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Head-On Impact Deflection of NEAs: A Case Study for 99942 Apophis

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Near-Earth asteroid (NEA) 99942 Apophis provides a typical example for the evolution of asteroid orbits that lead to Earth-impacts after a close Earth-encounter that results in a resonant return. Apophis will have a close Earth-encounter in 2029 with potential very close subsequent Earth-encounters (or even an impact) in 2036 or later, depending on whether it passes through one of several less than 1 km-sized gravitational keyholes during its 2029-encounter. A pre-2029 kinetic impact is a very favorable option to nudge the asteroid out of a keyhole. The highest impact velocity and thus deflection can be achieved from a trajectory that is retrograde to Apophis orbit. With a chemical or electric propulsion system, however, many gravity assists and thus a long time is required to achieve this. We show in this paper that the solar sail might be the better propulsion system for such a mission: a solar sail Kinetic Energy Impactor (KEI) spacecraft could impact Apophis from a retrograde trajectory with a very high relative velocity (75-80 km/s) during one of its perihelion passages. The spacecraft consists of a 160 m $\times$ 160 m, 168 kg solar sail assembly and a 150 kg impactor. Although conventional spacecraft can also achieve the required minimum deflection of 1 km for this approx. 320 m-sized object from a prograde trajectory, our solar sail KEI concept also allows the deflection of larger objects. For a launch in 2020, we also show that, even after Apophis has flown through one of the gravitational keyholes in 2029, the solar sail KEI concept is still feasible to prevent Apophis from impacting the Earth, but many KEIs would be required for consecutive impacts to increase the total Earth-miss distance to a safe value.

I. Introduction

In June 2004, a NEA with a diameter of about 320 m was discovered, which will have a very close encounter with Earth on 13 Apr 2029 and, with a non-negligible probability, subsequent very close encounters or even an impact on 13 Apr 2036, 13 Apr 2037, or later (Refs. 1, 2, and 3). This NEA first got the provisional designation 2004 MN4 and later 99942 Apophis. The currently estimated probability that Apophis impacts the Earth is 1/45 000 for a 2036-encounter and 1/12 346 000 for a 2037-encounter (Ref. 2, October 2006). Note that the current probability of a catastrophic impact in 2036 is higher than, e.g., the probability for an airplane to crash during a flight. Apophis would impact the Earth with a velocity of about 12.6 km/s and the released energy would equal about 875 Megatons of TNT (Ref. 2). Whether or not Apophis will impact the Earth in 2036 or 2037 will be decided by its close encounter in 2029. If the asteroid passes through one of several so-called "gravitational keyholes", it will get into a resonant orbit and impact the Earth in one of its later encounters, if no counter-measures are taken.

Apophis' size (H = 19.2) and taxonomic type are not definitely known at this time (Ref. 2). According to Ref. 1, e.g., Apophis has a diameter of $430 - 970$ m. In accordance with Ref. 2, however, we assume for

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our calculations that it is a spherical 320 m diameter asteroid with a typical S-class density of 2 720 kg/m^3 and thus an estimated mass of 4.67×10^{10} kg.

During November and December 2005, ESA's Advanced Concepts Team (ACT) has organized the 1st Global Trajectory Optimisation Competition. The goal was to find the trajectory that yields the maximum deflection of asteroid 2001 TW229 using a nuclear-electric propulsion (NEP) system within a maximum mission duration of 30 years. The winning trajectory came from JPL's Outer Planets Mission Analysis Group (Ref. 4). An even improved post-competition trajectory that will be published in Ref. 4 uses an Earth-Venus-Venus-Earth-Earth-Venus-Venus-Earth-Venus-Earth-Jupiter-Saturn-Jupiter gravity assist to make the trajectory retrograde and impact the target at one of its perihelion passages. The flight time is 28.4 years and the used propellant mass is only 3% of the launch mass. Therefore, a similar trajectory would also be feasible for a chemically propelled spacecraft. Although the trajectory for such a mission concept was not yet calculated for Apophis, the flight times for achieving a retrograde orbit would be in the same order as for the ACT competition problem. This renders chemical and electrical propulsion systems prohibitive for propelling a retrograde deflection mission to impact Apophis before the close Earth-encounter in 2029 or even before the potential Earth-impact in 2036.

The solar sail might be the better propulsion system for such a mission. The use of solar sails to achieve impacts from retrograde orbits was first proposed (and elaborated in a more general way) by McInnes in Refs. 5 and 6. Wie employed in Refs. 7 and 8 the same idea for a fictional asteroid deflection problem by AIAA and made a preliminary conceptual mission design. In Refs. 9 and 10, Dachwald and Wie made a more rigorous trajectory optimization study for this fictional AIAA mission scenario. The results in Refs. 9 and 10 show that solar sail Kinetic Energy Impactor (KEI) spacecraft that impact the asteroid with very high relative velocity from a retrograde trajectory are a realistic option for mitigating the impact threat from NEAs. This paper is about the application of the solar sail KEI concept to remove the real threat from this real asteroid.

II. Asteroid Deflection Using Kinetic Energy Impacts

The simplest approach to deflect a NEO is to impact it with a massive projectile at a high relative velocity. The highest impact velocity can be achieved from a trajectory that is retrograde to the target's orbit, impacting it during one of its perihelion passages. The change in the object's Earth-miss distance due to the impact depends on the time between the KEI's impact and the object's Earth impact, i.e. the lead time Δt_{L}, and the velocity change Δv of the asteroid caused by the impactor. In rough terms, the KEI's impact causes an along-track position shift of (see Refs. 3 and 11)

$$\Delta x = 3\Delta t_{\mathrm{L}}\Delta v \tag{1}$$

Thus a (typical) Δv of 0.25 mm/s provides a Δx of about 24 km in 1 year.

A successful asteroid deflection mission will require accurate modeling and prediction of the velocity change caused by the impactor. The effective impulse imparted to the asteroid will be the sum of the pure kinetic impulse (linear momentum) of the impactor plus the impulse due to the "thrust" of material being ejected from the impact crater. The last term can be very significant (even dominant), but its magnitude depends strongly upon the density, yield strength, and porosity of the material of which the asteroid is composed, as well as the mass and relative velocity of the impactor. For example, a head-on collision (at a typical relative velocity of $v_{\mathrm{imp}} = 75$ km/s) of a 150 kg impactor on a 4.67×10^{10} kg asteroid yields a pure kinetic-impact Δv of approx. 0.24 mm/s. If the asteroid was composed of hard rock, the modeling of crater ejecta impulse from previous studies by Ahrens and Harris in Ref. 11 would predict an additional Δv of 0.25 mm/s, which yields an "enhancement factor" of about $\xi \approx 2$. If the asteroid was composed of soft rock, the previous studies would predict an even larger additional Δv of 0.67 mm/s, which yields $\xi \approx 3.8$. More recent studies by Holsapple in Ref. 12 also indicate $\xi \approx 4$ for a non-porous asteroid, while it might be as low as $\xi \approx 1.16$ for a porous asteroid, like asteroid 25143 Itokawa, the target of the Hayabusa mission (Ref. 13). In any case, those values are associated with a large uncertainty. An accurate modeling and prediction of the ejecta impulse for various asteroid compositions is therefore a critical part of any kinetic-impact approach. To be on the safe side, we assume the worst case, $\xi = 1.16$, which gives

$$\Delta v = \xi \frac{m_{\mathrm{KEI}}}{m_{\mathrm{Apophis}}} v_{\mathrm{imp}} = 3.73 \times 10^{-9} v_{\mathrm{imp}} \tag{2}$$

Another practical concern of any kinetic-impact approach is the risk that the impact could result in the fragmentation of the asteroid, which could substantially increase the damage upon Earth impact (Ref. 14). The energy required to fragment an asteroid depends upon its composition and structure. For example, the specific disruption energy for ice is about 9 J/kg (Ref. 15). Hence the disruption energy for a 320 m-diameter asteroid composed largely of ice (density $917\,\mathrm{kg/m^3}$, Ref. 16) is approximately 1.4×10^{11} J. Because the kinetic energy of a 150 kg impactor at a typical relative velocity of 75 km/s would be 4.2×10^{11} J, the ice asteroid would likely fragment. If the asteroid was composed largely of silicates, it would have a disruption energy of approximately 9.3×10^{12} J (the specific disruption energy of silicates is about 200 J/kg, Ref. 15), which is much larger than the kinetic energy delivered by the impactor; such an asteroid would likely stay intact. Therefore, further studies are needed to optimize impactor size, relative impact velocity, and the total number of impactors as functions of the asteroid's size and composition, to ensure that the target will not be fragmented.

III. Scenario

To demonstrate the different possibilities that solar sails offer for mitigating the impact threat from NEOs, we assume the following *fictive* scenario:

1. During the very favorable radar and optical observations in 2013 (see Ref. 3), it is found that Apophis is likely to fly through the gravitational 2036-keyhole in its 2029-encounter and thus have a resonant return to hit the Earth in 2036.

2. At 01 Jan 2020, a solar sail KEI that consists of a 160 m × 160 m, 168 kg solar sail assembly and a 150 kg impactor is launched from Earth (inserted with zero hyperbolic excess energy, $C_3 = 0\,\mathrm{km^2/s^2}$). It has a characteristic acceleration (maximum acceleration at 1 AU solar distance) of $a_c = 0.5\,\mathrm{mm/s^2}$. The solar sail film temperature limit is $T_{\mathrm{lim}} = 240°\mathrm{C}$.

3. After having attained a trajectory that is retrograde to Apophis' orbit, the targeting of the asteroid begins. The solar sail KEI is brought onto a collision trajectory, from where it can impact Apophis on 02 Jan 2026 in the case that Apophis is still likely to fly through the keyhole in 2029. Two kinds of collision trajectories are investigated, a trajectory that maximizes v_{imp} and an exactly retrograde orbit (ERO) that encounters Apophis at every perihelion and aphelion passage. For steps 4-6, the former collision trajectory will be assumed.

4. For comparison with the pre-2029-encounter scenario: the mission is aborted before the 2029-encounter because it is found that Apophis is not likely anymore to fly through the keyhole. The impact on 02 Jan 2026 is changed into a close flyby. Instead of aborting the mission, however, the solar sail KEI is brought to a trajectory that maximizes the deflection for a post-2029-encounter impact, for the case that this might be necessary. Note that Apophis' post-encounter orbit is not exactly known at that time, but the worst case orbit (leading to a close encounter in 2036) can be estimated with sufficient accuracy.

5. After the close Earth-encounter on 13 Apr 2029 it is found that Apophis really flew through the 2036-keyhole and thus has a resonant return to hit the Earth on 13 Apr 2036.

6. The solar sail KEI impacts the asteroid shortly after the 2029-encounter on 11 Jun 2029.

6b. Alternatively, for comparison, after its launch on 01 Jan 2020, the solar sail KEI is directly sent onto a collision trajectory that maximizes v_{imp} on 11 Jun 2029.

Because of its large ΔV-capability, a solar sailcraft with a relatively modest characteristic acceleration of $0.5\,\mathrm{mm/s^2}$ can achieve a trajectory that is retrograde to Apophis' orbit within 4.4 years. After the trajectory is made retrograde to Apophis' orbit, the KEI is brought onto a collision trajectory, so that it impacts Apophis with a large head-on velocity at its perihelion of 0.746 AU (where the impact is most effective). Such a head-on collision yields an impact velocity in the order of $75 - 80\,\mathrm{km/s}$, which is much larger than the typical impact velocity of about 10 km/s of prograde missions such as NASA's Deep Impact mission (Refs. 17 and 18) or ESA's projected Don Quijote mission (Ref. 19). For the small Apophis target, the impactor is to be separated from the solar sail prior to the impact because of the extremely demanding terminal guidance and targeting requirements. With $v_{\mathrm{imp}} \approx 75\,\mathrm{km/s}$, each impactor will, depending on Apophis' porosity, cause an estimated Δv of about $0.25 - 1.0\,\mathrm{mm/s}$ in Apophis' trajectory. Figure 1 shows a potential trajectory for a pre-2029-encounter impact.

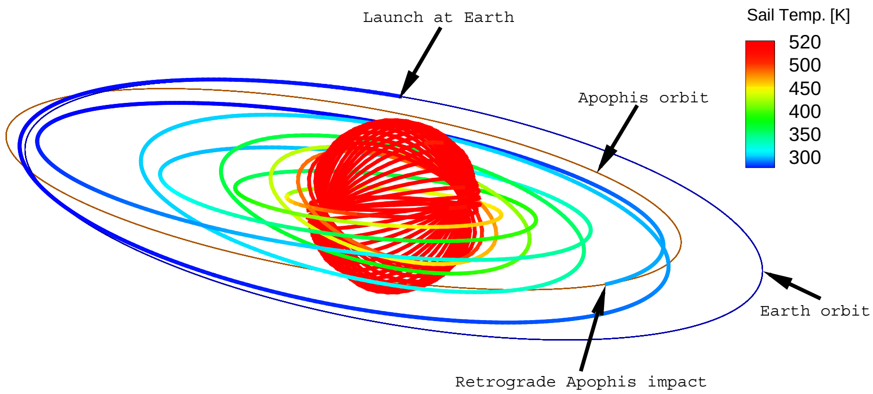


Figure 1. Potential trajectory for a pre-2029-encounter impact

IV. Technological Readiness

The critical technologies required for the proposed mission include: (1) deployment and control of a $160\,\mathrm{m} \times 160\,\mathrm{m}$ solar sail, (2) development of a solar sail and a micro-spacecraft bus that is able to withstand the extreme space environment at less than only 0.25 AU from the sun, (3) autonomous precision navigation, terminal guidance and targeting, and (4) accurate impact-crater ejecta modeling and Δv-prediction. A $160\,\mathrm{m} \times 160\,\mathrm{m}$ solar sail is currently not available. However, a $20\,\mathrm{m} \times 20\,\mathrm{m}$ solar sail structure was already deployed on ground in a simulated gravity-free environment at DLR in December 1999, a $40\,\mathrm{m} \times 40\,\mathrm{m}$ solar sail is being developed by NASA and industries for a possible flight-validation experiment within 10 years, and thus a $160\,\mathrm{m} \times 160\,\mathrm{m}$ solar sail is expected to be available within about 10–20 years of a sharply pursued technology development program.

V. Simulation Model

In this paper, the standard non-perfectly reflecting solar radiation pressure (SRP) force model by Wright is employed.[20] For a detailed description of this model, the reader is referred to Ref. 21.

Besides the gravitational forces of all celestial bodies and the SRP force, many disturbing forces influence the motion of solar sails in space, as they are caused, e.g., by the solar wind, the finiteness of the solar disk, the reflected light from close celestial bodies, and the aberration of solar radiation (Poynting-Robertson effect). Furthermore, a real solar sail bends and wrinkles, depending on the actual solar sail design (Ref. 22). Finally, for a mission that is to target the center of mass of a 320 m-object with a relative velocity of more than 75 km/s, relativistic corrections may have to be applied for the final targeting phase. All these issues have to be considered for high precision trajectory determination and control, as it is required for this mission. For mission feasibility analysis, however, as it is done within this paper, the following simplifications can be made:

1. The solar sail is a flat plate.
2. The solar sail is moving under the sole influence of solar gravitation and radiation.
3. The sun is a point mass and a point light source.
4. The solar sail attitude can be changed instantaneously.

In an heliocentric inertial reference frame, the equations of motion for a solar sail are:

$$\dot{\boldsymbol{r}} = \boldsymbol{v}, \qquad \dot{\boldsymbol{v}} = -\frac{\mu}{r^3}\boldsymbol{r} + \boldsymbol{a}_{\mathrm{SRP}} \tag{3}$$

where $\boldsymbol{r}$ is the solar sail position, $\boldsymbol{v}$ is the solar sail velocity, μ is the sun's gravitational parameter, and $\boldsymbol{a}_{\text{SRP}}$ is the SRP acceleration.

VI. Mission Design

Within this paper, evolutionary neurocontrol (ENC) was used to calculate the trajectories. This method is based on a combination of artificial neural networks (ANNs) with evolutionary algorithms (EAs). For a description of this method, the reader is referred to Refs. 23–25. ENC was implemented within a low-thrust trajectory optimization program called InTrance, which stands for **In**telligent **Tra**jectory optimization using **n**euro**c**ontroller **e**volution. InTrance is a global trajectory optimization method that requires only the target body/state and intervals for the initial conditions as input to find a good solution for the specified problem. It works without an initial guess and does not require the attendance of a trajectory optimization expert.

Generally, orbits with $i < 90\,\text{deg}$ are termed prograde orbits and orbits with $i > 90\,\text{deg}$ are termed retrograde orbits. It was first found by Wright in Refs. 26 and 27 and further examined by Sauer in Ref. 28 that the best way to attain a retrograde orbit with a solar sail is to first spiral inwards to a solar distance that is given by the temperature limit of the solar sail (and the spacecraft), and then to use the large available solar radiation pressure to crank the orbit (although the sail temperature does not only depend on the solar distance but also on the pitch angle, as it will be seen later, Sauer used a minimal solar distance instead of a temperature limit). To simplify the terminology within this paper, we speak of a retrograde orbit (or trajectory), when the orbital angular momentum vector of the spacecraft $\boldsymbol{h}$ and the target $\boldsymbol{h}_{\text{T}}$ are anti-parallel, i.e. $\angle(\boldsymbol{h}, -\boldsymbol{h}_{\text{T}}) = 0\,\text{deg}$. The strategy to attain such a retrograde is to spiral inwards until the optimum solar distance for cranking the orbit is reached and then to crank the orbit until the orbit is retrograde. Thereby, it might become necessary to change the ascending node of the orbit, so that the inclination change is $\leq 180\,\text{deg}$. This "orbit-cranking phase" has to be followed by a second phase, which we call "targeting phase". The goal of the targeting phase is to bring the spacecraft onto a collision trajectory that impacts the target at perihelion with maximum head-on velocity.

A. Trajectory Optimization for the Orbit-Cranking Phase

If solar sail degradation is not considered, the acceleration capability of a solar sail increases $\propto 1/r^2$ when going closer to the sun. The minimum solar distance, however, is constrained by the temperature limit of the sail film and the spacecraft (here, however, we consider only the temperature limit of the sail film but not of the spacecraft). The equilibrium temperature of the sail film (see Ref. 29) does not only depend on the solar distance, but also on the sail pitch angle (that is also the light incidence angle). It was demonstrated in Ref. 30 that faster trajectories can be obtained for a given sail temperature limit, if not a minimum solar distance but the temperature limit is used directly by constraining the pitch angle in a way that it cannot become smaller than the critical pitch angle, where the temperature limit would be exceeded.

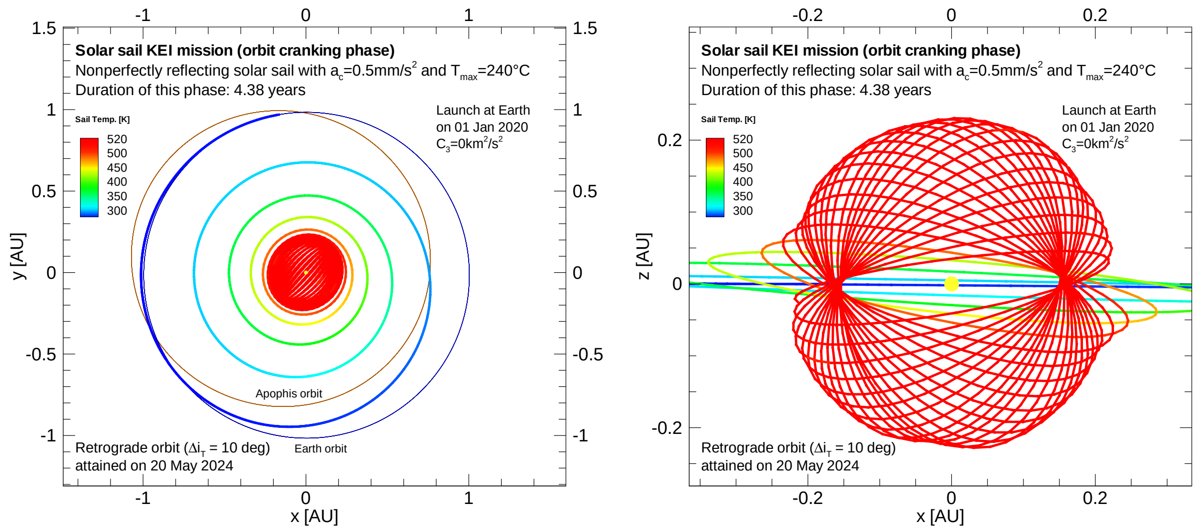
The results in Refs. 9 and 10 show that for a temperature limit of 240°C the optimal orbit cranking distance is 0.22 AU (where the inclination change is 0.1642 deg/day for $a_c = 0.5\,\text{mm/s}^2$). InTrance yields 1601 days for the duration of the orbit-cranking phase (Fig. 2).

B. Targeting Trajectory Optimization for the Pre-2029-Encounter Impact

The goal of the targeting phase is to bring the spacecraft onto a collision trajectory that impacts the target at perihelion with maximum head-on velocity. Therefore, the impact date was constrained to be at one of Apophis' perihelion passages and the optimization objective used for InTrance was: maximize $\boldsymbol{v} \cdot (-\boldsymbol{v}_{\text{NEA}})$!

Two different targeting options can be conceived. The first one is a collision trajectory that maximizes the head-on impact velocity, the second one is an exactly retrograde orbit (ERO), where the solar sail KEI encounters the target at every perihelion and aphelion passage. The resulting deflections achieved with the different strategies, as well as the parabolic limit case (spacecraft is on a parabolic trajectory), are shown in Table 1 for different pre-2029 impact dates.

The effectiveness of both options can be assessed by comparing the impact velocities with the maximum possible impact velocity that results from the parabolic limit case. The third column in Table 1 shows the lead time Δt_{L} before the 2029-encounter, the fourth column shows the impact velocity v_{imp}, the fifth column shows the resulting velocity change Δv of the asteroid, as calculated from Eq. (2), and the sixth column



(a) Trajectory for the orbit-cranking phase

(b) Trajectory for the orbit-cranking phase

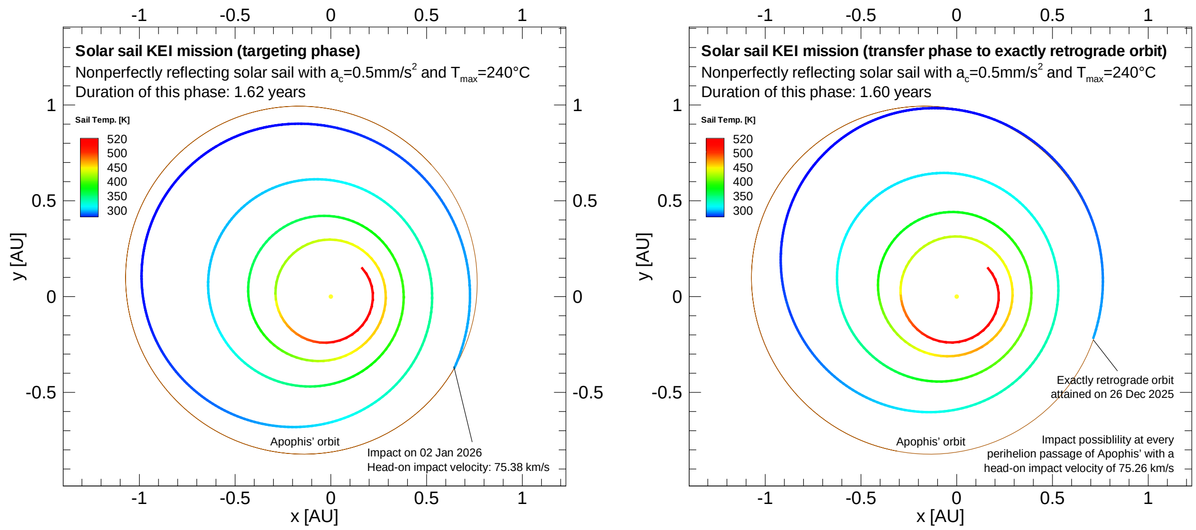
Figure 2. Baseline mission scenario: orbit-cranking phase

Table 1. Pre-2029-encounter impacts

Impact Date	Days before 2029-encounter	KEI head-on impact velocity [km/s]	Worst case velocity change from a single KEI [mm/s]	Deflection from a single KEI estimated [km]	Deflection from a single KEI calculated [km]	Fig.
From trajectory that maximizes the impact velocity:						
02 Jan 2026	1198.0	75.38	0.2811	87.3	93.2	3(a)
22 Nov 2026	874.4	77.91	0.2905	65.8	71.6	
11 Oct 2027	550.8	80.28	0.2993	42.7	48.7	
30 Aug 2028	227.2	80.95	0.3018	17.8	23.3	
From exactly retrograde orbit:						
02 Jan 2026	1198.0	75.26	0.2806	87.1	93.2	3(b)
22 Nov 2026	874.4	75.26	0.2806	63.6	69.5	
11 Oct 2027	550.8	75.26	0.2806	40.1	45.8	
30 Aug 2028	227.2	75.26	0.2806	16.5	21.9	
Parabolic limit case:						
02 Jan 2026	1198.0	86.39	0.3221	100.0	107.0	
22 Nov 2026	874.4	86.39	0.3221	73.0	79.8	
11 Oct 2027	550.8	86.39	0.3221	46.0	52.5	
30 Aug 2028	227.2	86.39	0.3221	19.0	25.1	

shows the deflection, as calculated from Eq. (1). The seventh column shows the deflection, as calculated by numerical integration.

For trajectories that maximize the impact velocity, Table 1 shows how v_{imp} increases for later impact dates. This, however, is over-compensated by the shorter lead times before the 2029-encounter, so that the earliest possible impact yields the largest 2029-deflection and is therefore preferable. The earliest possible impact opportunity is 02 Jan 2026 because for the earlier perihelion passage on 12 Feb 2025, the available time is not sufficient to reach the asteroid. The targeting trajectory that maximizes the impact velocity for this date is shown in Fig. 3(a).



(a) Trajectory that maximizes the impact velocity

(b) Transfer trajectory to exactly retrograde orbit

Figure 3. Targeting trajectories for an impact on 02 Jan 2026

If the impact does not take place on 02 Jan 2026 but is turned into a flyby (by intention or accidence), the next impact opportunity is 11 Oct 2027. An impact on 22 Nov 2026 is not possible because a 1:1 resonant trajectory cannot be achieved in this short time.

The second targeting option impacts Apophis from an exactly retrograde orbit. Being in a 1:1 resonance (at least when the sail is jettisoned or oriented perpendicular to the sun), the solar sail KEI encounters the target at every perihelion and aphelion passage. Consequently, v_{imp} does not change for the different perihelion impact opportunities. The trajectory to achieve such an ERO is shown in Fig. 3(b). Because this orbit is already attained on 26 Dec 2025, it can also impact Apophis on 02 Jan 2026. The v_{imp} for the first option is only 0.16% higher. Also for later impacts, the slightly lower achievable impact velocities from an ERO are compensated by the flexibility in choosing the impact date, which is only given by this option.

If not a single KEI but more KEIs are used to impact on Apophis before its 2029-encounter, it could be nudged farther out of the keyhole but unfortunately not out of the geostationary orbit because this would only be possible with a prograde impact. This is because a retrograde KEI impact decreases Apophis' orbital energy and thus decreases Apophis' orbital period so that it will arrive earlier at the "impact point", so that the trailing-side flyby distance will become reduced. This way, every retrograde impact moves the closest encounter about 90 km closer to Earth. Because a single KEI might fail to hit the target, however, the use of more KEIs adds redundancy and is thus advisable.

C. Targeting Trajectory Optimization for the Post-2029-Encounter Impact

In Ref. 31, Kahle has generated 20 000 potential Apophis orbits by random variation of the orbital elements within the 3σ-accuracy. Two of them (here termed Ap1 and Ap2) have been found to collide with the Earth, both during a 7:6 resonant return on 13 Apr 2036. They are used as potential impact-trajectories within this paper. Their orbital elements, before and after the 2029-encounter, are listed in Table 2, and their impacting orbits are shown in Fig. 4. Figure 4(a) shows a graphical comparison of Ap1's and Ap2's pre- and post-2029-encounter orbit (the orbits are so similar that they cannot be distinguished in plot 4(a)).

Two different targeting options are considered. The first one is a collision trajectory that maximizes right after launch the head-on impact velocity for an impact on the earliest possible post-2029-encounter impact date, 11 Jun 2029, shortly after the 2029-encounter (Fig. 5). The second one is from the previous pre-2029-encounter impact trajectory that was turned into a flyby on 02 Jan 26 and is now also determined for an impact with maximum head-on velocity on 11 Jun 2029 (Fig.6). The resulting deflections achieved with the different strategies, as well as the parabolic limit case, are shown in Table 3 for two different post-2029-encounter impact dates.

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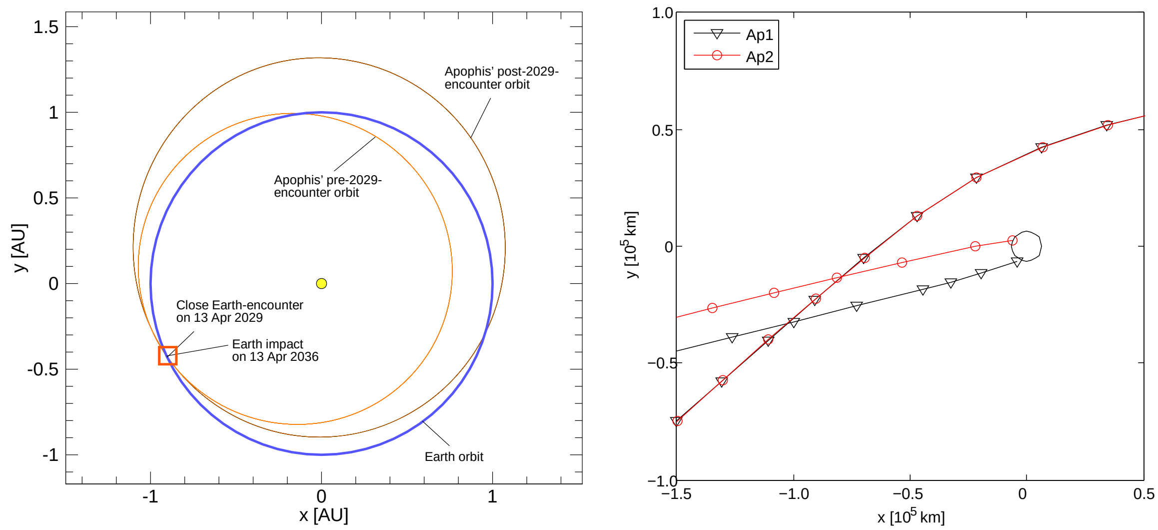
Table 2. Orbital elements of the Earth-impacting Apophis orbit variations Ap1 and Ap2

	before 2029-encounter		after 2029-encounter	
	Ap1	Ap2	Ap1	Ap2
MJD	53459.0	53459.0	64699.0	64699.0
a[AU]	0.9223913	0.9223912	1.1082428	1.1082581
e	0.191038	0.191038	0.190763	0.190753
i[deg]	3.331	3.331	2.166	2.169
ω[deg]	126.384	126.383	70.230	70.227
Ω[deg]	204.472	204.472	203.523	203.523
M[deg]	203.974	203.974	227.857	227.854



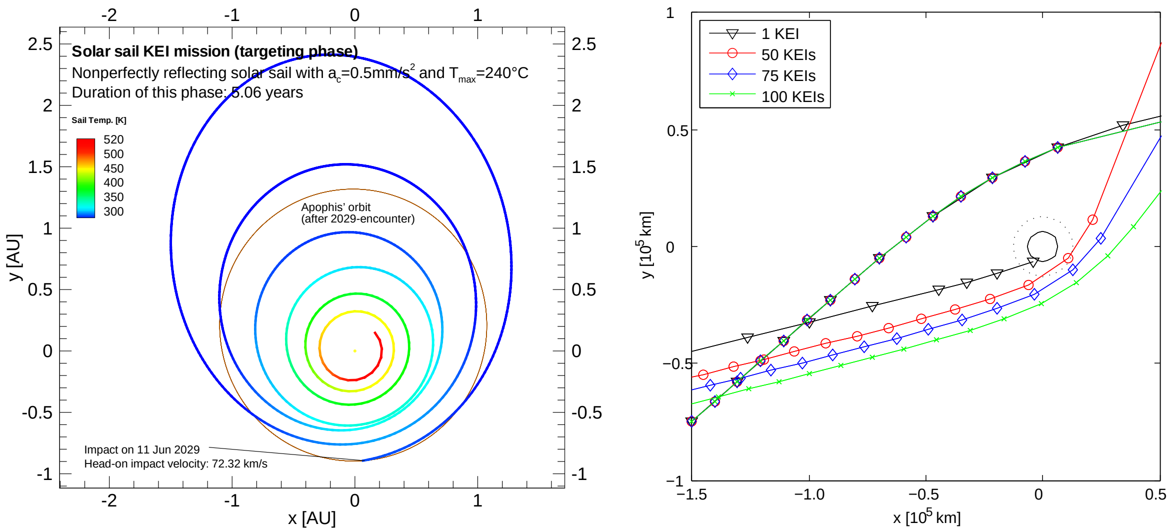
(a) Comparison of Ap1's and Ap2's pre- and post-2029-encounter orbit

(b) Closeup of the 2029-encounter and the impact (geocentric reference frame)

Figure 4. Earth-impacting Apophis variations

Table 3. Post-2029-encounter impacts

Impact Date	Days before 2036-impact	KEI head-on impact velocity [km/s]	Worst case velocity change from a single KEI [mm/s]	Deflection from a single KEI estimated [km]	Deflection from a single KEI calculated [km]	Fig.
From trajectory that maximizes the impact velocity:						
11 Jun 2029	2498.9	72.32	0.2697	174.7	104.0	5
11 Aug 2030	2072.8	74.11	0.2763	148.5	25.8-74.3	
From pre-2029-encounter impact trajectory (02 Jan 26 flyby):						
11 Jun 2029	2498.9	71.44	0.2664	172.5	102.1	6
Parabolic limit case:						
11 Jun 2029	2498.9	78.80	0.2938	190.3	114.1	
11 Aug 2030	2072.8	78.80	0.2938	157.9	26.7-81.2	



(a) Impact from trajectory that maximizes the impact velocity

(b) Deflection for different numbers of KEIs (Ap1, geocentric reference frame)

Figure 5. Targeting trajectory for an impact on 11 Jun 2029

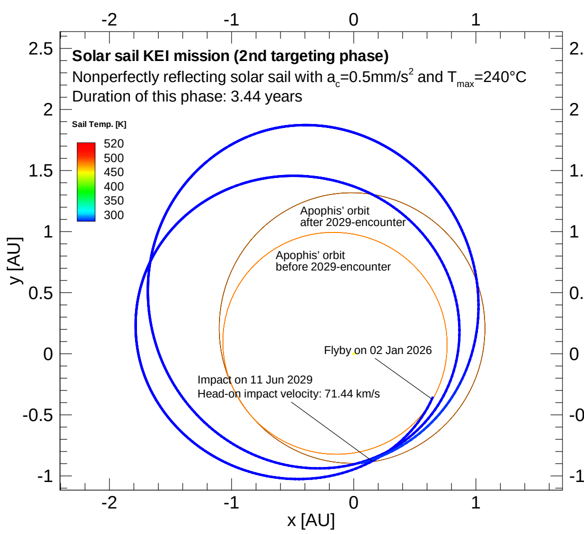


Figure 6. Targeting trajectory for an impact on 11 Jun 2029 (impact from a pre-2029-encounter impact trajectory, i.e. 02 Jan 2026 flyby)

The effectiveness of both options can be assessed by comparing the impact velocities with the maximum possible impact velocity that results from the parabolic limit case. Again, v_{imp} increases for the later impact date, but is over-compensated by the shorter lead time before the 2036-impact, so that the earliest possible impact yields the largest 2036-deflection and is therefore preferable. Note that the deviations between the estimated and the numerically calculated deflections in Table 3 result from the simplifying assumptions that underly Eq. (1) (e.g. the neglect of Earth's gravitational field).

Figure 7 shows the Δv that is required for a successful deflection of Ap1 and Ap2 to a safe distance of 2 Earth radii, as well as the optimal deflection angles according to the analysis performed in Ref. 31.

One can see that after the 2029-encounter a successful deflection of Apophis requires in the best case less than about 100 KEIs, assuming that every consecutive KEI impact has the optimal deflection angle and provides the same Δv of 0.2697 mm/s, which might not be possible for a "rubble-pile". Numerical integration shows that 70-75 KEIs are required for a successful deflection of Ap1. For Ap2, the situation is

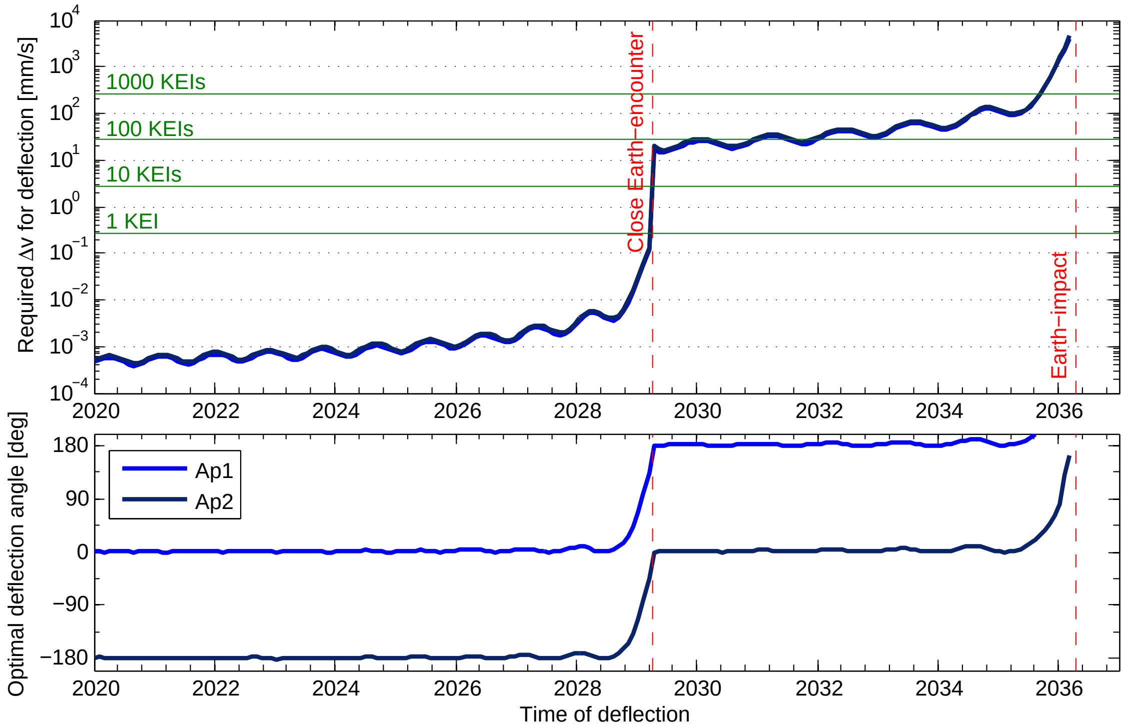


Figure 7. Required velocity change and optimal deflection angle for Ap1 and Ap2

worse because the optimal post-2029-deflection requires a prograde impact (which is not possible with very high impact velocities), as can be seen from Ap2's optimal deflection angle in the lower diagram, so that the deflection has to "cross" the Earth. Numerical integration shows that in this case 130-140 KEIs are required. Because it is not known before whether the real Apophis-orbit would be Ap1-like or Ap2-like, a worst case scenario should be assumed, which might require about 200 KEIs (also taking into account that some KEIs might miss the target). Even if the asteroid fragments, the largest fragments could be crushed. The interplanetary insertion mass for 200 KEIs is 63.2 mt. This would require 7 Delta IV Heavy (9.3 mt to $C_3 = 0\,\mathrm{km^2/s^2}$, Ref. 32), 10 Atlas 5 (6.5 mt to $C_3 = 0\,\mathrm{km^2/s^2}$, Ref. 32), or 6 Ariane 5 ESC-B (10.8 mt to $C_3 = 0\,\mathrm{km^2/s^2}$, Ref. 33). In comparison to the catastrophic results of an impact, this is very feasible. Of course a pre-encounter impact is clearly the better option for Apophis, but this option might not be available for other NEOs that do not have a close encounter before they impact the Earth.

VII. Conclusions

We have shown that solar sails are a realistic option to deflect asteroid 99942 Apophis with a kinetic impact from a retrograde orbit. For a launch at the beginning of 2020, we have considered two basically different scenarios. For both scenarios, we have used a 160 m × 160 m, 168 kg solar sail to bring a separable 150 kg kinetic energy impactor (KEI) onto a collision course with the asteroid. In the first scenario, a single KEI is used to impact Apophis before its close Earth-encounter in 2029, thus being able to nudge it out of a gravitational keyhole that would lead to a resonant return in 2036. An exactly retrograde orbit, where the KEI can impact the asteroid at every perihelion (and aphelion) passage, is the most flexible option for this scenario. In the second scenario, an impact after Apophis' close encounter in 2029 was considered. We have found that in this case many KEIs (up to 200, depending sensitively on the actual impact trajectory) would be necessary to prevent Apophis from impacting the Earth. Nevertheless, requiring less than 10 heavy lift launch vehicles, this option is still feasible. Of course a pre-encounter impact is clearly the better option for Apophis, but this option might not be available for other NEOs that do not have a close encounter before they impact the Earth. The required solar sail technology for the proposed mission, however, is not yet state-of-the-art, but would have to be developed in a sharply pursued technological program within the next

10 to 20 years. Other problems that have to be considered for the design of this mission are the extreme requirements for the terminal guidance prior to impact (accuracy much better than 100 m at a relative velocity of more than 75 km/s) and the thermal control that has to make the spacecraft withstand very close solar distances (0.2 − 0.25 AU).

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