATA

RECEBIDA __/__/__ DEVOLVIDA __/__/__

Encaminhado Por

Devolvido Por

CONTROLE E DIVULGAÇÃO

__/__/__ DATA

RECEBIDO POR : Yolanda

DEVOLVIDO PARA :

__/__/__ DATA

PRONTO PARA PUBLICAÇÃO EM : 22/01/01

No. QUANT. 3

INPE-8062-PRE/3875

Assinatura

OBSERVAÇÕES

Rio de Janeiro-RJ, 04 a 08 de janeiro de 1999. Publicado como Applied Mechanics in the Americas, Vol. 6, 1999, pp. 263-266. ISBN: 85-900726-1-4.