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Optimization of Transfers to Neptune

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Abstract: Here a mission to Neptune for the mid-term 2008–2020 is proposed. A direct transfer to Neptune is considered and also Venus, Earth, Jupiter and Saturn gravity assists are used for the trip to Neptune. Several mission options are analyzed, such as: Earth–Neptune, Earth–Jupiter–Neptune, Earth–Saturn–Neptune, Earth–Jupiter–Saturn–Neptune, Earth–Venus–Earth–Jupiter–Neptune, Earth–Venus–Earth–Jupiter–Saturn–Neptune. All the transfers are optimized in terms of the ΔV. The goal of this study is to compare the mission options in order to find a good compromise between the ΔV and time of flight to Neptune.

Keywords: *Neptune's system; swing-by; interplanetary mission.*

Mathematics Subject Classification (2000): 70F99, 70M20, 78M50.

1 Introduction

On August 20, 1977, the Voyager 2 was launched towards the exploration of our solar system. On August 25, 1989, it passed by Neptune. The gravity assist is a proven technique in interplanetary exploration, as exemplified by the missions Voyager, Galileo, Cassini etc. NASA's Solar System Exploration (Hammel et al. [1]) theme listed a Neptune mission as one of its top priorities for the mid-term (2008–2013). The interplanetary trajectory of the spacecraft is represented by a series of segments of undisturbed Keplerian motion in the gravispheres of relevant celestial bodies, while on the boundaries of these segments, the trajectory passes from the gravisphere into the heliosphere and vice versa. Studies of the interplanetary flight with gravity assist maneuvers are known to deal with cases where the spacecraft, on its way from one celestial body to another, approaches

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a third attracting body which causes a significant change in the spacecraft trajectory. Ordinarily, this planetary maneuver provides a non-propulsive change in the spacecraft's heliocentric energy which can reduce the amount of propellant needed to complete an interplanetary mission (Labunsky et al. [2]). The heliocentric energy may be increased or decreased, depending upon the geometric details of the encounters (turn of velocity vector over the sphere of influence of the planet). Several interplanetary's missions used this tecnique. For example Sukhanov [3] proposed a mission to Sun using gravity assist of the inner planets.

2 The Mission Options

Earth and Venus are the inner planets that have a gravity field large enough to be used. Jupiter and Saturn show optimum 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 braking cost. The optimal launches dates in the time interval 2008–2020 are 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.
- Earth - Venus - Earth - Jupiter - Saturn - Neptune (EVEJSN) transfer.

Transfer Scheme	Launch Date	ExcessVelocity $V_\infty(km/s)$	MinimumTotal $\Delta V(km/s)$
EN	13.04.2012	9.436	8.992
EJN	14.01.2018	11.728	6.506
ESN	13.02.2017	12.955	7.775
EJSN	18.11.2015	15.757	6.719
EVEJN	24.08.2016	14.578	6.646
EVEJSN	09.06.2015	17.275	7.206

Table 2.1: Optimal transfer schemes for flight time of 12 years.

As it is seen from the Table 2.1, the minimum total ΔV is 6.506 km/s for the scheme EJN , with a flyby altitude of $0.2\text{x}10^3$ km (Earth) and $1.2\text{x}10^3$ km (Neptune). The excess velocity near Neptune is 11.728 km/s. Other scheme with low ΔV (minimum total) is EVEJN, however the excess velocity near Neptune is higher than in the EJN option.

Figures 2.1-2.2 shows the configuration for the transfer scheme EJN and EVEJN. Table 2.2 shows the optimal launch date for several transfers. The minimum total ΔV is 5.441 km/s for the scheme EVEJSN and the total flight duration is 23.69 years, with flyby altitude of $0.2\text{x}10^3$ km (Earth) and $1.2\text{x}10^3$ km (Neptune). The excess velocity near Neptune is 5.083 km/s, however the EVEJN scheme have minor excess velocity near Neptune (3.748 km/s) for the optimal transfer time of 29.95 years.

Figure 2.3 shows the planetary configuration and the transfer trajectory for the scheme EVEJSN. It is a typical 2015 Earth–Venus–Earth–Jupiter–Saturn–Neptune flight path projected on the plane of the ecliptic. It is possible that all the trajectories after Neptune (depending on the targeting conditions selected) have energy enough to escape from the solar system.

Figure 2.4 shows several transfer schemes from Earth to Neptune. Looking the curves of minimum total ΔV as function of the time of the transfer, the EJN, EJSN EVEJN, and EVEJSN schemes are most acceptables if the transfer duration is limited by the time of 12 years.

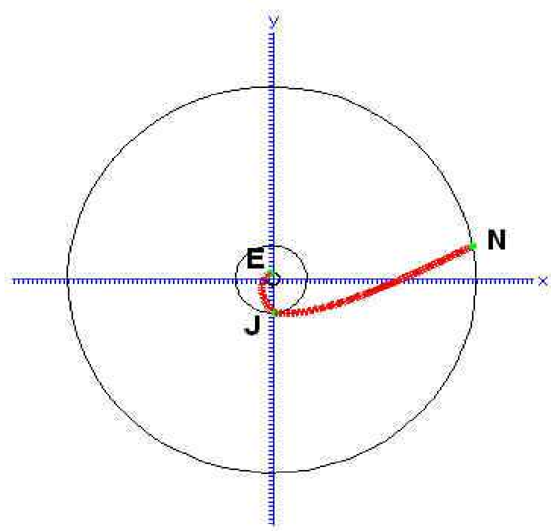

Figure 2.1: Planetary configuration and transfer trajectory for 2018 Earth–Jupiter–Neptune.

Transfer Scheme	Optimal Launch Date	ExcessVelocity $V_\infty(km/s)$	MinimumTotal $\Delta V(km/s)$
EN	09.04.2009	6.258	8.691
EJN	13.01.2018	7.050	6.367
ESN	17.01.2014	7.468	7.273
EJSN	26.11.2015	4.124	6.428
EVEJN	28.05.2013	3.748	5.642
EVEJSN	30.05.2015	5.083	5.441

Table 2.2: Optimal launch date for several transfers.

The EVEJSN scheme has several minimum total ΔV equal to the EJN, EJSN, EVEJN schemes. For a time of transfer larger than 14 years, the EVEJSN scheme is optimal, in terms of minimum total ΔV. Figure 2.5 shows the excess velocity near Neptune. The

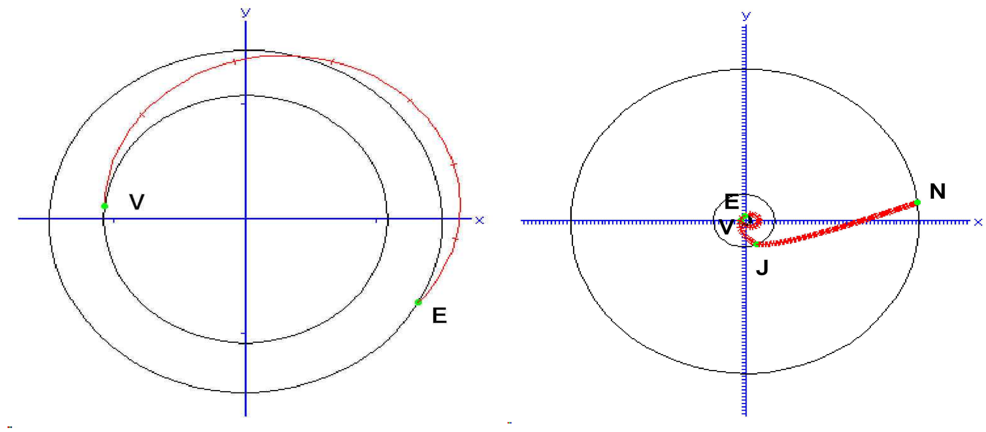

Figure 2.2: Planetary configuration and transfer trajectory for 2016 Earth–Venus–Earth–Jupiter–Neptune.

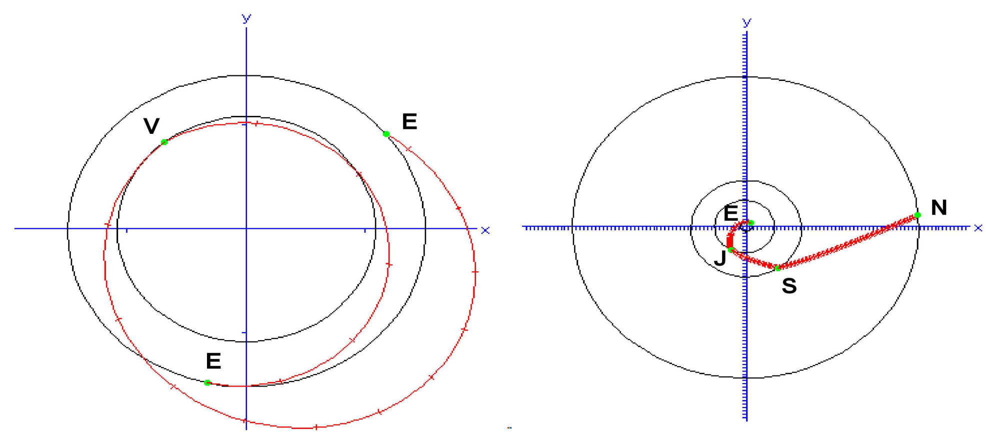

Figure 2.3: Planetary configuration and transfer trajectory for 2015 Earth–Venus–Earth–Jupiter–Saturn–Neptune.

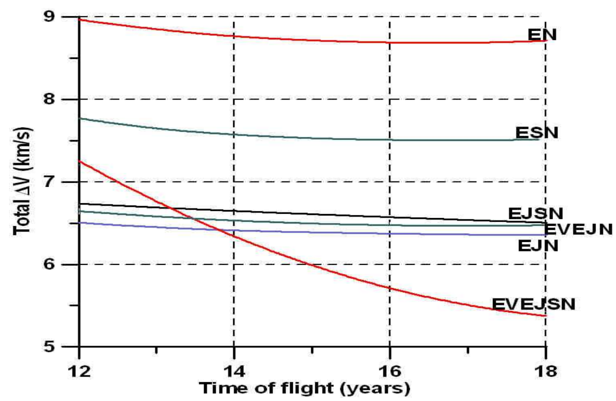

Figure 2.4: Total ΔV vs. time of flight for the spacecraft.

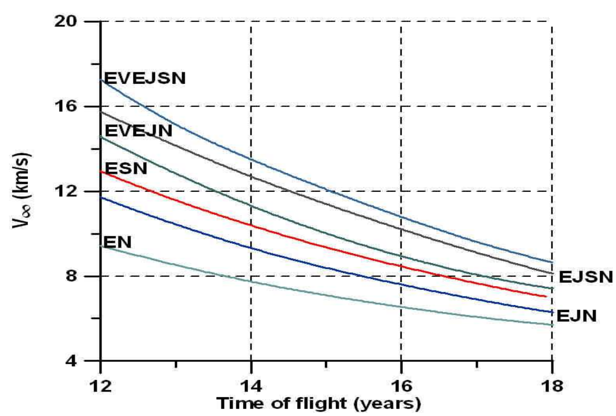

Figure 2.5: V_∞ vs. time of flight of the spacecraft.

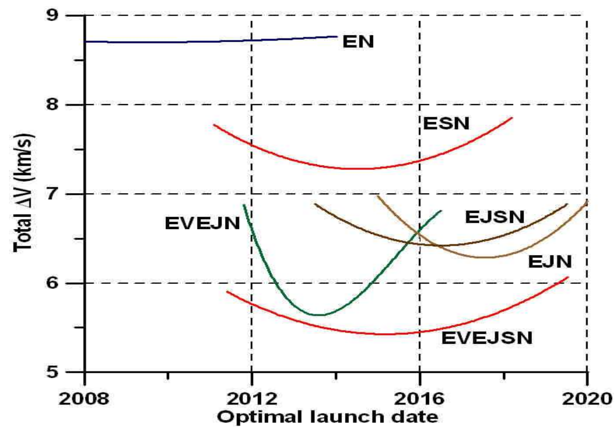

Figure 2.6: Optimal launch date for several transfer schemes.

EVEJSN scheme is optimal in terms of minimum total ΔV, however excess velocity near Neptune is very high in this scheme. The EJN and EVEJN schemes are more efficients for low excess velocity near Neptune and for minimum of ΔV.

Figure 2.6 shows the minimum total ΔV as a function of the optimal launch date for several transfer schemes in the time interval 2008–2020. The results are shown in Table 2.2. The gravity assists maneuvers with Jupiter and Saturn has enormous potential to reduce the total ΔV for trajectories to Neptune, however for the time interval considered Mars and Uranus are not in good positions.

Remember that it is also possible to use Earth gravity assists and Venus flybys as another way to increase the heliocentric energy of the trajectory to reach Jupiter. Besides the synodic period between Earth and Venus is 1.6 years, and the synodic period between Earth and Jupiter is 1.09 years.

For an initial Venus flyby (EVEJN, EVEJSN), we considered that the minimum flyby altitude at Venus is $0.3 \times 10^3 km$. When the launch ΔV decreases, the V_∞ at Venus also decreases.

Considering an initial Jupiter flyby, look that when the spacecraft have a flyby altitude at Jupiter of $4.22 \times 10^5 km$ (EJN scheme and time of flight of 12 years), the launch ΔV decreases, but the excess velocity in Jupiter increases.

For an Earth–Neptune direct transfer, when the launch ΔV decreases, the V_∞ at Neptune also decreases. This is the result of low energy launch, however, this is sufficient for arrival at Neptune. For the Earth–Jupiter–Neptune scheme, the transfer angle E-J undergoes to a decrease in the time interval considered. This is possible for the planetary configuration and for the initial conditions, however Jupiter is capable of the largest transfer angles for a given excess velocity due to its great mass. Following an initial Jupiter flyby (Earth-Jupiter-Saturn-Neptune), the transfer angle is too high and it decreases in the time interval considered. The others transfer angles are quasi-constant (J-N, J-S, S-N).

The launch ΔV for the Earth–Saturn–Neptune option also decreases, and the transfer angle E-S also decreases. This angle have the largest value for the excess velocity. The Saturn–Neptune angle is quasi-constant. For the Earth–Venus–Earth–Jupiter–Neptune and Earth–Venus–Earth–Jupiter–Saturn–Neptune schemes, the transfer angle E-V decreases, however the others transfer angles are quasi-constant. The transfer angle of V-E is high. The exploration of our outer solar system can also be increased by taking advantage of asteroid flyby opportunities, when the spacecraft passes through the asteroid belt. To incorporate an asteroid flyby, we first need to optimize a trajectory to Neptune with planetary flybys and then search for asteroids that pass close to this trajectory, to finally reoptimize the trajectory including one or more asteroid flybys.

3 Conclusions

In this paper, two important parameters, namely the minimum total ΔV and the excess velocity near Neptune V_∞ were obtained as functions of the launch date and flight duration. These two parameters determine the fuel consumption to launch from LEO, midcourse and to brake the spacecraft near Neptune, respectively. However, the braking near Neptune, in principle, can be performed using an aerobraking maneuver, so the launch ΔV was considered the most important parameter. Remember that in this paper an active braking was not used. The EJN scheme provides minimum total ΔV for the transfer duration with less than 14 years. This scheme also gives relatively low V_∞. For longer transfers the EVEJSN scheme is optimal in terms of minimum total ΔV, however V_∞ is high in this scheme. The EJN and EVEJSN schemes are most acceptables. If the transfer duration is limited by the time of 14 years or less, the EJN scheme is preferable in all respects. The EVEJSN scheme is getting preferable for transfers longer than 14 years.

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