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Near Earth Objects deflection strategies: a multicriteria comparison for the target asteroid 2023 PDC

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Abstract

The Solar System is populated by many asteroids and comets which orbit around the Sun. Some of these objects' trajectories can cross Earth's orbit, causing a collision. In particular Near Earth Objects (NEOs) can represent a collision threat to our planet. Historically, asteroids and comets have been impacting our planet, as the Chelyabinsk event, in 2013. This has motivated space agencies to set planetary defence programs, with the aim of selecting and developing different technologies for the deflection of potentially lethal asteroids and protect Earth from their resulting impact.

Continuing and extending the work of Sanchez et al. (2009), in this paper all the deflection strategies discussed in literature are described and compared, considering asteroid 2023 PDC as a target, a fictitious asteroid presented by NASA as an exercise in the Planetary Defence Conference (PDC). In the proposed solution by NASA in B. Barbee et al. (PDC 2023 simulated impact threat scenario, April 2023), only two strategies, kinetic impactor and nuclear standoff explosion were considered, and it was concluded that only the second one is useful for the deflection of 2023 PDC.

In addition to these two, in this article more strategies are considered, namely: multiple kinetic impactor, gravity, electrostatic and magnetic tractor, mass driver, ion beam shepherd, tugboat, laser ablation, tether ballast system and deviation through exploitation of the Yarkovsky effect.

Based on a trade-off considering TRL, Δv provided to the asteroid to deflect it, effectiveness of the strategy, warning time, mission complexity and sensitivity to asteroid properties uncertainties of each technology, four of the listed strategies are considered for the following analysis: kinetic impactor, nuclear explosion, gravity tractor and laser ablation. A genetic algorithm based multi-objective optimisation process is used to maximise the deviation and to minimise the probability of collision. The results in terms of deflection are shown in Pareto fronts, using the deviation at Minimum Orbital Interception Distance (MOID), the initial spacecraft mass and the warning time as variables for the optimisation.

The paper concludes that, in addition to nuclear explosion, as suggested by NASA, also a multiple kinetic impactor missions, exploiting deep-space manoeuvres, with seven spacecraft of mass equal to 5700 kg, and a multiple gravity tractor strategy consisting of eight satellites (each one with mass of 11000 kg) disposed in two artificial Halo orbit, and laser ablation can be used to completely deviate the trajectory of asteroid 2023 PDC and avoid collision with Earth.

Keywords: NEOs, Deflection strategies, Planetary protection, multiobjective optimisation

Nomenclature

β = momentum enhancement factor
λ = scatter factor
δr_{MOID} = variation of the position at MOID
σ = standard deviation
d_{ast} = asteroid diametre
G = constant of gravitation
M_{ast} = asteroid mass
m_{sc} = spacecraft mass
t_w = warning time
t_{MOID} = time at MOID
v_e = ejection velocity

Acronyms/Abbreviations

IBS = Ion Beam Shepherd
MOID = Minimum Orbital Interception Distance
NEO = Near-Earth Object
PDC = Planetary Defence Conference
PoC = Probability of Collision
TRL = Technology Readiness Level
MKI = Multiple Kinetic Impactor

1. Introduction

In our Solar System thousands of asteroids and comets are orbiting around the Sun. Some of them may have a trajectory which could intercept Earth orbit, bringing to a collision.

For this reason space agencies have planned Planetary Defence programs. NASA, during the 2023 Planetary Defence Conference, proposed a fictitious asteroid (called 2023 PDC) to simulate an emergency response.

The goal of the article is to determine which deflection strategies can be used to deflect the asteroid and avoid collision with the Earth. First of all the deflection strategies are discussed, mathematically modelled and then compared in terms of Δv given to the asteroid.

A genetic algorithm multiobjective optimisation is then performed on four selected strategies in order to compute precisely the maximum deflection that can be obtained and also which strategies guarantee the minimum PoC with the Earth.

2. Asteroid Deflection strategies

The deflection strategies are divided into impulsive deflections, mainly kinetic impactor and nuclear explosion, and slow push deflection [1].

2.1 Impulsive deflection strategies

Impulsive deflection means that the deflection action is instantaneous.

The kinetic impactor strategy is the simplest one since it consists in an impact with the target asteroid through a massive projectile at a high relative speed. The variation of velocity given to the asteroid depends indeed on the relative velocity between spacecraft and asteroid, on the masses and on the momentum enhancement factor β, introduced because in reality the collision is not inelastic. So:

$$\Delta v_{KI} = \frac{\beta m_{sc}}{M_{ast} + m_{sc}} \Delta v_{sc} \tag{1}$$

Where β is the momentum enhancement factor, m_{sc} and M_{ast} are respectively the mass of the spacecraft and the mass of the asteroid and Δv_{sc} is the final relative velocity between them.

In the nuclear standoff explosion a nuclear warhead explodes at a certain optimal distance from the surface and deflects the asteroid through the debris which hits the surface and through radiations: X-rays, neutrons and γ-rays [2]. So the total Δv obtained is:

$$\Delta v_{nuc} = \Delta v_{debris} + \Delta v_{X-rays} + \Delta v_{\gamma-rays} + \Delta \mathrm{v}_{\mathrm{neutrons}} \tag{2}$$

The process to compute each terms of eq. (2) can be found in [17].

2.2 Slow push deflection strategies

If the action is continuous in time then the strategy is considered a slow push deflection.

In literature many different strategies have been proposed.

The starting point is the simplest slow push strategy, which is the gravity tractor [3]: the deflection is obtained exploiting the gravitational attraction between asteroid and spacecraft, which hovers around the object. The acceleration acting on the asteroid is [3]:

$$a_{GT}(t) = \frac{Gm(t)}{d^2} \tag{3}$$

where *d* is the hovering distance and *m* is the mass of the satellite, which decreases in time since propellant is consumed.

This deflection can be augmented through an in situ mass collection (enhanced gravity tractor), or exploiting the electrostatic and magnetic force [17].

The mass driver strategy is simply based on Newton's third law of dynamics, so for every action it corresponds an equal and opposite reaction. In this case the idea is to remove material from the asteroid and to eject it, in this way a force in the opposite direction is generated on the asteroid: momentum is conserved. The velocity variation obtained is [4]:

$$\Delta v_{MD} = n_{launches} \frac{m_{mat}}{m_{ast}(t)} v_e \tag{4}$$

Where m_{mat} is the mass of the material removed, v_e is the ejection velocity and $n_{launches}$ is the number of launches.

The ion beam shepherd (IBS) consists in pointing an high velocity ion beam, produced by an ion thruster on board of a shepherd spacecraft, towards the asteroid and in this way modify its orbit [5][17].

The concept of asteroid tugboat consists in deflecting the NEO by docking with it for a long period of time and push (or pull) with the thrusters in the correct direction to modify the trajectory and avoid the collision with Earth [2].

The solar collector strategy makes use of a collector which focuses sunlight on the asteroid surface to ablate the material. The escaping gas and particles produce a continuous thrust which changes the trajectory of the asteroid.

The same concept is exploited by the laser ablation strategy, which substituted the solar collector one, since it is less sensitive to degradation problems [6]. In this case the laser plays the role of the collector: it focuses the beam on the surface of the asteroid to generate sublimation. The force obtained depends on the mass flow rate of the sublimated material $\dot{m}$:

$$F_{sub} = \lambda v \dot{m} \tag{5}$$

where λ is the scatter factor and *v* is the average velocity of the ejecta gas particles. Then the velocity variation is obtained by integration:

$$\Delta v_{las} = \int_{t_i}^{t_f} \frac{F_{sub}}{M_{ast}(t)} dt \tag{6}$$

The detailed process to obtain eq. (6) can be find in [17].

Another possible slow push strategy exploits the Yarkovsky effect, which is a non gravitational force caused by thermal radiation from a body which have non uniform surface temperatures. If the albedo or the thermal conductivity of the asteroid is modified, the effect can be enhanced [7].

Lastly the tether-ballast system is considered: it involves the use of a long tether and a ballast mass attached to the NEO (Near-Earth Object). The trajectory is modified by a immediate center of mass offset after the attachment of the ballast mass, so also the orbit changes, and by the tether tension that adds a perturbing force which affects the trajectory [8].

3. Comparison between strategies

In order to compare the strategies the velocity variations are computed considering as a target asteroid 2023 PDC (dimension and mass considered are the median values). The numerical results shown in Fig. 1 are obtained using the equations reported in section 2 and in [17].

Concerning the impulsive strategies, the kinetic impactor is the only flight proven technology (DART mission). So the TRL is very high. Anyway the problem is that it is strongly affected by the uncertainties in the asteroid composition, which defines the coefficient β .

So, while the kinetic impactor technique can be very useful for small asteroids, a nuclear explosion is more effective for larger ones. Standoff nuclear explosion carries the highest energy density among all the deviation methods and it is less sensitive to possible uncertainties in the asteroid composition and surface morphology. On the contrary more critical studies are needed to verify the safety, more than in other mission, because in case of a failure during the launch a huge quantity of radioactive materials would be released in the atmosphere.

As far as the slow push methods are concerned, the problem of accidentally destroy the asteroid is no more present, but other issues arise, specific for each strategy.

Starting from the Gravity Tractor, the main advantages of this technique are that it is a contactless deflection and it is insensitive to structure, composition and rotation of the NEA. The main disadvantage is the very long warning time needed for the deflection, otherwise the Δv provided is not enough.

A variation of the gravity tractor is the Enhanced Gravity Tractor (EGT), which considers to collect mass in loco to augment the mass of the spacecraft. In this case the deflection is augmented, but the TRL is very low since the mission complexity is higher than the standard GT.

Both the electrostatic and the magnetic tractor augment the gravitational effect, but they generate other issues: in the first case both the spacecraft and the asteroid must be charged (low TRL), while in the second case a magnet has to be attached to the asteroid, so a correct and strong attachment system has to be designed. With the Mass Driver strategy a controlled application of perturbing force is obtained and it provides more impulse with respect to the tractor strategies (see Fig. 1). On the other hand, as explained before for the Enhanced Gravity Tractor, the TRL is low.

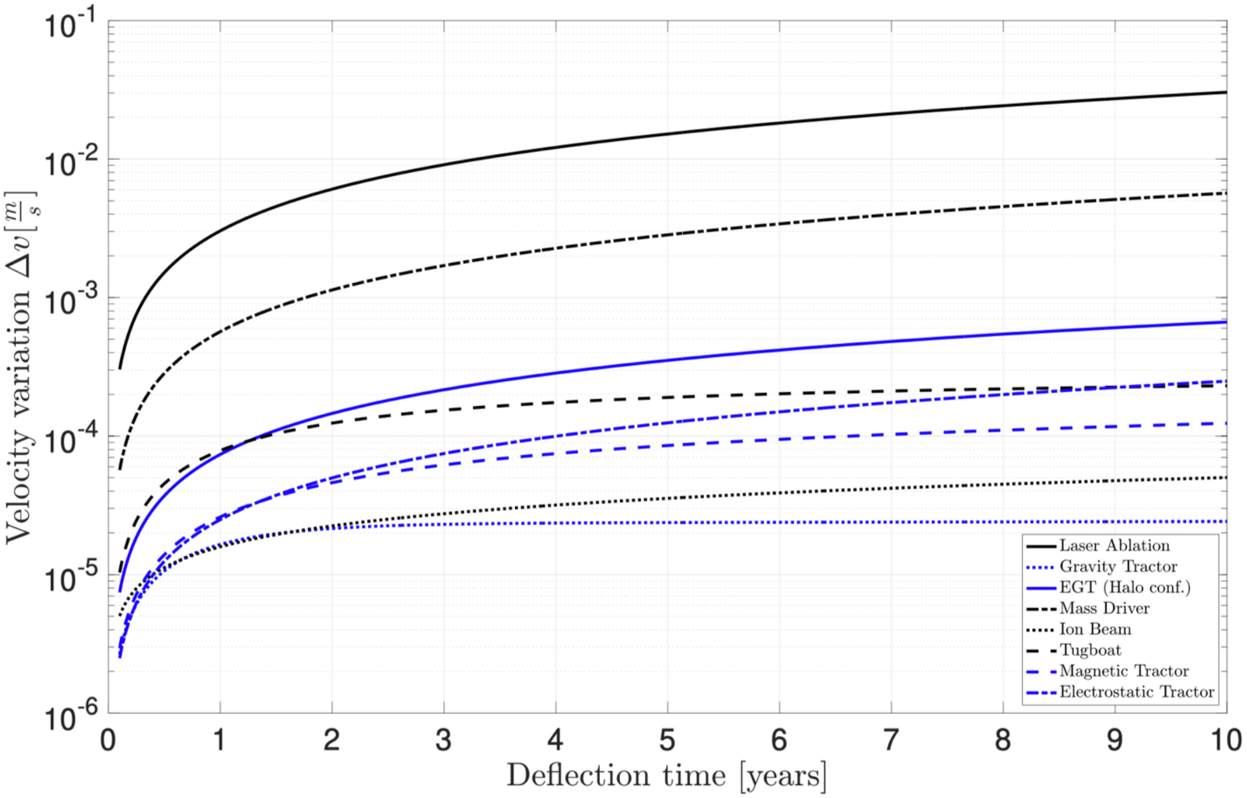


Fig. 1: Comparison between all the strategies, $M_{ast} = 5 \times 10^{11}$kg and $d_{ast} = 1100$ m

With the Ion Beam Shepherd strategy the deflection is performed in a precise manner and can be accurately predicted, it is a contactless deflection and the force generated depends on the power and propulsion subsystem not on the mass. The Δv produced with IBS is a little bit higher than the one obtained with GT, but the mission complexity is higher.

Asteroid Tugboat is a conceptually simple strategy, but there are some problems to be considered: the first one is the rotation of the asteroid (the thruster is no more able to provide a constant pointing), a second issue is the need of a strong attachment system and the third problem is the creation of a transient atmosphere made of dust around the spacecraft.

The Solar Collector strategy is strictly connected to the Laser Ablation strategy, both of them exploit the sublimation of the asteroid surface. With the solar collector technology the energy is theoretically unlimited, but the lifetime of the collector is very short because of plume influence and degradation of solar cells, radiators and insulation. The advantages of the Laser Ablation technique are that there is no need of phisycally land or attach a system to the surface of the NEA and the required spacecraft mass for the deflection is lower with respect to other strategies. It provides the highest Δv with respect to all the other slow push strategies. Problems also in this case are caused by optical degradation.

The deflection exploiting Yarkovsky effect is unfeasible, in particular for very large asteroid, since the mass of dirt needed to cover the surface to change the albedo would be hundreds of tons.

The tether-ballast system is useful only for small asteroids since for bigger ones the mass of the ballast would be too high, increasing the complexity of the mission.

4. Strategy selection for optimisation

The strategies selected for the optimisation technique are four: kinetic impactor, nuclear standoff explosion, gravity tractor and Laser Ablation.

In the work of Sanchez et Al. [2] a multicriteria comparison has been already performed, but they considered solar collector instead of laser ablation strategy.

The kinetic impactor strategy has been selected because of its high TRL level and because it is conceptually very simple, there's no need of landing and attaching to the asteroid. The nuclear standoff explosion has been chosen mainly because it is the most effective technique, so considering the same mass, it produces the highest values of deflection with respect to all the other strategies.

The Gravity Tractor strategy is considered because of its relatively simple mission design and because it is not sensitive to the asteroid composition (low uncertainties).

In addition there is the possibility to use Multiple Gravity Tractor displaced in an artificial Halo orbit (fig. 2), such that the deviation achieved increases [9].

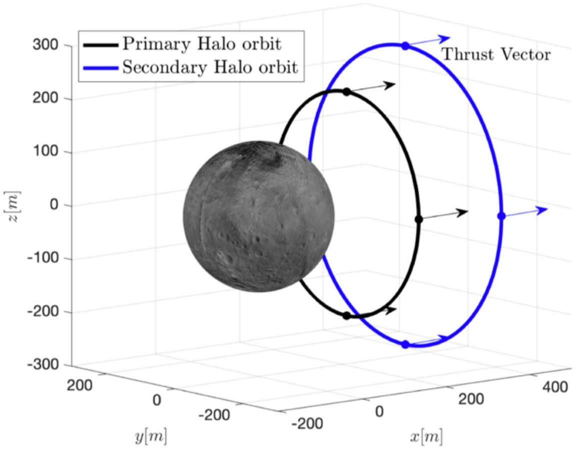


Fig. 2: Eight spacecraft disposed in two Halo orbits

The laser ablation technology is chosen for the optimisation process because it is able to provide the highest Δv with respect to all the other slow push technologies, even if in this case the TRL is very low.

5. Trajectory to the asteroid

For the Kinetic Impactor strategy the trajectory chosen to reach the asteroid consists in a Deep Space Manoeuvre (DSM) and a Lambert transfer [1] [2]. So the spacecraft is placed into an orbit around the Sun by the launcher, than at a certain time a DSM is performed, using on board chemical thrusters, in order to reach the correct velocity to place the spacecraft into a Lambert arc and so reach the correct final position (which is the asteroid position).

For the Nuclear explosion strategy instead a direct launch to the asteroid is used, since in this case it is maximised the mass for the payload and there's no need to maximise the final relative velocity between spacecraft and asteroid. For the slow-push technologies instead a low thrust trajectory has been implemented. In order to reduce the computational cost the trajectory is shape-base, which means that the position of the satellite is defined as a function of the initial and final orbital elements. Fourier series are used for the shaping functions, following the work of Zeng [10].

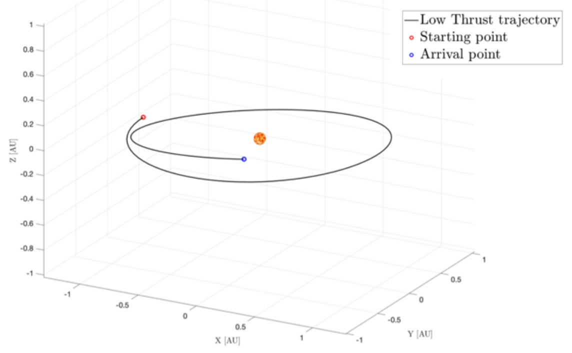


Fig. 3: LT trajectory with Fourier series

6. Asteroid deflection problem

As done by Colombo and Vasile in [11], the variation of the position at MOID $\delta\vec{r}(t_{MOID})$ is linked to the velocity variation $\delta\vec{v}$ (at the deviation time) through a transition matrix $\boldsymbol{T}$, considering the vector of the orbital parameter variation $\delta\vec{\alpha}(t_{dev})$.

$$\delta\vec{r}(t_{MOID}) = \boldsymbol{A}_{MOID}\delta\vec{\alpha}(t_{dev}) = \boldsymbol{A}_{MOID}\boldsymbol{G}_{dev}\delta\vec{v}(t_{dev}) = \boldsymbol{T}\,\delta\vec{v}(t_{dev}) \qquad (7)$$

This relation directly links the perturbation applied at the deviation time to the displacement at MOID. The matrix $\boldsymbol{A}_{MOID}$ and $\boldsymbol{G}_{dev}$ are 6x3 and can be computed starting from the Gauss' equations and the proximal motion equations.

The objective is to maximize the deviation at MOID, so the functional to be maximised is [12]:

$$J_{\delta r} = \|\delta\vec{r}(t_{MOID})\| = \|\boldsymbol{T}\delta\vec{v}(t_{dev})\| = \delta\vec{v}(t_{dev})^T\boldsymbol{T}^T\boldsymbol{T}\delta\vec{v}(t_{dev}) \qquad (8)$$

Since the hyperbolic trajectory of the asteroid as it encounters Earth will be very close to a straight line it is possible to approximate the pericenter radius of its trajectory with the impact parameter b^*.

The functional to be optimised becomes [13]:

$$J_{\delta b} = \left\|\delta\overrightarrow{b^*}\right\| = \delta\vec{v}^T\boldsymbol{Z}^T\boldsymbol{Z}\delta\vec{v} \qquad (9)$$

where the matrix $\boldsymbol{Z}$ is the matrix $\boldsymbol{T}$ transformed in the B-plane.

In the case of a slow-push strategy the deviation at MOID is defined as:

$$\delta\vec{r}_{MOID} = \vec{r}_{ast,MOID,deviated} - \vec{r}_{ast,MOID,nominal} \qquad (10)$$

7. Multiobjective optimisation

The four strategies selected in section 4 are optimised using a multibjective genetic algorithm approach.

As in Sanchez et Al. [2], the variables considered to build the Pareto fronts are, in addition to the deviation at MOID δr_{MOID}, the warning time $t_w = t_{MOID} - t_0$ (where t_0 is the launch date), and the spacecraft initial mass $m_{sc,0}$.

Then the optimal solution, so the one that guarantee the highest value of deviation (maximum deflection mission), is selected from the 3D Pareto front which combine the three variables listed before.

It is also considered another type of mission, which consists in minimizing the collision probability.

Since uncertainties are still present at Epoch 3, three different dimensions and masses of the asteroid are considered, as done by NASA in [7]. The values are selected at a determine percentile level. The first case considers the 5% percentile level, the second one 50% percentile level, the third one the 95% percentile level.

Table 1. Asteroid properties at selected percentile levels

	5th %	**50th %**	**95th %**
Diametre [m]	290	617	1539
Mass [kg]	$2.6 \cdot 10^{10}$	$2.5 \cdot 10^{11}$	$3.8 \cdot 10^{12}$

7.1 Maximum deflection mission

From the 3D Pareto fronts obtained minimizing the functional $J = [-J_{\delta b}\ m_{sc,0}\ t_w]$ it is selected the optimal Pareto solution which guarantee the highest deviation at MOID.

7.2 Minimum collision probability mission

Following Chan's method [15] [16], it is possible to derive a solution in a similar way to the one of the maximum deflection, such that the functional that has to be maximised is:

$$J_P = \delta\vec{r}^T\boldsymbol{Q}^*\delta\vec{r} = \delta\vec{b}^T\boldsymbol{Q}^*\delta\vec{b}$$

The matrix $\boldsymbol{Q}^*$ depends on the covariance of the asteroid position (ξ ζ) in the B-plane at MOID and on the statistical correlation between the two parameters.

$$\boldsymbol{Q}^* = \begin{bmatrix} 1/\sigma_\xi^2 & 0 & -\rho_{\xi\zeta}/\sigma_\xi\sigma_\zeta \\ 0 & 0 & 0 \\ -\rho_{\xi\zeta}/\sigma_\xi\sigma_\zeta & 0 & 1/\sigma_\zeta^2 \end{bmatrix}$$

From the 3D Pareto fronts obtained minimizing $J = [-J_P\ m_{sc,0}\ t_w]$ it is selected the solution which brings to the maximum value of J_P, so to the minimum collision probability.

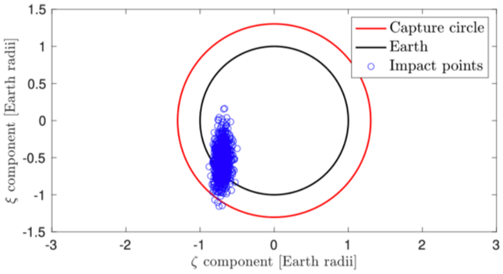


Fig. 4: Monte Carlo analysis for the impact points in the B-plane

8. Asteroid 2023 PDC deflection

The required deflection for asteroid 2023 PDC has been defined by NASA in [14]. If a westward deflection is performed 23000 km of deviation are needed to avoid collision, while if the deflection is eastward 9500 km are enough.

In table 2 it is shown if the strategy is able to completely deflect the asteroid or not. A red color is used if it is not possible, in the other case the box is green.

A preliminary spacecrfat design, with the mass breakdown and the detailed information about the mission, for each type of strategy can be found in [17].

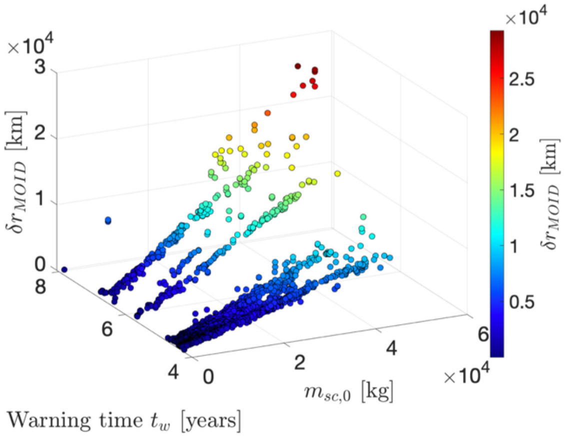
Table 2. Final comparison

	Deviation obtained [km]		
Strategy	**First case**	**Second case**	**Third case**
Kinetic impactor	3304.3	370.9	Not possible
Multiple kinetic impactor (7 s/c)	29301	Not possible	Not possible
Nuclear standoff explosion	1074158	129340	24639
Gravity tractor	169.2	34.1	Not possible
Multiple gravity tractor (8 s/c)	9652.7	Not possible	Not possible
Laser ablation	1544862	51671	Not possible

9. Results: Pareto fronts

In this section the Pareto fronts of the strategies which leads to a possible complete deflection of the asteroid are reported.

The first useful strategy is the multiple kinetic impactor one (Fig. 5) with 7 satellites, needed to obtain the correct deflection in the first case of asteroid dimension and mass.



For the nuclear standoff explosion the third case is directly reported (Fig. 6), since it is the most demanding one in terms of deflection needed.

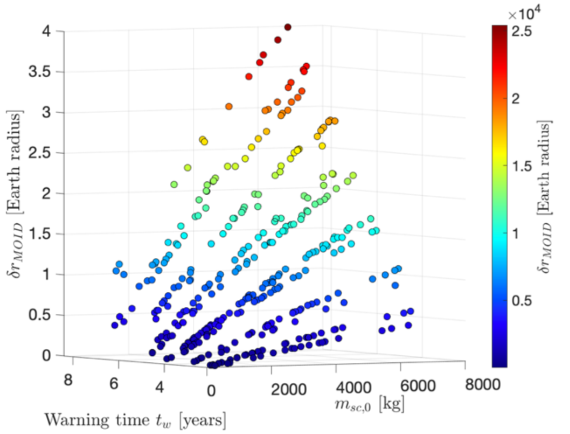


Fig. 6: Nuclear explosion third case Pareto front

The gravity tractor strategy with only one satellite hovering around the asteroid is not useful in any case, but exploiting 8 satellites deployed in two Halo orbits (which requires less propellant consumption with respect to simple hovering) is enough to deflect 2023 PDC in the first case.

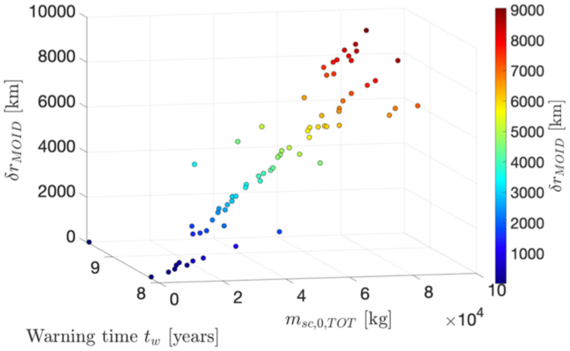


Fig. 7: Multiple GT first case Pareto front

The last strategy considered is the laser ablation one, in Fig. 8 it is reported the Pareto front in the second case, when a correct deviation is reached.

For this strategy the mass of the laser system tends to be maximised in the optimisation process, since the higher is this quantity the higher is the power available for the laser and so the higher is the deflection obtained (see [17] for the detailed analysis).

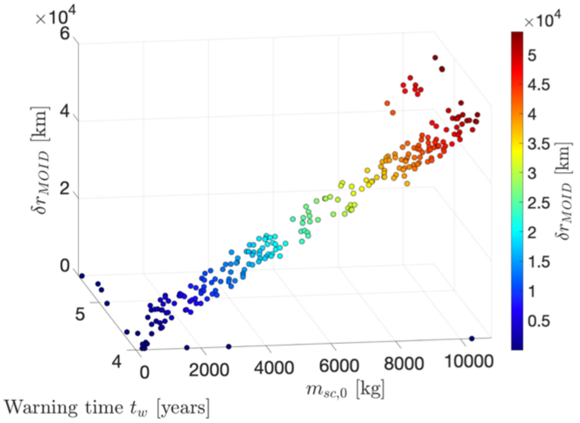


Fig. 8: Laser ablation second case Pareto front

9. Conclusions and future developments

The results obtained using the selected strategies of section 4, optimised as described in section 7, for the deflection of asteroid 2023 PDC (dimension and mass are listed in table 1) are summed up in table 2 and will be discussed in this section.

The kinetic impactor strategy cannot be used, but a MKI configuration with 7 launches is useful for the full deflection in the first case. Instead, nuclear standoff explosion can be used in all the three cases.

The gravity tractor strategy, consisting in one single spacecraft hovering above the asteroid, is not useful since the mass is too high.

However a multiple gravity tractor has been proposed. It consists in eight satellites disposed in two Halo orbits. The strategy can be used to deflect the asteroid in the first case. Anyway further studies have to be performed, in particular on the multiple simultaneous launches.

The laser ablation strategy is able to deflect the asteroid in the first two cases, but when the mass of the asteroid is very high ($10^{12}\ kg$, third case) the propellant needed for the hovering becomes too high and the technology is no more useful. Also in this case further considerations must be carried on, especially on the generation of the laser input power. A more detailed study can be found in [17].

The work is limited by the information available at this Epoch and can be improved once further data are provided by the reconnaissance missions, in particular from the rendezvous mission, on the asteroid size, mass and composition becomes fundamental in order to fully characterise the asteroid properties and then choose the best strategy. In addition the mathematical models of the strategies can be further improved in order to obtain more precise results.

Another possibility that can be studied is using laser ablation strategy with more than one satellite displaced in Halo orbits, as done for gravity tractor. Moreover this work has to be updated with the new data on asteroid properties now available (Epoch 3 and 4), with a reduction of the uncertainties.

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