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NEOSHIELD: FINDING SAFE HARBORS IN ASTEROID DEFLECTION MISSIONS

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ABSTRACT

Many strategies for deflecting potentially hazardous asteroids have been developed over the past decades. Depending on an asteroid's physical properties and the estimated time to collision, either impulsive deflection methods such as Kinetic Impacts or Nuclear Blast Deflection or slow push methods such as Gravity Tractors, Laser Ablation or Ion Beam Shepherds may be most suitable to avoid a disastrous impact. This has been shown, for instance, in the framework of the NEOShield project, an international initiative under European leadership aimed at developing a comprehensive picture of current asteroid deflection options. Constructing optimized end-to-end deflection mission designs is one of the topics addressed by the NEOShield consortium. Here we present results from a recent collaboration regarding the assessment and avoidance of post mitigation impact threats.

We argue that deflection mission designs should consider more than optimizing the miss distance between the Earth and the asteroid at the time of the potential impact. In fact, we propose to alter the orbit of a dangerous asteroid in such a way as to ensure that no encounter with the Earth over the next decades yields an unacceptable impact risk. Thus, scenarios where an emergency deflection action sets the asteroid on a trajectory that may lead to a later collision with the Earth can be avoided. To this end, we present a self-consistent approach that integrates mission design and post mitigation impact risk assessment based on identifying so-called “safe harbors”. Those are regions in deflection phase space which guarantee that the mitigation mission will not only result in avoiding the primary impact, but also minimizes the collision probability with the Earth in the foreseeable future. An example of such an optimal deflection shall serve to illustrate the proposed procedure.

1.) Introduction

Over the past decades global efforts to complete the census of Near-Earth Asteroids (NEAs) have resulted in a catalog containing more than 12000 objects.[a] Once discovered, almost all NEOs are monitored on a regular basis in order to rule out potential collisions with the Earth (e.g. SENTRY and NEODyS services). Despite the astounding success in finding and tracking asteroids that are larger than one kilometer, the majority of sub kilometer sized asteroid population remains unknown (e.g. Mainzer et al. 2011). Unfortunately, even sub kilometer sized asteroids can cause substantial damage if they enter the atmosphere over populated areas (e.g. Brown et al. 2013). Impacts of dangerous NEAs on our planet are believed to be avoidable, though, if a potential threat can be spotted early enough and the means for a successful orbit deflection mission procured. Several deflection options have been proposed in the past ranging from nuclear blasts over kinetic impactors to laser ablation and gravity tractors (e.g. Ahrens & Harris 1992, Colombo et al. 2012, Wie 2013, Vasile et al. 2014). Those deflection techniques can be broadly be categorized as

1. Destructive
   Such methods aim at obliterating the potentially hazardous asteroid (PHO) through fragmentation and dispersion, thus reducing the remaining mass that impacts the Earth as much as possible. This may either be achieved through the detonation of a nuclear device within (Kaplinger et al. 2012) or close to (Syal et al. 2012) the PHO or through a kinetic impact delivering energy above the fragmentation threshold. Chemical explosives are considered to be less effective than either of these two options (Ahrens & Harris 1992).

2. Impulsive
   Given reasonable warning times, a relatively small change in the PHO's orbit can be sufficient to avoid an Earth impact. Kinetic impacts or evaporation of surface material due to stand-off nuclear blasts can be means to impart such changes in an asteroid's momentum (Ahrens & Harris 1992). Since those changes are practically immediate the corresponding methods are termed impulsive.

3. Continuous
   In contrast, continuous deflection approaches such as solar sails, gravity tractors, ion beam shepherds or laser ablation aim to alter a potential impacting asteroid's orbit by exerting a steady acceleration, often over years or even decades (Melosh et al. 1992, Lu & Love 2005, Bombardelli & Peláez 2011, Vasile et al. 2014).

Past investigations, for instance those conducted in the framework of the NEOShield project, an international initiative under European leadership to study asteroid deflection options (Harris et al. 2013), have shown that all concepts are theoretically

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a) http://neo.jpl.nasa.gov/stats/, retreived 28.03.2015 capable of protecting the Earth from asteroid impacts. The main differences lie in the time that is required to divert a potential impactor, the susceptibility to uncertainties in the physical and orbital parameters of the target asteroid, and their capability to prevent further potential impacts in the future. In contrast to the first two points, the latter issue has received little attention so far, partly because it seems self evident that creating situations where a deflection action inadvertently postpones rather than eliminates an impact threat should be avoided at all cost. However, as we will discuss later on in this article, it may be necessary to address post mitigation impact risk reduction explicitly in some deflection mission designs.

At a first glance destructive methods seem preferable to other mitigation techniques in this respect, because they are, in principle, capable of eliminating any future threat from a targeted PHO. However, considerable uncertainties in both our understanding of the fragmentation process and the asteroid's material properties make accurate predictions of destructive deflection success difficult. Smooth Particle Hydrodynamics (SPH) simulations of kinetic impacts, for instance, tend to predict a complete pulverization of the target while an extrapolation of experimental size distributions often foresees remnants that contain as much as half of the original asteroid's mass (Michel et al. 2003, Sanchez et al. 2008, Jutzi et al. 2010, Kaplinger et al. 2012). Moreover, even if the PHO can be fragmented into sufficiently small parts, a substantial number of debris do not carry away the necessary momentum to avoid a collision with the Earth. In a best case scenario, those bolides would be small enough to burn up during the entry in the Earth's atmosphere (Kaplinger et al. 2012). If nuclear devices have been used to destroy the asteroid, however, radioactive fallout may be the result. This outcome is certainly undesirable. For extremely short warning times destructive measures may remain the only option, though, as they can at least partly reduce the damage of a single catastrophic impact.

Given sufficient warning time non-destructive methods may be a better alternative, especially if it is possible to “safely park” a PHO in a region of phase space that does not yield a significant future impact risk with the Earth. Such regions in phase space are referred to as “parking zones” or “safe harbors” (Michel et al. 1996, Yeomans et al. 2011).

Continuous deflection methods are known to offer great flexibility and control allowing to potentially reduce overall impact risks (see Chesley et al. 2008, Eggl et al. 2015b). Some continuous methods such as the gravity tractor have the additional advantage that uncertainties in the composition of a target do not influence deflection results as strongly as they do for other techniques. The applicability of continuous deflection methods is currently limited to targets with diameters less than several hundred meters, however, due to the traditionally feeble accelerations achievable (cm/sec/year). For larger targets, the corresponding decrease in accelerations would result in unrealistic warning time requirements.

The previous arguments favor impulsive deflection, especially for threat scenarios with sub-kilometer sized bodies and intermediate warning times. Impulsive methods do have a disadvantage compared to continuous deflection techniques, though. Once the deflection is performed, eventual corrections in the target's trajectory require another (costly) deflection mission. Chesley et al. (2008) offered a solution to this shortcoming in the form of a combined kinetic impactor and gravity tractor mission concept. Thereby, the impulsive method carries out the brunt of the deflection work while the gravity tractor is then used to fine tune the asteroid's trajectory to keep it out of post mitigation key holes.

In this work we demonstrate that a combined impulsive and continuous deflection mission may not be necessary, if the impulsive deflection attempt is carefully planned in advance. In other words we show that it is possible to make sure that impact risks during all close encounters between the asteroid and the Earth over the next century are insignificant by carefully tuning the deflection parameters.

To this end, we present a methodology that is capable of injecting PHOs into safe harbors. This approach is elaborated in section 2. Section 3 is dedicated to describe the particle swarm optimization algorithm which is then applied to a simplified asteroid deflection model in section 4 to generate safe harbor deflections. Our results are discussed in section 5 and summarized in section 6.

2.) Identifying Safe Harbors

Whether for the deflection of a real hazardous NEO or a possible asteroid deflection demonstration mission, it is either desirable or necessary (in the latter case) that the initial deflection should not worsen the situation at subsequent encounters in comparison to what it would have been absent the deflection. This condition is referred to as creating a “safe harbor” orbit for the asteroid.

If it becomes necessary to consider events subsequent to the first post-deflection encounter, in particular how it will affect the next (and future) close approaches, if any, the question arises of the best analytical or numerical approach to use. If all forces other than the sun’s gravity are ignored, the system state transition matrix (STM) could be used to determine the effect of an initial deflection impulse on the position of the asteroid at any future time (Conway 2001, Battin 1999). However this approach would be too imprecise to use since over multiple orbits relatively small perturbations such as planetary gravity and the Yarkovsky effect can have significant influence on future close approach (to Earth) distances (Farnocchia 2013, 2014).

A numerical propagation of the post-deflection-impulse asteroid orbit is thus required in order to determine the initial and all subsequent close approaches of the asteroid to the Earth. Unfortunately, in contrast to the analytical approach using the STM, the close approach distances are then found by trial-and-error, i.e. a deflection impulse magnitude, direction, and epoch of application are chosen and then forward propagation yields the future close approach radii. Of course there is some *a priori* guidance for at least the first encounter, for example, that earlier application of the impulse is virtually always beneficial and that, given sufficient time, the direction of the impulse should be parallel to the velocity of the asteroid (Park & Ross 1999, Conway 2001, Vasile & Colombo 2008). But these rules do not apply to subsequent encounters.

Our concept is to treat the asteroid mitigation problem as a problem in numerical optimization. That is, we allow a numerical optimizer to choose the appropriate decision parameters, such as the deflection timing and direction, with the objective of improving the miss distance (or distances) and, if desired, of creating a safe harbor orbit for the asteroid. Since the optimization is done numerically, in fact using the particle swarm metaheuristic, it is very simple to change the objective function to accomplish a desired objective.

In most of our work to date the objective function has been a weighted sum of the magnitudes of the close approach distances. This objective function does not explicitly yield a safe harbor orbit but can as a consequence. To simply create a safe harbor orbit a penalty function approach could be used that creates a penalty (i.e. a cost) if any post-deflection close approach is to a smaller radius than would have been obtained absent the deflection. Another interesting and potentially useful objective, for example for a deflection demonstration mission, would be to maximize the deflection obtained for the first close approach (so that it may be more easily measured), but add a penalty function for any subsequent close approach that is to a smaller radius than would have been obtained absent the deflection (that is, enforcing the “do no harm” constraint of a demonstration mission).

3.) Particle Swarm Metaheuristic

The particle swarm optimization (PSO) method is a heuristic method for unconstrained parameter optimization problems. It is a population-based method, with the population consisting of a “swarm” of *N* particles. Descriptions of the PSO method are easily found so that only a concise summary is provided here.

Each particle *i* (*i* = 1, 2, …, *N*) has associated “position” and “velocity” vectors. The scalar measure numbers of the position vector are the *n* unknown parameters of the problem, i.e.

$$x(i) = \left[\, x_1(i),\; x_2(i) \ldots\; x_n(i) \right]$$

The velocity vector *w(i)* determines the position update for the *i* th particle, i.e. it is added to the position vector at each iteration to determine the new position:

$$x^{j+1}(i) = x^{j}(i) + w^{j+1}(i)$$

where

$$w_k^{j+1}(i) = c_I w_k^{j}(i) + c_C\left[\psi_k^{j}(i) - x_k^{j}(i)\right] + c_S\left[Y_k^{j}(i) - x_k^{j}(i)\right]$$

and the superscript j refers to the iteration index, k is the index of the measure number, $\psi_k^j(i)$ is the k^{th} component of the best position ever visited by particle *i* (up to iteration *j*) and $Y_k^j(i)$ is the k^{th} component of the best position yet located by any particle in the swarm. The first term on the RHS is the so called *inertial* term and for each particle is proportional to its velocity in the preceding generation; the second term is the so called *cognitive* component, directed toward the personal best position, and the third term is the *social* component, directed toward the global best position.

The (stochastic) weights are:

$$c_I = \frac{1 + r_1(0,1)}{2},\ c_C = 1.49445 + r_2(0,1),\ c_S = 1.49445 + r_3(0,1)$$

where the r_i represent independent uniform random numbers chosen in the range [0,1).

The initial population of particles (positions) is generated randomly within user chosen bounds for each unknown parameter. The positions of each particle are updated according to the formulas above at each iteration. The process is continued either for a specified number of iterations or until the objective function fails to improve for several consecutive iterations.

If a sufficient number of particles are employed the PSO method can do a very thorough search of the solution space; since it employs no gradient information it is less likely to get trapped in a local minimum than other methods. Of course these remarks are subjective; there is no *a priori* way to know the size of the swarm or number of iterations required for a good solution (quantities which are in any case problem dependent), so that the user is guided to some degree by experience with the method.

An unconstrained parameter optimization method such as PSO would also appear to be unsuited for problems with constraints, where a nonlinear programming method might appear to be more suitable. However, there are ways to accommodate them. Bounds on the parameters sought are easily implemented by bounding the search space of the particles. Equality constraints on functions of the unknown parameters or functions that can be derived from the values of the unknown parameters, if they represent initial conditions for a numerical integration, for instance, can be incorporated using a penalty function method.

4.) A Simplified Model for Asteroid Deflection

A simple 2D model illustrates the deflection concept. In order to have periodic close approaches the asteroid is given a 5/4 commensurability with the Earth's orbit. The initial longitude of the asteroid and initial longitude of the Earth are chosen so that a "collision" would occur at first asteroid perihelion and then of course at perihelion 5 years later because of the commensurability. The time of the first close approach is π/2 in normalized units = 3 months. Figure 1 shows the orbits and describes the initial positions of the bodies.

Without any deflection impulse the first approach is to 0.13 R and second approach is to 1 R, where R is the scaled planetary radius.[b)]

b) In order to allow for a grazing second impact we have scaled the planetary radius in our simplified model to R=0.65 $R_{Earth.}$

The PSO (particle swarm optimizer) is given the opportunity to add a ΔV of 10^{-5} astronomial units per time unit (au/TU = 30 cm/sec) at the initial time, i.e. 3 months prior to the first close approach, in a direction of its choice, with the objective of maximizing a linear combination of the deflection at the first close approach and the deflection at the second close approach 5 years later. The direction of the deflection impulse is the same as the angle beta in Figure 2.

Every particle in the swarm must, at each iteration, have its objective (cost) value determined. To do this, the system equations of motion are integrated forward from the initial conditions, which are the Cartesian position and velocity (+ the ΔV of 10^{-5} au/TU = 30 cm/sec applied in the direction chosen by the particle) of the asteroid at t = 0. The MATLAB routine ODE45 is used for the numerical integration. ODE45 has the ability to locate a point in time when a specified algebraic condition is satisfied, even if this point lies between integration steps, and this feature is used to determine the times and distances of closest approach to the Earth at the first and second close encounters.

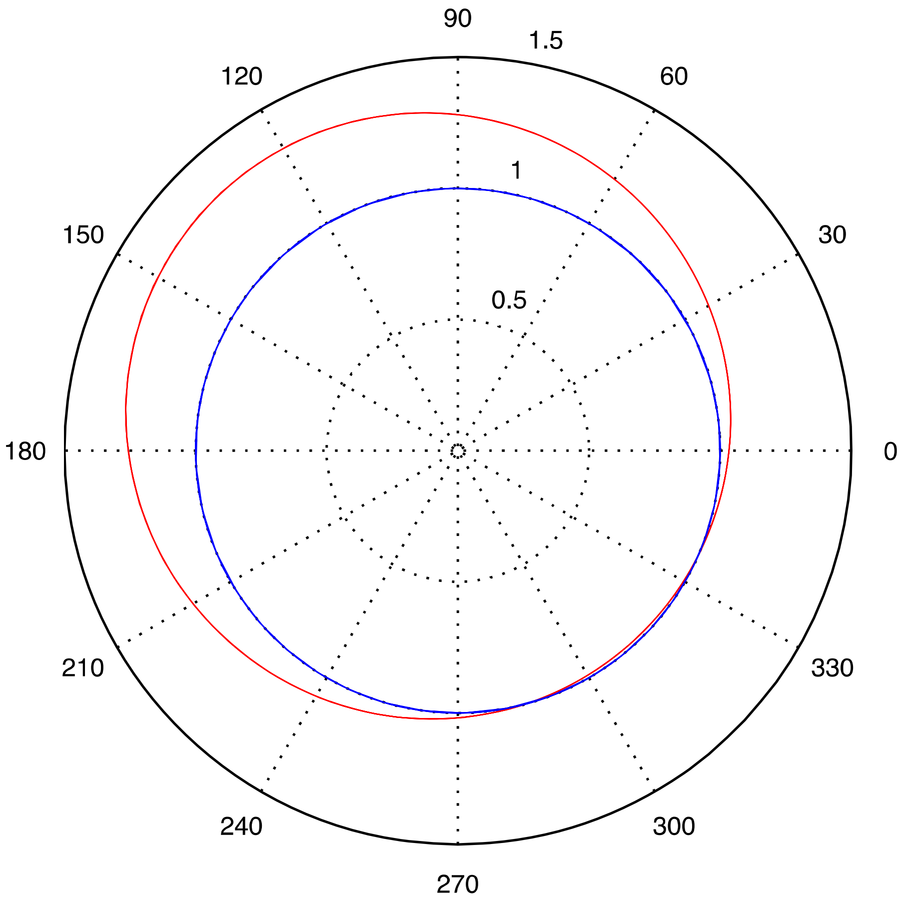

Figure 1: Asteroid orbit in 5/4 commensurability with the Earth. Initial position of the Earth is $\theta = 247^o$. Initial position of asteroid is $\theta = 243^o$ and $a_{asteroid}$=1.1604 au, $e_{asteroid}$ =0.1382.

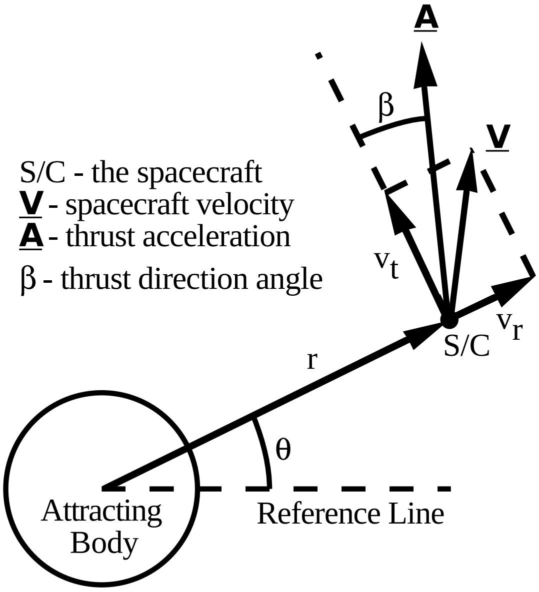

Figure 2: Definition of angle β at which deflection impulse is applied.

Let Δ_1 be the resulting deflection at the first close approach and Δ_2 be the resulting deflection at the second approach (5 years later). Then Δ_2 can be expected to be much larger than Δ_1 because the deflection velocity change has had much more time to act to change the position of the asteroid. Maximizing both miss distances could now be considered a multi-objective optimization problem where we need to calculate the corresponding Pareto fronts. Here, however, we will adopt a simpler approach:

- The first case considered maximizes the sum of the deflections, $\Delta_1 + \Delta_2$, but by default, since the second deflection is so much larger, that is what is being optimized.

- The second case maximizes $\Delta_1 + \Delta_2/25$, i.e. it emphasizes the deflection at the first close approach by weighing it more heavily in the objective function.

- The third case maximizes $\Delta_1 + \Delta_2/125$. This is essentially the opposite of the first case; emphasizing the deflection at the first close approach almost exclusively.

Table 1 contains the corresponding simulation outcomes.

Objective function	$\Delta_1 + \Delta_2$	$\Delta_1 + \Delta_2/25$	$\Delta_1 + \Delta_2/125$
Δ_1 (R)	0.8	1.04	1.13
Δ_2 (R)	28.8	26.3	21.7
β	3.067 = 175.7°	3.461 = 198.2°	3.775 = 216.3°

Table 1. Optimal deflections for two close encounters.

Interestingly, the first case yields a solution that does not prevent an impact on the planet. This fact results from the lack of additional constraints on the optimizer that would prohibit such solutions. We did not impose those restrictions in order not to cloud the effect of weighting the close encounter distances. Given this setup, cases two and three would constitute successful deflection operations.

For instance, even when the deflection distance at the first close approach is very heavily weighted (third column) it increases only a small amount, from 0.8 R to 1.13 R. This is reasonable because there is a limit to what this small deflection impulse (30 cm/sec) can accomplish with only 3 months time between deflection and impact. Yet, in the latter case the increase in close encounter distance is sufficient to avoid an impact on the planet.

The deflection at the second close approach (5 years later) is larger when it is weighted equally (column 1) and smaller when it is almost ignored in the objective function (column 3).

The deflection (through angle β) is applied almost opposite to the direction of motion when the deflection at the second close approach (column 1) is emphasized, i.e. when the deflection has 5 years to create a result.

On the contrary, when the deflection at the first close approach (column 3) is emphasized, and thus the impulse has only a brief 3 months to act, the optimal deflection direction is retrograde but not opposite the velocity. This is consistent with a previous analysis (Conway 2001).

Case of Worsened 2nd Close Approach

In a study on post mitigation impact risks of deflection demonstration missions Eggl et al. (2015a) indicate that it is at least possible that a deflection impact prior to a close approach can have the undesirable effect of worsening the close approach distance at the next approach, or some other subsequent approach. This is unacceptable for a demonstration mission whose first requirement is to “do no harm”.

In the following analysis we generate an example case of two close approaches due to a 5/4 commensurability in the ratio of the period of the asteroid to the period of the Earth (as in Figure 1) in which precisely this happens, and then show how the PSO based numerical optimizer can improve the situation at the second close approach.

Table 2 shows the results for four different numerical simulations.

- The first case is a straightforward numerical integration of unperturbed two-body EOM (the planet is assumed to move in a circular orbit) from the initial conditions shown in Figure 1. The near-commensurability yields two very close approaches, the first to 0.3 R and the second to 2.16 R.[c)]

In the second case a perturbation in the form of a transverse acceleration (similar to the Yarkovsky effect) having a magnitude of 10^{-6} in the normalized units is applied to

[c)] In order to produce a clear miss the second time without changing the initial conditions we have rescaled R=0.3 R_{Earth}.

the asteroid. The first close approach is not significantly changed, owing to the brief period (3 months) before the first encounter occurs, but the second close approach is increased from 2.16 R to 98.7 R since the Yarkovsky effect has 5 years to act on the asteroid before the 2nd encounter.

In the 3rd case a particle swarm-based optimizer is used to choose the direction of application (β) of a deflection impulse (applied at t = 0) of the same magnitude as before, 10-5 au/TU = 30 cm/sec. For this case the objective is to maximize the deflection at the first close approach $\left(\Delta_1\right)$ *with no regard for how the approach radius at the 2nd close approach is affected.* With only 3 months between deflection and first encounter a large deflection isn't possible, but the close approach radius is increased from 0.3 R to 2.47 R. However note that the radius at the 2nd encounter (5 years later) decreases from 98.7 R to 59.3 R. That is, the deflection has worsened the situation at the 2nd encounter. Note that the angle of impulse application has a substantial radial component; it is retrograde but not at all opposite the velocity vector. This is consistent with the previous result and is consistent with analysis for the short-warning-time cases (Conway 2001).

In the final case the PSO now has an objective function that is a weighted sum of the radii at the two encounters, i.e. $\Delta_1 + \Delta_2 / 5$. The radius at the second encounter is now increased from 59.3 to 161. R, i.e. the radius at the second encounter now *is not reduced* compared to what it would be (98.7 R) absent any deflection whatsoever. This occurs of course at the expense of a less-efficient deflection at the first encounter, now 1.33 R rather than 2.47 R. Note that the β angle is now closely aligned with the asteroid velocity; this is consistent with the well-known result that if the time available is long (as it is now because the optimizer is now more concerned with the second encounter 5 years subsequent to the first) the optimal deflection strategy is to apply the impulse parallel to the velocity in order to make the largest possible change in the asteroid semimajor axis (Park & Ross 1999, Conway 2001, Vasile & Colombo 2008).

Objective func.	None	None	Δ_1	$\Delta_1 + \Delta_2/5$
Yarkovsky?	No	Yes	Yes	Yes
Δ_1 (R)	0.30	0.23	2.47	1.33
Δ_2 (R)	2.16	98.7	59.3	161.
Beta (rad)	NA	NA	3.922	.016

Table 2. Case in which optimal (first close approach) deflection worsens situation at second close approach.

This simple 2D model shows the feasibility of choosing the direction of the deflection impulse with more than just a consideration of the result at the first encounter. By maximizing a weighted sum of the distances at the first and subsequent encounters, the PSO can guarantee that the constraint, that no subsequent approach distance be worsened by a deflection demonstration, is satisfied. Of course there is a penalty that is paid to satisfy this constraint; the amount of deflection that results from the mitigation will be smaller than it would be if future close approaches were not considered.

5.) Discussion

While the model presented in the previous section is only 2D, uses only 2-body gravity (+ Yarkovsky effect), and assumes that the planet is in a circular orbit, none of these simplifications is critical to the result. This model also only considers the first close approach and one subsequent close approach after 5 years. However, there is no reason why this method, in which the asteroid mitigation problem is considered as a problem in numerical optimization, should not apply to a case with more encounters, as might be expected to occur if the “do no harm” constraint is required to be satisfied for a long time span, e.g. to 2125.

Naturally, additional constraints should be added, such as mission (delta-v) cost or deflection failure penalties. The former may cause the PSO algorithm to rule out retrograde spacecraft trajectories for being too expensive and favor prograde mission designs instead. While weighting of consecutive close encounter distances has worked in our simplified model, we recommend to use penalty functions on the minimum Earth encounter distances instead (see Eggl et al. 2015a), especially if the method presented here is to be used in practice.

Of further relevance is the fact that in this work the mitigation action has been modeled without due consideration of uncertainties. In fact, Sugimoto et al. (2014) and Eggl et al. (2015a) have shown that uncertainties in the physical and orbital properties of target NEOs can have a substantial impact on deflection outcomes. Those will have to be taken into account in a future study.

6.) Summary

A comprehensive asteroid deflection mission should not only be aimed at eliminating an immediate impact threat. Thought has to be given as to precisely how the potentially hazardous asteroid orbit should be altered in order to minimize the risk to inadvertently insert the asteroid into an orbit that yields a collision with the Earth at a later date. In this work we have presented a straightforward way to tune mitigation parameters so as to park a potentially hazardous asteroid in so-called “safe harbors”. Those regions in phase space will guarantee that the asteroid does not pose a significant threat even after its orbit has been changed to avoid a primary impact on the Earth. To this end we have reformulated the deflection mission design into an optimization problem. Combining a particle swarm algorithm together with a simple asteroid deflection model we have shown that this combination of tools is indeed capable of finding solutions that guarantee the Earth's safety from an immediate impact danger and then also for an arbitrary time into the future.

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