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ScienceDirect
Advances in Space Research 40 (2007) 125–133
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

A study of trajectories to the Neptune system using gravity assists

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Received 6 September 2006; received in revised form 21 February 2007; accepted 21 February 2007

Abstract

At the present time, the search for the knowledge of our Solar System continues effective. NASA's Solar System Exploration theme listed a Neptune mission as one of its top priorities for the mid-term (2008–2013). From the technical point of view, gravity assist is a proven technique in interplanetary exploration, as exemplified by the missions Voyager, Galileo, and Cassini. Here, a mission to Neptune for the mid-term (2008–2020) is proposed, with the goal of studying several schemes for the mission. A direct transfer to Neptune is considered and also Venus, Earth, Jupiter, and Saturn gravity assists are used for the transfer to Neptune, which represent new contributions for a possible real mission. We show several schemes, including or not the braking maneuver near Neptune, in order to find a good compromise between the ΔV and the time of flight to Neptune. After that, a study is made to take advantage of an asteroid flyby opportunity, when the spacecraft passes by the main asteroid belt. Results for a mission that makes an asteroid flyby with the asteroid 1931 TD3 is shown.

Keywords: Astrodynamics; Swing-by; Orbital maneuvers; Neptune mission

1. Introduction

Among the first researches that approached the problems of interplanetary missions, we have the study made by Hollister and Prussing (1966), which considered a Mars transfer through Venus, analyzing the advantages of an impulsive maneuver during the close approach with Venus. One of the pioneering works in its time, for the vision of trips to our solar system using the concepts of the gravity-assist maneuver, was the work developed by Flandro (1966), which planned a mission to the exterior solar system using the energy of the gravitational field of Jupiter.

Later, D'Amario et al. (1981) developed several procedures with the goal of minimizing the total impulse ΔV for multiple-flyby trajectories with constraints on the flyby parameters and in the times of the maneuvers. This procedure successfully optimized the Galileo satellite tour, which contained up to eleven flybys. After that, D'Amario et al. (1982) modified the procedure for minimizing the total impulsive ΔV for application to interplanetary trajectories. Examples of the application of this new method are given for several types of Galileo interplanetary trajectory options. Then, Carvell (1986), studied the Ulysses mission that used a close approach with Jupiter to change its orbital plane to observe the poles of the Sun.

Longuski and Williams (1991) analyzed multiple encounter trajectories to the far outer planets. The most significant result is the last four-planet grand tour, with encounters with Jupiter, Uranus, Neptune, and Pluto. Other missions were designed, including Jupiter and only one or two of the other planets, but they have short flight times. Then, Longuski et al. (1991) considered a new approach to planetary mission design. This new design tool is applied to the problems of finding multiple encounter trajectories to the outer planets and Venus gravity-assist trajectories to Mars.

Striepe and Braun (1991) analyzed missions to Mars using the technique of maneuvers assisted by the gravity of Venus. This maneuver provides a non-propulsive change

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0273-1177/$30
doi:10.1016/j.asr.2007.02.070

in the heliocentric energy of the spacecraft that can reduce the amount of propellant necessary to complete the interplanetary mission and/or to reduce the duration of some missions. For certain positions of the planets, it incorporates a propulsive maneuver.

Swenson (1992) considered a mission to Neptune using a gravity assist maneuver with the Earth and Jupiter, besides considering multiple gravity assists with Venus (VVEJGA, which means Venus–Venus–Earth–Jupiter–gravity-assist). It also considered a combination with propulsive maneuvers.

Patel et al. (1995) investigated multiple-encounter missions to the outer planets which can also include a passage by Pluto. A particularly important result of this analysis is the discovery of a three-planet trip opportunity that includes Uranus, Neptune, and Pluto.

Peralta and Flanagan (1995) planned the interplanetary trajectories of the Cassini mission. The trajectory with multiple gravity assists with Venus–Venus–Earth–Jupiter supplies the energy required to reach Saturn. In this way, the geometry of the trajectory VVEJGA provides one technique to double the gravitational assistance with Venus.

Sims et al. (1997) analyzed several trajectories to Pluto using a gravity-assist maneuver with Jupiter. They also analyzed a gravity-assist maneuver with Mars, in conjunction with three maneuvers assisted by Venus.

Sukhanov (1999) studied a mission to the Sun, by means of gravity assists with the interior planets. It considers maneuvers with the Earth, Mars, and Venus. There are advantages in the cost, when compared to the gravity-assist maneuver with Jupiter, making it possible to use multiple maneuvers with the planet Mercury.

Exploration of small bodies in the solar system, in particular with asteroids, is among the most promising lines of space trajectory studies. In this way, Galileo was the first space mission to make a close approach to the asteroids (Belton and Delamere, 1992) denominated Gaspra (951) and Ida (243). It was the beginning of a refined study of the asteroids "in situ," exemplified by the satellite Near, which went to Eros (433).

In the present paper, a mission to Neptune is proposed for the time period 2008–2020. The main goal is to study several schemes for the mission. A direct transfer is considered, as well as trajectories that perform gravity assists with the planets Venus, Earth, Jupiter, and Saturn. The results represent new contributions for a possible real mission. Schemes including or not the braking maneuver near Neptune are considered, in order to find a good compromise between the ΔV and the time of flight to Neptune. Then, a study is made to consider an asteroid flyby, when the spacecraft passes by the main asteroid belt. Simulations are made considering the asteroid 1931 TD3.

2. Method for the development of the mission

The trajectory of the spacecraft is represented by a series of segments of undisturbed Keplerian motion around the gravispheres of relevant celestial bodies while, on the boundaries of these segments, the trajectories goes from the gravisphere into the heliosphere and vice-versa. Ordinarily, this planetary maneuver provides a non-propulsive change in the spacecraft's heliocentric energy which can reduce the amount of propellant required to complete an interplanetary mission. The heliocentric energy may be increased or decreased, depending on the geometric details of the encounters (turn of velocity vector over the sphere of influence of the planet).

The planetary orbits are elliptic and non-coplanar, and take into account the phasing of the planetary motion along the orbits for our analysis. The analysis is made for specific dates of the interplanetary flights (or their intervals) with estimates of minimum energy expenditure for the mission. Segments of heliocentric motion from the Earth to the flyby planet and from the flyby planet to the destination planet are constructed. These segments of the interplanetary trajectory are joined based on the incoming and outgoing excess velocity vectors to the flyby planet. Since the "patched conics" approximation is used, the incoming and outgoing excess velocities with respect to the planet that is in use for the swing-by are equals in the non-propelled swing-by and, when the impulse is applied, they differ by the amount of the impulse applied. For the case of multiple flybys, a similar construction is made for the subsequent segments of the trajectory. With this information, the optimal trajectory is sought based on the criterion of minimum total characteristic velocity (ΔV). After using the model described above, the optimization problem become a parametric optimization that can be easily solved.

For the schemes that considered the braking near Neptune, the hyperbolic excess velocity at Neptune contributes to the total ΔV. In this case, the braking impulse is applied when the spacecraft reaches a distance that corresponded to 5% of radii of Neptune, independent of the keplerian elements of the incoming orbit. Thus, the impulsive maneuver changes the hyperbolic orbit to a parabolic orbit near Neptune.

Earth and Venus are the inner planets that have a gravity field large enough to be used. Jupiter and Saturn show optimum launch opportunities for flights to Neptune using the energy gained during the close approach. However, to approach Neptune closely, the spacecraft should have low excess velocity to reduce the cost of the braking maneuver. The optimal launch date in the time interval 2008–2020 is considered. The following transfer schemes are analyzed: Direct Earth to Neptune (EN) transfer, Earth–Jupiter–Neptune (EJN) transfer, Earth–Saturn–Neptune (ESN) transfer, Earth–Jupiter–Saturn–Neptune (EJSN) transfer, Earth–Venus–Earth–Jupiter–Neptune (EVEJN) transfer and Earth–Venus–Earth–Jupiter–Saturn–Neptune (EVEJSN) transfer.

3. The mission options

Considering the requirement of a good compromise between the characteristic velocity (ΔV) and the time of