Acta Astronautica ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Mission opportunities for the flight validation of the kinetic impactor concept for asteroid deflection

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ARTICLE INFO

Article history:
Received 12 November 2013
Received in revised form
9 April 2014
Accepted 15 April 2014

Keywords:
Kinetic impact
Asteroid deflection
Mission design

ABSTRACT

The kinetic impactor technique for deflecting near-Earth objects (NEOs), whereby a spacecraft is directed to collide with a NEO to alter its orbit via momentum transfer, is one of several proposed methods for defending Earth against hazardous NEOs (asteroids and comets). In this paper we present detailed mission design concepts for a feasible and affordable kinetic impactor flight validation mission deployed to a currently known near-Earth asteroid (NEA). Several filter steps are devised that utilize relevant criteria to optimally balance key parameters, such as approach phase angle, estimated NEA diameter, relative velocity at intercept, and current NEA orbit knowledge, and produce refined lists of the most promising candidate target NEAs.

1. Introduction

The kinetic impactor technique for deflecting near-Earth objects (NEOs), whereby a spacecraft is directed to collide with a NEO to alter its orbit via momentum transfer, is one of several proposed methods for defending Earth against hazardous asteroids and comets [1–4]. Other proposed methods for deflection of NEOs include nuclear detonation, gravity tractor, and laser ablation [5–9]. NEOs are asteroids and comets whose orbit perihelia are <1.3 AU, which means that they approach or cross Earth's orbit, creating the possibility of collisions with Earth.[1] NEOs consist of both near-Earth asteroids (NEAs) and near-Earth comets (NECs).

The kinetic impactor technique must be validated by one or more flight validation missions in order to be considered reliable during an actual incoming NEO scenario. An asteroid deflection flight validation concept was studied by ESA in the Don Quijote mission [10], and, more recently, the AIDA mission has been proposed to deflect the binary asteroid Didymos in 2022 [11]. However, much research still needs to be performed for kinetic impactor deflection missions. In previous work [12] a survey was performed on a subset of the known NEA population whose orbits are completely exterior or interior to Earth's orbit (for safety reasons) to identify all target NEAs that offer feasible opportunities for kinetic impactor flight validation missions. The previous survey was conducted using a filter that is based on optimized mission mass. Also, a detailed model was developed for predicting the deflection of the NEA's orbit as a proxy for the experimental observability of the change in the NEA's velocity.

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[1] http://neo.jpl.nasa.gov/neo/groups.html. Last accessed on 03-22-2014.

http://dx.doi.org/10.1016/j.actaastro.2014.04.013
0094-5765/

Since the kinetic impactor concept has never been tested before, we want to ensure that regardless of what might go wrong during the experiments, we ensure that Earth will not be threatened by the flight validation mission. For this reason, the subpopulation of NEAs chosen for our study are those whose orbits are entirely exterior or interior to Earth's orbit. We also seek low ΔV missions for the sake of affordability, and therefore only selected NEAs with heliocentric orbit inclination $\leq 20^{\circ}$ for this study. Besides safety and affordability, an additional constraint is that the deflection imparted to the NEA by the kinetic impactor must be easily measured by an observer spacecraft that has rendezvoused with the NEA prior to the collision of the kinetic impactor. In fact, the constraint on inclination is mainly relevant for affordability purposes of the observer spacecraft rendezvousing with the asteroid. The mission trajectories are designed such that the observer and impactor launch together on a single launch vehicle into an Earth escape trajectory that takes the observer directly to rendezvous with the NEA. The impactor separates from the observer after launch but before observer arrival at the NEA by performing a maneuver such that it will collide with the NEA after the observer has spent adequate time gathering data on the NEA. This trajectory design is chosen over other types of missions, such as launching the observer and impactor spacecraft on two separate launch vehicles, in order to reduce the cost of the mission. To ensure a measurable experiment we require that the difference in position between the NEA's deflected and undeflected orbits reaches at least 100 km by 2 years after impact.

We build upon the results from the previous study [12] by augmenting the target NEA filter to incorporate additional criteria such as the approach phase angle of the spacecraft with respect to the NEA. The approach phase angle should be $\leq 90^{\circ}$ to provide an operationally realistic scenario in which the spacecraft's onboard sensors are able to acquire the NEA (by virtue of the NEA being adequately illuminated from the spacecraft's perspective) during approach and terminal guidance. Additionally, new filter steps are devised that utilize all criteria to optimally balance key parameters such as approach phase angle, estimated NEA diameter, relative velocity at intercept, and current NEA orbit knowledge to produce a refined list of the most promising candidate target NEAs for future flight validation missions.

Finally, we combine all of the aforementioned analysis to produce complete detailed mission designs for feasible and affordable kinetic impactor flight validation test missions deployed to currently known target NEAs. We provide extensive detail on the trajectory design, terminal guidance, and orbit determination for a specific mission to NEA 1998 KG_3. We also present a list of the most promising target NEAs for kinetic impactor flight validation test missions.

2. Flight validation mission target selection

Here we describe our methodology for surveying the NEA population to identify the best candidates for kinetic impactor flight validation missions, beginning with an overview of the known NEA population and its subgroups.

2.1. Initial NEA candidate population

We begin with a brief overview of the NEAs used in this study, which are based on the NEA population used in Ref. [12]. NEAs are classified into four groups based on their orbital characteristics[2]:

1. *Amors* have orbits exterior to Earth's. The perihelion of an Amor's orbit is therefore between 1.017 and 1.3 AU. There were 3017 Amors known at the time of our study (late June of 2011).
2. *Apollos* are Earth-crossing NEAs with semi-major axes larger than Earth's (>1 AU), but with perihelia less than 1.017 AU. There were 4392 Apollos known at the time of our study and they continue to comprise the majority of the currently known NEA population.
3. *Atens* are Earth-crossing NEAs, with semi-major axes smaller than Earth's (<1 AU), but with aphelia greater than 0.983 AU. There were 660 Atens known at the time of our study.
4. *Atiras* have orbits completely interior to Earth's and therefore have aphelia less than 0.983 AU. There were only 11 known Atiras at the time of our study and only 1 more has been discovered since. It is possible that many more exist but are difficult to find using ground-based observatories since Atiras spend most of their orbits in our daytime sky.

Apollos and Atens tend to be more accessible, in terms of low ΔV, to spacecraft missions because they are Earth-crossing NEAs and their orbits are often rather similar to Earth's orbit. It should be pointed out, however, that they may also have a long synodic period, making the mission not feasible. However, for our study we selected only Amor and Atira NEAs as candidate mission targets because their orbits are either completely exterior or interior to Earth's orbit. This ensures that Earth will never be threatened by deflection system testing activities, regardless of what might go wrong during the test missions. For example, if the spacecraft hits the asteroid in the wrong direction, and/or the ejecta flies away from the impact site in an unexpected direction due to the actual shape of the asteroid (which may not be known well in advance), it could harm the Earth. Even though only considering Amors and Atiras is a fairly conservative subpopulation, the safety of Earth is a high priority, especially since there are many unknowns in a first deflection validation mission. Looking at a bigger subpopulation is something we may consider in future work, but in such cases we would employ statistical analyses to show that the likelihood of turning a harmless asteroid in a dangerous one is small enough to be acceptable.

Additionally, we imposed the constraint of heliocentric orbit inclination $\leq 20^{\circ}$ in the interests of keeping mission ΔV manageable. Thus, the candidate target NEAs for our

[2] http://neo.jpl.nasa.gov/neo/groups.html. Accessed on 03-22-2014.

Please cite this article as: S. Hernandez, et al., Mission opportunities for the flight validation of the kinetic impactor concept for asteroid deflection, Acta Astronautica (2014), http://dx.doi.org/10.1016/j.actaastro.2014.04.013