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OUT OF THE SHADES – ANALYSIS OF NEO DEFLECTION USING PLANETARY SUNSHADE SAILCRAFT FOR PLANETARY DEFENCE

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Extended Abstract—

1) *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. [2] Several methods for active climate control have been proposed. Unlike most of them, solar radiation management by a planetary sunshade does not directly interfere with the Earth’s atmosphere and ecosystems. 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 football-field-sized (factor 1.25-1.5) sunshield sailcraft could operate as one large "occulting disk". These sailcraft would be positioned near the Sun-Earth Lagrange point 1 (L_1) and therefore, as an additional benefit, may provide a viable option for planetary defence through PHA deflection.

This work analyses 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).

Assuming that a planetary sunshade has already been successfully deployed, the high mass already present in interplanetary space provides a significant advantage. 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. Since many "impact-sails" are available, a high impact success rate per sail is not mandatory, which significantly relaxes requirements regarding sailcraft control right before the impact. The high available mass also allows relaxations concerning the specific impact energy required per sail, reducing the lead time, and consequently shortening the overall trajectory.

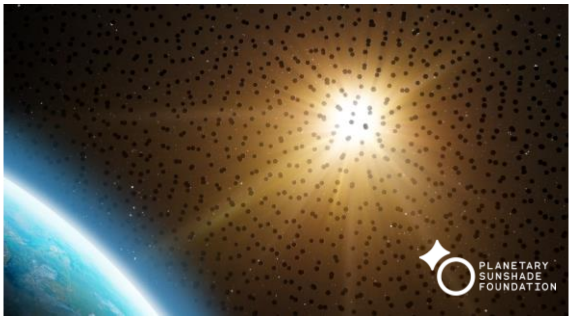
a) Objectives

The 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. The simulations are implemented within the programming environment *Python* with the complementary use of *Poliastro,* a library for astrodynamics and orbital mechanics.

Important to 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.

2) *Planetary Sunshield Sailcraft*

As mentioned before, the purpose of the planetary sunshade sailcraft is to operate as one large sunshield placed near the Sun-Earth Lagrange point (L_1). The individual sailcraft are intended to form a loose constellation and a discontinuous occulting disk. Furthermore, the desired occultation effect does not necessarily presuppose the occurrence of umbral shadows. (*Figure 1*) Concerning the optimal occultation effect and the influence of the solar radiation pressure, the ideal position of the sunshield-disk deviates from the exact L_1 -position. Research by McInnes et. al. identifies the optimal location of the sailcraft to be about 2.4 million kilometres sunward from Earth. [3] The physical properties of the sailcraft, which are used for further calculations can be taken from *Table 1*.



. *Figure 1: Possible arrangement of the planetary sunshade sailcraft. [1]*

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

Table 1: General Data of one Sunshield Sailcraft [3,4]

In the case of this sailcraft arrangement, the total mass of the entire disk amounts to 3.4×10^{10} kg. [4]

3) Analysis of the Deflection Trajectory

a) Implementation of the Kinetic Energy Impacts

In general, 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. Therefore, the change in 2023 PDC's velocity ($\Delta \boldsymbol{V}$) can be determined by

$$\Delta \boldsymbol{V} = \beta \frac{m_{\text{sail}}}{M_{\text{PDC23}}} (\boldsymbol{V}_{\text{sail}} - \boldsymbol{V}_{\text{PDC23}}) \tag{1}$$

where $\boldsymbol{V}_{\text{sail}}$ and $\boldsymbol{V}_{\text{PDC23}}$ are the tangential velocity vectors of sailcraft and asteroid during the impact. [5] Since the sunshade sails are primarily composed of a thin and lightweight film, the momentum enhancement factor β is set to one for further calculations. Consequently, the following analysis includes no momentum enhancement caused by impact ejecta and the deflection distance is solely conducted by the collision-induced momentum transfer to the asteroid. In addition, this work assumes a perfectly executed impact between sail and asteroid, where the complete sail mass is used for the momentum transfer. Referred to studies dealing with the investigation of asteroids located in the inner asteroid belt, the density of 2023 PDC can be assumed to be ≈ 2.0 g/cm³. [6] Together with the given diameter of 470 m a corresponding asteroid mass (M_{PDC23}) can be estimated and amounts to 1.087×10^{11} kg for this study. Important to mention, a comparison of 2023 PDC's diameter with the size of common NEO's such as 99942 Apophis, reveals that the dimensions of 2023 PDC, and therefore it's corresponding mass properties, exceed the average values. [7] The simulation is conducted within the programming environment Python and the usage of Poliastro.

b) Determination of the Required Momentum Transfer

The selection of the optimal impact dates is mainly influenced by the required total change in the asteroid's momentum (ΔI) and thus by the required impactor mass (m_{sail}), which in turn determines the number of necessary impacting sailcraft. In this work, the minimum safe deflection distance for the analysis of the deflection efficiency is chosen as one Earth diameter or roughly two Earth radii ($2R_{\oplus} \approx 12760$ km). [8] From *Equation (1)* yields the relation $\Delta I = m_{\text{sail}} V_{\text{imp}}$, where the impact velocity V_{imp} equals the difference between V_{sail} and V_{PDC23}. Therefore, the impacting sail mass and velocity must be weighed up to realise a sufficient ΔI for a given impact date. 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. (*Figure 2*) Due to the temperature limitations concerning the material of the sunshade sailcraft assembly, the chosen perihelion distance amounts to 0.4 au. [4,5] *Figure* 2 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.

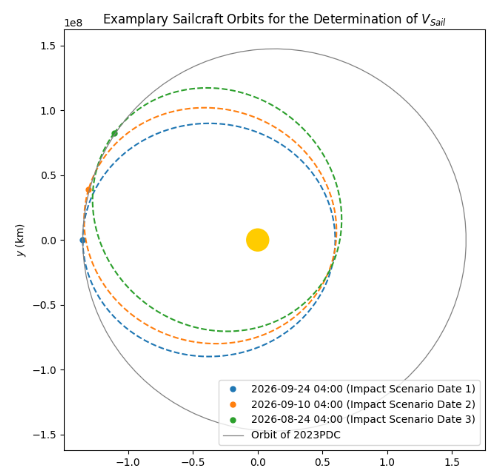


Figure 2: Three exemplary impact scenarios and the corresponding sailcraft orbits to determine the sail velocity at impact.

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 and is shown in *Figure 3.* As expected, the trendline of the required ΔI rises exponentially over time. The simulation results imply, the optimisation of the deflection process is concerned about a trade-off between sufficient impact velocity and mass as well as a suitable impact time. The latter is limited by the flight time of the sailcraft from the start location near to L_1 until they reach the asteroid.

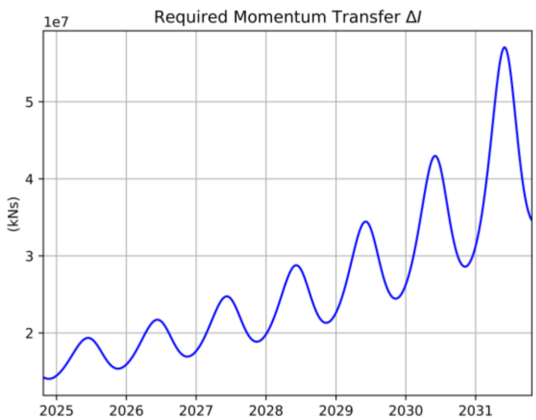


Figure 3: Required ΔI for deflection over several impact dates (from 22 October 2024 to 22 October 2031)

c) *Distribution of Impacts over Time*

Due to the large number of sailcraft already present in interplanetary space, the planetary sunshade constellation would also allow a series of sequenced impacts over several days. 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. In other words, this scenario would imply *one* sail-impact *per hour.*

In *Figure 4*, also the cases for 2000 and 3000 impacting sailcraft per day are shown.

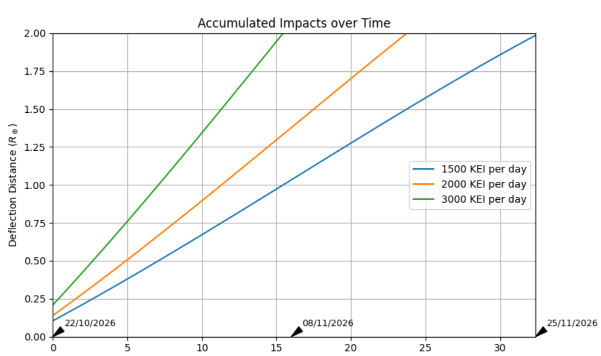


Figure 4: Accumulated impacts per day to achieve the safe deflection distance. Date of first impact: 22/10/2026

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 2023 PDC 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.

4) *Prospective Trajectory Calculation of the Sunshade Sailcraft*

As mentioned before, 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. The respective calculations are based on the general parameters of the planetary sunshade sailcraft shown in *Table 1.*

5) *Conclusion*

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, which enables relaxations concerning the impact success rate as well as the required specific impact energy per sailcraft. This simplifies the sailcraft control right before the impact as well as the preliminary trajectory design. Therefore, this study represents an estimate of the required framework conditions and capacities needed to realise a successful asteroid 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.

6) *Outlook*

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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