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Evaluating Accessibility of near-Earth Asteroids via Earth Gravity Assists

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I. Introduction

ASTEROIDS exploration missions attract many scientists, because asteroids hold the key clues to understanding the origin of the solar system and the formation of the planets. Selecting the target for a space mission requires trying to maximize the superposition between "scientifically significant" and "technically feasible" targets. As far as the technical feasibility of the targets is concerned, the primary consideration is its accessibility. The measure of accessibility is generally the minimum total velocity increments for two-impulse transfer to rendezvous with the target body. In previous literature, two measures of accessibility were introduced: one was the global minimum total ΔV for a two-impulse rendezvous mission profile,[1–3] and another was to calculate minimum total ΔV by the classical Hohmann transfer strategy based on Keplerian motion.[4] By using these classical two-impulse transfer strategies, some asteroids in orbits similar to that of the Earth are usually the easiest to reach. However, some high-priority targets for science, particularly the large-eccentricity ones, appear to be out of reach at the present technological level when considering basic rendezvous missions because too much launch energy and total ΔV is required. It is highly possible that these targets would be discarded in selection of target for space exploration mission.

So, the aim of this Note is to provide an approach to basic trajectory design, which allows extension of the classical two-impulse transfer strategy by using the planetary swingby techniques in order to reduce the launch energy and the total ΔV for a rendezvous mission and present a significant reference for mission designer when selecting the scientifically significant and technically feasible target for a space mission.

II. Extending the Two-impulse Transfer Trajectory

Using these classic two-impulse transfer strategies, targets moving on large-eccentricity orbits require too much launch energy and total ΔV for a rendezvous mission. This leads us to adopt the planetary swingby technique to extend the classical two-impulse transfer strategy. To reduce the dynamical requirements and avoid time dependency, the Earth swingby strategy [the Earth gravity assist with deep-space maneuver (ΔV-EGA) transfer] will be used. This swingby strategy can be described as follows: a spacecraft is launched from Earth into a heliocentric orbit with a period slightly greater than an integer number of years and a perihelion radius equal to the heliocentric orbit radius of Earth [1 astronomical unit (AU)]. At aphelion, a deep-space maneuver ΔV is applied to lower the perihelion to intercept nontangentially the Earth with a V_∞ higher than that of launch. The deep-space maneuver enables the Earth to be used as a gravity-assist body to increase the heliocentric energy of the spacecraft.

The generation of the transfer trajectory proceeds as follows: first, the two-impulse transfer trajectory of the global minimum total ΔV for a rendezvous mission is found. The mean anomaly of Earth at launch for this two-impulse transfer trajectory can be obtained. Then it is regarded as the mean anomaly of Earth at swingby for ΔV-EGA transfer orbit. Second, according to the characteristic of target orbit, we select an appropriate type of ΔV-EGA transfer orbit. Third, we search a mean anomaly of Earth at launch for the ΔV-EGA transfer orbit and propagate the orbit to the aphelion. The deep-space maneuver can be performed at aphelion, and the maneuver enables the Earth to be used as a gravity-assist body. After swingby, the spacecraft flies to the target asteroid.

The detailed design proceeds as follows.

A. Classical Optimum Two-impulse Transfer Trajectory

In previous literature, the accessibility consideration for the near-Earth asteroids is usually the ΔV budget for two-impulse transfer mission. This is the function of the velocity increment need 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. The details of ΔV budget and the method of calculating the optimal total ΔV on the space of the launch and arrival true anomalies for two-impulse transfer trajectory is introduced in Ref. 1. Here, it will not be reviewed.

It is assumed that the parking orbit at launch body and target body is a circular orbit and the height of parking orbit is 200 and 10 km, respectively. In the case 4015 Wilson-Harrington ($a = 2.644$ AU, $e = 0.622$), which is regarded as high-priority target for science because of possible cometary origin, the entire space of optimum rendezvous trajectories from the Earth to the target is displayed in Fig. 1.

According to the Fig. 1, a region that contains the smallest total ΔV of two-impulse transfer trajectory is identified. The exact value of the global minimum total ΔV is found by using the sequential-quadratic-programming algorithm.

The trajectory parameters are listed in Table 1. The mean anomaly of Earth at launch for the globally optimal two-impulse transfer trajectory is regarded as that of Earth at swingby for ΔV-EGA transfer orbit. So, according to Table 1, we know that the mean anomaly of Earth at swingby M_s is 257.175 deg. The outgoing hyperbolic excess velocity $V_{\infty 2}$ at swingby can be obtained by using the patched conic method.

In the next stage, we should consider which type of the ΔV-EGA transfer would be selected and how to search a proper mean anomaly of Earth at launch for ΔV-EGA transfer orbit.

B. Selecting the Type of ΔV-EGA Transfer Orbit

The type of ΔV-EGA transfer orbit is various and can be found in the literature[5] and will not be reviewed here. To select the type

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Table 1 Comparison of optimum two-impulse and 2:1 $(\pm)\Delta V$-EGA profiles

Transfer profiles	Mean anomaly of Earth at launch M_L, deg	Mean anomaly of asteroid at arrival M_a, deg	Total ΔV, km/s	Launch energy C_3, km^2/s^2	Postlaunch ΔV, km/s	Flight time T, days
Optimum two-impulse	257.175	311.274	6.799	67.119	0.857	1328.9
2:1(+)ΔV-EGA	210.871	311.274	6.409	26.497	2.057	2106.4
2:1(−)ΔV-EGA	301.289	311.274	5.632	25.630	1.315	2014.7

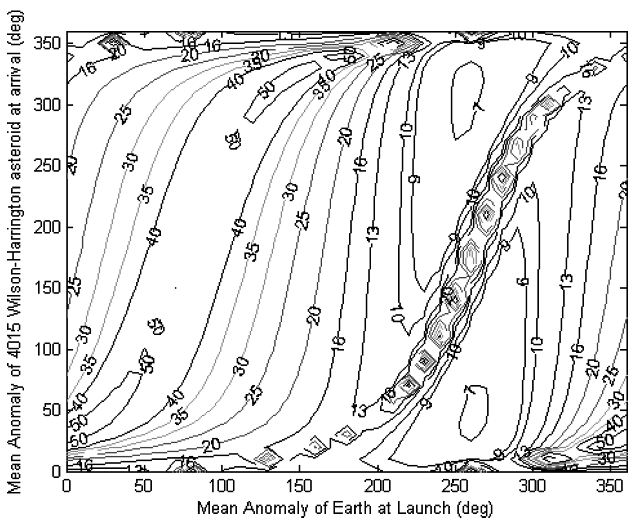

Fig. 1 Contours of minimum total ΔV for two-impulse transfer trajectory to rendezvous with 4015 Wilson-Harrington.

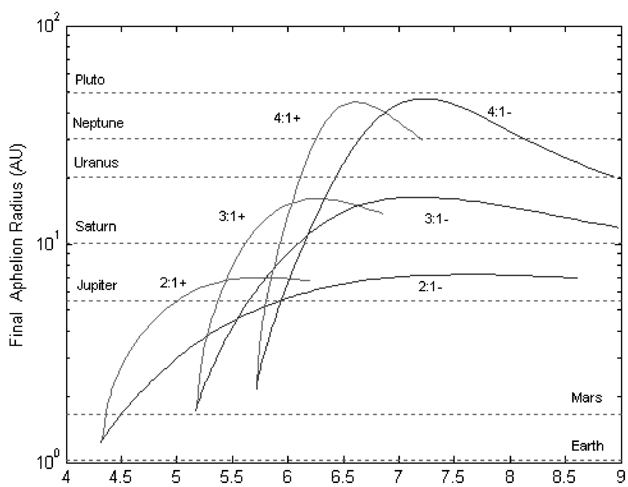

Fig. 2 Performances of ΔV-EGA transfer.

of the swingby orbit, the performance of this transfer strategy is discussed. It is assumed that the minimum flyby altitude is 200 km. The aphelion radius of the spacecraft orbit after the Earth flyby as a function of total ΔV for Earth swingby [the total ΔV consists of the launch from an Earth parking orbit (circular, 200 km altitude) ΔV_L and the deep-space maneuver ΔV_m at aphelion] is shown in Fig. 2.

As can be seen in Fig. 2, the 2:1$(\pm)\Delta V$-EGA has lower total ΔV than other types for the final aphelion radii between approximately 1.6 and 5.5 AU. This is a significant observation because the orbits of many near-Earth asteroids, including the 4015 Wilson-Harrington asteroid, are located in this range.

So we select the 2:1$(\pm)\Delta V$-EGA profiles to generate transfer trajectories. The 2:1$(\pm)\Delta V$-EGA profiles contain a deep-space maneuver and an Earth gravity assist. The flight time between launch from Earth and the Earth gravity assist approximates two years.

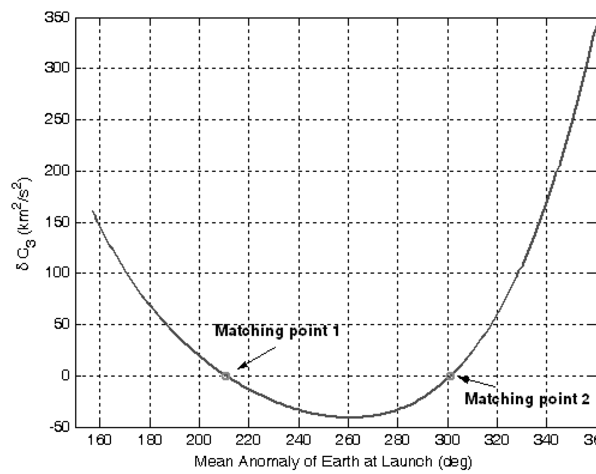

Fig. 3 Relationship of the guessed M_{L0} and matching errors.

C. Searching the Mean Anomaly of Earth at Launch for the ΔV-EGA Transfer Orbit

If we guess a value for the mean anomaly of Earth at launch M_{L0}, the spacecraft is launched from the Earth at the mean anomaly into a heliocentric orbit with a two-years period and a perihelion radius equal to 1 AU. At aphelion, a retrograde ΔV is applied to lower the perihelion to intercept the Earth nontangentially. The flight time from the point of deep-space maneuver to the crossing point is given by

$$t_e = \begin{cases} \dfrac{(M_S - M_{L0})\pi}{180}\left(\dfrac{\text{year}}{2\pi}\right) & \pi < M_S - M_{L0} < 2\pi \\ \left[\dfrac{(M_S - M_{L0})\pi}{180} + 2\pi\right]\left(\dfrac{\text{year}}{2\pi}\right) & 0 < M_S - M_{L0} < \pi \end{cases} \tag{1}$$

We solve the Lambert problem from the position of deep-space maneuver to the swingby target body. (In the case of a heliocentric trajectory, a conic solution is found with the sun as the attracting center.) The solution to the Lambert problem supplies a particular incoming $V_{\infty 1}$. The outgoing $V_{\infty 2}$ had been given in Sec. II.A. It patches gravity-assist trajectories together by the method of C_3 matching,[6] where C_3 defines the hyperbolic excess velocity squared V_∞^2. The C_3 matching problem involves matching the magnitude of an incoming $V_{\infty 1}$ with the magnitude of the outgoing $V_{\infty 2}$ to effect encounter with target body in the trajectory path. Here, it is assumed that the matching error is δC_3, and then

$$\delta C_3 = V_{\infty 1}^2 - V_{\infty 2}^2 \tag{2}$$

The relationship of the guessed mean anomaly of Earth at launch M_{L0} and matching errors δC_3 is shown in Fig. 3.

Figure 3 shows that there are two times matching for the Earth swingby because the errors curve goes through zero twice. When the magnitude of one of the incoming $V_{\infty 1}$ vectors is relatively close to the magnitude of the outgoing $V_{\infty 2}$ vectors, a C_3 matching is found using a root solver.

The total ΔV for the 2:1$(\pm)\Delta V$-EGA transfer profiles consists of the velocity increments at launch ΔV_L, the deep-space maneuver at aphelion ΔV_m, and the velocity increments at rendezvous ΔV_a. Some parameters of the optimal two-impulse profile and

Table 2 Comparison of total ΔV required for rendezvous with asteroids

			This work					
			Earth gravity assist		Global optimal two-impulse		Perozzi et al. (2001)	Lau et al. (1987)
Number/designation	Q, AU	e	ΔV_{total}, km/s	C_3, km^2/s^2	ΔV_{total}, km/s	C_3, km^2/s^2	ΔV_{total}, km/s	ΔV_{total}, km/s
(7341) 1991 VK	2.776	0.506	4.968	25.34	5.776	56.80	7.6	——
(4179) Toutatis	4.122	0.635	5.092	25.15	6.159	63.45	8.3	——
(3288) Seleucus	2.962	0.457	5.180	26.48	5.887	51.24	8.0	5.912
(3908) Nyx	2.812	0.459	5.193	25.41	5.595	38.62	6.9	——
(8034) 1992 LR	2.579	0.409	5.339	26.49	5.578	34.73	6.6	——
(1627) Ivar	2.603	0.397	5.389	26.36	6.108	50.59	8.2	6.117
(3551) Verenia	3.113	0.488	5.398	25.65	6.476	63.92	8.9	6.483
(6489) Golevka	4.009	0.605	5.446	26.48	6.499	63.94	8.3	——
(433) Eros	1.783	0.223	5.547	25.40	5.935	38.38	7.6	5.947
(3352) McAuliffe	2.572	0.369	5.552	25.26	5.891	36.48	7.4	5.900
(4015) Wilson-Harrington	4.285	0.623	5.632	25.63	6.799	67.12	8.6	——
(887) Alinda	3.885	0.563	5.635	25.38	6.812	69.24	9.4	6.852
(13651) 1997 BR	1.744	0.306	5.668	26.20	8.155	128.7	9.5	——
(31345) 1998 PG	2.805	0.392	5.948	25.37	6.437	42.75	8.2	——
(3102) Krok	3.116	0.449	6.039	26.02	6.845	53.54	8.8	6.855
(1685) Toro	1.963	0.436	6.051	25.47	7.675	71.52	7.6	7.675
(1620) Geographos	1.663	0.335	6.148	25.67	8.795	88.50	8.2	8.537
(2100) Ra-Shalom	1.195	0.437	6.353	25.62	7.939	85.52	9.7	7.949
(6178) 1986 DA	4.457	0.587	6.355	26.42	7.622	74.16	9.1	——
(2063) Bacchus	1.455	0.349	6.386	25.30	7.094	49.36	6.8	7.105
(7753) 1988XB	2.174	0.482	6.421	25.65	6.750	36.61	6.8	——
(B3671) Dionysus	3.389	0.542	6.631	26.48	7.795	68.75	9.8	——
(35396) 1997 XF11	2.141	0.484	6.701	26.05	7.174	41.07	7.0	——
(8201) 1994AH2	4.330	0.709	6.899	26.31	8.111	67.69	9.9	——
(2201) Oljato	3.721	0.713	6.911	26.40	8.040	68.34	9.4	8.037

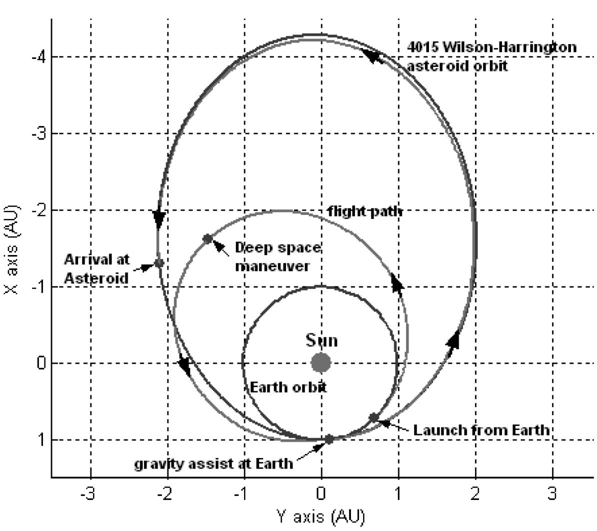

Fig. 4 The 2:1(–) ΔV-EGA profile for rendezvous with 4015 Wilson-Harrington asteroid.

the 2:1($\pm$)ΔV-EGA profiles for rendezvous with 4015 Wilson-Harrington asteroid are listed in Table 1. The flight path of the 2:1($-$)ΔV-EGA profile is shown in Fig. 4.

As can be seen in Table 1, the total ΔV and launch energy C_3 of the 2:1($-$)ΔV-EGA transfer profile, compared with the optimal two-impulse profile, can reduce by 1.168 km/s and 41.489 km^2/s^2, respectively.

III. Evaluating Accessibility of near-Earth Asteroids

It is well known that the gravity assist is an available approach for reducing launch energy and total velocity increments in interplanetary exploration missions. In this Note, we extend the two-impulse transfer trajectory with the Earth gravity-assist technique. First, we determine the two-impulse transfer trajectory from the Earth to asteroid. Then, through adjusting the mean anomaly of Earth at launch and matching the C_3, we add the ΔV-EGA to the beginning of the two-impulse transfer trajectory to reduce the required launch energy and the total ΔV for exploration missions. From the process of designing transfer trajectory, we can also see that the flight path of ΔV-EGA transfer profile is described by using the mean anomaly at launch M_L, the mean anomaly at swingby M_s, and the mean anomaly at rendezvous M_a, and is the "time-open" or "ephemeris-free" solution. It is suitable for evaluating the accessibility of near-Earth asteroids. The total velocity increments of ΔV-EGA transfer trajectory technique include the velocity increments at launch, a minor deep-space maneuver at aphelion, and the velocity change at rendezvous. The ΔV-EGA transfer trajectory technique can reduce the launch energy requirements and the total velocity increments at the cost of a deep-space maneuver and flight time. This approach is suitable for target with large eccentricity or a large semimajor axis. In Table 2 we show the comparison between the results of this work and the studies by Perozzi et al.[4] and Lau and Hulkower.[3]

In Table 2, the Q and e stand for the aphelion distance and eccentricity of asteroid, respectively. These asteroids that are listed in Table 2 have higher priority for science.[4] As the Table 2 shows, the total ΔV and launch energy C_3 required for rendezvous with asteroids are reduced obviously by using ΔV-EGA transfer technique, especially for these candidates such as 4015 Wilson-Harrington ($e = 0.623$) that has a possible cometary origin (see the Table 1), 4179 Toutatis ($e = 0.635$) that was extensively imaged by radar and possibly in a peculiar rotation state (compared with the optimal two-impulse transfer, the total ΔV and launch energy of ΔV-EGA transfer decreased by 17.32 and 60.36%, respectively), 6489 Golevka ($e = 0.605$) that is regarded as a primary target because of its supposed origin as fragments of the basaltic surface of Vesta (the ΔV-EGA transfer profile has 1.0530 km/s and 37.46 km^2/s^2 decrease in total velocity increment and launch energy, respectively; see the Table 2), and so on. As also can be seen in Table 2, some targets (such as 4179 Toutatis, 1627 Ivar, 3551 Verenia, 6489 Golevka, 4015 Wilson-Harrington, 887 Alinda, 13651 1997 BR, and so on) appear reasonably accessible: these display a very low total ΔV and launch energy when using the ΔV-EGA transfer strategy.

IV. Conclusions

Because a rendezvous mission for asteroid calls for a nontrivial technical and financial support, most of the effort required during the preliminary studies is to try to maximize the superposition between scientifically significant and technically feasible targets. In this Note, an approach to basic trajectory design, which allows extension of the classical two-impulse transfer strategy by using the planetary swingby techniques, is presented. This approach can effectively reduce the launch energy and the total velocity increments, thereby including a larger number of potentially accessible targets. This work presents a significant reference for mission designer when selecting the scientifically significant and technically feasible target for a space mission.

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