

TRAJECTORY OPTIONS FOR LOW-COST MISSIONS TO EASILY RETRIEVABLE OBJECTS

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Near-Earth Objects (NEOs) are of contemporary, since asteroids and comets hold the key clues to understanding the origin of the solar system and the formation of the planets, and also have a speculated wealth of material resources. The exploitation of these resources has been discussed as a means to lower the cost of future space endeavours. Recent, a new family of so-called Easily Retrievable Objects that can be transported from accessible heliocentric orbits into the Earth's neighbourhood at affordable costs, have been presented. In this paper, the trajectory options for low-cost missions to EROs are explored. We consider a wide variety of multi-impulse transfer, gravity-assist transfer and gravity-assist transfer with mid-maneuvres to obtain low launch energy and rendezvous trajectories to EROs. These trajectories are constructed by analytic and numerical search methods, and hybrid optimization algorithms including global search and local search to find the optimal rendezvous opportunities. The best rendezvous opportunities for currently known EROs in the next 20 years are reported. The relevant mission costs are analyzed. A discussion of general characteristics of the various trajectory types is followed.

INTRODUCTION

Asteroids and comets hold key clue to understanding the formation, evolution and composition of the solar system. Among asteroid and comet populations, the Near-Earth asteroids are of particular interest because of their accessibility from Earth, but also their speculated wealth of material resources. Near-Earth asteroids are usually divided into four classes, depending upon their orbital characteristics: Atens, Apollos, Amors and Atiras. Atens and Apollos are Earth-crossers. Orbits of Amors and Atiras have completely outside and inside the orbit of the Earth, respectively.

Recent, a new family of so-called Easily Retrievable Objects (EROs)¹ is presented. EROs are defined as objects that can be gravitationally captured in bound periodic orbits around the collinear libration points L1 and L2 of the Sun-Earth system under a certain Δv threshold, arbitrarily selected for this work at 500m/s. These objects include 2006 RH120, 2010VQ98, 2007 UN12, 2010UE51, 2008EA9, 2011UD21, 2009BD, 2008UA202, 2011BL45, 2011MD, 2000SG344 and 1991VG. The EROs with capture costs and types are listed in Table1. Orbital elements of EROs are listed in Table 2.

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In this work, we focus on the outbound trajectories and opportunities to EROs. The capture phase is not considered here. The multi-impulse transfer, gravity-assist transfer and gravity-assist transfer with mid-maneuvers are considered to lower launch energy and total velocity increments. A hybrid optimization approach including global search and local search is used to find the low-cost transfer trajectories. The general characteristics of the various trajectory types are discussed.

Table 1. NEO Characteristics for Transfer Trajectories with Δv Below 500m/s.

Asteroid name	MOID (AU)	Diameter (m)	Δv (km/s)/capture type
2006 RH120	0.0171	2.3-7.4	0.058/2Hs; 0.107/2Hn; 0.187/2V; 0.298/2P
2010 VQ98	0.0048	4.3-13.6	0.181/2V; 0.393/2Hn; 0.487/2Hs;
2007 UN12	0.0011	3.4-10.6	0.199/2P; 0.271/2Hs; 0.327/2Hn; 0.434/2V
2010 UE51	0.0084	4.1-12.9	0.249/2Hs; 0.340/2P; 0.470/2V; 0.474/2Hn
2008 EA9	0.0014	5.6-16.9	0.328/2P;
2011 UD21	0.0043	3.8-12.0	0.356/1Hs; 0.421/1V; 0.436/1Hn
2009 BD	0.0053	4.2-13.4	0.392/2Hn; 0.487/2V
2008 UA202	0.0003	2.4-7.7	0.393/2Hn; 0.425/2P; 0.467/2Hs
2011 BL45	0.0040	6.9-22.0	0.400/2V
2011 MD	0.0018	4.6-14.4	0.422/2V
2000 SG344	0.0008	20.7-65.5	0.443/1P; 0.449/1Hs; 0.468/1Hn
1991 VG	0.0037	3.9-12.5	0.465/2Hs; 0.466/2V;

Note: the type of transfer is indicated by a 1 or 2 indicating L1 or L2 plus the letter for Planar Lyapunov, V for vertical Lyapunov, and Hn or Hs for north and south halo.

Table 2. Orbital Elements of EROs.

Asteroid name	Major semi-axis, a (AU)	Eccentricity, e	Inclination, i (deg.)	Longitude of ascending node, Ω (deg.)	Ascending node-perihelion angle, ω (deg.)	Mean anomaly, M (deg.)	Orbital elements at Epoch
2006 RH120*	1.033244	0.024486	0.024486	51.14552	10.18774	315.0344	2456300.5
2010 VQ98	1.023149	0.027066	1.475927	46.16582	341.6317	337.6236	2456600.5
2007 UN12	1.053742	0.060481	0.235263	216.1032	134.3419	242.7026	2456600.5
2010 UE51	1.055239	0.059680	0.624412	32.28553	47.22822	243.0871	2456600.5
2008 EA9	1.059135	0.079834	0.424560	129.4679	335.8608	123.9744	2456600.5

2011 UD21	0.978817	0.030367	1.062538	22.35797	209.6922	190.6708	2456600.5
2009 BD*	1.061719	0.051550	1.267116	253.3269	316.7272	205.2121	2456300.5
2008 UA202	1.033317	0.068708	0.264245	21.05432	300.8913	345.4208	2456600.5
2011 BL45	1.037850	0.020999	3.049076	134.7844	155.1223	62.16631	2456600.5
2011 MD	1.056318	0.037099	2.445655	271.6291	5.941064	59.42011	2456600.5
2000 SG344	0.977526	0.066918	0.111267	192.0956	275.1380	108.0862	2456600.5
1991 VG	1.027016	0.049178	1.445459	73.97961	24.55356	358.9310	2456600.5

Note. * The orbital elements of 2006RH120 and 2009BD come from <http://smallbodies.ru/>. Others take from JPL solar system dynamics <http://ssd.jpl.nasa.gov/sbdb.cgi>.

MISSION MODELING AND TRAJECTORY OPTIMIZATION

Mission Assumptions

It assumes that a spacecraft departs from low-altitude circular parking orbit above the Earth for an interplanetary trip to an asteroid. The primary mission design consideration for a rendezvous is usually the velocity increments budget. This is some function of the velocity increments needed at the point of departure to insert the spacecraft into the transfer trajectory, and the change required to cancel the relative velocity between spacecraft and target at arrival. Since orbital properties of EROs are similar to that of Earth, the relative phase angle between target asteroid and Earth becomes the important factor to influence on the total velocity increments or launch energy. The midcourse impulse or planetary gravity-assist will be used to reduce it.

During the outbound transfer, in fact, the departure velocity increment accounts for a large proportion of fuel consumption. It assumes that the spacecraft escapes from 200km-altitude circular parking orbit above the Earth. The relation between departure velocity increment Δv_L and hyperbolic excess velocity v_∞ is shown in Figure 1.

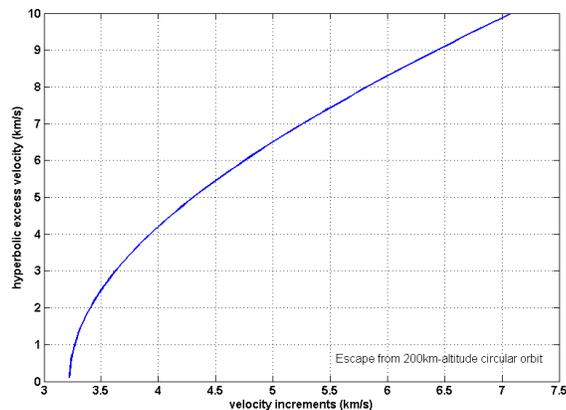


Figure 1. Relation between departure velocity increment and hyperbolic excess velocity (200km-altitude circular parking orbit).

As shown in Figure1, when the hyperbolic excess velocity v_∞ is about 1km/s, the departure velocity increment Δv_L is about 3.2697km/s. the v_∞ grows from 1km/s to 2km/s, the velocity increments will add 0.1349km/s. If the v_∞ increases to 3km/s, namely launch energy C_3 is equal to $9\text{km}^2/\text{s}^2$, the departure velocity increment Δv_L will be 3.6258km/s. Of course, if the v_∞ reaches 4 km/s, the Δv_L is also close to 4km/s, about 3.9286km/s. It is worth noting that the minimum hyperbolic excess velocity v_∞ transferred from Earth to Venus is more than 2 km/s, but less than 3km/s. For the Mars, the minimum hyperbolic excess velocity v_∞ will be more than 3km/s, but less than 4km/s. it is important observation for designing the interplanetary mission. If the hyperbolic excess velocity transferred directly from Earth to asteroid is less than 3 km/s, the Venus or the Mars will not be considered as the gravity-assist body.

If the parking orbit is elliptic orbit, the departure velocity increment will closely relate with semi-major axis of parking orbit. It assumes that the perigee of parking orbit is 200km altitude above Earth. The relation between departure velocity increment, hyperbolic excess velocity and apogee of parking orbit is shown in Figure 2.

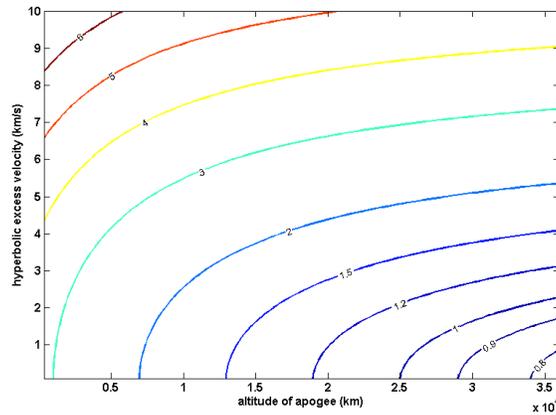


Figure 2. Relation between departure velocity increment, hyperbolic excess velocity and apogee of parking orbit

As can be seen in Figure 2, the departure velocity increment will reduce as the altitude of apogee increases. Compared with the 200km-altitude circular parking orbit, the required velocity increments, departed from GTO that altitude of perigee and apogee are 200km and 35000km, respectively, have 2.5km/s decrease in the case that hyperbolic excess velocity is about 1km/s. If the hyperbolic excess velocity reaches 3 km/s, the departure velocity increment of GTO grows from 0.8 km/s to 1.2km/s.

It assumes that the chemical rocket engine is used and initial mass of spacecraft is about 5000kg. According to Tsiolkovsky's rocket equation, the fuel consumption can be evaluated. For the different specific impulse, the relation between velocity increment and remaining mass of spacecraft is shown in Figure 3.

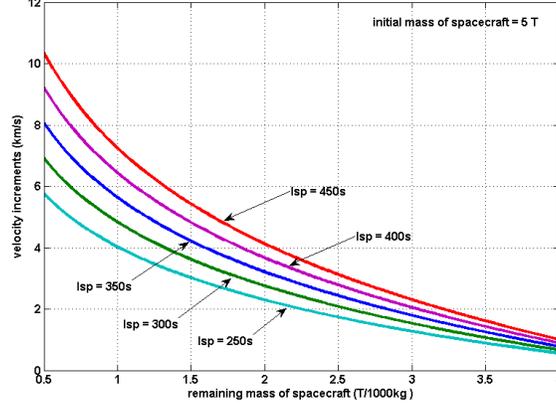


Figure 3. Relation between velocity increment and remaining mass

As shown in Figure 3, if the rocket engine with 250s specific impulse is used, 4000kg of fuel consumption only produce about 4.0km/s of velocity increments. It assumes that the 450s-specific-impulse engine is selected. 4.0km/s of velocity increments need about 3000kg of fuel. 6km/s of velocity increments require about 3700kg of fuel. The specific impulse of bi-propellant liquid rocket can attain the 450s. For example, the space shuttle main engine (SSME) produces a specific impulse of 453 seconds in a vacuum. Of course, if the Ion thruster is selected, the situation will change. it will not be discussed here.

Trajectory Optimization

To the rendezvous with EROs, the procedure searches for the trajectory that satisfies with rendezvous, which minimizing the characteristic velocity, which is the performance index:

$$J = \Delta v_{total} = \Delta v_L + \sum_i \Delta v_{mi} + \Delta v_a$$

The characteristic velocity Δv_{total} is the arithmetic sum of the velocity changes that are performed by expending the propellant. Δv_L is the velocity increments required to leave the Earth's parking orbit and travel along a heliocentric transfer trajectory to reach the target asteroid. It obtains

$$\Delta v_L = \sqrt{(v_L - v_E)^2 + v_e^2} - v_{Ep}$$

Where $v_E(t)$ and $v_L(t)$ are the velocity vector of Earth and spacecraft around the sun, respectively. The v_e and v_{Ep} are the magnitudes of the Earth-relative escape and actual velocities, respectively, at the perigee. Δv_{mi} is the midcourse impulse. The contribution of midcourse burns to characteristic velocity is related only to the change of the sun-relative velocity.

$$\Delta v_{mi} = \sqrt{(v_{mi+} - v_{mi-})^2}$$

Δv_a is the velocity increments required to rendezvous with target asteroid. Neglecting the gravity effect, we can estimate the rendezvous impulse as follows:

$$\Delta v_a = \sqrt{(v_a - v_r)^2}$$

Where $v_r(t)$ and $v_a(t)$ is the velocity vector of target asteroid and spacecraft around the sun.

In this paper, a hybrid optimization approach is used to search the optimal transfer opportunities. In the hybrid optimization approach, the differential evolution (DE) algorithm² serves as a starter engine that identifies regions of global minima within the trajectory solution space. Then the best candidate of the DE algorithm parameter population is submitted as an initial parameter set to the sequential quadratic programming³ (SQP) module for refinement. Some detail about DE and SQP algorithm will not be reviewed.

TWO-IMPULSE DIRECT TRANSFER

According to the above model and approach, the optimal two-impulse rendezvous opportunities for currently known EROs in the 2015-2035 years are shown in Figure 4a and 4b.

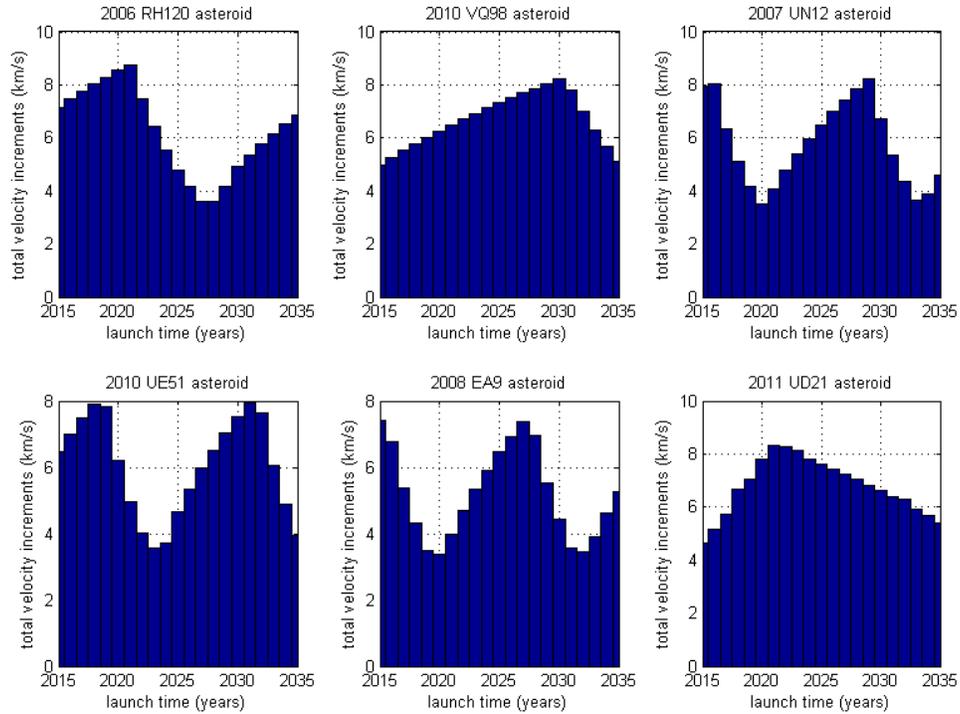


Figure 4a. The optimal two-impulse rendezvous opportunities for EROs in the 2015-2035 years

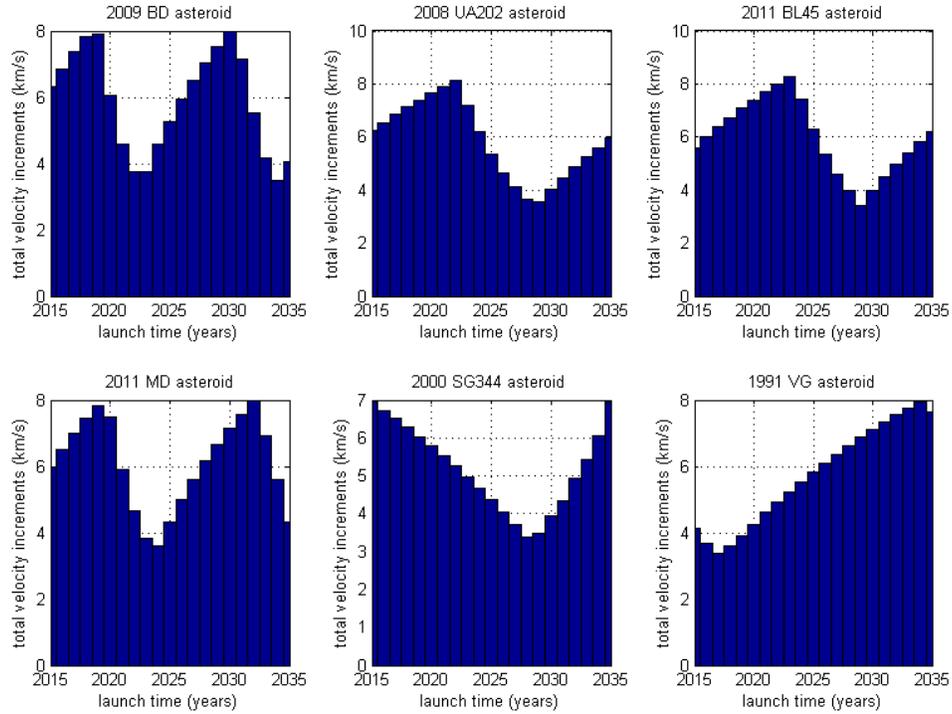


Figure 4b. The optimal two-impulse rendezvous opportunities for EROs in the 2015-2035 years

As shown in Figure 4a and 4b, the maximum total velocity increment of the optimal two-impulse rendezvous opportunities for all of currently known EROs in the 2015-2035 years is about 8.76km/s. the corresponding object is 2006 RH120 asteroid and launch time is about 2021 years. The maximum total velocity increment of the optimal two-impulse opportunities for 2010UE51, 2008EA9, 2009BD, 2011MD, 2000SG344, 1991VG, is less than 8.0 km/s. At the same time, the minimum total velocity increment of the optimal two-impulse opportunities for all of EROs in the 2015-2035 years is about 3.37km/s. the corresponding asteroid is 2000SG344 and the launch time is 2028 years. The minimum total velocity increment of all of EROs is less than 4.0km/s except 2010VQ98 and 2011UD21 asteroid.

From the Figure 4a and 4b, we also can see that the rendezvous opportunities show quasi-periodicities. In the 2015-2035 years, the quasi-periodicities are found for the following three cases: one rendezvous period (such as 2006 RH120, 2008 UA202 and 2011 BL45), more than one period (2007 UN12, 2010 UE51, 2008 EA9, 2009 BD and 2011 MD), and less than one period (2010 VQ98, 2011 UD21, 2000 SG344 and 1991 VG). The main reason for the emergence of quasi-periodic phenomenon is the periodic changes of relative phase angle of Earth and asteroid. These periodic changes also reflect in the flight path.

For above three cases, we choose 2006 RH120, 2007 UN12 and 2010 VQ98 as examples to analyze transfer trajectories and trajectory parameters. In the one-period case, according to the velocity increment and flight time, the transfer trajectories can be divided into three families. These transfer families are shown in Figure 5.

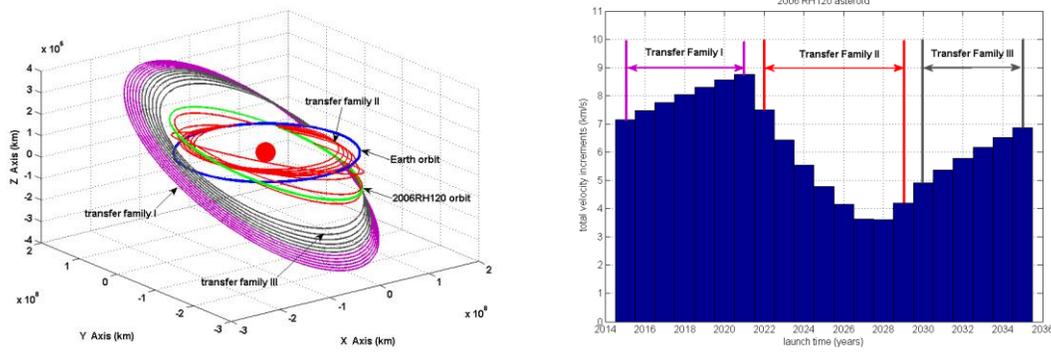


Figure 5. The transfer families and corresponding parameters for 2006 RH120 asteroid

As can be seen from Figure 5, transfer family I requires more velocity increments and more flight times than others. It also implies that the relative phase angles between Earth and 2006 RH120 asteroid in this time area are not suitable for mission design. The transfer family II, compared with transfer family I, needs less flight times and lower velocity increments. From the Figure 5, we also can see that the transfer trajectories of low-cost opportunities get close to 2006 RH120 asteroid's orbit, such as flight paths in 2027 and 2028 years. For the family III, the required velocity increment and flight time grow over time.

For the more-than-one-period case, we take 2007 UN12 asteroid as an example. On basis of the velocity increment and flight time, the two transfer families are found. The corresponding flight paths and trajectory parameters are shown in Figure 6.

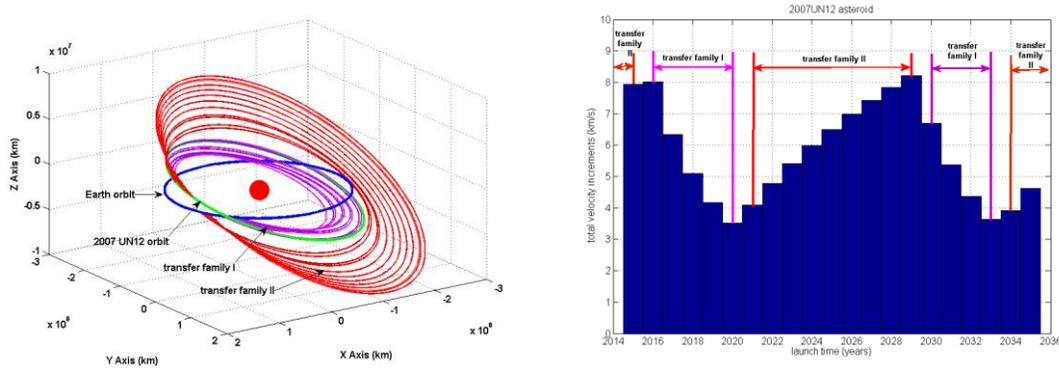


Figure 6. The transfer families and corresponding parameters for 2007 UN12 asteroid

As shown in Figure 6, the flight paths of transfer family I are located inside 2007 UN12 asteroid's orbit, and that of transfer family II are of outside. In the transfer family I, with time passing, the required velocity increment will decrease and the flight path will close to the 2007 UN12 asteroid's orbit. However, in the transfer family II, it is quite the reverse.

For the less-than-one-period case, the transfer trajectories are obviously divided into two transfer families. For example, 2010 VQ98 asteroid, the flight paths and trajectory parameters are shown in Figure 7.

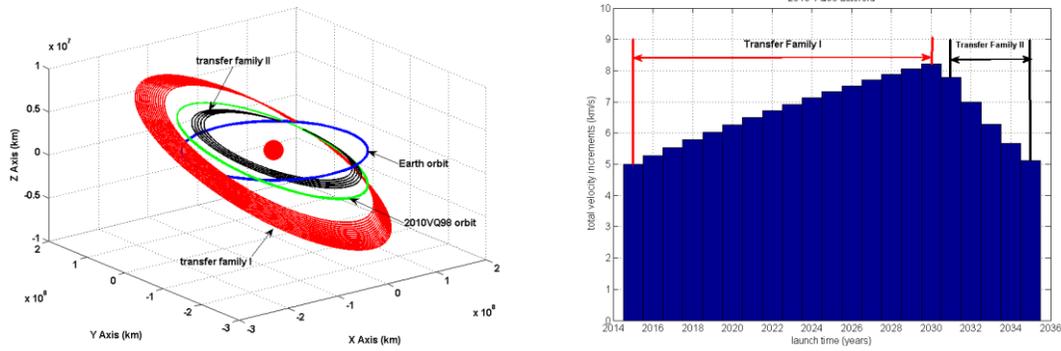


Figure 7. The transfer families and corresponding parameters for 2010 VQ98 asteroid

As can be seen in Figure 7, there is similar motion phenomenon. For the transfer family I case, when time goes by and flight times and velocity increments of transfer trajectories will grow up. The flight paths will also extend outward and be away from the 2010 VQ98 asteroid's orbit. The transfer family II case will be quite the reverse.

MULTI-IMPULSE TRANSFER

Multi-impulse transfer is one of important transfer types for interplanetary mission. In this section, the three-impulse transfer and four-impulse transfer will be considered. These added mid-course impulses are mainly used to adjust the phase angle and reduce the velocity increment. Comparisons of optimal two-impulse and multi-impulse transfer for EROs in the 2015-2035 years are shown in Figure 8a, 8b and 8c.

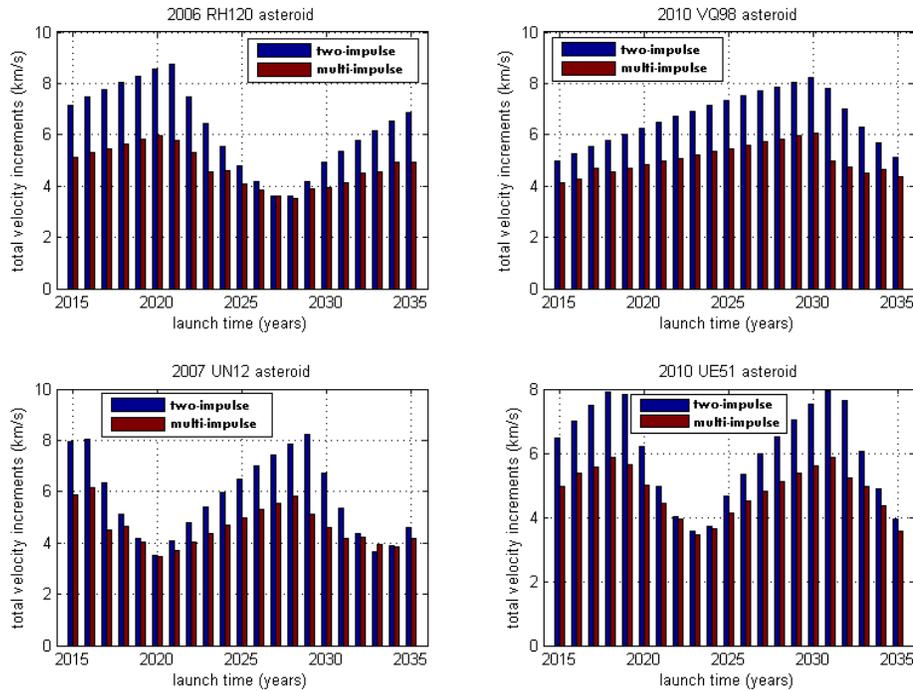


Figure 8a. Comparison of two- and multi-impulse transfer for EROs in the 2015-2035 years

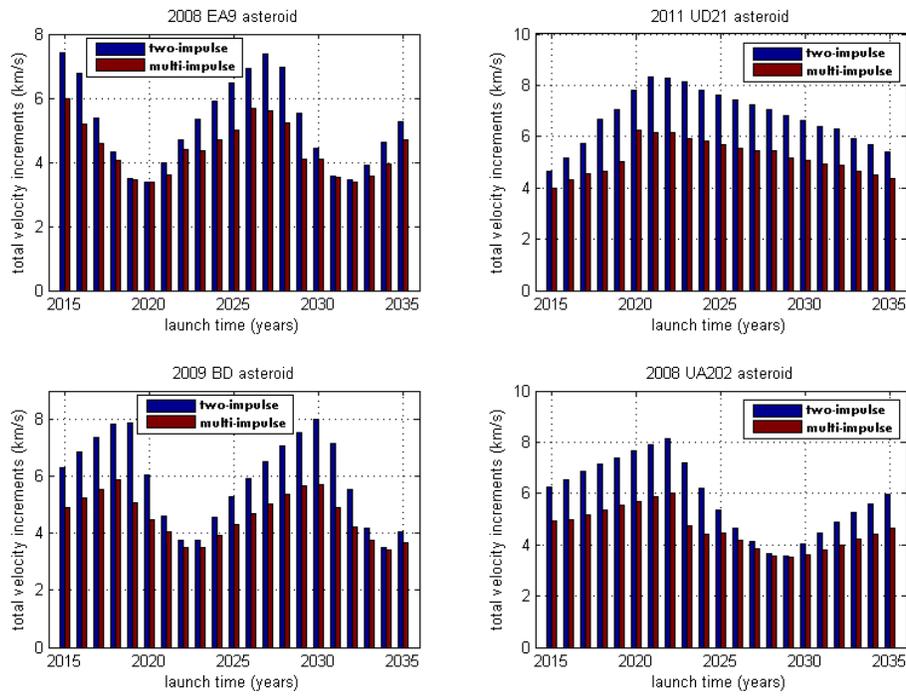


Figure 8b. Comparison of two- and multi-impulse transfer for EROs in the 2015-2035 years

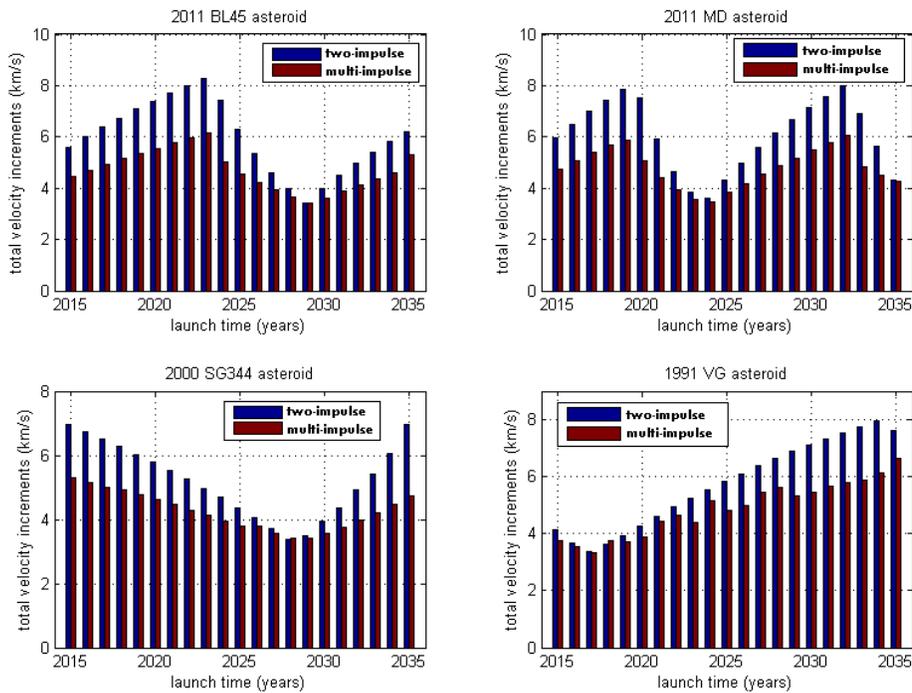


Figure 8c. Comparison of two- and multi-impulse transfer for EROs in the 2015-2035 years

As shown in Figure 8a, 8b and 8c, compared with optimal two-impulse transfer, the total velocity increments of optimal multi-impulse transfer, especially of the maximum total velocity increment, are obviously reduced. The maximum total velocity increment of all of optimal multi-impulse transfer for EROs in the 2015-2035 years is about 6.64km/s. the corresponding object is 1991 VG asteroid and launch time is about 2035 years. All of the maximum total velocity increments of optimal multi-impulse transfer opportunities for EROs are less than 6.20 km/s, except 1991 VG asteroid. This is a significant observation because the 6.0km/s of velocity increments can reach by using the normal bi-propellant liquid rocket on basis of above evaluation. At the same time, we also can find that although there are a little changes in velocity increment over time, rendezvous quasi-periodicities still keep up.

GRAVITY-ASSIST TRANSFER

The gravity-assist technique is an effective approach to reduce launch energy and total velocity increment in interplanetary mission. In this paper, considering the orbital characteristic of EROs is similar to the Earth's orbit, we select the Earth as the gravity-assist body. So the transfer strategy of the Earth gravity assist with deep-space maneuver (ΔV -EGA) will be used. The gravity-assist strategy can be simply described as follows: a spacecraft is launched from Earth into a heliocentric orbit with a period slightly greater or smaller than an integer number of years. At aphelion or perihelion, a deep-space maneuver is applied to lower the perihelion or higher the aphelion to intercept nontangentially the Earth with hyperbolic excess velocity higher than that of launch. The deep-space maneuver enables the Earth to be used as a gravity-assist body to increase or decrease the heliocentric energy of the spacecraft. The type of ΔV -EGA transfer orbit is various and can be found in the literature⁴ and will not be reviewed here.

According to above calculations and analysis, the 2006 RH120, 2010 VQ98, 2011 UD21 and 1991 VG are selected as the target to use the ΔV -EGA transfer to reduce the velocity increment further. We don't use the gravity-assist strategy for all of EROs, because some rendezvous opportunities with the optimal two-impulse or multi-impulse have shown lower velocity increments. The gravity-assist strategy can reduce the velocity increment, but increase the flight time. The compromise between fuel consumption and flight time is considered. Comparisons with optimal two-impulse, multi-impulse transfer and gravity assist of 2006 RH120, 2010 VQ98, 2011 UD21 and 1991 VG asteroid in different years are shown in Figure 9 .

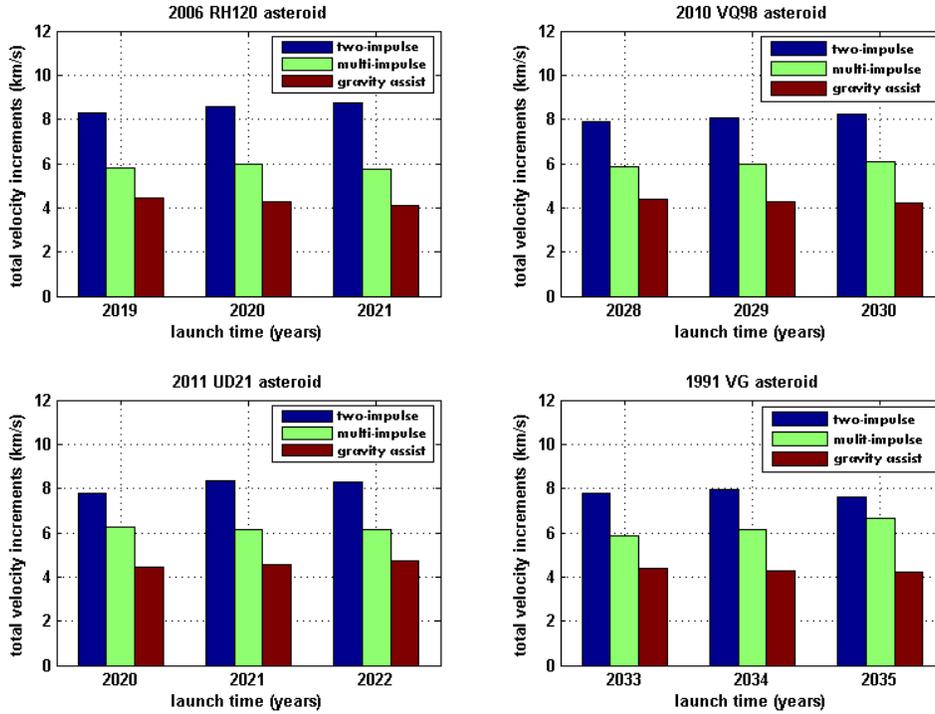


Figure 9 Comparison of two-, multi-impulse transfer and gravity-assist transfer for some EROs

As shown in Figure 9, the total velocity increment of the ΔV -EGA transfer, compared with the maximum total velocity increments of optimal two-impulse transfer of 2006 RH120 asteroid in 2021 years, can be reduced by 4.63 km/s. Compared with the maximum total velocity increments of optimal multi-impulse transfer of 1991 VG asteroid in 2035 years, the ΔV -EGA transfer has a 2.41 km/s decrease. At the same time, we also can see that all of the total velocity increments of selected targets in the corresponding time are less than 4.70 km/s. These targets appear reasonably accessible.

CONCLUSION

In this paper, we focus on the rendezvous opportunities to EROs in 2015-2035 years. The low-cost transfer trajectories are found by using optimal two-impulse, multi-impulse and ΔV -EGA transfer methods. According to the above analysis, the total velocity increments of all of the currently known EROs can be reduced to 5.50 km/s or less. The best opportunities, such as 2000 SG344, are less than 3.40 km/s.

For some targets, it shows longer low-cost rendezvous periods. For example, the better rendezvous periods of 2006 RH120 and 2008 UA202 asteroids remain for 6 years, from 2025 years to 2030 years and from 2027 to 2032 years, respectively. At the period, the total velocity increment is less than 4.0 km/s. For 2000 SG344 asteroid, the better rendezvous period keeps for 9 years, namely starting from 2024 years and ending to 2032 years.

Some targets also show stable requirements of velocity increments. For example, the total velocity increments of 2010 VQ98 and 2011 UD21 asteroids are about more than 4.0 km/s and less than 6.0 km/s. For 2007 UN12, 2010 UE51, 2008 EA9, 2009 BD, 2011 BL45, 2011 MD and 1991 VG asteroids, the total velocity increments have larger changes. The higher velocity incre-

ments are close to 6.0 km/s and the lower can reach to 3.50km/s. If the gravity-assist transfer applies for every target, the maximum total velocity increments will be expected to reduce to about 5.0km/s.

ACKNOWLEDGMENTS

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