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# Post mitigation impact risk analysis for asteroid deflection demonstration missions

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## Abstract

Even though mankind believes to have the capabilities to avert potentially disastrous asteroid impacts, only the realization of mitigation demonstration missions can validate this claim. Such a deflection demonstration attempt has to be cost effective, easy to validate, and safe in the sense that harmless asteroids must not be turned into potentially hazardous objects. Uncertainties in an asteroid's orbital and physical parameters as well as those additionally introduced during a mitigation attempt necessitate an in depth analysis of deflection mission designs in order to dispel planetary safety concerns. We present a post mitigation impact risk analysis of a list of potential kinetic impactor based deflection demonstration missions proposed in the framework of the NEOShield project. Our results confirm that mitigation induced uncertainties have a significant influence on the deflection outcome. Those cannot be neglected in post deflection impact risk studies. We show, furthermore, that deflection missions have to be assessed on an individual basis in order to ensure that asteroids are not inadvertently transported closer to the Earth at a later date. Finally, we present viable targets and mission designs for a kinetic impactor test to be launched between the years 2025 and 2032.

*Keywords:* Near Earth Objects; Asteroid deflection; Impact risk analysis; Asteroid deflection demonstration mission

## 1. Introduction

Over the past decades, the international community has undertaken serious efforts to establish mitigation strategies for natural disasters caused by Near Earth Object (NEO) impacts. The NEOShield project (Harris et al., 2013), for instance, constitutes an international consortium under European leadership to provide a comprehensive picture of the current state of NEO deflection possibilities. While local civil defense measures are mostly deemed sufficient to protect ourselves against small rocky asteroids such as the one that caused the Chelyabinsk air blast (Brown et al., 2013), active orbit deflection has to be considered for bodies above the hundred meter size range (Ahrens and Harris, 1992). So-called kinetic impactor (KI) concepts offer a relatively straightforward option for deflecting small to medium sized objects, if sufficiently long warning times, for instance several years, can be assumed. The backbone of a KI mission is a hypervelocity impact of a spacecraft (S/C) on a potentially hazardous asteroid's surface. The resulting momentum transfer yields a change of the asteroid's velocity vector ($\Delta\vec{V}$):

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$$\Delta\vec{V} = \beta\frac{m}{M+m}\Delta\vec{v}, \tag{1}$$

where $m$ is the mass of the spacecraft, $M$ is the mass of the asteroid, $\Delta\vec{v}$ denotes the relative impact velocity of the S/C with respect to the asteroid and $\beta$ is the so-called momentum enhancement factor resulting from the additional momentum carried by the impact ejecta (e.g. Holsapple and Housen, 2012). The first successful kinetic impact on a small solar system body has been conducted in 2005 during NASA's Deep Impact mission (A'Hearn et al., 2005). As part of the mission an object of approximately 370 kg was decoupled from the observing S/C and hit the comet 9P/Temple at a relative speed of roughly 10 km/s (Taylor and Hansen, 2005). The aim was to study the comet's subsurface constituents from the ejecta produced during the collision. Although Deep Impact has shown that it is possible to target comet sized bodies, its value to better understand orbit deflection remains limited. The actual change in the comet's orbit was far below its orbit uncertainty. Hence, no connection between e.g. the measured ejecta and the resulting momentum transport could be established. In addition, the 9P/Temple has a diameter of approximately 6 km. Successful hypervelocity impacts on objects that are considerably smaller in size are more demanding with regard to Guidance Navigation and Control (GNC) (Saks et al., 2012). Up to a certain degree, impact simulations and laboratory experiments with asteroid analog materials can be used to model deflections of NEOs in the size range of several hundred meters. Some parameters may not be easily constrained by Earth-bound laboratory experiments and numerical simulations alone, though. The momentum enhancement factor $\beta$ in Eq. (1), for instance, is believed to range between 1 and 2 depending on the impact velocity and the asteroid's surface composition (Jutzi and Michel, 2014). Yet, certain material and impact velocity combinations may yield $\beta$ values up to 12 (Holsapple and Housen, 2012). Order of magnitude uncertainties in the deflection process are undesirable. Not only can they diminish the likelihood of success of the primary deflection event, they are especially relevant to post mitigation impact risk assessment. Situations where the asteroid is deflected from its primary collision with the Earth only to end up having another potential impact a couple of years later should be avoided at all costs. Accurate constraints on all the parameters relevant during a deflection event are required to confidently exclude catastrophic scenarios. Conducting asteroid deflection test missions is, thus, an essential step in validating our current understanding of hypervelocity impacts and their effects on NEO orbits.

Unfortunately, even in best case scenarios limits in observation precision and data accuracy can cause uncertainties in an asteroid's mass and the beta parameter to remain of order one. This naturally raises questions which influence those uncertainties have on the deflection process itself as well as on resulting impact probabilities. Recently, Zuiani et al. (2012) and Sugimoto et al. (2014) investigated the role of uncertainties in an asteroid's physical parameters on the success of asteroid deflection missions for various mitigation techniques. Their findings suggest that uncertainties in the deflection process have to be incorporated in the mission design in order to guarantee successful mitigation, as the range of possible deflection outcomes can deviate substantially from nominal solutions.

In this article we focus on the role of uncertainties in an asteroid's physical and orbital parameters in KI deflection demonstration mission scenarios that were developed in the NEOShield project. Following a brief introduction on current techniques used for NEO threat assessment in Section 2, we attempt to answer the following key questions: How do combined orbital and physical parameter uncertainties in the deflection process influence the future impact risk of potential mitigation demonstration targets? This is discussed in Sections 3 and 6. Section 4 contains details on the dynamical model used in the consequent asteroid deflection simulations. How well pre-mitigation uncertainties have to be constrained in order to allow for an indisputable validation of a specific orbit deflection is defined in Section 5. Our findings are then discussed and summarized in Sections 7 and 8, respectively. A list of acronyms and variables used in this article is provided in Appendix A. Appendix B contains initial conditions for an impact risk analysis test-case. Appendix C discusses an alternative method for estimating low impact probabilities and Appendix D presents possible KI test mission scenarios.

## 2. Standard NEO threat assessment

Given the fact that our knowledge of the exact orbit of a NEO at any given time is limited by observational as well as modeling uncertainties, threat assessments have to be conducted on a probabilistic basis. There are two ways commonly found in literature of investigating the influence of initial orbit uncertainty on a NEO's impact probability. One option is to study projections of the uncertainties of the nominal orbit onto close encounter target planes (b-planes), which are a 2D analog of the impact parameter commonly used in two body scattering processes (e.g. Milani et al., 2002; Bancelin et al., 2012). The uncertainty hyper-volume defined by the orbital element covariance matrix is propagated to a later close approach by solving a set of (linearized) variational equations together with the equations of motion for the nominal orbit. Then the impact probability is simply calculated by evaluating the common cross-section of the projected (and scaled) figure of the Earth and the projection of the uncertainty hyper-volume on the target plane (Milani et al., 2002). Naturally, linearized maps cannot fully incorporate the potentially nonlinear behavior of admissible asteroid orbits. Recent advances in the application of numerical differential algebra are capable of mitigating this shortcoming (Armellin et al., 2010). The implementation of those methods is challenging, however.