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A simplified approach to uncertainty quantification for orbits in impulsive deflection scenarios

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A R T I C L E I N F O

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A B S T R A C T

For the majority of near-Earth Asteroid (NEA) impact scenarios, optimal deflection strategies use a massive impactor or a nuclear explosive, either of which produce an impulsive change to the orbit of the object. However, uncertainties regarding the object composition and the efficiency of the deflection event lead to a non-negligible uncertainty in the deflection delta-velocity. Propagating this uncertainty through the resulting orbit will create a positional uncertainty envelope at the original impact epoch. We calculate a simplified analytic evolution for impulsively deflected NEAs and perform a full propagation of uncertainties that is nonlinear in the deflection delta-velocity vector. This provides an understanding of both the optimal deflection velocities needed for a given scenario, as well as the resulting positional uncertainty and corresponding residual impact probability. Confidence of a successful deflection attempt as a function of launch opportunities is also discussed for a specific case.

1. Introduction

Throughout its history, Earth has been impacted by passing asteroids and comets [2,11]. Collisions have played an important role in Earth's evolution and are cited as the main delivery mechanism for water [27,19], the progenitor for moon ([9] and references therein) and the source of several mass extinctions ([3] and references therein). The present day population of asteroids passing near Earth's orbit are called near-Earth Asteroids (NEAs). It is hypothesized most that near-Earth Asteroids (NEAs) are main-belt objects that were perturbed into Earth-crossing orbits through both gravitational and non-gravitational effects [4,6].

Over the last hundred years there have been numerous small, but notable, NEA events: the 2013 Chelyabinsk meteor (~20 m, [17]), the 1963 Price Edward Island event [10], and the 1908 Tunguska event (~50 m, [30,5]). The probability of a strike by another small NEA over the course of the next century is relatively high, while large asteroid and comet collisions with Earth represent a much lower-probability but potentially higher-consequence threat [26]. Asteroids with absolute magnitudes (H) 22.0 or brighter ($\gtrsim$150 m diameter) and minimum orbit intersection distances (MOIDs) less than 0.05 AU (~20 lunar distances) are classified as Potentially Hazardous Asteroids (PHAs). According to the International Astronomical Union Minor Planet Center, at least 600 PHAs will pass near the Earth over the next century [14]. An illustration of the PHA population and its orbital characteristics over the next century is shown in Fig. 1, with special attention given to objects with known diameters over 270 m in size (i.e. Apophis-size and greater). Note, the small population of near-Earth comets (NECs) are not included in Fig. 1. While this is another important class of objects, they are extremely few in number compared to asteroids and have less predictable orbits due to velocity changes from outgassing and gravitational perturbations [33].

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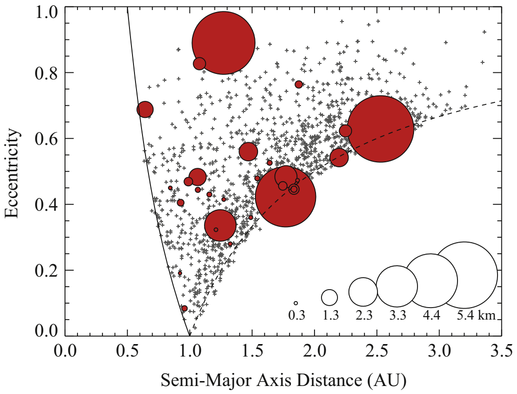

Fig. 1. Semi-major axes and eccentricities of known PHAs. Red circles show a subset of PHAs with known diameters greater than 270 m (the size scale is shown on the lower right) that will have a close-approach with Earth over the next century. The solid line on the left denotes orbits that reach 1 AU at aphelion, the dashed line on the right denotes orbits that reach 1 AU at perihelion. The largest three circles, from right to left: Phaethon, Florence and Toutatis. Data courtesy of IAU [14] and JPL (small-Body Database Search Engine) [18] (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.).

Over the last few decades, there has been increased interest in developing mitigation strategies to deal with the potential threat [20,22,24,12,26]. For scenarios where the object is large or there is little lead time, kinetic impactors and/or nuclear explosives are the most efficient means of providing the necessary change in velocity to an NEA to avoid an impact [1,28,23]. Both of these deflection methods provide a sudden impulse to the NEA, where the orbital parameters governing the motion of the object are changed on timescales that are much shorter than orbital evolution timescales. As such, these changes can be approximated to an extremely high degree as being instantaneous, taking an object with an initial set of orbital parameters and moving it to a new set. If the intended outcome is to deflect the object (as opposed to disruption), then velocity changes less than the escape velocity (typically of order a few cm s^{-1}) are desirable, since above this limit the likelihood of breaking the object up is dramatically increased for most object compositions.

A variety of uncertainty sources are present in any mitigation scenario. The orbital parameters of the object will be known only with limited accuracy, and uncertainties in the deflection delta-velocity resulting from uncertainties in the magnitude and direction of the impulse, energy coupling efficiency, and the properties of the target (mass, composition, porosity, etc.) introduce additional uncertainties. For example, in the case of an impact or nuclear explosion, slight changes in the angle of approach of the spacecraft and/or detonation distance (for the nuclear case) will affect the magnitude and direction of the resulting deflection. Furthermore, the magnitude of the deflection will be influenced by the properties of the target. A porous target has a lower energy transfer efficiency than a non-porous target [13]. Errors in the total mass estimate of the NEA also lead to uncertainties in the final deflection delta-velocity, since the deflection delta-velocity goes as p/m, where p is the momentum imparted to the NEA and m is the mass of the NEA minus the material ejected (with equal and opposite momentum $-p$) as a result of the impulse. These examples illustrate a subset of the sources of error due to uncertainties in the properties of the object and/or the accuracy of the mission planning that must be considered when planning a deflection mission. In a deflection attempt these orbital uncertainties propagate through to the new, perturbed orbit and contribute to an uncertainty in the final position at the original impact epoch.

In this paper, we extend the work of B [7] and present a simplified, nonlinear analytic determination of the effect an instantaneous, planar change in velocity has on an orbit, and examine the propagation of uncertainties in this velocity change through the resulting orbit. We approximate the motion using the two body problem where keyholes, interactions with planets, gravitational influence by Earth in the final approach, etc. are not considered. We believe that consideration of these important, higher order effects are best studied using detailed N-body calculations.

The purpose of this work is to provide a quick scoping tool that translates uncertainties in velocity changes due to a deflection attempt into uncertainties in position at predefined times in the orbit. While there are several already existent methods for calculating orbits and changes to those orbits, most are difficult for a non-specialist to use and/or are computationally expensive. Direct numerical simulations of N-body interactions, as stated above, provide the most complete solution to the problem but are numerically tricky to get right and usually require more sophisticated numerical techniques beyond the standard Runge–Kutta integrators. Applying Monte Carlo techniques to a stable numerical integrator provides the necessary uncertainty quantification, but this can get prohibitively expensive and again relies on the underlying stability of the numerical integrator. One can always simplify this approach to the 2-body case, but then one is usually left with the determination that the analytical approach, defined here, is superior. Again, we stress that the fully numerical N-body approach is best for detailed studies, but that it is overkill for most quick scoping studies, which is what the tool derived in this paper aims to address.

There are also analytical methods available that do not require the same level of computational power. The most widely used is the simple linear approximation created by Aherns et al. However, while this approach obtains results that are correct in an orbit-average sense, it does not account for variations within each orbit. As shown below, these can be factors of $2\times$ in the required deflection delta-velocity and when coupled with mission planning scenarios this difference can become appreciable. A more recent analytical approach ([16,29], and references therein) using elliptical Hill–Clohessy–Wiltshire equations is a promising alternative approach. However, in this paper we are seeking an approach that non-experts in astrodynamics could easily understand and utilize, in an effort to reach the broad and very diverse backgrounds of the asteroid deflection community.

This type of analysis is useful in a number of applications, for example, in exploring how deflection delta-velocity