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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

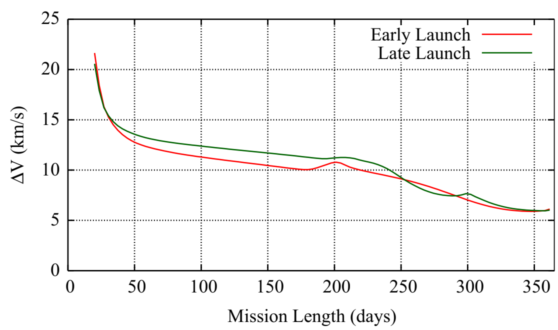

Fig. 1. Plot of minimum ΔV required for the early and late launch as a function of the mission length.