Rapid Reconnaissance and Characterization of Potentially Hazardous Asteroids and Comets with Solar Sailcraft

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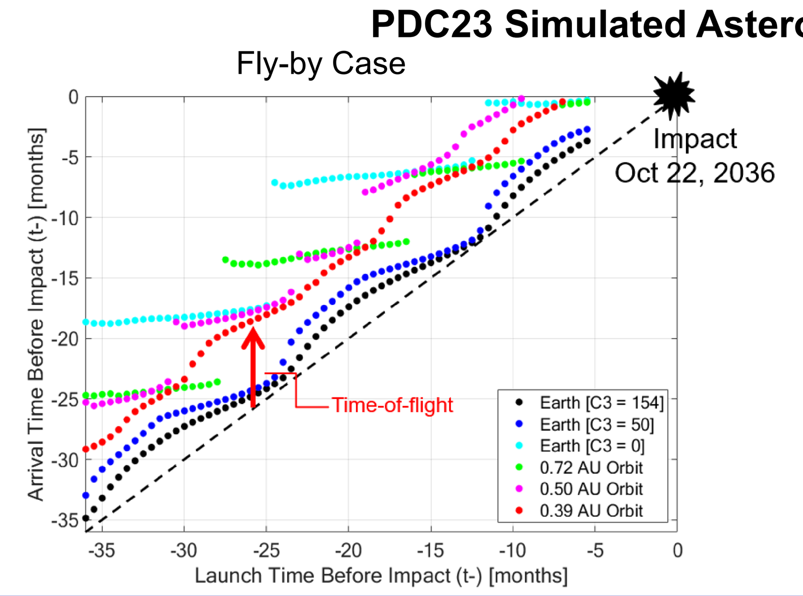
Introduction

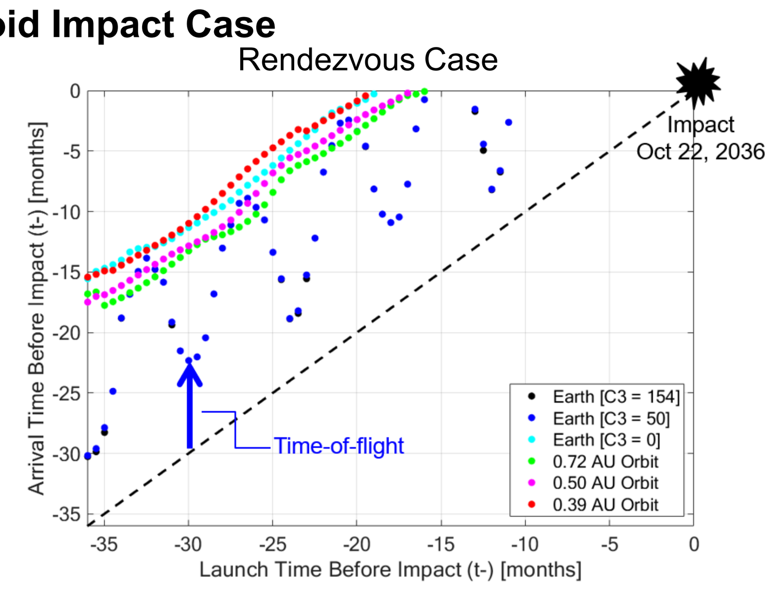
- *One of the goals in the 2018 National Near-Earth Object Preparedness Strategy and Action Plan states the need to develop technologies and designs for rapid-response NEO reconnaissance missions [2].*
- *A capability to rapidly launch a spacecraft to rendezvous with or fly by a NEO and perform reconnaissance is the only clear way to provide detailed and accurate information for an effective deflection or disruption mission.*
- *This study investigates mission scenarios options that provide a swift response to inspect a potentially hazardous asteroid (PHA) in-situ using modern solar sailcraft capability.*
- *There are several mission trades to consider from the perspective of launched versus strategically deployed sailcraft or PHA flyby versus rendezvous or the timeliness of the sailcraft to reach a PHA based its orbital geometry.*
- *This study will highlight simulated and real PHA cases, such as PDC25, PDC23, Apophis, cPDC 2019 Comet, 2024-YR4, where it is advantageous to employ a sailcraft reconnaissance mission with three or less years of warning time with several alternatives to demonstrate the flexibility in mission design space.*

Methodology

- *To investigate mission options for a sailcraft to reach an asteroid or comet via flyby or rendezvous, a parameter sweep was conducted over different impactful variables: launch conditions, asteroid reach conditions (rendezvous/flyby), the sailcraft's area to mass ratio, and launch time.*
- *For each combination of variables, the sailcraft trajectory was optimized using ASSET, a trajectory optimization program that allowed the sail to continuously change its orientation to minimize time-of-flight [3].*
- *The parameters were chosen to be based on realistic projections and possible scenarios. The values for area to mass ratio of the solar sail were 20, 30, 40, and 50 m2/kg [1]. The time of launch was as varied between 3 and 0.5 years before the asteroid impacting/flying-by Earth in one-month intervals. For each asteroid, both rendezvous and flyby options were considered.*
- *For the launch conditions, three Earth-based options were examined: leaving Earth with a C3 of 154, 50, or 0 km2/s2. A C3 of 154 km2/s2 was achieved for the Parker Solar Probe, so this was treated as the maximum energy that can be realistically expected for a launch vehicle to provide to the spacecraft.*
- *For the non-Earth based launch options, three circular orbits smaller than that of Earth were chosen as conceptual constellation of sailcraft deployed in advance near the orbits of Mercury or Venus.*
- *The launch time vs arrival time plots below are flyby and rendezvous trajectory cases for a simulated impact scenario PDC23. Each dot represents a solar sailcraft trajectory that was optimized for minimal time-of-flight, and the launch condition was parametrized for both Earth-based launches of different C3 and circular ecliptic constellations of different radii in the inner solar system.*

PDC23 Simulated Asteroid Impact Case





Solar Sail Acceleration

A solar sail generates acceleration by using the light from the Sun. Some of the sunlight is absorbed, pushing the sailcraft directly away from the Sun, while some of the sunlight is reflected. The direction of the force imparted on the sailcraft by the reflected light can be controlled by turning the face of the sail. Turning the face of the sail also affects the area that is facing the Sun, which controls the magnitude of the force.

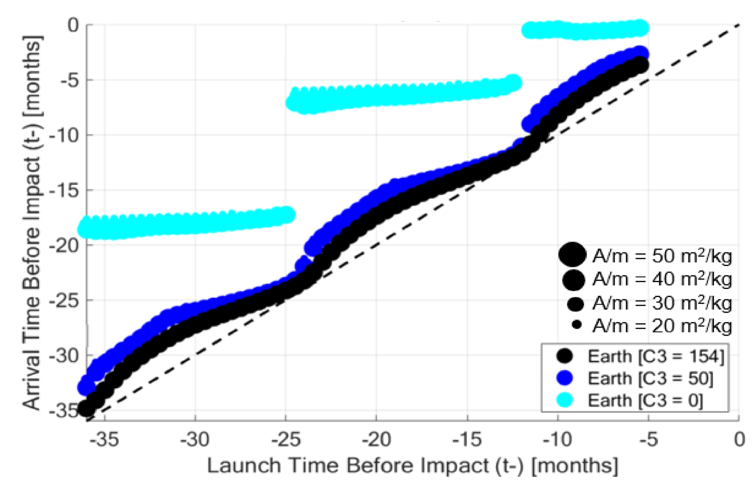
The equation to determine the acceleration imparted on the sail by the Sun is defined as

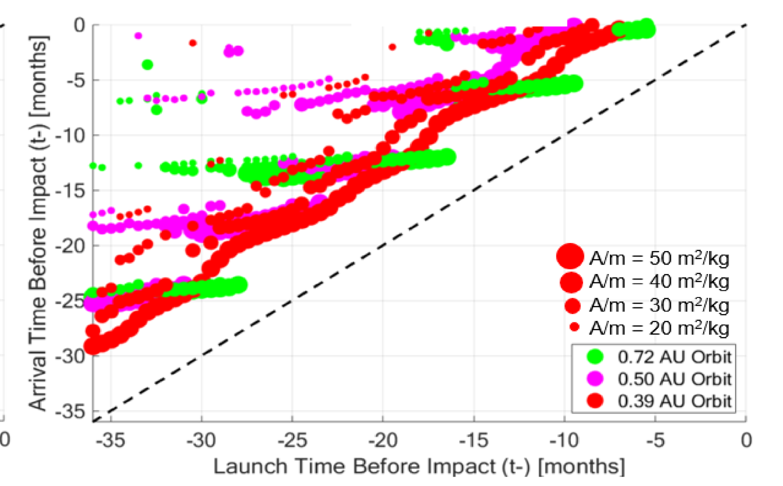
$$\boldsymbol{a}_{sail} = \Phi\eta\left(\frac{R}{s}\right)^2\left(\frac{A}{m}\right)\cos\theta\,[C_A\hat{\boldsymbol{s}} + 2C_M\cos\theta\,\hat{\boldsymbol{n}}]$$

where Φ is the solar flux as measured at R = 1 A.U., A is the net sail area oriented at angle θ, the vehicle mass m, and the reflectivity C_M and absorptivity C_A of the sail [1]. The control is the normal direction of the sail, $\hat{n}$, and $\hat{s}$ represents the direction outward from the Sun. The acceleration is also proportional to the inverse square of the distance from the Sun. This means that the sail will provide more acceleration as it gets closer to the Sun, providing a higher control authority.

Sailcraft Area to Mass Ratio Dependence on the Mission

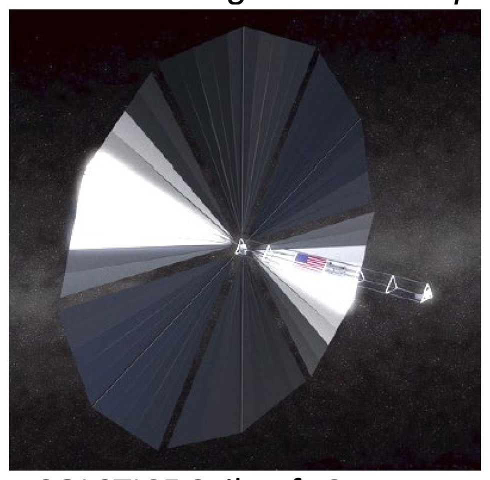
The flyby results for sailcraft reaching asteroid PDC 2023 are plotted for different area to mass ratios of the sail, with the righthand plot showing results from an inner orbit and the lefthand plot showing results with launches from Earth. The area to mass ratio of a solar sail can be very influential in amount of time it would take to fly-by an asteroid, but it is not a uniform effect and must be evaluated on a case-by-case basis.





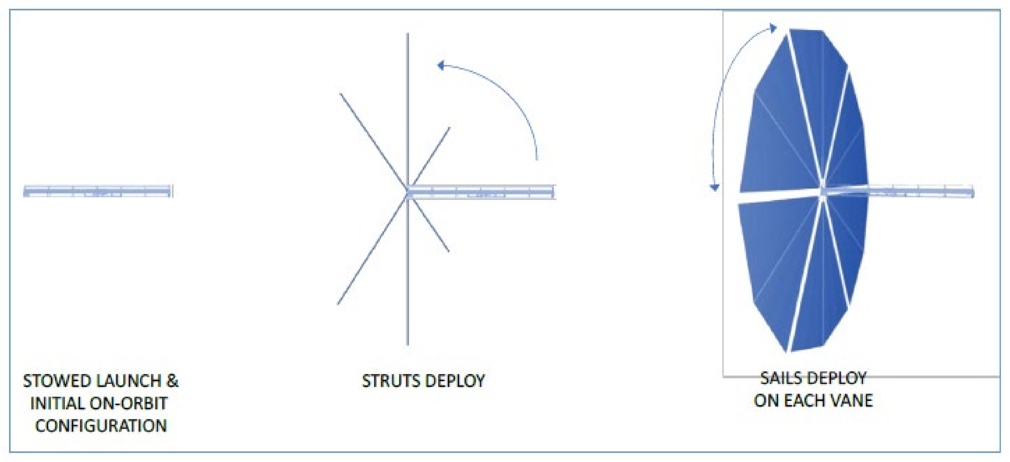
SOLSTICE-1 Vectored Sailcraft for Rapid Reconnaissance of PHAs

- *SOLSTICE* concept is a modern solar sail approach using articulating vanes to resolve multiple competing pointing and control constraints inherent in the planar sail designs.*
- *Multi-degree of freedom available for power generation, trajectory/thrust, communication, and maintaining line of sight for payloads [1].*
- *Fully 3-axis stabilized vehicle, set of reaction control wheels for pointing and multifunctional articulating sails with embedded photovoltaics and thin film phased array antenna elements [1].*
- *Carbon fiber truss-based design alleviates the need for deployment mechanisms, motors, and other unnecessary masses allowing more payload mass and better acceleration potential [1].*
- *Simplified deployment sequence akin to a large golf umbrella with single deployment action reducing overall complexity [1].*



SOLSTICE Sailcraft Concept

*SOLSTICE is covered under a patent with LGarde and NXTRAC, with permission



Deployment Sequence of a Stowed SOLSTICE vehicles

*The SOLSTICE concept was developed by NXTRAC/L.Garde and approved for use by The Aerospace Corporation to support planetary defense studies

Conclusions

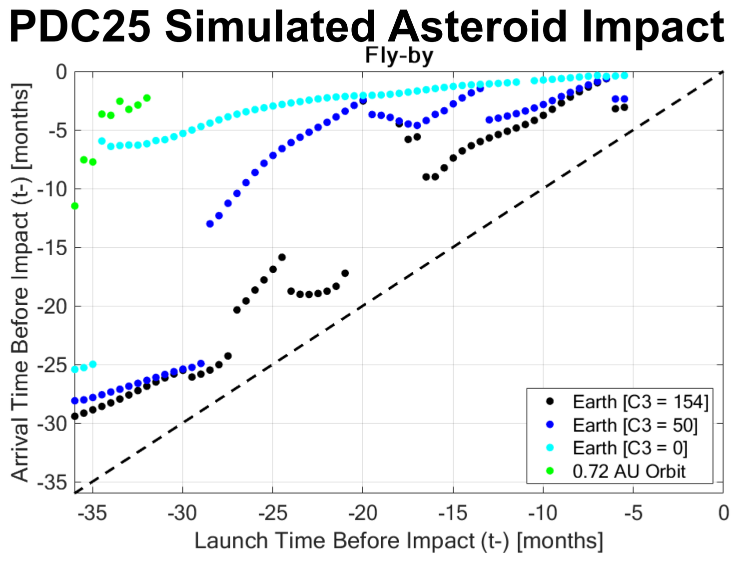
- *This SOLSTICE sailcraft concept attempts to address the desire for a rapid response capability to observe and collect science data on potentially hazardous asteroids and comets to better characterize these objects to act if necessary.*
- *Offers practical benefits of being low cost to develop in ~$9 - $12M per vehicle, and low launch costs being compact with low mass to launch multiple vehicles, and so are viable as a rideshare or primary on a smaller launch vehicle.*
- *For all target bodies considered in this study, there are flyby and/or rendezvous mission options available in three years or less.*
- *The benefits of developing and deploying these sailcraft ahead of time shortens the build time to launch in the event of a short warning time scenario, thus improving readiness.*

References

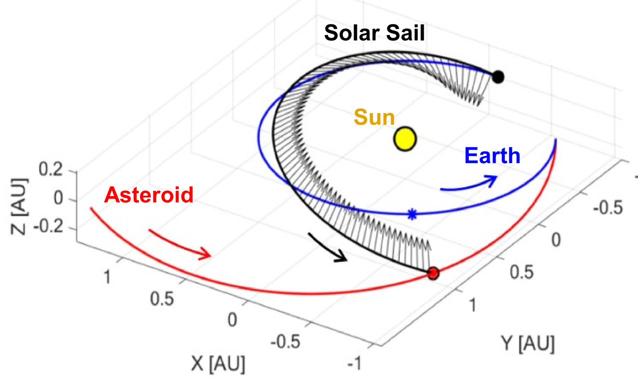
1. Conway, D., Garber, D., "A Vectored Sail Trajectory in Cislunar Space", 2024 SciTech Forum, Orlando, FL, Jan. 2024. DOI: 10.2514/6.2024-1809.
2. "National Near-Earth Object Preparedness Strategy and Action Plan," A Report by the interagency working group for detecting and mitigating the impact of earth-bound near-earth objects, June 2028
3. Pezent, James B., et al. "ASSET: Astrodynamics Software and Science Enabling Toolkit." Proceedings of the AIAA SciTech Forum 2022: Trajectory Design and Optimization I, AIAA 2022-1131, American Institute of Aeronautics and Astronautics, 29 Dec. 2021, https://doi.org/10.2514/6.2022-1131.

Rapid Reconnaissance Sailcraft Mission Cases

PDC25 Simulated Asteroid Impact Case



PD25: Aside from a handful of successful trajectories from an orbit of 0.72 AU that depart over 30 months from impact time, the only feasible departure point is Earth. The asteroid has a perihelion of 1 AU and an aphelion of 2.29 AU, so it is always relatively far from the Sun, where a solar sail is ill-suited because of the diminishing power of the Sun. From the Earth, the dedicated launches have windows of opportunity where it is more optimal to launch, separated by distinct regimes. Note that for this case, no fly-by trajectories were possible for a constellation of 0.50 AU or 0.39 AU



PDC25: This solar sail trajectory launched from Earth ten months before impact and did a flyby with the asteroid three months before impact, for a time-of-flight of seven months. The launch provided the sail with 50 km2/s2 of C3.

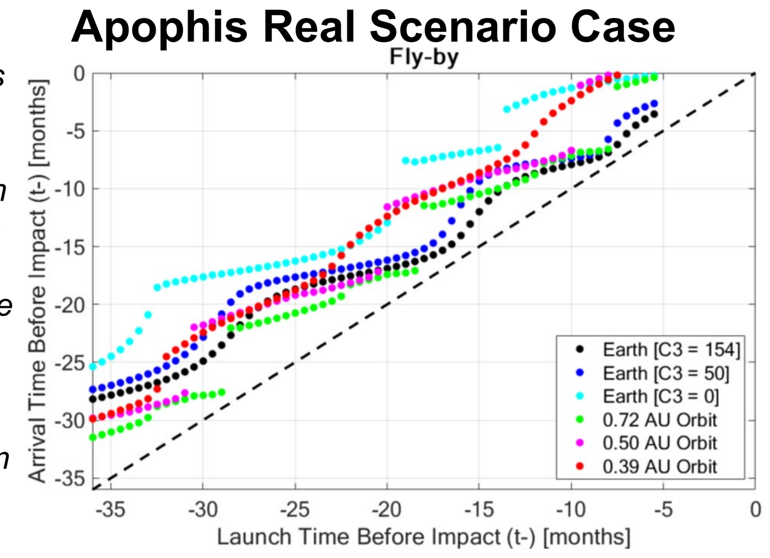
Asteroid and Comet Orbit Details

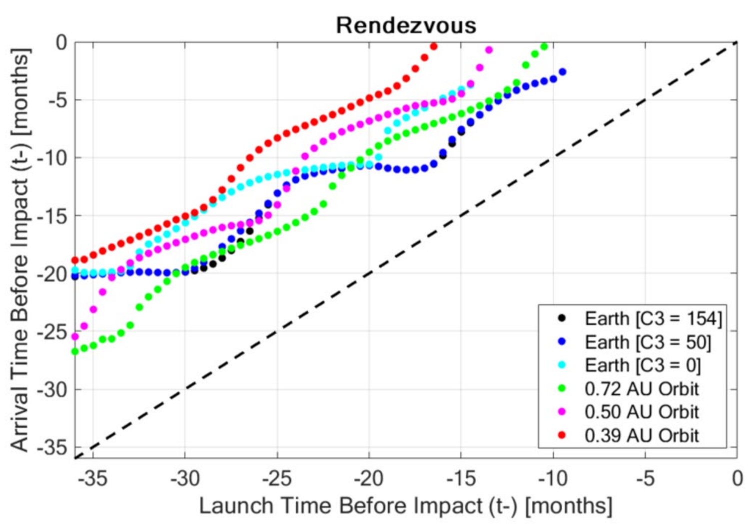
Asteroid	Potential Impact Date	Inclination (deg)	Perihelion (AU)	Aphelion (AU)	Period (days)
PDC 2025	4/24/2041	10.7	1.0	2.29	774
PDC 2023	10/22/2036	10.17	0.90	1.08	359
cPDC 2019	2/28/2021	128	0.92	444	1,214,265
Apophis	4/13/2029	3.3	0.75	1.10	324
2024 YR4	12/22/2032	3.46	0.84	4.2	1,467

The asteroids that were investigated for this study included three simulated asteroids (PDC 2025, PDC 2023, and cPDC 2019) and two real asteroids (Apophis and 2024 YR4).

Apophis Real Scenario Case

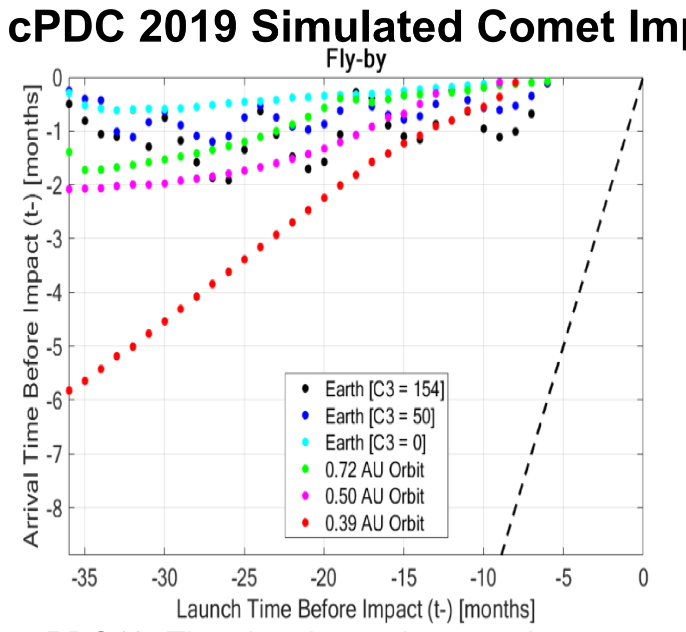
Apophis Flyby: The time-of-flight does not get longer than 15 months in this scenario, meaning the asteroid is relatively well positioned to fly-by from any launch condition. This is because of the small inclination and Earth-like orbit. One notable takeaway is that the sailcraft that begin in a 0.72 AU orbit, represented by green dots, consistently out-perform all other launch options for launches more than 18 months before the asteroid nearly impacts Earth.



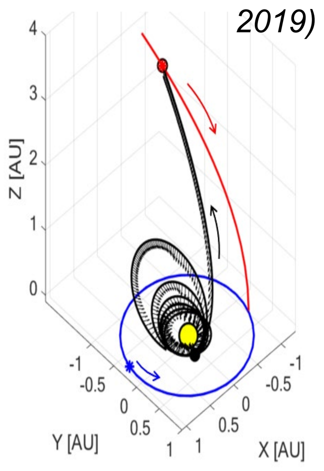


Apophis Rendezvous: The results from a 0.72 AU orbit and the Earth dedicated launches intertwine, meaning that the best launch condition is dependent on launch time. For launch times earlier than 20 months before potential impact, a sail starting at an orbit of 0.72 AU has the best results, with limited exceptions. This is because sails starting from this inner orbit have the benefit of more power from the Sun, while also being phased in the most opportune place.

cPDC 2019 Simulated Comet Impact Case

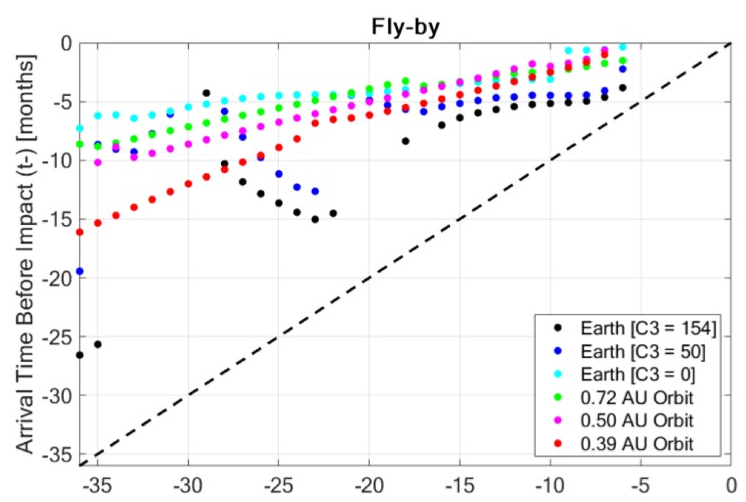


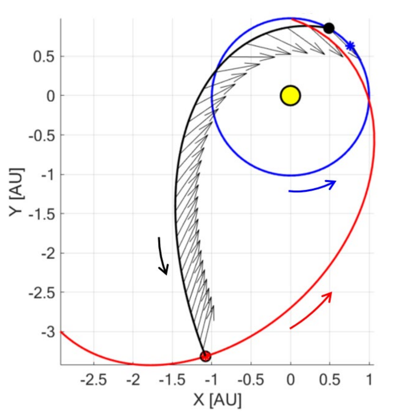
cPDC19: The plot above shows a clear advantage for a solar sail that begins closer to the Sun. This advantage is because the solar radiation pressure is greater at closer range to the Sun. The solar sailcraft can use this power boost to change its orbital inclination and increase its aphelion revolution by revolution. The Earth-based launch results stay near the one-month arrival time because they can only reach the asteroid as it is nearly impacting the Earth.



cPDC19: This solar sail trajectory that launched from Earth 36 months before impact and did a fly-by with the asteroid six months before impact, for a time-of-flight of 30 months. The sail began in an ecliptic orbit with a radius of 0.39 AU.

2024 YR4 Real Scenario Case





YR4: Solar sail trajectory that launched from Earth 25 months before impact and did a flyby with the asteroid 13.5 months before impact, for a time-of-flight of 11.5 months. The launch provided the sail with 154 km2/s2 of C3

YR4: Similar to the results from other asteroids that have a large aphelion, the time-of-flight from the inner orbit constellations are faster from orbits of smaller radii. The results from the 0.39 AU orbit were better than that of 0.50 AU, which are better than that of the 0.72 AU. The launches from Earth are very dependent on phase, as the point of launch is most optimal when the Earth's velocity can be utilized best to aide the sail trajectory. Earth launch is preferable to inner orbit launches only during optimal phasing windows of time.

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