CLOSE APPROACH TO NEPTUNE USING GRAVITY ASSISTS

Carlos Renato Huaura Solórzano
Departamento de Mecânica e Controle - INPE
Av. dos Astronautas - C.P. 515, CEP 12201-970 - São José dos Campos – SP - Brazil
renato@dem.inpe.br

Alexander Alexandrovich Sukhanov
Space Research Institute (IKI) of the Russian Academy of Sciences
84/32 Profsoyuznaya St., 117810 Moscow, Russia
sukhanov@iki.rssi.ru

Antônio Fernando Bertachini de Almeida Prado
Departamento de Mecânica e Controle - INPE
Av. dos Astronautas - C.P. 515, CEP 12201-970 - São José dos Campos – SP – Brazil
prado@dem.inpe.br

Abstract. *The gravity assist is a proven technique in interplanetary exploration, as exemplified by the missions Voyager, Galileo, Cassini etc. On August 20, 1977, the Voyager 2 was launched towards the exploration of our solar system. On August 25, 1989, it passed by Neptune. NASA's Solar System Exploration theme listed a Neptune mission as one of its top priorities for the mid-term 2008-2013 (Hammel et al 2002). 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 DV. The goal of this study is to compare the mission options in order to find a good compromise between the DV and the time of flight to Neptune.*

Keywords*:gravity assist,interplanetary trajectories,Neptune System*

1. Introduction

Among the first researchs that approach the problems of the interplanetary missions, we have the study made by Hollister and Prussing (1966), which consider a Mars transfer through Venus, analysing the advantages of an impulsive maneuver during the close approach with Venus. One of the pioneering works in its time, for the vision of trip to our solar system using the concepts of the gravity assisted maneuvers was the work of Flandro (1966), which plans a mission to the exterior solar system using the energy of the gravitational field of Jupiter.

Striepe and Brauns (1991) analysed missions to Mars using the technique of maneuver assisted by the gravity of Venus. This maneuver provides a non-propulsive change 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 position of the planets it incorporates a propulsive maneuver. Swenson (1992) considers a mission to Neptune using a gravity assist maneuver with the Earth and Jupiter, besides considering multiple gravity assist with Venus (VVEJGA). It also considers a possible combination with propulsive maneuver.

Peralta and Flanagan (1995) plan the interplanetary trajectories of the Cassini mission (launched in 15/10/1997). This mission has the objective of studing the saturnian system. The spacecraft uses flights assisted by the gravity to gain the energy necessary to reach Saturn in July, 2004. Thus, the trajectory with multiples gravity assist with Venus-Venus-Earth-Jupiter supplies the energy necessary 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 (1995) consider the use of the planetary atmosphere for the interplanetary flights and analyses the trajectories aero-assisted with the exterior planets. This type of maneuver can reduce the requirements in the energy of launching, and the time of flight. Analysing the development of a future mission to Jupiter, Saturn, Uranus, Neptune and Pluto using Venus and/or Mars for the aero-assisted trajectories. The technique of the use of the planetary atmosphere can be used to reduce the requirements in the launching energy and or to develop the capacity of the mission for new encounters with planets, asteroids, satellites etc. In this situation, the space vehicle approaches the planet in a hyperbolic orbit and after reaching the periápside in the interior of the superior atmosphere of the planet, the spacecraft can after energy (when one definitive turn in the vector speed is reached) which it abandons the atmosphere and continues to the long one of its hyperbolic orbit.

Sims, Staugler, and Longuski (1997), analyzes several trajectories for Pluto using maneuvers assisted by the gravity of Jupiter.They also analyze the maneuver assisted by gravity with Mars in conjunction with three maneuver assisted by Venus. Sukhanov (1999) studies the mission to the Sun, by means of gravity assist with the interior planets. It considers maneuvers with the Earth, Mars, and Venus there are advantages in the cost with respect the maneuver assisted by Jupiter, being possible to use multiple Mercury maneuvers.

2. Method for the development of the mission

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. 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. 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).

That is the model that approximates the spacecraft trajectory by segments of nonperturbed Keplerian motion. This represents the planetary motion in more detail, making allowance for the planetary orbits to be elliptic and noncoplanar, and taking into account the phasing of the planetary motion along the orbits. The analysis is made for specific dates of interplanetary flights (or their intervals) with estimates of minimum energy expenditure for the mission. The essence is as follow, within the framework of the technique of the spheres of influence, 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 vectors incoming and outgoing excess velocity to the flyby planet. For the case of multiple flybies a similar construction is made for the subsequent segments of the trajectory. The optimal trajectory are sought based on the criterion of minimum total characteristic velocity.

The spacecraft performs several gravity assists with the inner and outer planets in order to turn the velocity vector over the sphere of influence of the planet. 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 braking cost. 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, Earth - Venus - Earth - Jupiter - Saturn - Neptune (EVEJSN) transfer.

3. The mission options

Considering the requirement of a good compromise between the characteristic velocity (DV) and the time of flight, we analyze the several options of transference in the time interval 2008-2020. In the frame studied, Uranus does not have a good position that can supply an improvement in the fuel consumption through a gravity assists maneuver. As it is observed in Fig. 1 the best configuration for the gravity assists maneuver is given by the planets: Venus, Earth, Jupiter, Saturn. The best options with the best dates where they must be effected are shown.

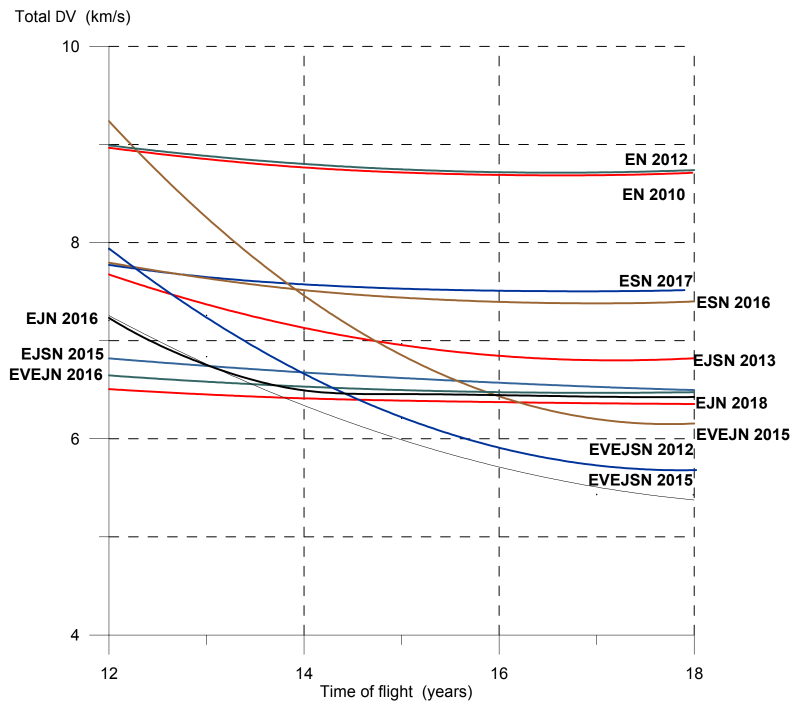

Figure 1. Total DV vs. time of flight for the spacecraft for several schemes.

Table 1 shows that the minimum total DV is 6.506 km/s for the scheme EJN and the total flight duration is 12 years, with a flyby altitude of $0.2\text{x}10^3$ km (Earth) and $1.2\text{x}10^3$ km (Neptune). This option has a radius of periapse of $147.1\text{x}10^6$ km in the orbit around the Earth, and radius of periapse of $766.5\text{x}10^6$ km in orbit around Jupiter. The excess velocity near Neptune is 11.728 km/s. Other scheme with low DV (minimum total) is EVEJN, however the excess velocity near Neptune is higher than in the EJN option.

Table 1. Optimal transfer scheme for 12 years.

Transfer Scheme	Launch Date	Excess Velocity $V_{¶}$ (km/s)	Minimum Total DV* (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

Figures 2-3 shows the planetary configuration for the transfer scheme EJN and EVEJSN. Table 2 show the optimal launch date for several transfers, it considers the free time. The minimum total DV 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). This option have a radius of periapse of $98\text{x}10^6$ km in the orbit around the Earth, and radius of periapse of $1017.6\text{x}10^6$ km in the orbit around Saturn. 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.

However the Tab. 1 and 2 and Fig. 1 show that the direct Earth to Neptune transfer do not allow a lower bound of energy requirements for such flight, however the most important condition allowing the route with a flyby to be accepted is that it should reduce energy consumption when compared to an analogous direct flybys. For the mission options with gravity assist flybys, the criterion of minimum total energy expenditure is usualy used for several schemes.

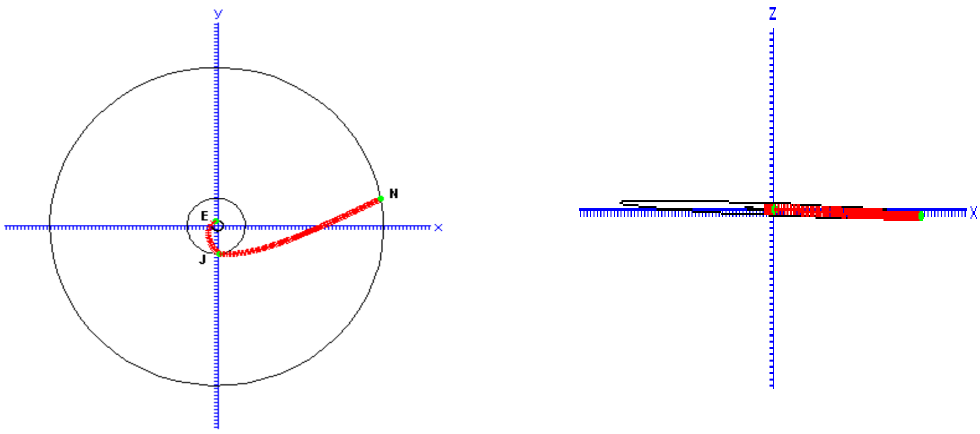

Figure 2. Planetary configuration and transfer trajectory for 2018 Earth-Jupiter-Neptune

Figure 4 shows the planetary configuration and the transfer trajectory for the EVEJSN scheme. 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 5 shows several transfer schemes from Earth to Neptune. Looking the curves of minimum total DV as function of the time for transfer, the EJN, EJSN EVEJN, and EVEJN schemes are most acceptable if the transfer duration is limited by the time of 12 years. The EVEJSN scheme have a minimum total DV equal to the EJN, EJSN, EVEJN schemes between an time of transfer in the interval 13-14 years. For a time of transfer of 14 years and less, the EVEJSN scheme is optimal, in terms of minimum total DV. Figure 6 shows the excess velocity near Neptune. The EVEJSN scheme is optimal in terms of minimum total DV, however $V_{¶}$ is very high in this scheme. The EJN and EVEJN schemes are more efficients for low excess velocity near Neptune and for minimum of DV.

Figure 7 shows the minimum total DV as a function of the optimal launch date for several transfers scheme in the time interval 2008–2020. The results are shown in Table 2. It seems that the gravity assists maneuvers with Jupiter and Saturn has enormous potential to reduce the total DV for trajectories to Neptune, however for the time interval considered Mars and Uranus are not in good positions. For a free time all the schemes are reduced. This fact happen for the configuration of the planets for the years in study.

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. Remember that 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 $0.3x10^3$ km.

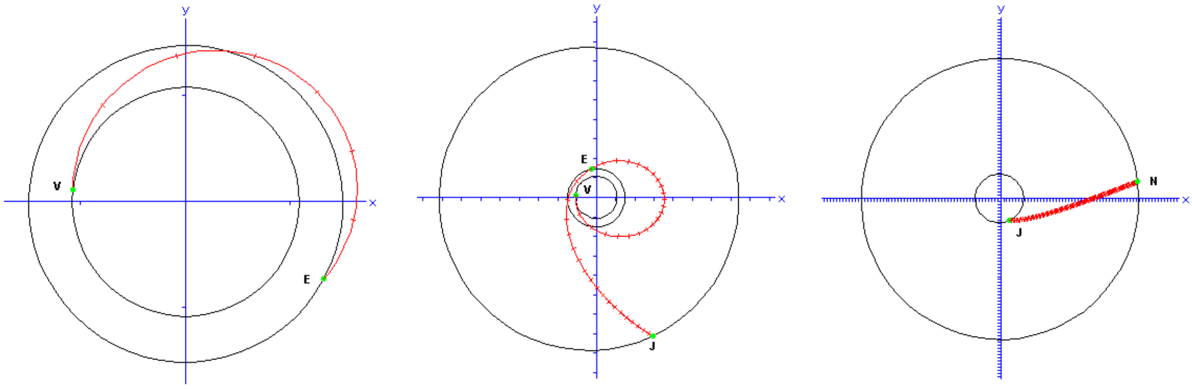

Figure 3. Planetary configuration and transfer trajectory for 2016 Earth-Venus-Earth-Jupiter-Neptune

Table 2. Optimal launch date for several transfers.

Transfer Scheme	Optimal Launch Date	Excess Velocity $V_{¶}$ (km/s)	Minimum Total DV (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

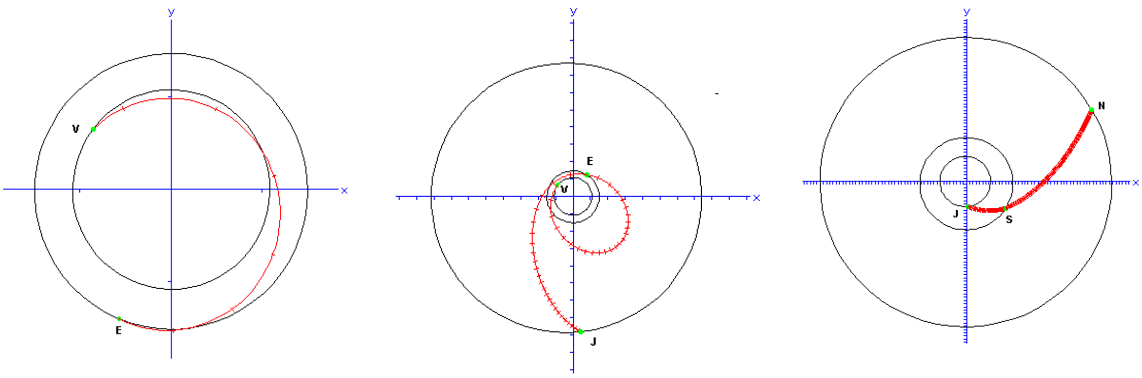

Figure 4. Planetary configuration and transfer trajectory for 2015 Earth-Venus-Earth-Jupiter-Saturn-Neptune.

Considering an initial Jupiter flyby, look that when the spacecraft have a flyby altitude at Jupiter of $421.8\ x10^3$ km (EJN scheme and time of flight of 12 years), the launch DV decreases, but the excess velocity in Jupiter increases.

For an Earth-Neptune direct transfer, it is shown that, when the launch DV decreases, the $V_{¶}$ at Neptune also decreases. The transfer angles have similar behavior. 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), due to the long periods of the comparative planets to the transfer time.

The launch DV for the Earth-Saturn-Neptune option also decreases, and the transfer angle E-S also decreases. The Saturn-Neptune angle is quasi–constant. For the E-V-E-J-N and E-V-E-J-S-N schemes, the transfer angle E-V decreases, however the other transfer angles are quasi-constant, the transfer angle of Venus–Earth 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. Figure 8 shows the total DV, which considers DV of launching and braking near Neptune as a function of the time of flight. We observe that in the first option with 14 years, EVEJSN has high fuel consumption. However, for larger times of transference, in this case between the 17-18 years, this option shows a better performance when referring to the fuel consumption.

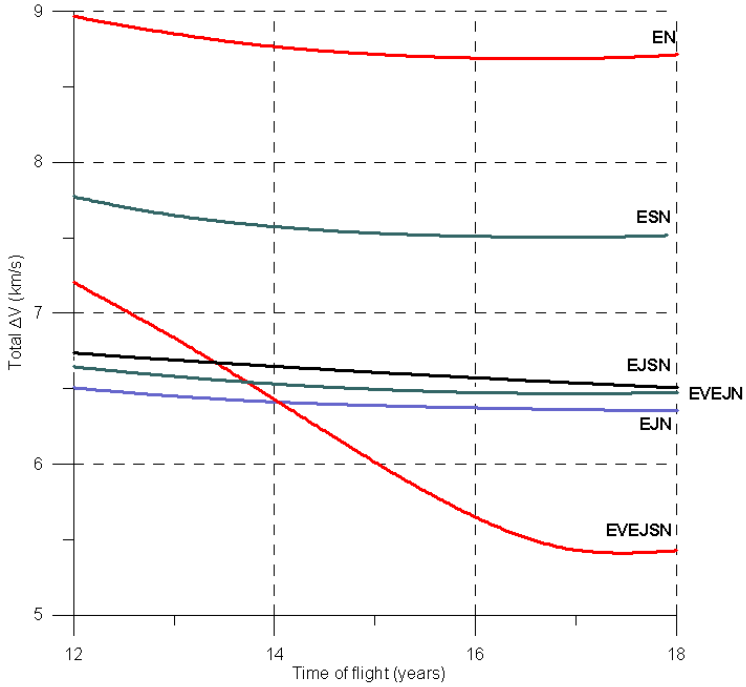

Figure 5. Total DV vs. time of flight for the spacecraft

The option EJN reveals to be excellent, due to the fact that for a time of flight of 12 years it has a minimum DV of 9.298 km/s and keeps a comparative excellent behaviour with respect the other options until a time of flight of 17 years. However, there is a region with multiple points of intersection of all the options. This happens when the time of flight is next to the 14 years. For an time of flight of 14 years or more, the EN, ESN, and EJSN options has one high fuel consumption comparative to EVEJN, EJN and EVEJSN options.

The option EVEJN approximately has also a low fuel consumption until a time of flight of 15.5 years, but the EVEJSN option results with lower consumption. The options shown had been simulated considering dates of launching in 2012 for the Earth to Neptune transfer, in 2018 for Earth - Jupiter - Neptune transfer, 2016 for Earth - Saturn - Neptune transfer, 2015 for the Earth - Jupiter - Saturn - Neptune transfer, 2016 for the Earth - Venus - Earth - Jupiter - Neptune transfer, and 2015 for the Earth - Venus - Earth - Jupiter - Saturn - Neptune transfer. Figure 9 supplies information of optimal launch date with breaking near Neptune in the time interval 2008-2020.

In these simulations the time of flight is a free variable. Our interest is to determine the minimum fuel consumptions, independent of the time of flight, so determining the optimal launch date in a certain interval of time. The EVEJSN option has the best values of DV, thus the minimum value is 5.899 km/s for a time of flight of 31.20 years. Another option with a low value of DV is EVEJN. Figure 8 show that the option EJN has better results when compared to the option EVEJN for times of flight between the 12-18 years. However we see that for larger times of flight the EVEJN option presents better results.

The option EJN supplied the best values of DV for a time of flight next to 17 years, being the third option with better values of minimum DV. Option EN shows higher values of minimum DV when compared with the other options of transference. However it has a comparative improvement to the curves of DV as a function of the time of flight between the 12 and 18 years.

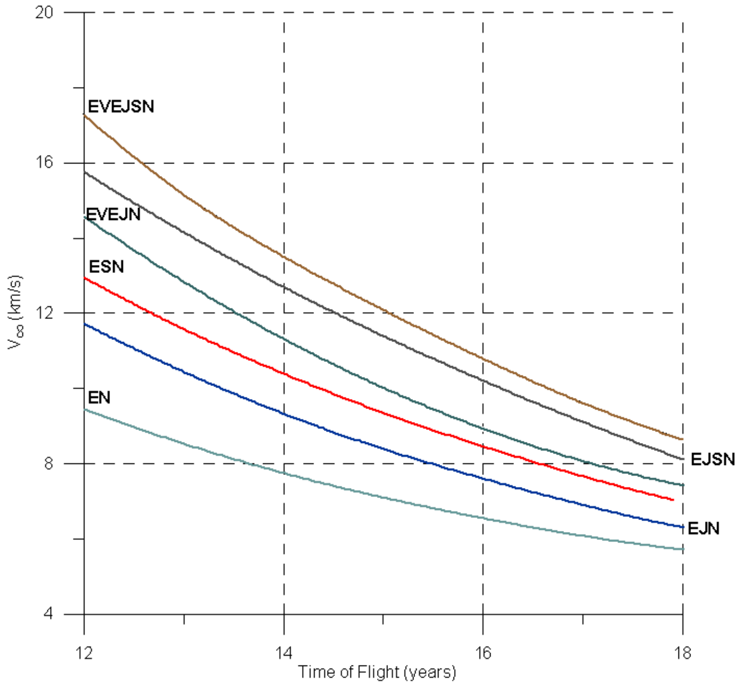

Figure 6. V¶ vs. time of flight of the spacecraft

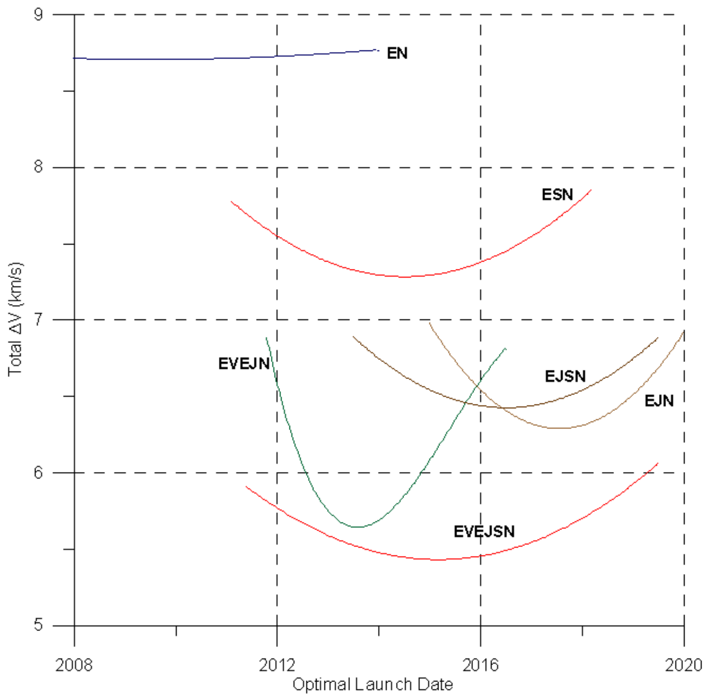

Figure 7. Optimal launch date for several transfer schemes

We studied two important parameters, the DV of launching and the excess velocity V¶ near Neptune. They are considered as a function of the date of launching and the time of flight. These two parameters determine, respectively, the consumption of fuel to leave an orbit LEO and the breaking one, next to Neptune. However the braking near Neptune can also be obtainded by means of an aero-braking maneuver, so the DV was considered the most important parameter. The option EJN without braking in leg has a minimum DV for a transference whose duration is less than 14 years. This option also determines low values for V¶. For larger times of transference, option EVEJSN is excellent in terms of minimum DV, however V¶ is high in this option. To find the optimal dates of launching, the options EJN, EVEJN, and EVEJSN are more acceptable. If the duration of the transference is limited to the 14 years or less option EJN is preferable in all the aspects. The EVEJSN option is preferable for times of transference larger than 14 years.

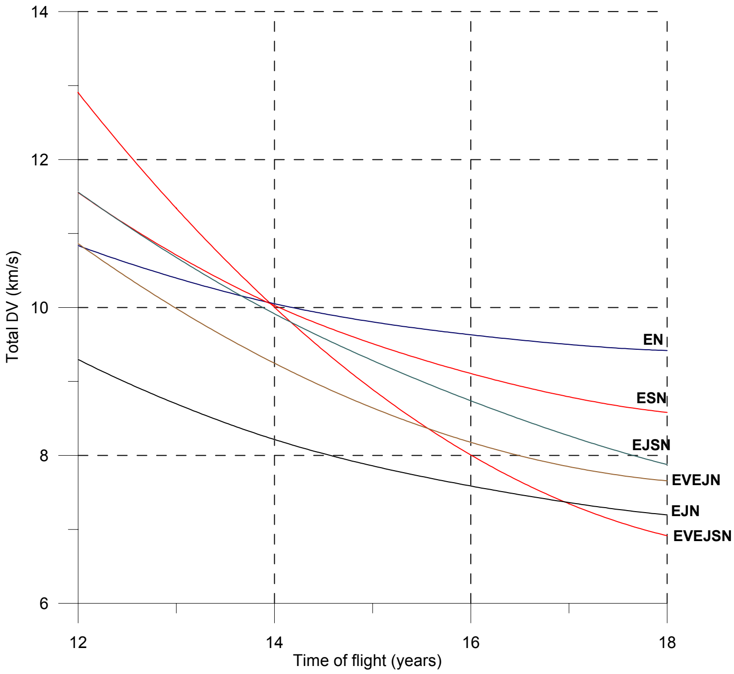

Figure 8. Total DV vs. time of flight for the spacecraft with breaking near Neptune

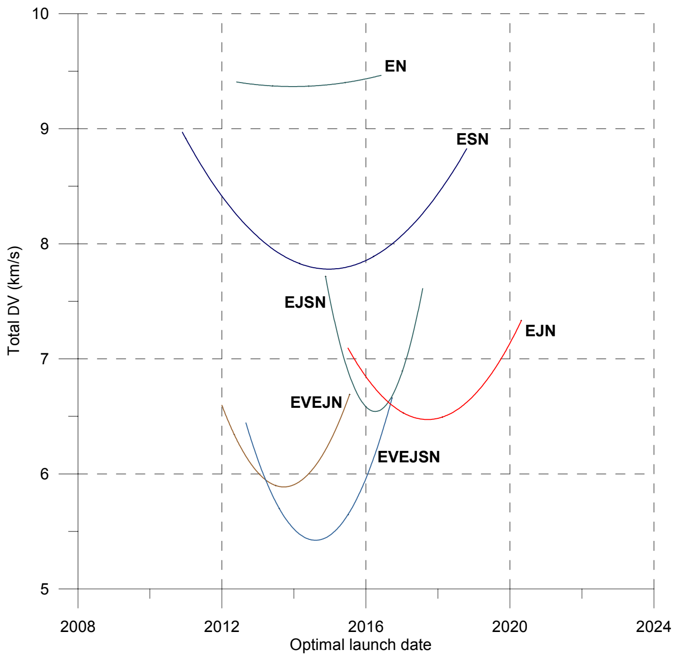

Figure 9. Optimal launch date for several transfer schemes for trajectories with breaking

The transfer scheme with breaking have a high bound of energy requirements. The optimal launch date for each one of the transfer options had been kept with the end to make the comparison between them better. Thus, we observe that the EVEJSN option continues being preferential for times of flight near 18 years (Fig. 5 and 8). This option has a similar behaviour in the two cases why initially it presents high values. The EJN option with braking has an excellent behaviour in the comparative fuel consumption to the many options for an time of flight between 12 and 17 years, however in the simulations made without braking (Fig. 5), we observe that the variations are small in the interval of time of flight. The similar behaviour in both figures for times of transference close to 18 years. The best ones are given by EVEJSN, EJN, EVEJN, and EJSN options, being the larger consumptions given by ESN and EN. The regions with this options EJSN, EVEJN, EJN, does not appear in the breaking simulations. However, in the simulations with braking the options EN, ESN, and EJSN, they alternate behaviours between them of larger and smaller consumptions.

The main characteristic for optimal launch date (not observed in the figures) with free time is the fact that in the case of the transferences with braking the transference time is greater than in the cases without braking this is observed that the options with braking have a larger fuel consumption, however to find the optimal launch date needs larger times of transference.

As it was mentioned in the beginning of this work, Uranus is not in advantageous position for the years considered in the present research. This fact also is justified in the work of Logunski and Williams (1991), which show optimal launches to Neptune between 2005 - 2007, and 2021 -2022, through diverse gravity assists with Jupiter and Uranus. A point of agreement with the mentioned work is the consideration of possible gravity assists with Jupiter, and Saturn to arrive in Neptune in the years 2016 – 2019.

4. Conclusions

In this paper, two important parameters, namely the minimum total DV and the excess velocity $V_{\P}$ near Neptune were obtained as a function 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. The launch DV was considered the most important parameter. The EJN scheme provides minimum total DV for the transfer duration with less than 14 years. This scheme also gives relatively low $V_{\P}$. For longer transfers, the EVEJSN scheme is optimal in terms of minimum total DV, however $V_{\P}$ is high in this scheme. Although in very long EVEJSN and EVEJN schemes, the $V_{\P}$ is getting relatively small with the DV value close to the minimum. The EJN and EVEJSN schemes are most acceptables for longer transfers (free time). 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.

All the previous schemes allow a passage near Neptune, depending on the objectives of the mission, it is possible to make a flyby or to remain in orbit around some of moons of the planet. In our case we need to change the trajectory of the spacecraft to keep it in orbit around Neptune. Then we apply the braking in the proximity of Neptune. The EJN scheme provides minimum total DV for the transfer duration with less than 17 years. For longer transfers (17-18 years) the EVEJSN scheme is optimal in terms of minimum total DV. The EJN and EVEJSN schemes are most acceptables for longer transfers (free time).

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