Out of the Shades – Analysis of NEO Deflection using Planetary Sunshade Sailcraft for Planetary Defence

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Introduction

According to the latest IPCC report, it is unlikely that the +1.5°C target for the limitation of global warming can be achieved by the reduction of emissions on the ground alone. Several authors have studied the mitigation of severe effects of climate change on Earth by introducing solar radiation management from space. For this purpose, over 1.5 billion sunshield sailcraft could operate as one large "occulting disk". Therefore, the influence of re-directing a large number of sunshade sailcraft as kinetic impactors towards a fictitious asteroid, 2023 PDC, within the scenario created for the Planetary Defence Conference 2023 (PDC 2023) is analysed.

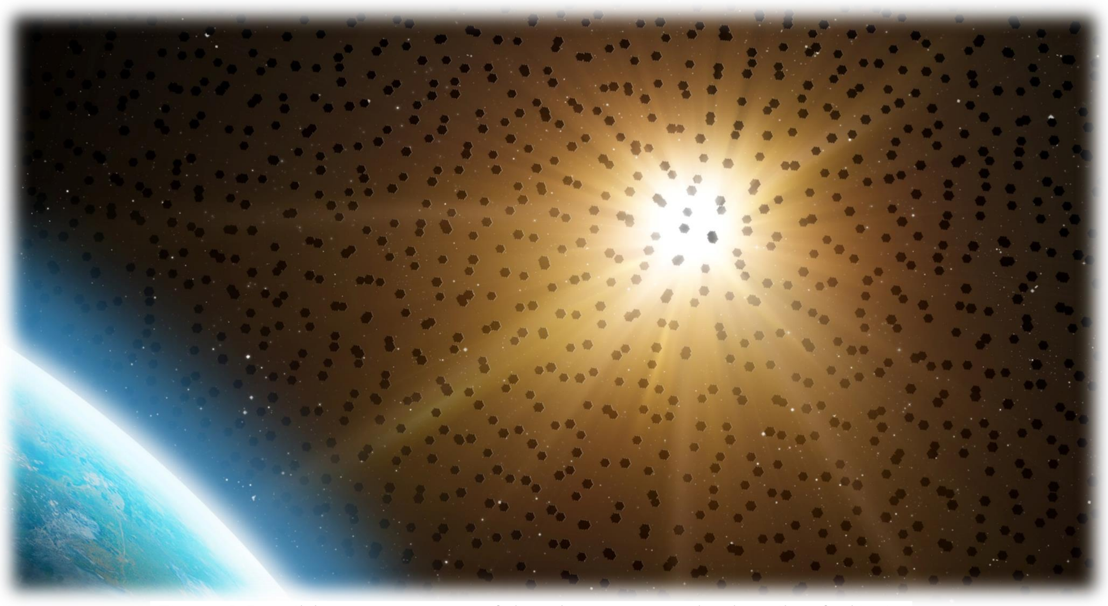

Figure 1: Possible arrangement of the planetary sunshade sailcraft. (Artist Impression)

Sunshade Sailcraft as Kinetic Impactors

- 1.5 billion sunshade sailcraft positioned near to L_1
- Loose sailcraft formation acts as a discontinuous occulting disk
- Overall mass of 3.4×10^{10} kg in orbit

→ High impact mass already available in interplanetary space
→ No need for high impact success rate due to large number of available sails
→ No need for high specific impact energy per sail

Objectives

Goal of this work is to determine the required mass and, therefore, the required number of sails colliding with the asteroid at a specified impact-time-range to achieve the desired deflection distance from Earth (roughly one Earth diameter). Furthermore, our work is concerned with identifying optimal trajectories for sailcraft from this sunshield to achieve an optimal execution of the kinetic impacts. Note: This research is still in progress and provides a midterm report of the investigations done so far. Especially the design and optimisation of the sailcraft trajectories, to get from the origin position (L_1) to the impact-orbits, is still part of the future work.

Table 1: General Data of one Sailcraft

Mass	81 kg
Area	9000 m²
Characteristic Acceleration	0.9 mm/s²

Methodology

In this study, optimisation is a trade-off between the flight time to improve the impact trajectory and the time to accumulate the deflection from each impact.

Specification of impact orbits → Determination of the required momentum transfer → Calculation of sail departure trajectories → Date selection for the KEI

Implementation of the Kinetic Energy Impacts

The momentum transfer to the asteroid occurs through cumulative collisions between the asteroid and the sailcraft, meaning the sails take on the role of the kinetic energy impactors (KEI). For the theoretical implementation, these kinetic impacts are assumed to be conducted prograde to the heliocentric orbital movement of 2023 PDC. The momentum enhancement factor is set to one (β = 1).

$$\Delta \boldsymbol{V} = \beta \frac{m_{\text{sail}}}{M_{\text{PDC23}}} (\boldsymbol{V}_{\text{sail}} - \boldsymbol{V}_{\text{PDC23}})$$

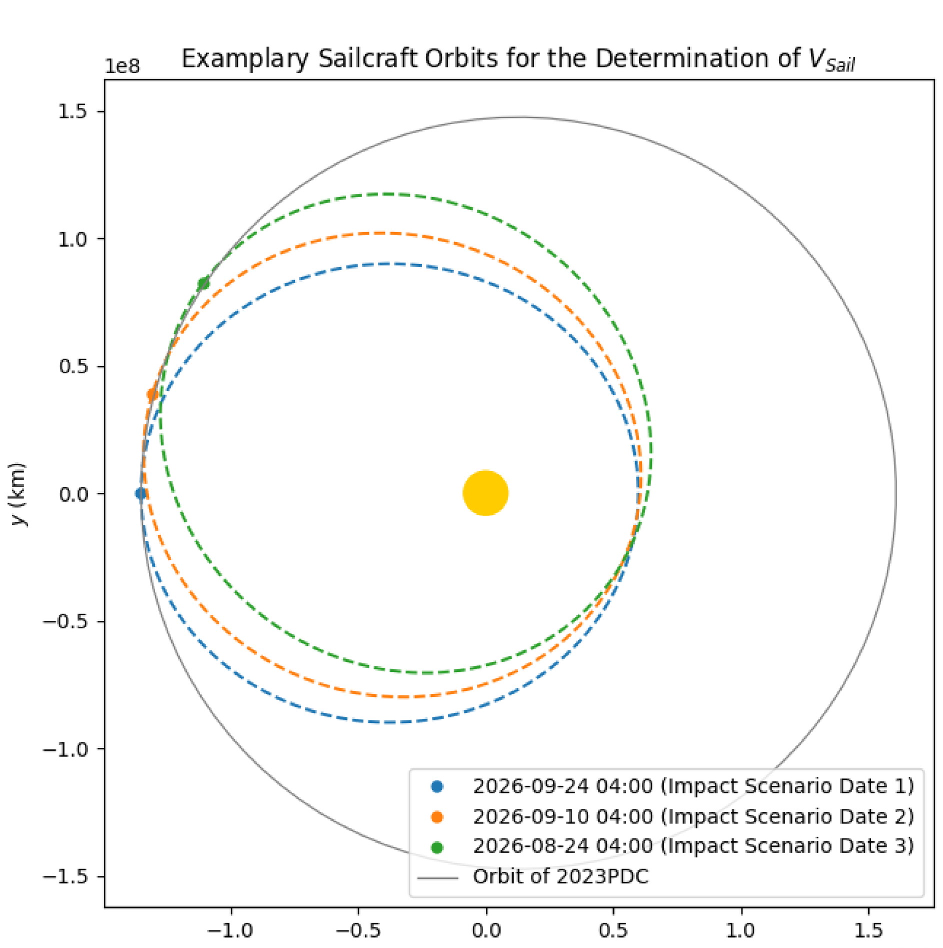

Figure 2: Three exemplary impact scenarios and the corresponding sailcraft orbits to determine the sail velocity at impact.

Specification of Impact Orbits for the Determination of the Sail Velocity

To determine the velocity of the sailcraft at a certain impact date, the corresponding sailcraft orbits to reach 2023 PDC are specified. These orbits are designed to meet the asteroid at the sailcraft's solar apoapsis, which consequently equals the solar distance of 2023 PDC at the according impact time.

Due to the temperature limitations concerning the material of the sunshade sailcraft assembly, the chosen perihelion distance amounts to 0.4 au. (*Figure 2*)

The Figure shows three exemplary impact scenarios with the according impact orbits of the KEI, where e.g., *Impact Scenario 1* (blue orbit) includes a kinetic impact at the asteroid's perihelion.

Determination of the Required Momentum Transfer

To determine the required ΔI, the deflected impact trajectory is simulated over several years with the following conditions:

- $\Delta I = m_{sail}\, V_{imp}$, with $V_{imp} = V_{sail} - V_{PDC23}$
- Safe deflection distance is $2R_{\oplus} \approx 12760$ km
- Estimated asteroid mass is $M_{PDC23} = 1.087 \times 10^{11}$ kg
- Ideal Impact execution (entire mass is used for momentum transfer)
- Simulation is conducted within Python & Poliastro

Prospective Trajectory Calculation of the Sunshade Sailcraft

The determination of the according sailcraft trajectories represents an obligatory part of the future work. This optimisation process is essential in order to navigate the sunshade sailcraft from the departure location, near to L_1, to the desired impact orbits.

The specified departure trajectories will set a frame of feasible dates for the impacts and the associated required number of KEI.

Results

Required Momentum Transfer over Time

By simulating the deflected asteroid trajectory over several impact dates (from October 2024 to October 2031), the course of the required momentum transfer can be specified. As expected, the trendline of the required ΔI rises exponentially over time. (*Figure 3*)

Consequently, also the required impactor mass and the according number of sails rises the later the kinetic impact is carried out.

Distribution of Impacts over Time

By assuming the 22 October 2026 as the date of the first impact, the application of 1500 KEI per day would take 32 days to achieve the desired safe deflection distance from Earth. (*Figure 4*) This scenario would imply one sail-impact per hour. Also the cases for 2000 and 3000 impacting sailcraft are shown. A significant aspect of the calculation is the comparatively high mass of the asteroid, which is one of the main reasons for the large number of KEI required. If 2023PDC had the mass of asteroid 99942 Apophis, it would only require 550 impactors per day to deflect it within the same impact-period of 32 days.

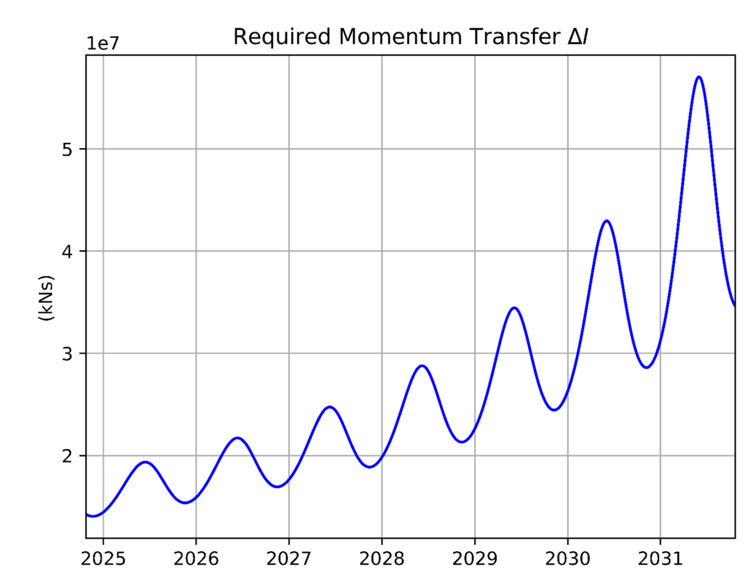

Figure 3: Required ΔI for deflection over several impact dates (from 22 October 2024 to 22 October 2031)

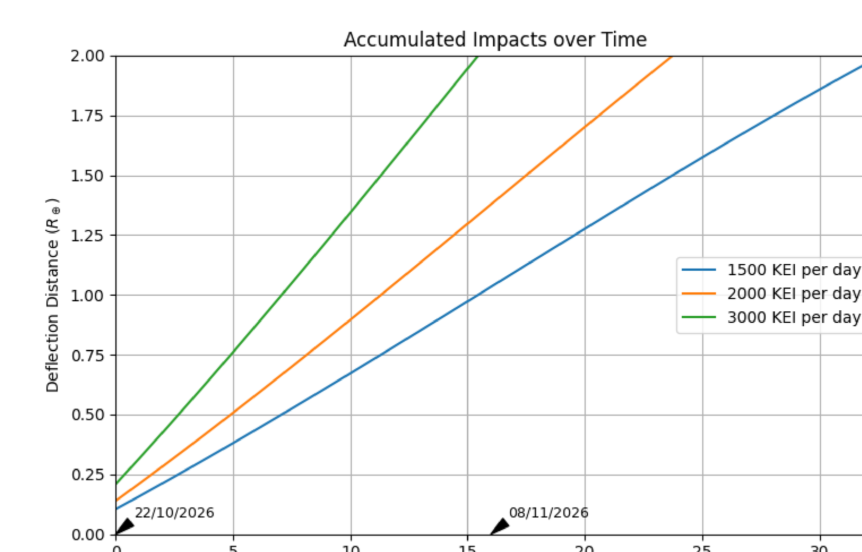

Figure 4: Accumulated impacts per day to achieve the safe deflection distance. Date of first impact: 22/10/2026

Conclusion & Outlook

For this research, the application of planetary sunshade sailcraft as KEI for asteroid deflection is analysed within the context of the PDC 2023. The significant advantage of this concept is the availability of a high amount of mass already located in interplanetary space. Therefore, this study represents an estimate of the required framework conditions and capacities needed to realise a successful deflection procedure of 2023 PDC. The results show that the safe deflection distance of $2R_{\oplus}$ could be reached within an impact period of 32 days using 1500 KEI per day. For this purpose, one KEI is assumed to have one sunshade sail mass of 81 kg. However, this scenario presupposes the 22 October 2026 as the date of the first impact.

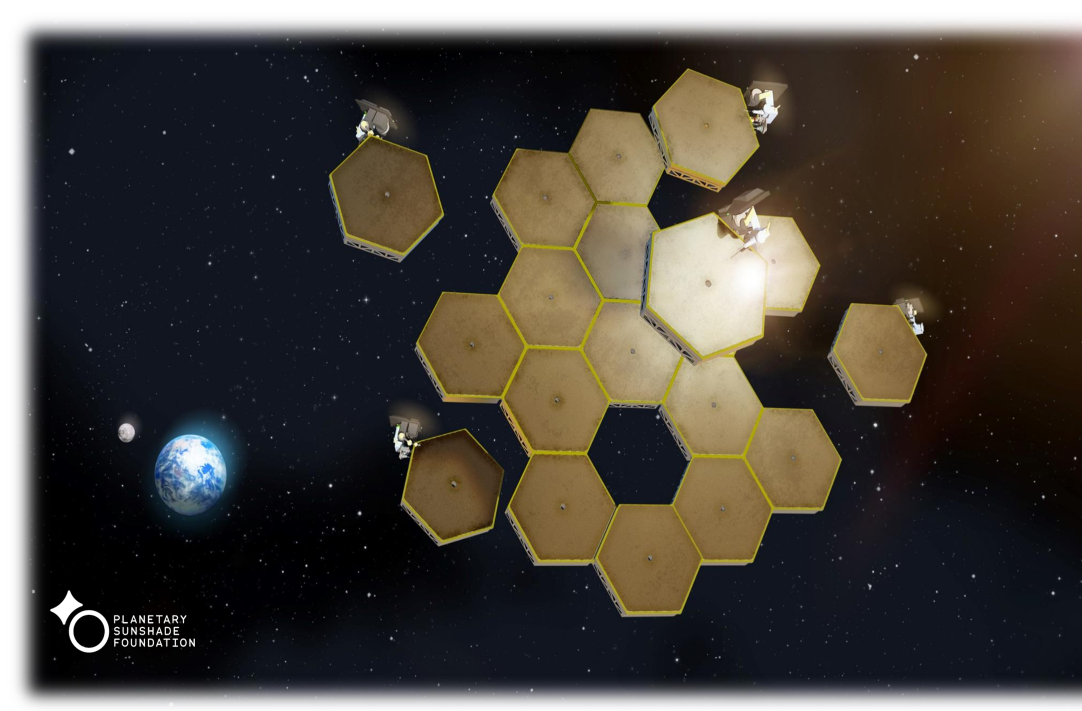

Figure 5: Possible formation of the planetary sunshade sailcraft. (Artist Impression)

Our future work is concerned with the determination of the departure trajectories of the sunshade sailcraft in order to set a time frame for the impact dates to complete the optimisation process and to select an appropriate deflection scenario. For this, optimal sailcraft trajectories from L_1 to the final impact orbits must be determined under the conditions of the planetary sunshade sailcraft properties. Subsequently, a more precise time schedule, would enable a much more detailed specification of the required momentum transfer and thus the required impactor-mass (sailcraft number). With this knowledge, the mission procedure can be extended and adapted to further planetary defence missions involving asteroid deflection. Furthermore, a comprehensive analysis of the ejecta evolution and the resulting momentum enhancement due to sail-impacts into asteroids would also provide a more precise analysis.

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