Solar Sailing Kinetic Energy Impactor (KEI) Mission Design Tradeoffs for Impacting and Deflecting Asteroid 99942 Apophis

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Outline

Near-Earth Asteroids (NEAs)

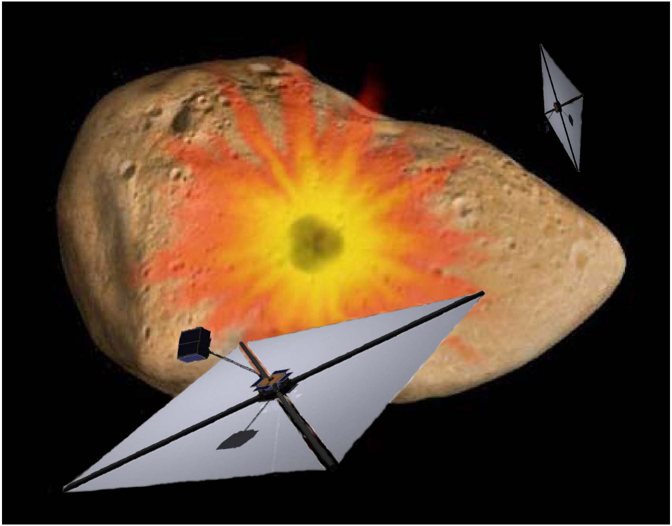
- The orbits of NEAs intersect or pass near the orbit of Earth
- 838 NEAs with a diameter $d \gtrsim 1\,\text{km}$ are currently known
- The entire population contains perhaps more than 1 000 objects of this size
- All NEAs with MOID $\leq 0.05\,\text{AU}$ and $d \gtrsim 200\,\text{m}$ are Potentially Hazardous Asteroids (PHAs)
- There are currently 790 known PHAs, 161 of them with $d \gtrsim 1\,\text{km}$
- Even asteroids that do not intersect Earth's orbit may evolve into Earth-crossers, since their orbits are chaotic, having a relatively short dynamical lifetime ($\sim 10^7$ years)

The Case of 99942 Apophis

- In June 2004, a NEA with a diameter of about 320 m was discovered (firstly designated 2004 MN4 and later 99942 Apophis)
- Very close encounter with Earth on 13 Apr 2029
- With a non-negligible probability subsequent very close encounter or even impact on 13 Apr 2036 or later
- Currently estimated probability that Apophis impacts the Earth in 2036 is $1/45\,000$
- Earth impact velocity of about 12.6 km/s
- Released energy would equal about 875 Megatons of TNT
- Whether or not Apophis will impact the Earth in 2036 or later will be decided by its close encounter in 2029. (If the asteroid passes through one of several so-called "gravitational keyholes" ($\varnothing \approx 600$ m), it will get into a resonant orbit and impact the Earth in one of its later encounters, if no counter-measures are taken)

Solar Sail Kinetic Energy Impactors (KEIs)

(Multiple) KEIs impact Apophis at perihelion from a trajectory that is retrograde w.r.t. Apophis' orbit ($\Rightarrow v_{\mathrm{imp}} \approx 75\,\mathrm{km/s}$)



Scenario I

(fictional)

1. In 2013 (very favorable radar and optical observations), it is found that in its 2029-encounter Apophis is likely to fly through the 2036-keyhole $\Rightarrow$ resonant return to hit the Earth in 2036
2. At 01 Jan 2020, a solar sail KEI is launched from Earth
   - 160 m $\times$ 160 m, 168 kg solar sail assembly
   - 150 kg impactor
   - $a_c = 0.5\,\mathrm{mm/s^2}$
   - $T_{\mathrm{lim}} = 240°\mathrm{C}$
   - $C_3 = 0\,\mathrm{km^2/s^2}$
3. After having attained a trajectory that is retrograde to Apophis' orbit, the solar sail KEI is brought onto a collision trajectory, from where it can impact Apophis in 2026 in the case that Apophis is still likely to fly through the keyhole

   Two kinds of collision trajectories are investigated:
   - A trajectory that maximizes v_{imp}
   - An exactly retrograde orbit (ERO) that encounters Apophis at every perihelion and aphelion passage

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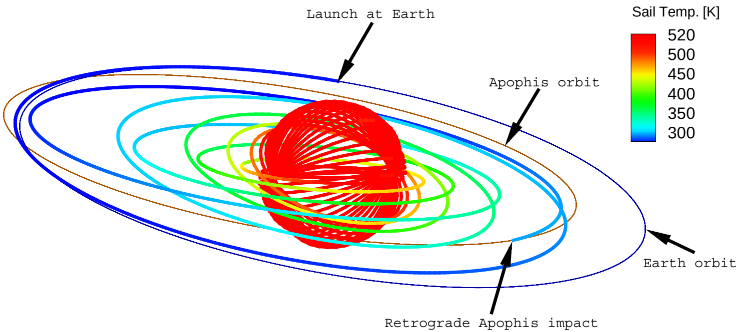
Potential Trajectory for a Pre-2029-Impact

Trajectory that maximizes v_{imp}



Mission duration: 6 years

Impact velocity: 75.4 km/s

Kinetic Energy Impacts Issues

- Effective impulse imparted to the asteroid is sum of pure kinetic impulse of the impactor plus impulse due to "thrust" of material being ejected from impact crater
- Last term can be very significant, but magnitude depends strongly upon density, yield strength, porosity, impactor mass, impact velocity

$$\Delta v = \xi \frac{m_{\mathrm{KEI}}}{m_{\mathrm{Apophis}}} v_{\mathrm{imp}}$$

- Enhancement factor for hard rock: $\xi \approx 2$
- Enhancement factor for soft rock: $\xi \approx 4$
- Enhancement factor for porous asteroids: $\xi \approx 1.16$

$$\Rightarrow \Delta v = 3.73 \times 10^{-9} v_{\mathrm{imp}}$$

- Values are associated with large uncertainty $\Rightarrow$ accurate modeling and prediction of ejecta impulse is critical part of any kinetic-impact approach
- Risk that impact could result in fragmentation of the asteroid (depends upon its composition and structure)

The Non-Perfectly Reflecting Solar Sail

The non-perfectly reflecting solar sail model parameterizes the optical behavior of the sail film by the optical coefficient set

$$\mathcal{P} = \{\rho, s, \varepsilon_\mathrm{f}, \varepsilon_\mathrm{b}, B_\mathrm{f}, B_\mathrm{b}\}$$

The optical coefficients for a solar sail with a highly reflective aluminum-coated front side and with a highly emissive chromium-coated back side are:

$$\mathcal{P}_{\mathrm{Al|Cr}} = \{\rho = 0.88, s = 0.94, \varepsilon_\mathrm{f} = 0.05, \varepsilon_\mathrm{b} = 0.55, B_\mathrm{f} = 0.79, B_\mathrm{b} = 0.55\}$$

S_0: solar constant ($1368\,\mathrm{W/m^2}$)

c: speed of light in vacuum

r: radius

r_0: 1 astronomical unit (1 AU)

ρ: reflection coefficient

s: specular reflection factor

ε_f and ε_b: emission coefficients of the front and back side, respectively

B_f and B_b: non-Lambertian coefficients of the front and back side, respectively

Simulation Model

Considerations for high-precision trajectory control:

- Solar sail bends and wrinkles, depending on actual solar sail design
- Gravitational forces of all celestial bodies
- Reflected light from close celestial bodies
- Solar wind
- Finiteness of solar disk
- Finite low-precision attitude control maneuvers
- Aberration of solar radiation (Poynting-Robertson effect)
- Relativistic corrections required for final targeting phase

Allowed simplifications for mission feasibility analysis:

- Solar sail is a flat plate
- Solar sail is moving under sole influence of solar gravitation and radiation
- Sun is a point mass and a point light source
- Solar sail attitude can be changed instantaneously

Evolutionary Neurocontrol (ENC)

A smart global trajectory optimization method

- We used ENC to calculate near-globally optimal trajectories
- ENC is based on a combination of artificial neural networks with evolutionary algorithms
- ENC attacks trajectory optimization problems from the perspective of artificial intelligence and machine learning
- ENC was implemented within a low-thrust trajectory optimization program called InTrance (**In**telligent **Tra**jectory optimization using **n**euro**c**ontroller **e**volution)
- InTrance requires only the target body/state and intervals for the initial conditions as input to find a near-globally optimal trajectory for the specified problem
- InTrance works without an initial guess and does not require the attendance of a trajectory optimization expert

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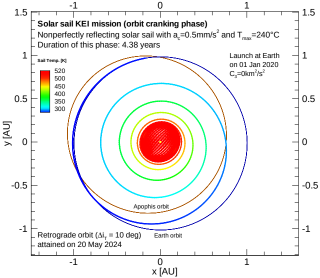
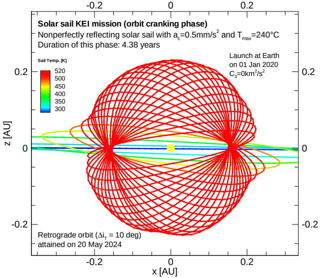
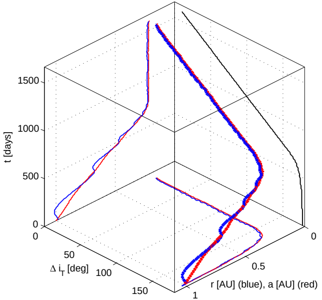
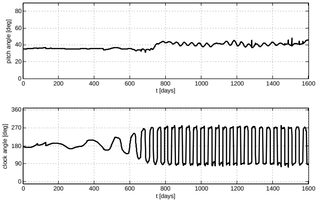
Orbit Cranking Phase

Trajectory, $\Delta i_{\frown_T}$-(r, a)-t-diagram, and solar sail control angles



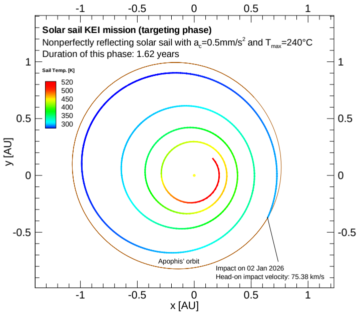




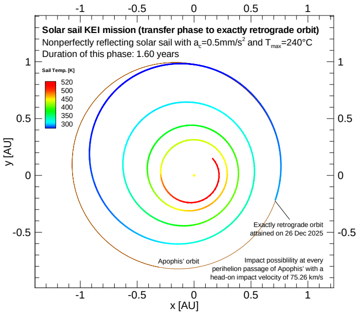


Targeting Phase

Trajectory that maximizes v_{imp} vs. exactly retrograde orbit



Trajectory that maximizes v_{imp}



Transfer trajectory to exactly retrograde orbit (ERO)

- From an ERO, the solar sail KEI encounters the target at every perihelion and aphelion passage
- The slightly lower achievable impact velocity from an ERO is compensated by the flexibility in choosing the impact date

Targeting Phase

Trajectory that maximizes v_{imp} vs. exactly retrograde orbit

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 [km]
From trajectory that maximizes the impact velocity:				
02 Jan 2026	1198.0	75.38	0.2811	93.2
22 Nov 2026	874.4	77.91	0.2905	71.6
11 Oct 2027	550.8	80.28	0.2993	48.7
30 Aug 2028	227.2	80.95	0.3018	23.3
From exactly retrograde orbit:				
02 Jan 2026	1198.0	75.26	0.2806	93.2
22 Nov 2026	874.4	75.26	0.2806	69.5
11 Oct 2027	550.8	75.26	0.2806	45.8
30 Aug 2028	227.2	75.26	0.2806	21.9
Parabolic limit case:				
02 Jan 2026	1198.0	86.39	0.3221	107.0
22 Nov 2026	874.4	86.39	0.3221	79.8
11 Oct 2027	550.8	86.39	0.3221	52.5
30 Aug 2028	227.2	86.39	0.3221	25.1

Scenario II

(fictional)

4.
- Impact is aborted before 2029-encounter because it is found that Apophis is not likely anymore to fly through the keyhole
- 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

5. After close Earth-encounter on 13 Apr 2029 it is found that Apophis really flew through the 2036-keyhole $\Rightarrow$ 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 launch on 01 Jan 2020, the solar sail KEI is directly sent onto a collision trajectory that maximizes v_{imp} on 11 Jun 2029

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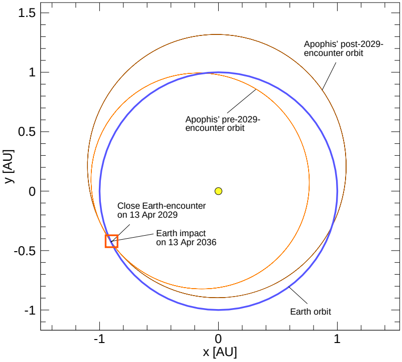
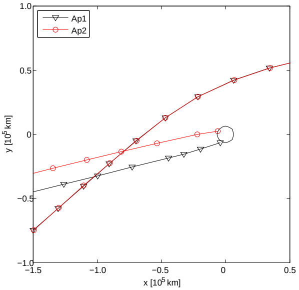
Earth-Impacting Apophis Variations

- Kahle has generated 20 000 potential Apophis orbits by random variation of the orbital elements within the 3σ-accuracy
- Two of them have been found to collide with Earth, both during a 7:6 resonant return on 13 Apr 2036 (Ap1 and Ap2)
- We have used them as potential impact-trajectories



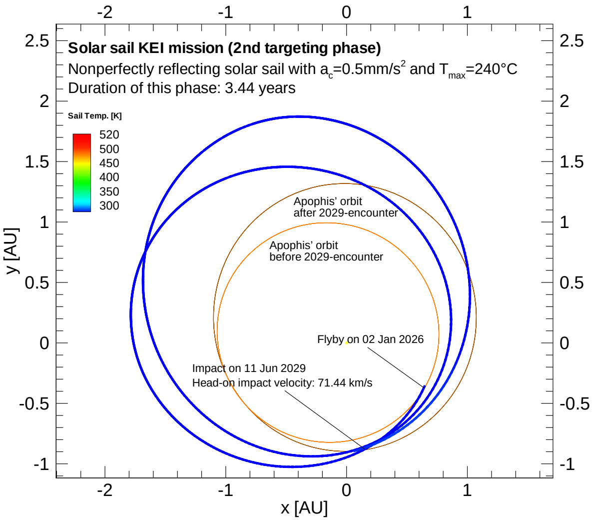
Comparison of Ap1's pre- and post-2029-encounter orbit



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

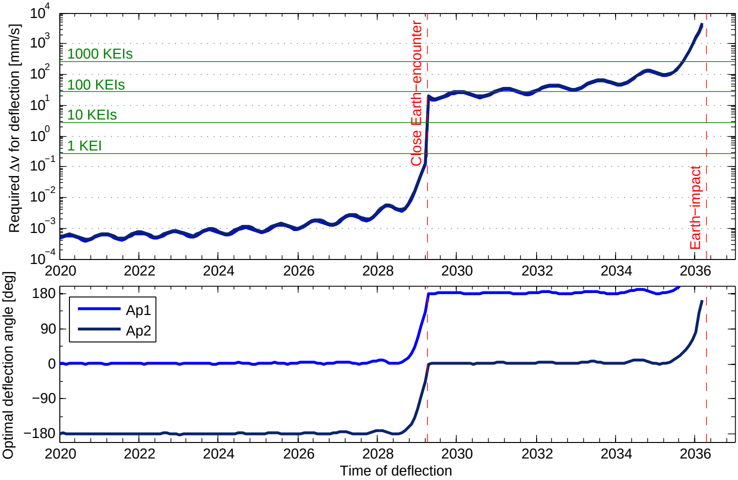
Scenario Step 6

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



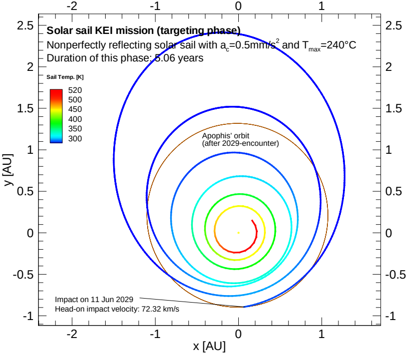
Post-2029-Encounter Deflection

Required velocity change and optimal deflection angle for Ap1 and Ap2

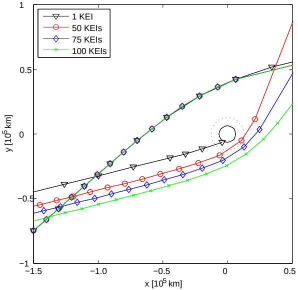


Scenario Step 6b

Maximizing v_{imp} right after launch (Scenario 6b)



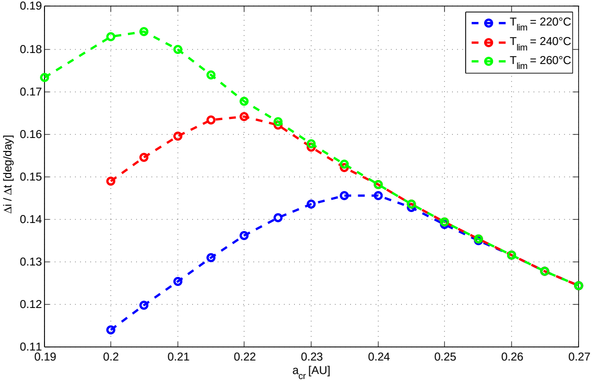
Impact from trajectory that maximizes the impact velocity



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

- 70-75 KEIs are required for a successful deflection of Ap1
- 130-140 KEIs are required for a successful deflection of Ap2
- Assuming the worst case, 200 KEIs (63.2 mt) should be launched
- This would require 7 Delta IV Heavy, 10 Atlas 5, or 6 Ariane 5 ESC-B

Variation of the Sail Temperature Limit



- The optimal orbit-cranking semi-major axis can be approximated with an error of less than 2% by

$$\tilde{a}_{\mathrm{cr,opt}} \approx 1.4805 - 0.23 \cdot \ln(\tilde{T}_{\mathrm{lim}})$$

- The maximum inclination change rate can be approximated with an error of less than 2% by

$$\widetilde{(\Delta i/\Delta t)}_{\mathrm{max}} \approx 0.0224 \cdot \tilde{a}_{\mathrm{cr,opt}}^{-1.32}$$

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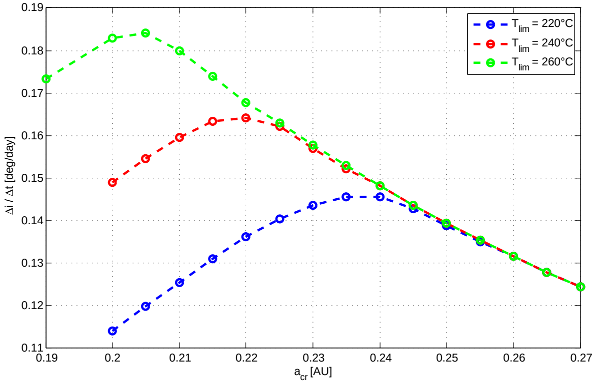

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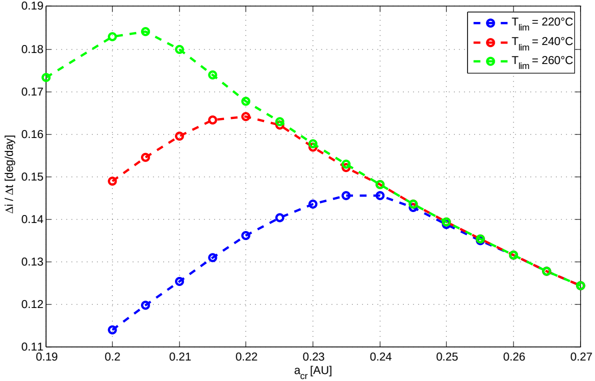

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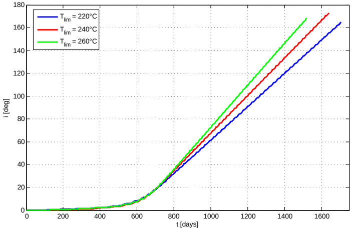
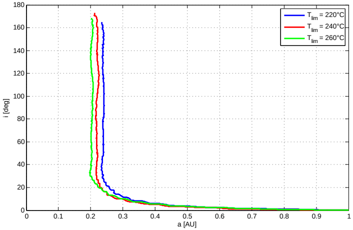


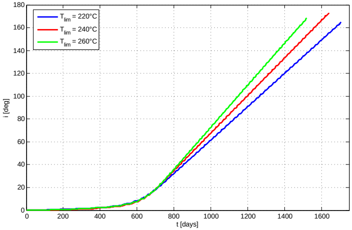
Inclination over flight time, $i(t)$



Inclination over semi-major axis, $i(a)$

The InTrance-trajectories match the determined optimal orbit-cranking semi-major axes very closely.

Variation of the Sail Temperature Limit



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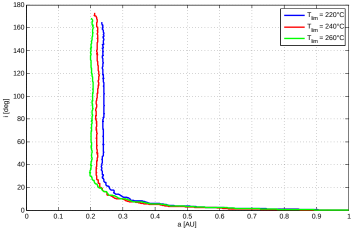

Inclination over semi-major axis, $i(a)$

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Variation of the Sail Temperature Limit

T_{lim} [°C]	$a_{\text{cr,opt}}$ [AU]	$(\Delta i/\Delta t)_{\text{max}}$ [deg/day]	Δt_{oc} [days]
220	0.236	0.1461	1722
240	0.220	0.1648	1604
260	0.205	0.1838	1513

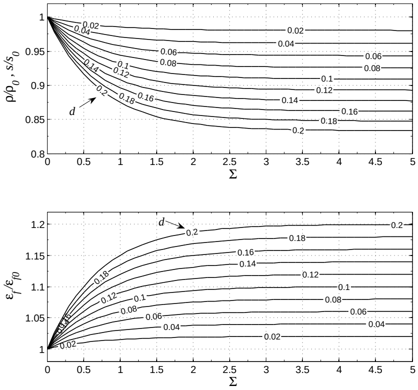
The time required for the orbit-cranking phase can be approximated with an error of less than 1% by

$$\widetilde{\Delta t_{oc}} \approx 765(1 - \tilde{a}_{\text{cr,opt}}) + \frac{166.7}{\widetilde{(\Delta i/\Delta t)}_{\text{max}}}$$

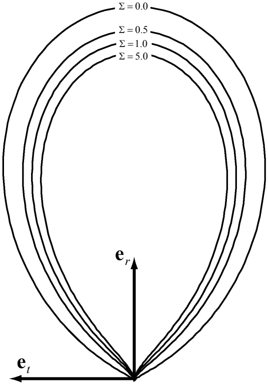
Note that 166.7 is the required inclination change in degrees and $1 - \tilde{a}_{\text{cr,opt}}$ is the spiralling-in distance in astronomical units

Solar Sail Degradation Model

(by Dachwald et al.)



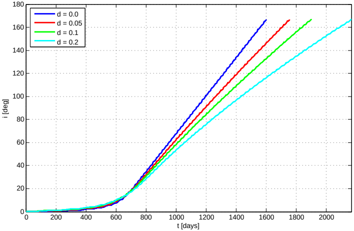
"degradation" of optical coefficients



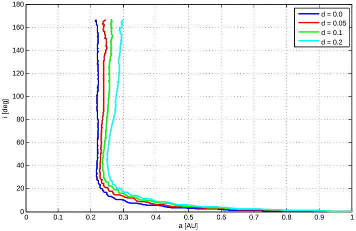
"degradation" of SRP force bubble

Solar Sail Degradation

"Half life" solar radiation dose $\hat{\Sigma} = 25\, S_0 \cdot \mathrm{yr} = 394\, \mathrm{TJ/m^2}$



Inclination over flight time



Inclination over semi-major axis

Degradation factor	Transfer time to ERO [days]	Attainment of ERO	Earliest possible Apophis impact Date	Calculated deflection from a single KEI [km]
0.0	2186	26 Dec 2025	02 Jan 2026	93.2
0.05	2395	23 Jul 2026	22 Nov 2026	69.5
0.1	2574	18 Jan 2027	11 Oct 2027	45.8
0.2	2816	17 Sep 2027	11 Oct 2027	45.8

Summary and Conclusions

- A single solar sail ($160\,\mathrm{m} \times 160\,\mathrm{m}$, 168 kg plus 150 kg impactor, $a_c = 0.5\,\mathrm{mm/s^2}$ and $T_{\mathrm{lim}} = 240^\circ\mathrm{C}$) is a realistic option to deflect Apophis with a kinetic impact before its 2029-Earth-encounter with very high velocity from a retrograde orbit
- Only a small and thus cheap launch vehicle is required
- Conventional KEI spacecraft (chemical, electrical) is also able to prevent Apophis from flying through a 600-m keyhole in 2029
- Our solar sail KEI mission concept, however, is also able to deflect larger asteroids out of a keyhole
- Using solar sail KEIs, it is still feasible to deflect asteroids that do not pass through a keyhole before impacting Earth
- In the latter case, however, a short lead time requires many KEIs

KEI Mission Challenges

- The mission performance might be seriously affected by optical degradation of the sail surface, as it is expected in the extreme space environment close to the sun
- Ground and in-space tests are required due to the unknown degradation behavior of solar sails in the space environment
- Extreme requirements for terminal guidance prior to impact (accuracy much better than 100 m at a relative velocity of $\approx 75\,\mathrm{km/s}$)
- Extreme requirements for thermal control that has to withstand very close solar distances ($0.2 - 0.25\,\mathrm{AU}$)

Solar Sailing Kinetic Energy Impactor (KEI) Mission Design Tradeoffs for Impacting and Deflecting Asteroid 99942 Apophis

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