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Robotic and human exploration/deflection mission design for asteroid 99942 Apophis

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ABSTRACT

Design and analysis of a 2028–2029 human-piloted exploration mission to asteroid 99942 Apophis is studied in this paper. A fictional scenario is also examined in which Apophis is assumed to have passed through a keyhole in 2029, resulting in an Earth impact in 2036, is also examined. Several mission architectures are developed and analyzed for such a fictional scenario. Although Apophis currently has a very low impact probability estimated of approximately four-in-a-million, it is one of the most likely to impact the Earth, warranting further examination. Both human-piloted and robotic exploration missions are designed for missions prior to and after the April 13, 2029 Earth-Apophis close encounter.

1. Introduction

Asteroids and comets have collided with the Earth in the past and will do so again in the future. Throughout Earth's history these collisions have had a significant role in shaping Earth's biological and geological histories. One major example of this is the extinction of the dinosaurs, which is widely believed to have been caused by the collision of an asteroid or comet. In recent years, near-Earth objects (NEOs) have also collided with the Earth, the most notable example in recent history is an impact in Siberia, known as the Tunguska event. This impact is estimated to have released an explosive energy of approximately 3–5 megatons. While, the impact occurred in a sparsely populated area, such an impact in a highly populated area would be extremely devastating.

Of all the NEO's found to date, the asteroid 99942 Apophis has been one of the hazardous NEOs, which has received much attention from the planetary defense community. However, an impact from Apophis does appear unlikely, with an estimated impact probability of approximately four-in-a-million in 2036. On April 13, 2029, Apophis will pass by the Earth inside geostationary orbit. If Apophis passes through a relatively small 600-m keyhole, impact will occur on April 13, 2036. Thus, a fictional scenario in which Apophis has passed through a keyhole in 2029, resulting in an Earth impact in 2036, is studied in this paper. The purpose of this paper is to perform the mission analysis and design for robotic and human exploration mission to Apophis, using software developed by the Asteroid Deflection Research Center (ADRC). Possible launch windows, trajectories, and accompanying ΔV's for both robotic rendezvous and human piloted return missions prior to the April 13, 2029 Earth-Apophis close encounter will be analyzed. In addition, mission analysis and design will be performed for robotic and human piloted missions for the fictional scenario in which Apophis passes through a keyhole on April 13, 2029, resulting in an impact on April 13, 2036. The orbital current estimated orbital elements of Apophis, the fictional orbital elements, and the estimated physical characteristics can be found in Table 1(a)–(c), respectively. For the fictional Apophis mission, launch windows will be determined throughout the 7-year period (keyhole

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Table 1
Orbital and physical parameters used for the hypothetical, Earth-impacting Apophis orbit [9].

Elements	Value
(a) Current orbital elements	
Epoch	6/18/2009
a, AU	0.9224
e	0.1912
i, deg	3.3314
Ω, deg	204.443
ω, deg	125.404
θ_0, deg	134.713
(b) Fictional orbital elements	
Epoch MJD	64,699
a, AU	1.108243
e	0.190763
i, deg	2.166
Ω, deg	70.23
ω, deg	203.523
M_0, deg	227.857
Physical parameters	**Value**
(c) Physical parameters	
Rot. Per. (hr)	30.5
Mass (kg)	2.1E+10
Diameter (m)	270
H	19.7
Albedo	0.33

passage through impact), which allow sufficient time for a fictional high-energy nuclear deflection mission.

A preliminary Interplanetary Ballistic Missile (IPBM) architecture, designed by the ADRC, will be used as the reference robotic space system throughout this paper. The most capable IPBM architecture, uses the Delta-IV Heavy launch vehicle, and is capable of a total ΔV of 4 km/s, carrying a 1500-kg nuclear payload. In addition, the reference departure orbit for the robotic mission analysis, used when determining the Earth-departure ΔV, is assumed to be a geostationary transfer orbit [5]. Using this baseline IPBM architecture and ΔV capabilities, launch windows for both the pre-2029 and post-2029 missions have been determined in [7].

2. Human-piloted mission

To determine the feasibility of a human-piloted mission to Apophis, the mission requirements must first be determined. In particular, the minimum total ΔV necessary to complete the mission and the accompanying launch windows must be found. A computer program has been developed at the ADRC, which combines Lambert solvers with ephemeris data, various other functions, and optimization methods to determine optimal launch opportunities.

The program(s) are used to find the required ΔV's for each maneuver, find optimal launch windows, and to plot of resulting trajectories and other necessary information. The program performs this search by determining the minimum ΔV for each launch date by performing and exhaustive search of all the possible Apophis arrival and departure date combinations, given only a desired mission length. An exhaustive search is used to ensure no minimums are missed. For the following analysis, a 185-km circular orbit is used for the departure parking orbit. To help minimize the total required ΔV, the atmospheric entry velocity is limited to a maximum of 12 km/s. Throughout this entire section an Apophis stay time of 10 days is assumed. Increasing or decreasing the stay time will result in a slight increase or decrease of the required ΔV. Results obtained for both the 180- and 365-day missions to Apophis near the 2029 close encounter, as well as the 2036 human-piloted deflection mission are presented and analyzed in this section.

2.1. 2028–2029 Launch opportunities

For a human-piloted return mission to an asteroid, two possible launch windows are always found near the Earth-asteroid close encounter. One launch always returns to the Earth near the Earth-Apophis encounter date, while the other launch date occurs on the date of the close encounter. Throughout the rest of this paper the mission prior to the Earth-Apophis close encounter will be referred to as the early launch date/window, while the launch occur refers to mission launch at or near the close encounter.

A plot of the total ΔV required for both the early and late launch dates versus mission length (ranging from 20 to 365 days) is shown in Fig. 1 [6]. As shown in Fig. 1, the total ΔV is, in general, reduced as the length of the mission increases. Fig. 1 shows that a local minimum for the required total ΔV occurs near the 180-day mission length. Current crewed NEO studies have limited the maximum mission length to 180 days for supply and maximum radiation dose limitations. Therefore, a complete mission analysis and launch window search for a 180-day mission length results in a required ΔV in the 10–11 km/s range. Lowering the total mission length may be possible depending on the mission architectures and ΔV capabilities.

2.1.1. 180-day mission analysis

With a total mission length selected, further analysis can be performed to find the dates and length of each

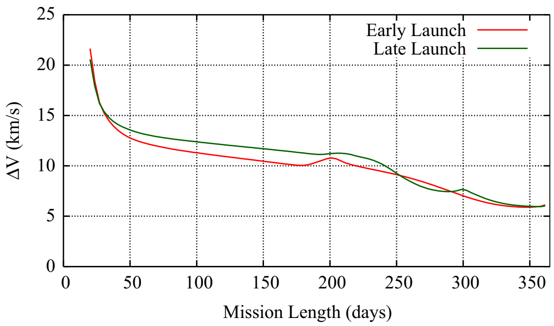

Fig. 1. Plot of minimum ΔV required for the early and late launch as a function of the mission length.

launch window. This can be obtained by calculating the minimum launch ΔV for launch dates near the Earth-Apophis encounter. Launch opportunities can be found from Fig. 2, which is a plot of launch dates versus the total required ΔV for the selected 180-day mission. The first optimal launch date occurs approximately 180 days prior to the April 13, 2029 Apophis encounter, while the late launch date occurs during the asteroid close flyby on April 13, 2029.

Further examination of Fig. 2 reveals that the launch windows near the asteroid flyby are the last opportunities to launch a quick return mission to Apophis. Any human missions to Apophis after the April 13, 2029 launch date would likely require significantly increased mission times, possibly even multiple revolutions around the sun prior to rendezvous, to reduce the required ΔV to an obtainable amount. A mission of this length would likely require significant modifications to the Orion spacecraft to allow for greater radiation shielding and amount of supplies carried. For a short quick return mission to Apophis, the April 13, 2029 launch is the last easily obtainable launch date.

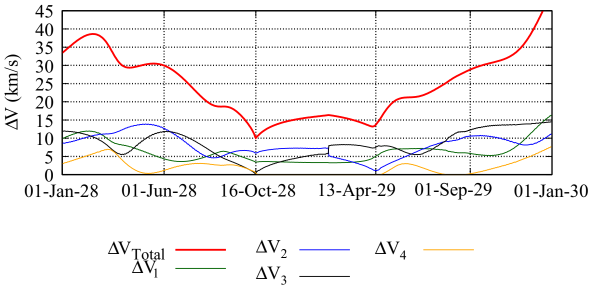

Fig. 2. Launch date(2028–2038) versus minimum ΔV required for 180-day return mission.

Limiting the maximum allowable launch ΔV to 11.5 km/s allows for sufficiently large launch windows. The minimum ΔV capability requirements for the mission are determined by allowing for a 0.5–1 km/s error margin. Adding this error margin to the maximum allowable launch ΔV results in a required ΔV capability of 12–12.5 km/s. Using a 11.5 km/s limit, the launch windows can be found for both launch dates. Fig. 2 shows the total ΔV plot as well as the required ΔV for the Earth departure, Apophis arrival, Apophis departure, and Earth arrival burns. As Fig. 2 shows, the early launch window is approximately 12 days starting on October 12, 2028 and ending on October 24, 2028. The late launch window is significantly shorter at just over 2 days in length, ranging from April 12–14, 2029.

A summary of nominal launch dates for both launch opportunities can be found in Table 2. The dates for each maneuver as well as the ΔV magnitude and C_3 values are given for each maneuver. For the early launch date, all of the maneuvers, with the exception of the Earth departure burn, are carried out in the last 3 weeks of the mission. The return date of the early launch date mission is just after the April 13, 2029 Earth-Apophis encounter, which allows for a small return ΔV because the Orion spacecraft departs Apophis a few days prior to the Earth-Apophis encounter. The opposite is true for the late launch date mission. Earth departure occurs during the Earth-Apophis close approach, with the Apophis rendezvous occurring a few days after Earth departure. Within the first 2–3 weeks, the mission is completed, with the remaining time spent on the return cruise. No burn is necessary when the Orion spacecraft returns to the Earth because the atmospheric reentry speed is less than 12 km/s.

2.1.2. 365-Day mission analysis

From Fig. 1, it is clear that longer missions result in significantly lower ΔV requirements. It can be seen that extending the mission to 1 year in length results in a

Table 2
Mission information for each launch opportunity.

	Early-180	**Late-180**	**Early-365**	**Late-365**	**2036**
Earth departure					
Date	10/16/28	4/13/29	4/20/28	4/13/29	4/16/35
C_3	4.887	30.355	18.025	30.762	38.021
ΔV (km/s)	3.448	4.528	4.017	4.545	4.836
Apophis arrival					
Date	3/26/29	4/19/29	2/21/29	5/11/29	3/3/36
V_∞^2	34.504	0.136	2.211	0.065	4.185
ΔV (km/s)	5.874	0.369	1.487	0.255	2.046
Apophis departure					
Date	4/5/29	4/29/29	3/3/29	3/21/29	3/13/36
C_3	0.113	40.686	0.546	1.946	1.254
ΔV (km/s)	0.336	6.379	0.739	1.395	1.120
Earth arrival					
Date	4/14/29	10/10/29	4/20/29	4/13/30	4/15/36
V_∞^2	30.474	1.896	24.053	21.269	31.569
ΔV (km/s)	0.391	0.000	0.129	0.014	0.435
Entry vel. (180 km alt)	12.000	11.111	12.000	12.000	12.000
Total ΔV (km/s)	10.049	11.276	6.373	6.208	8.436

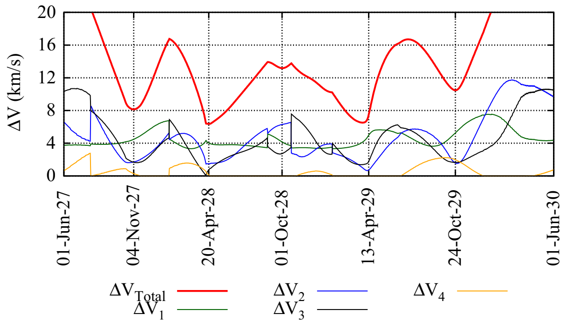

Fig. 3. Launch date (2028–2029) versus minimum ΔV required for 365-day return mission.

mission requiring a total ΔV of 6–7 km/s, significantly lower than the 10–12 km/s required for a 180-day mission. Such a mission could likely be executed using the previously proposed Constellation or similar mission architecture. This mission would likely be used as a stepping stone between the first asteroid mission, in the 2025 time frame, and the first Mars flyby mission, to occur in the 2035 time frame. Such a mission could serve as a test bed for systems needed for a Mars flyby or landing mission, with a reduced mission time when compared to a Mars mission.

A plot of the total ΔV needed for 2028–2029 time frame missions can be seen in Fig. 3. Fig. 3 shows the total ΔV needed for both the early and late launch date is just under 6.5 km/s, which is likely within the limits of Ares V/Ares I class of launch vehicle(s), carrying a CEV such as the Orion crewed capsule. Both launch windows can be determined by limiting the total ΔV to 7 km/s. The early launch window has a length of 27 days lasting from April 12, 2028 to May 9, 2028. The second launch window is slightly longer at 35 days, ranging from March 11, 2029 to April 15, 2029.

A summary of the two nominal launch dates is shown in Table 2. For the early launch date, all of the maneuvers, with the exception of the Earth departure burn, are carried out in the last 2 months of the mission. The return date for the early launch date is just after the April 13, 2029 Earth-Apophis close encounter, which allows for a small return ΔV because the CEV departs Apophis a few days prior to the Earth-Apophis encounter. The opposite is true for the late launch date. Earth departure occurs during the Earth-Apophis close approach, with the Apophis rendezvous occurring a few days after Earth departure. Within the first 4–5, weeks the mission is completed, with the remaining time spent on the return cruise. In each case a burn is necessary when the CEV returns to the Earth because of the required atmospheric reentry speed of 12 km/s or less.

2.2. Launch opportunities prior to the 2036 impact

This section provides an outline of the fictional human mission requirements necessary for an Apophis deflection mission prior to impact on April 13, 2036. This was done by ensuring that the Apophis departure date occurs on or before the impact date. All figures and tables in this section represent this requirement. For this mission there is no equivalent launch date for what was referred to as the late launch.

A plot of minimum ΔV for mission lengths from 20 to 500 days is shown in Fig. 4. Examination of Fig. 4 reveals that there is a minimum required ΔV of just under 8.5 km/s. A 180-day mission requires a ΔV of over 14 km/s, which is not feasible given current space propulsion technology. The 12 km/s ΔV required for a 180-day mission in 2029 is very difficult to achieve and would likely involve the use of orbital transfer vehicles that currently don't exist. This would be inappropriate for an Apophis deflection mission, if the livelihood of so many people is at stake. For this reason, the only mission analysis performed in this section will be a 365-day mission, which is near the minimum total ΔV shown in Fig. 4.

From Fig. 5 it can be seen that there is only one minimum, which occurs approximately one year prior to impact of the fictional Apophis. This plot shows the ΔV values for each maneuver as well. Limiting the total ΔV to 9 km/s allows for a 2 week launch window starting on April 11, 2035 and ending on April 25, 2036. Depending on the specific architecture chosen this windows may be adjusted.

A complete summary of the nominal launch date can be found in Table 2. For this mission, the majority of the maneuvers, with the exception of the Earth departure burn, occur within that last 43 days of the mission. The Earth arrival date occurs just after the April 13, 2036 impact, assuming that the crewed deflection mission is failed or aborted. The entry velocity of the CEV is 12 km/s,

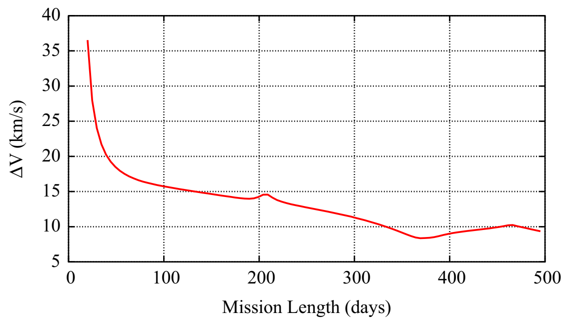

Fig. 4. Plot of minimum ΔV required for the 2036 human-piloted human deflection mission.

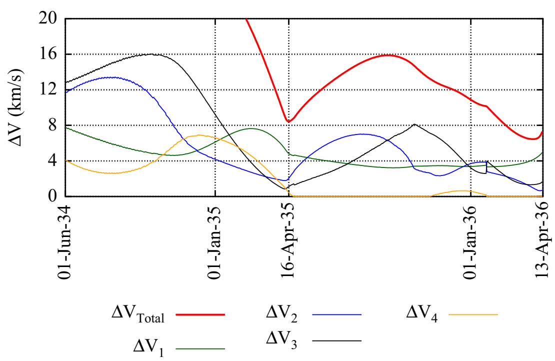

Fig. 5. Launch windows found in the 2035–2035 time frame.

the maximum allowed by the searching software, and may require a skip re-entry depending on CEV requirements. It may also be possible to perform a skip re-entry in order to eliminate the Earth arrival burn and bring the total required ΔV down to approximately 8 km/s.

3. Robotic mission to Apophis

Prior to the execution of a human-piloted mission to Apophis, it may be necessary to have a robotic precursory mission. The objective of this mission would likely be to further refine the position of Apophis, send fuel/supplies prior to the manned mission, or for a robotic deflection mission. For this reason, mission analysis will be performed for Apophis up to the close encounter and for the fictional Apophis that will collide with the Earth in 2036. The mission analysis and design conducted in this section was performed using a similar computer program to the one used for human-piloted mission analysis.

3.1. Mission analysis prior to the 2029 close encounter

Launch opportunities were found by searching for the minimum total ΔV for each launch by allowing the arrival date to vary. The results of the search are shown in Fig. 6. Examinations of this plot shows several possible launch opportunities in the 2027–2029 date ranges, using the capabilities of the IPBM architectures. A summary of the launch opportunities can be found in [8]. A total of 6 launch windows were found, however only the first 4 launch windows allows for an arrival date before or during the manned mission. Additional launch windows could be found, if needed, by allowing multiple revolutions/phasing orbits prior to arrival at Apophis or allowing a deep space correction maneuver. Additional information on a robotic mission to Apophis prior to 2029 can be found in [8].

3.2. Fictional post-2029 robotic mission analysis

A robotic mission after a close encounter, which results in an impact on April 13, 2036, would likely be a robotic deflection mission. Given this short period of time, missions other than a direct 0-revolution transfer may be necessary, to determine launch windows during times such missions don't allow. In this section, both 0-revolution and multiple revolutions missions will be analyzed. It will also be shown that a direct intercept mission, in which no arrival burn is necessary, is possible during nearly the entire 7 year period. Additionally, recent studies have concluded that is may be feasible to significantly reduce the impact damage from an Earth-impacting NEO using a nuclear subsurface explosion as late as 15 days prior to impact [10].

3.2.1. 0-revolution mission analysis

A contour plot of the total ΔV for the time-of-flight (the number of days to rendezvous) versus launch dates is shown in Fig. 8. This kind of contour plot is often called the porkchop plot. Careful analysis of this porkchop plot indicates that launch windows will be available from 2029 into the early 2030s. Although hard to see, there is one short 5 day launch windows in 2035 as well. The main constraint for launch windows after 2035 is that interception must occur at least 15 days prior to the Earth-Apophis collision [10,1]. For this reason, all figures and tables in this paper represent only missions which arrive at least 15 days prior to impact.

Launch windows can be determined by examining Fig. 7, which is a plot of minimum total ΔV versus launch date from 2029 to 2036. To determine the launch windows a maximum ΔV of 4 km/s was used, corresponding to the chosen IPBM configuration. There are 4 possible launch windows from 2029 to 2031 and a short 5 day launch window in April of 2035. Between 2031 and 2035 and after the 2035 launch window, there are no possible rendezvous launch windows prior to impact in 2036. Information for the nominal departure date for each windows can be found in Table 3. This table shows the magnitudes and dates for the Earth departure and Apophis arrival burns as well as the starting and ending dates for each corresponding launch window.

3.2.2. 0-revolution direct intercept mission

After April of 2035, there are no feasible rendezvous launch windows, which means that a direct intercept mission would be required for any "last minute" disruption missions. It is likely that developing and building a spacecraft such as the proposed IPBM system would take several years. It also seems likely that development would not start until after Apophis has passed through a keyhole in 2029, this is due to the four-in-a million chance

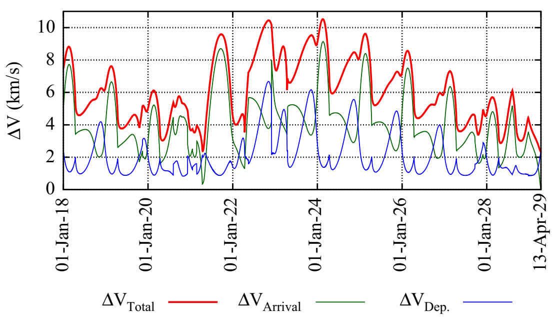

Fig. 6. ΔV required for rendezvous mission.

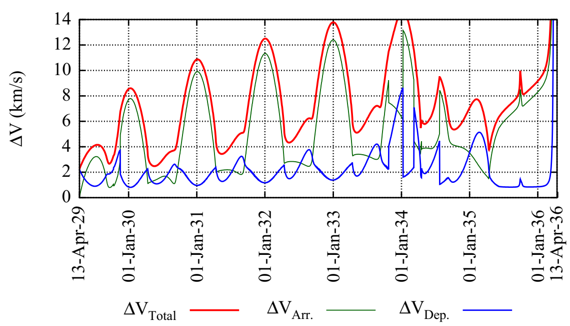

Fig. 7. ΔV required for rendezvous mission from 4/13/2029 to 4/13/2036.

Table 3
Minimum ΔV transfer trajectory for each optimal 0-revolution launch date. ΔV's are given in km/s.

0-Revolution launch windows								
Launch window	**Departure date**	**Departure ΔV**	**Arrival date**	**Arrival ΔV**	**Total ΔV**	**Start**	**End**	**Days**
1	4/13/29	2.186	4/16/30	0.102	**2.289**	4/13/29	6/23/29	**71**
2	9/12/29	1.867	7/26/30	0.801	**2.668**	8/12/29	10/24/29	**73**
3	5/20/30	1.091	6/2/31	1.460	**2.552**	4/11/30	9/12/30	**154**
4	5/15/31	1.281	8/30/32	2.156	**3.436**	4/20/31	6/28/31	**69**
5	4/15/35	2.045	3/28/36	1.702	**3.747**	4/13/35	4/18/35	**5**

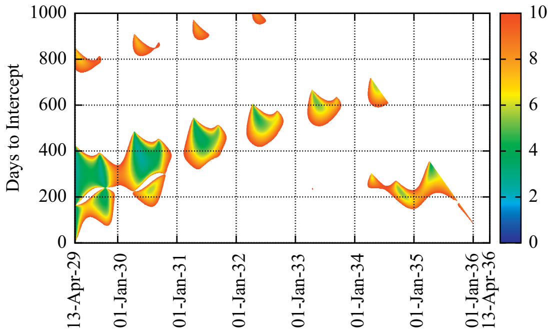

Fig. 8. Total ΔV porkchop plot of the time-of-flight versus launch date for the rendezvous mission.

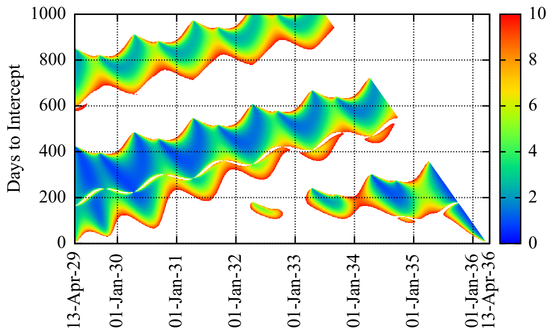

Fig. 9. Porkchop plot for the direct intercept mission.

this will happen. With the last low ΔV rendezvous 0-revolution launch window ending a little more than 2 years after the 2029 close encounter, it may be desirable to launch either a direct intercept or multiple revolution mission. For this reason, a direct intercept and multiple revolution missions will be analyzed in the following sections. A total ΔV contour plot of the time-of-flight versus launch date is shown in Fig. 9. From this plot, it can be seen that an intercept mission with a maximum ΔV of 4 km/s is possible at almost continuously from 2029–2036.

Recent research [1,10] has shown that it may be possible to prevent all but a few percent of the material from an asteroid from impacting the Earth by utilizing a nuclear subsurface explosion. However, such a disruption mission requires a rendezvous with Apophis to provide an acceptable penetrator velocity of 300 m/s. However, it may also be possible to design a high-speed penetrator. The objective of this section is to determine the feasibility of a last minute rendezvous mission launched anywhere from 2–3 years to as little as 20–30 days prior the 2036 impact. This requires further analysis of Fig. 9. An expanded version of Fig. 9 showing only this time span is provided in Fig. 10.

Careful analysis of Fig. 10 shows that late launch dates ranging from 3/28/2035 to 3/19/2036 are feasible for the intercept mission. The last feasible launch date is 25 days prior to impact. Using the IPBM system architecture, it may be feasible to launch a last minute intercept mission to disrupt an NEO similar to Apophis. No limits on the arrival velocity have been imposed in Figs. 9 and 10. Unfortunately, the penetrator's maximum impact velocity is currently limited by 300 m/s, which means that the late intercept mission concept may not be a viable option. In this situation either a nuclear surface explosion (contact burst) or high-speed penetrator (>5 km/s impact velocity) must be developed and employed. An example of late intercept trajectory is shown in Fig. 11, with all necessary mission data shown in Table 4.

To fully determine the feasibility of the late intercept mission, further information is needed on an intercept penetrator used for the nuclear subsurface explosion. In general, the later the intercept launch occurs the higher the arrival V_∞ at Apophis. Intercept launch dates in the 2034–2035 range generally have an intercept velocity (at Apophis) in the 5–6 km/s range.

3.2.3. Multiple revolution rendezvous mission analysis

For a search for multiple revolution missions two solutions are always found. A low-energy and high-energy solution. These indicate two solutions with a small and large eccentricity respectively. As implied by the name, ΔV's required for the high-energy solution are almost always larger than the corresponding low energy solution. Consequently, most of the additional launch dates determined by the multi-revolution (prior to Apophis arrival) search are part of the low-energy solutions. For this reason, only the low-energy missions will be analyzed in this section.

A porkchop plot of the number of days to Apophis interception versus launch date, similar to Fig. 9, is shown in Fig. 12. From this porkchop plot, it can be determined that the optimal mission lengths occur in the 600–1000 days range, slowly increasing as the launch date increases. Several launch dates similar to the 0-revolution rendezvous mission exist prior to May of 2031. However, it can be easily seen from the porkchop plot that additional

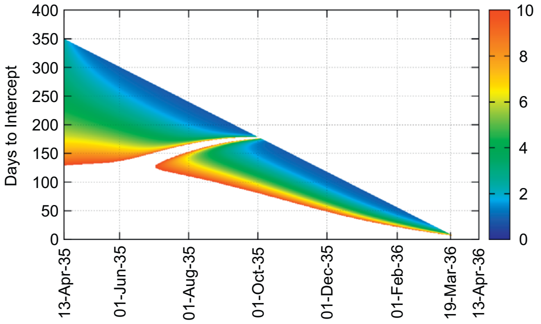

Fig. 10. Total ΔV contour plot of the flight-of-time versus launch dates from 4/13/2029 to 4/13/2036 for the intercept mission.

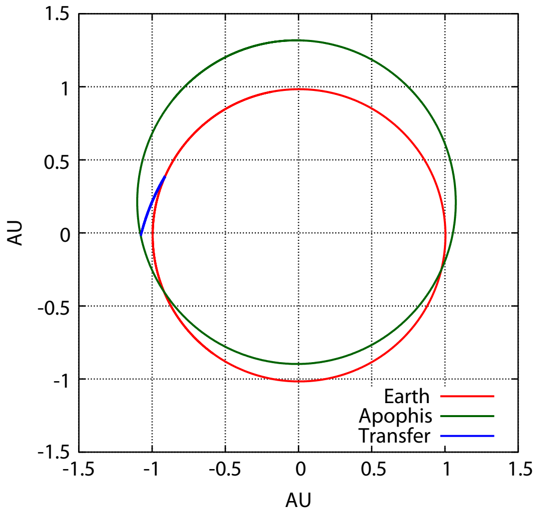

Fig. 11. Trajectory for a late intercept mission. Trajectory shown in (*X*,*Y*)-plane of J2000 coordinate system.

Table 4
Summary of a last minute intercept mission.

Example trajectory	
Departure date	26-Feb-36
Arrival date	19-Mar-36
Total ΔV, km/s	2.830
Semi-major axis, AU	1.714
Eccentricity	0.441
Inclination, deg	2.032
Ω, deg	336.944
ω, deg	153.860
Departure θ, deg	26.163
Arrival θ, deg	50.231

launch windows exist as well during other unaccessible period for the 0-revolution mission. These additional launch windows occur from April of 2031 to April of 2034, a period where rendezvous 0-revolution missions were not possible.

The 8 possible launch windows can be easily seen in Fig. 13. This is a plot of the total ΔV as well as the Earth

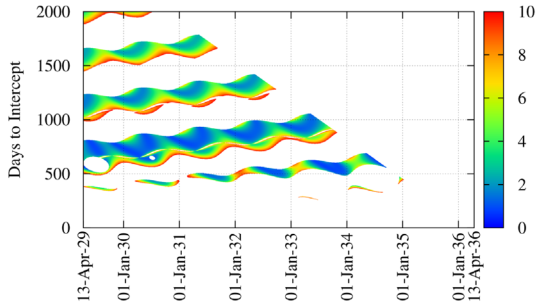

Fig. 12. Total ΔV contour plot of the time-of-flight versus launch dates from 4/13/2029 to 4/13/2036 for the 1-revolution low-energy solution rendezvous mission.

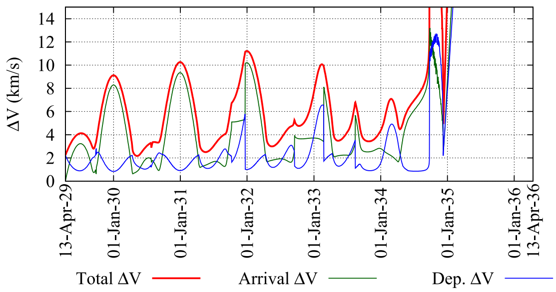

Fig. 13. ΔV required for rendezvous mission from 4/13/2029 to 4/13/2036 for the 1-revolution low-energy solutions.

departure and Apophis arrival ΔV's. For all dates searched, the last possible arrival date is March 29, 2036, 15 days prior to impact. The intercept date limitation is the reason that no 1-revolution solutions exist after early 2035, particularly low ΔV solutions. Analysis of this plot shows that a total of 8 launch windows exist, with the last 5 windows opening up launch dates that were previously unavailable for the 0-revolution rendezvous mission. The accompanying window ranges and information for the nominal departure date for launch window are shown in Table 5. In general the launch window lengths are similar, perhaps slightly longer for the 1-revolution case when compared to the 0-revolution windows. However, when performing a 2–3 revolution search, the early launch windows are drastically lengthened when compared to the 0-revolution case. No additional launch windows were found for 2+ revolution case, so no further analysis will be presented.

4. Summary

The mission requirements for the 2028–2029 human-piloted exploration mission have been discussed in this paper. It has been shown that a 180-day mission, currently the longest considered in many NASA studies [2,4,3], requires a ΔV of approximately 12 km/s. However, it has been shown that the ΔV requirements can be significantly lowered by extending the mission length to 1 year. In this case the required ΔV is in the 6–7 km/s range. This amount ΔV can be obtained with a mission architecture similar to the previously

Table 5
Minimum ΔV transfer trajectory for each optimal 1-revolution low-energy launch window. ΔV's are given in km/s.

1-Revolution low-energy launch windows								
Launch window	**Departure date**	**Departure ΔV**	**Arrival date**	**Arrival ΔV**	**Total ΔV**	**Start**	**End**	**Days**
1	4/13/29	2.242	5/7/31	0.013	**2.255**	4/13/29	6/16/29	**64**
2	9/24/29	2.053	9/25/31	0.7394	**2.793**	7/30/29	10/4/29	**66**
3	5/10/30	1.324	6/29/32	0.8449	**2.169**	4/5/30	9/18/30	**166**
4	5/20/31	1.123	10/3/33	1.3812	**2.505**	4/11/31	7/27/31	**138**
5	5/16/32	1.194	12/22/34	1.7989	**2.992**	4/13/32	7/18/32	**96**
6	5/13/33	1.293	3/2/36	2.1871	**3.480**	4/18/33	6/22/33	**65**
7	10/28/33	0.905	5/4/35	2.5233	**3.429**	9/18/33	12/17/33	**90**
8	4/15/34	2.008	3/28/36	1.7413	**3.750**	4/12/34	4/18/34	**6**

proposed Constellation systems carrying a crew exploration vehicle such as the proposed Orion capsule [8]. A mission of this length could be used as a stepping stone between the first human NEO mission and a Mars mission.

The requirement for the fictional Apophis human-piloted deflection has been determined as well. In this situation, only the early launch windows, which occurs prior to impact with an arrival occurring approximately 1 month prior to impact. In such a situation a high-energy nuclear method would likely have to be employed as the deflection/disruption technique. Similarly to the 2028–2029 exploration mission, the minimum ΔV occurs with a mission length of approximately 1 year. The required Δ for this deflection mission is higher than many proposed exploration mission, at approximately 8.5 km/s. [8].

Mission analysis has also been performed for robotic exploration and deflection missions prior to the 2029 close encounter and for the fictional orbit resulting in impact on April 13, 2036. A total of 6 launch windows, with 4 arriving prior to the April 13, 2029 close encounter. For the post-2029 fictional, Earth-impacting Apophis orbit, 5 launch windows were found for the 0-revolution mission. Additional launch windows were found utilizing a 1-revolution Lambert solution, resulting in eight possible launch windows, with many of these occurring when 0-revolution rendezvous missions were not possible. It has also been shown that a 0-revolution direct intercept mission is possible, depending on the final arrival velocity limits, for nearly the entire 7-year period.

5. Conclusion

Asteroid 99942 Apophis can be an excellent target for human exploration of NEOs. With a mission length of 1 year it could be used to learn valuable information about extended deep space missions, while remaining close to the Earth. This mission could prove invaluable for later Mars missions. In the unlikely event that Apophis passes through a keyhole in 2029, a deflection mission, such as those outlined in this paper, would become necessary. Research currently being done at the ADRC indicates that such a mission may be feasible using current technology and launch vehicles.

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