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NEOSHIELD: POST MITIGATION IMPACT RISK ASSESSMENT FOR ASTEROID DEFLECTION DEMONSTRATION MISSIONS

Siegfried Eggl(1), Nicolas Faber(2,3), Daniel Hestroffer(1)

(1)IMCCE - Observatoire de Paris, 77 Avenue Denfert-Rochereau, 75014 Paris, France, siegfried.eggl@obspm.fr
(2) SGT Inc., 7701 Greenbelt Road, Suite 400 Greenbelt, MD 20770, USA
(3) NASA Ames Research Center, Moffett Field 95035, Mountain View, CA, USA, nicolas.t.faber@nasa.gov

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ABSTRACT

Today, natural disasters caused by impacts of Near-Earth asteroids (NEAs) are believed to be avoidable, if the resources to launch a deflection mission can be made available. Laboratory experiments and numerical simulations provide a basis on which such deflection attempts can be built upon. This has been shown, for instance, in the framework of the NEOShield project, an international initiative under European leadership aimed at investigating asteroid deflection options. However, uncertainties in the physical characteristics of potentially hazardous asteroids as well as the deflection process itself can make accurate predictions of deflection outcomes difficult.

Only through a deflection demonstration mission can we assess the completeness of our understanding of the processes involved in deviating an asteroid from its nominal trajectory. As financial constraints play an important role in mitigation demonstration mission design, potential targets have to be cheap to reach. Asteroids orbiting in the vicinity of the Earth such as NEAs are, thus, a preferred option, as many of them retain small minimum distances to Earth in the medium term. Naturally, any orbit manipulation of potentially hazardous asteroids has to be carefully planned in order to avoid creating or increasing impact threats. To this end it is especially important to quantify the influence of uncertainties present in the mitigation process.

Here, we present a framework to perform a post mitigation impact risk assessment of deflection test missions based on Kinetic Impactor and Gravity Tractor concepts. Using a state of the art mission design and impact monitoring tools we show that deflection actions and their corresponding uncertainties have to be considered on a case by case basis to ensure that the target asteroid's threat potential is not increased due to mitigation demonstration attempts.

1. INTRODUCTION

Collisions between a near-Earth object (NEO) and the Earth can have dramatic consequences. While an asteroid with a characteristic diameter of 50 m has the potential to wipe out an entire city, a 300 m diameter object can release an impact energy equivalent to 1 Gt of TNT (Thuillot et al. 2015). This is sufficient to produce devastation on a continental scale. Yet, for the first time in the history of our planet, its inhabitants have the means necessary to predict and prevent such disasters. Current population estimates suggest that we are almost complete in our search for NEOs with diameters larger than 1 km (Mainzer et al. 2011). In contrast, smaller objects are far less easy to spot. The level of completeness for objects with diameters larger than 100 m may be as low as 30%, and our knowledge on the whereabouts of NEOs with diameters smaller than that is marginal at best (e.g. Brown et al. 2013). Contemporary and upcoming large scale deep sky surveys will certainly improve this condition over the next decades. Even if we had a complete catalog of asteroids at some point, though, remaining uncertainties in their orbits and physical properties would still present a challenge for long term impact risk assessment, since they are related to the spread of initial conditions due to non-gravitational forces such as the Yarkovsky drift. A natural way to take orbit and physical uncertainties into account in impact monitoring is to conduct probabilistic studies. Today, non-linear numerical methods are used to predict whether a future close approach of a near-Earth asteroid (NEA) yields an impact probability that is larger than a predefined background risk (e.g. Milani et al. 2000, 2002, 2005, Spoto et al., 2014). Impact monitoring programs such as NEODyS[1] or SENTRY[2] perform such predictions on a routine basis. If potential impact solutions of objects in the size range above 100 m are identified, and should those solutions still be present after more observational data becomes available, a possible deflection has to be considered. The main techniques that may be employed to reduce the risk of an asteroid impact can be divided into three categories (e.g. Ahrens & Harris 1992): (i) aim for a complete fragmentation of a potentially hazardous asteroid, (ii) impart a quasi-instantaneous change in the momentum of the NEO and (iii) attempt a slow but steady alteration of the asteroid's heliocentric orbit. Fragmentation options will not be discussed any further in this work. The most studied concept of class (ii) deflection methods are so-called kinetic impactors (KI). KIs rely on transferring linear momentum to the asteroid through a physical impact of a specially designed spacecraft. Gravity tractors (GT) on the other hand belong to class (iii) methods (Lu & Love 2005). A GT uses the gravitational attraction between the NEO and a hovering spacecraft to alter the orbit of the asteroid in a weak but continuous way over a long period of time. Of course, uncertainties in an asteroid's orbit as well as in its physique do play a significant role in deflection attempts. In fact, the importance of knowing the physical properties of targets is much more pronounced in asteroid deflection than it is in impact monitoring. Uncertainties in a target's physical properties can lead to a degradation in our ability to predict deflection mission success (Sugimoto et al. 2014). Recently, Eggl et al. (2015) presented a framework that is capable of taking the combined orbit and physical uncertainties of asteroids into account in order to study the potential outcomes of asteroid deflection missions. We shall refer to this article as E15 in future. One of the conclusions of this work was that in order to assess our capabilities to accurately predict orbit deflection

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[1] http://newton.dm.unipi.it/neodys/, retrieved March 2015

[2] http://neo.jpl.nasa.gov/risk/, retrieved March 2015

outcomes, a deflection demonstration mission may be required. Consequently, E15 conducted a post mitigation risk assessment of several suggested KI demonstration mission designs. Their findings indicate that the combination of uncertainties in the orbit and the physical properties of deflection targets changes the deflection behavior as well as the post mitigation impact risk. A post mitigation impact risk analysis (PMIRA) is, thus, mandatory, in order to avoid increased threats of test mission targets during future close approaches. While E15 focused on deflection demonstration missions based on kinetic impactors, the aim of our current research is to determine whether class (iii) missions based on a GT react to uncertainties in a similar fashion as class (ii) deflection concepts such as the KI. Preliminary results are presented in this article.

2. TARGET ASTEROIDS

Technical demonstration missions are a vital tool to test our understanding of the role of uncertainties in asteroid orbit deflection. In the framework of the NEOShield project (Harris et al. 2013) several deflection test mission scenarios were suggested (E15). Primary selection criteria for possible target asteroids were based on accessibility and size constraints that ensure compatibility with deflection validation requirements. For a detailed description of the selection process see E15. The proposed targets studied in this work are 2000 FJ10 and 2001 JV1. The former asteroid is currently suggested to be the primary target of the NEOShield GT demonstration mission as well as the backup target of the KI demonstration mission. Asteroid 2001 JV1 is another one of the five candidate asteroids identified by the NEOShield consortium as a potential target for a mitigation demonstration mission. This asteroid has approximately the same physical properties as 2000 FJ10. The main difference with 2000 FJ10 being the orbit type and initial orbital uncertainties, 2001 JV1 is an interesting candidate to put the mitigation results obtained for 2000 FJ10 in perspective. An overview of the relevant orbital and physical parameters of both asteroids is provided in Tables 1-4. Note that we assume a roughly spherical asteroid shape throughout this work.

3. PMIRA METHODOLOGY

The goal is to model all the uncertainties related to the two asteroids and to statistically quantify both the achievable deflection and the impact threat caused to Earth once the mitigation has been completed. To do this, the uncertainty domain of both mitigation techniques must be defined. The uncertainty domain of the PMIRA can be subdivided into 3 domains: propagator uncertainty, asteroid orbit uncertainty and mitigation uncertainty.

Name	**2000 FJ10**	**2001 JV1**
Orbit Type	Amor	Apollo
Classification as a PHA	No	Yes
Asteroid Class/Spectrum	S,Sq	Sq
Mass (approximated in kg; using $\rho = 2.4$ g/cm^3)	$3.45\ 10^9$	$2.76\ 10^9$
Semimajor axis (au)	1.32	1.70
Eccentricity	0.23	0.44
Inclination (deg)	5.3	6.6
Period (yrs)	1.51	2.23
Perihelion distance (au)	1.01	0.96
Aphelion distance (au)	1.63	2.45
Close approaches to Earth/Mars (in bold) until 2070	2011, 2014, 2017, 2018, 2020, 2050, 2052, 2053, 2055, 2056, 2058, 2061, 2064, 2067, 2068, 2070	2001, 2021, 2030, 2041, 2050, 2061, 2070

Table 1: Physical parameters and approximate orbital parameters of 2000 FJ10 and 2001 JV1. The close approaches occurring at a distance < 0.2 au are underlined. Courtesy: NEOShield consortium.

3.1 Propagator uncertainty

In order to validate our Numerical Integration and Risk Evaluation (NINE) propagator we focused on asteroid 2011 AG5 that hit the news in 2012 because an impact probability of roughly 1/580 for the year 2040 had been reported at that time by both NEOShield collaborators and NASA JPL[3]. We compared our results for the impact probability of 2011 AG5 against the numbers obtained in literature (Yeomans et al. 2012, Cano et al. 2013) and found a good agreement. For more information on the validation of the NINE propagator we refer to E15. As the propagator induced uncertainties are negligible compared to orbit and physical uncertainties, we do not consider the former in our simulations.

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[3] Additional observations of the asteroid in late 2012 did not confirm that risk and an impact of 2011 AG5 with Earth could be excluded.

3.2 Asteroid orbit uncertainty

Current orbital elements and related uncertainties of 2000 FJ10 and 2001 JV1 can be retrieved via the NEODyS and JPL Small Body Database Browser websites, respectively.[4] For a more human readable view, Table 2 shows the semi-major axis and along track uncertainties in the metric system.

Asteroid	Semi-major Axis Uncertainty (m; 1-σ)	Along Track Uncertainty (m, 1-σ)
2000 FJ10	432	~ 28 850
2001 JV1	11 010	~ 390 860

Table 2: Uncertainty on semi-major axis of 2000 FJ10 and 2001 JV1 in meters. http://ssd.jpl.nasa.gov/sbdb.cgi, retrieved March, 2015.

3.3 Mitigation uncertainty

For both the KI and the GT the uncertainty introduced during the mitigation attempt depends on the uncertainty on the set of relevant physical parameters of the target asteroid and on the uncertainty on the performance of the spacecraft during the mitigation attempt itself. Below we present these uncertainties for both the KI and the GT.

3.3.1 Gravity Tractor

For the GT, the set of asteroid physical parameters that affects the outcome of the deflection is relatively small. Indeed, only asteroid mass and diameter are of relevance. The achievable deflection is inversely proportional to asteroid mass. The diameter intervenes in the calculation of the optimal standoff distance between the S/C and the asteroid. For a given mass, a small diameter produces a larger deflection since the hovering can be performed closer to the center of mass of the asteroid. The uncertainty domain covered in the PMIRA are shown in Table 3 for 2000 FJ10 and Table 4 for 2001 JV1, respectively. The uncertainties introduced through the mitigation measures of the spacecraft are given in Table 5. We refer to Lu & Love (2005) for more detail on the parameters listed[5]. For both asteroids, the compounded effect of all the mitigation related uncertainties generates a range of net accelerations imparted by the GT that spreads over two orders of magnitude:

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[4] http://newton.dm.unipi.it/neodys/, http://ssd.jpl.nasa.gov/sbdb.cgi, retrieved March 2015

[5] Note that the canting angle β is not listed as one of the parameters subject to uncertainty. The reason for this is that the present design of the GT deflection demonstration mission foresees a canting angle fixed at β = 45° (Faber et al. 2015).

10^{-13} m/s^2 < a_{NEO} < 10^{-11} m/s^2 (bottom of Table 5).

	Nominal	Minimum	Maximum
Diameter (m)	140	95	300
Density (g/cm^3)	2.5	1	4
Mass (kg)	3.5 10^9	4.5 10^8	5.6 10^{10}

Table 3: Uncertainty domain on physical parameters of asteroid 2000 FJ10. The mass is a derived quantity using diameter and density.

	Nominal	Minimum	Maximum
Diameter (m)	128	95	300
Density (g/cm^3)	2.5	1	4
Mass (kg)	2.8 10^9	4.5 10^8	5.6 10^{10}

Table 4: Uncertainty domain on physical parameters of asteroid 2001 JV1. The mass is a derived quantity using diameter and density.

	Nominal	Minimum	Maximum
S/C mass at beginning of hovering (kg)	1150	500	1500
Thruster exhaust plume half angle φ (deg)	15	5	30
Operational standoff distance from asteroid com (m)	125	60	445
Net acceleration a_{NEO} imparted on asteroid (m/s^2)	10^{-12}	10^{-13}	10^{-11}

Table 5: Uncertainty domain on additional parameters of the GT deflection demonstration mission. The net acceleration imparted by the GT is a derived quantity using S/C mass, plume half-angle and standoff distance.

3.3.2 Kinetic Impactor

Instead of estimating the uncertainties for the KI deflection directly from the range of physical properties, we have chosen the deflection such that the transferred momentum corresponds exactly to the minimum and maximum deviations that would result form the GT after the end of the tractoring phase of two years, respectively. This way, we are able to directly compare the performance of KI and GT missions.

The resulting minimum and maximum changes in the target's velocities are 0.013 cm/s and 1.3 cm/s, respectively. Those values correspond to KI spacecraft of 500 kg mass with impact velocities between 9.5-11.8 km/s assuming a momentum enhancement factor of 1.2 (see e.g. E15). Additional uncertainties in the momentum enhancement factor will generally lead to a larger spread of possible deflection outcomes.

3.4 Uncertainty Propagation and Evaluation

In principle, we then follow the methodology described in E15 in our PMIRA study.

Current observational data on 2000 FJ10 as well as 2001 JV1 are used to construct covariance matrices. Those serve as initial condition pools for a set of virtual asteroids (clones). The clones are sampled and then propagated over the time interval of interest including the mitigation event. Taking the combined orbit and physical uncertainties of the targets as initial condition space for the clone sampling is very conservative. In fact, this situation corresponds to a scenario in which no “exploration” phase was planned. For the KI this is equivalent to not having an orbiter space craft around the target prior to the deflection. Equivalently, the GT starts tractoring immediately upon arrival without taking the time to reduce the asteroid's orbit uncertainty first.

The propagation is done numerically using the full set of equations of motion in an inertial reference frame centered at the barycenter of the solar system. The positions and velocities of the Sun, the 8 planets, the Pluto-Charon system and the Earth moon are extracted from JPL's DE432 ephemeris data. To account for possible additional perturbations, the four largest perturbing asteroids, 1 Ceres, 2 Pallas, 4 Vesta and 10 Hygiea are propagated together with the NEO and its clones.

All clones as well as the nominal NEO are considered to be test-particles, i.e. they do not perturb other objects. The corresponding Newtonian equations of motion of all asteroids are extended to include the PPN monopole term in the acceleration that is due to the Sun. The combined evolution equations are solved using Everhart's Gauss-Radau collocation algorithm of 15th order in time. Yarkovsky drift and Poynting-Robertson drag have been neglected for the lack of knowledge regarding the asteroid's physical and spin parameters. The impact of those effects on the results will have to be studied in a later work. We adopted ephemeris DE432 to perform the actual propagation. After the deflection, Minimum Encounter Distances (MEDs) with Earth are calculated throughout the whole propagation time. MEDs and the initial clone position with respect to the nominal orbit can be used to construct a probability mass function, i.e. to associate each minimum distance with a probability. This, in turn, generates the cumulative probability distribution (CPD) as a function of clone MEDs.

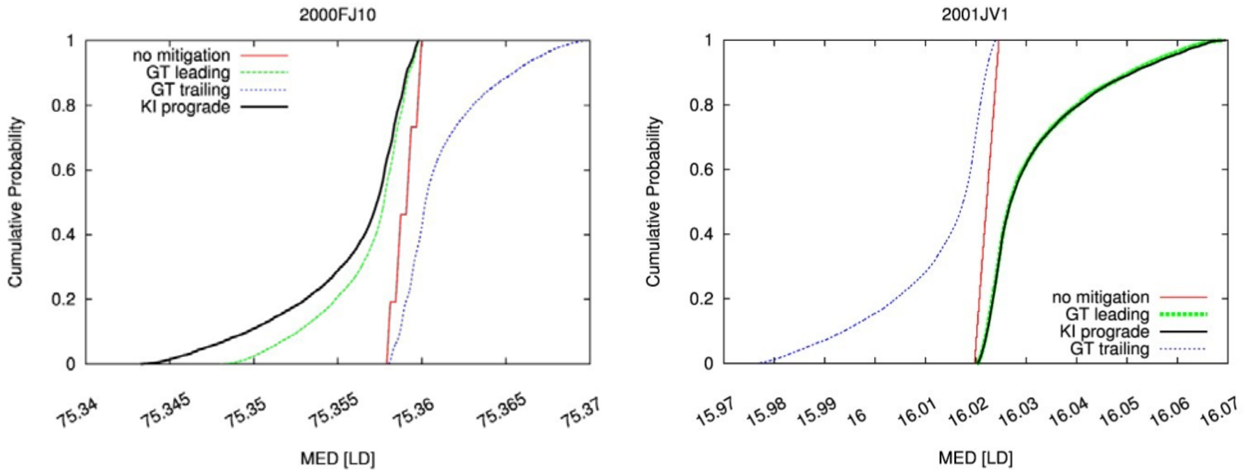

Figure 1: Cumulative distribution function of Minimum Encounter Distance (MED) with Earth expressed in terms of Lunar Distances (LD). Left: result for asteroid 2000 FJ10. Right: result for asteroid 2001 JV1.

4. SIMULATION AND PRELIMINARY RESULTS

We simulated the case of a deflection attempt of asteroids 2000 FJ10 and 2001 JV1. The KI and GT mitigation are started on September 1st, 2028. For the KI this date corresponds to the time of impact, whereas the GT tractoring lasts for the following two years. The resulting orbits were forward-propagated until 2080 to study the effect of the deflection achieved and the risk of an Earth impact during that time frame.

An excerpt of our results is presented in Figure 1. The figure shows the cumulative distribution of Minimum Encounter Distance (MED) probabilities for 9000 asteroid clones of 2000 FJ10 (left) and 2001 JV1 (right), respectively. The performance of both the Kinetic Impactor (solid line in black) and the Gravity Tractor (dotted, green and blue) are mapped against the baseline where no mitigation attempt is performed (red). The lines represent the final MED distribution for the time span between the deflection event and the year 2080. For asteroid 2000 FJ10 we find that, for both the KI and the GT positioned in a leading configuration (i.e. “in front” of the asteroid), the MEDs are reduced with respect to Earth for all of the 9000 clones. The maximum reduction is ≈1% of a Lunar Distance (LD) for the GT and ≈1.5% of a LD for the KI, i.e. roughly 3800 km and 5800 km, respectively. Since both mitigation attempts have approached the orbit of the asteroid with respect to Earth the risk of an Earth impact has slightly increased. The situation is better for the GT placed in trailing position “behind” the asteroid for which the mitigation attempt has been successful. The MED has increased for all clones and the impact risk has thus been reduced. For asteroid 2001 JV1 we find the opposite situation. The impact risk has been reduced for both the KI and the GT in leading position whereas for the GT in trailing position the situation has worsened. The magnitude of the deflection achieves a maximum of 4.5% of a LD.

5. CONCLUSIONS

Following conclusions were drawn from our work:

1. The outcome of the mitigation attempt depends on the selected target asteroid, the extent at which uncertainties on asteroid orbit and physical parameters are known, as well on the date the mitigation attempt is performed. Each scenario must be modeled carefully by mission design on a case-by-case basis.

2. For the range of net accelerations considered in this study (10^{-13} m/s^2 < a_{NEO} < 10^{-11} m/s^2) and the tractoring time of only two years, the post-mitigation evolution of the asteroid orbit does not depend significantly on whether the acceleration has been imparted instantaneously or continuously over a finite amount of time. In other words, the qualitative behavior of the asteroid orbit does not depend on whether the KI or GT the mitigation technique has been chosen. For much longer tractoring periods this is likely to change, however, especially if the NEO has close encounters with the Earth during the orbit modification. More studies need to be done to confirm this notion. Focus should also be put on applying the velocity increment at different positions of the asteroid orbit, and exploring a larger domain of phase space in the near solar system (i.e., a larger set of NEOs).

3. Since insertion into retrograde orbits is generally very costly, KIs will most likely impart a velocity increment in the prograde direction of the asteroid orbit in the framework of deflection demonstration missions. This does not always produce a net increase of the MEDs with respect to Earth as shown for the case of 2000 FJ10. For that asteroid, only a velocity decrement applied in the retrograde direction (by the GT) resulted in a net increase of the MEDs. Given our deflection demonstration mission to 2000 FJ10 around 2030, only the GT will do the job right from a planetary safety perspective.

4. It is safe to say that the NEOShield GT demonstration mission as currently proposed fulfills the “Earth safety first” criterion. The criterion stipulates the mitigation attempt should not approach the orbits of the NEO and Earth with respect to each other even if this occurs at a safe distance and a real threat of an Earth impact can be ruled out. For 2000 FJ10, MED distances with Earth are equal or larger compared to the “no mitigation” scenario provided the GT is placed in a trailing position with respect to the asteroid.

6. SUMMARY AND DISCUSSION

In this contribution we compared the effect of uncertainties on the outcomes of NEO threat mitigation missions based on kinetic impactor and gravity tractor concepts. In section 2 we presented potential deflection demonstration targets that have been brought forward by the NEOShield consortium. In section 3 our method for post-mitigation impact risk analysis (PMIRA) has been recapitulated. Section 4 contains

PMIRA results for the asteroids 2000 FJ10 and 2001 JV1. Assuming comparable deflection magnitudes, both techniques show a qualitatively similar behavior in their post mitigation impact risks. However, the advantage of the GT lies in the fact that leading or trailing configurations can be chosen in situ. This can ensure planetary safety without changing the general layout of deflection demonstration missions designs. KI concepts are much more rigid in this respect. Uncertainties in the momentum enhancement factor during KI missions have not been considered here. They will generally lead to a larger spread of potential deflection outcomes. This is a further argument in favor of GTs. The main difficulties of the latter lies in the long duration to achieve a given deflection as well as in the challenge to maintain station keeping over years.

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