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Momentum enhancement factor estimation for asteroid redirect missions

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ABSTRACT

An asteroid mitigation demonstration mission is gaining interest among the planetary defense community to better understand the challenges and the dynamics of a small solar system body (SB) impact scenario. The Kinetic Impactor (KI) deflection technique, considered the most mature and cost effective approach for deflecting SBs, gained credibility following both the numerous studies performed (Don Quijote, NEOShield-2, preparations for DART mission, …) as well as the successful targeting of the Deep Impact (DI) spacecraft (S/C) into comet 9 P/Tempel 1. A dual-satellite concept AIDA with KI (DART) and an Explorer S/C (AIM/HERA) is currently under study by the ESA and NASA. While one of the more mature deflection options, there are still a significant number of poorly constrained aspects of the KI deflection technique. Of particular interest are the complex ejecta cloud dynamics that can have a considerable impact on the deflection efficiency and the according β-factor. Understanding the momentum enhancement β-factor is considered paramount as it bears the potential of overall mission cost reduction and is inherently linked to the SB geotechnical properties. Therefore, estimating this β-factor is one of the top-level scientific requirements for future demonstration missions. First, this work presents a β-factor estimation technique with the focus on an SB orbit determination (OD) filter where radioscience tracking data of an Explorer S/C at the close proximity is fused with optical navigation information. Second, an extensive error analysis is presented where the major drivers of the β-factor error budget are identified based on a breakdown tree. The paper shows the estimation filter architecture and explicitly addresses the data fusion process. An extensive, high fidelity test campaign has been conducted to conclude on the achievable β-factor estimation performance for a KI impactor reference scenario with the SB 2001 QC34. An end-to-end momentum enhancement factor estimation technique is presented and it was found that the β-factor uncertainty is reduced to 0.33 (3σ) after only 1 week of monitoring with 67% availability of the tracking stations and a station-keeping manoeuver once a day. This estimation performance has shown that the momentum enhancement factor uncertainties can be constrained considerably and thus further advocates a KI demonstration mission.

1. Introduction

Asteroids and comets continue to shape surfaces of the solar system bodies via impacts. The morphological features characterizing the lunar surface are craters formed by impacts over the last billion of years. The Earth too has been threatened by solar system small bodies over its lifetime. Main Belt Asteroids (MBA) are deflected by the gravitational attraction of nearby planets into orbits that allow them to enter the Earth's vicinity. Impacts by < 100 m-diameter NEO's may only devastate a relatively small region [1]. The Tunguska Event in 1908 and the Chelyabinsk airburst event in 2013 are the most well-known examples over the last decades. Future impacts on century-to-millennium timescales are events to be regarded and to be prepared for by our civilization. The NASA Near-Earth Object Survey and Deflection Study provides an analysis of the alternatives to detect, track, catalogue and divert a NEO on a likely collision course with Earth [2]. The “slow-push” concepts make use among others of the Yarkovsky-effect, solar radiation pressure (SRP) and the gravity tractor pulling. The “impulsive” concepts cover the conventional explosives, kinetic impact and nuclear alternatives. The *Defending Planet Earth: NEO Surveys and Hazard Mitigation Strategies* of the US National Research Council (NRC) classified the mitigation options depending on the NEO diameter and warning time available before impact [3].

For the type of small bodies (SB) with a diameter < 300 m, where the most likely next Earth impactor is expected from, the KI concept is the most appropriate deflection measure, where a large, high-speed (i.e. momentum) Impactor S/C is flying on a collision course with the SB. Part of the mission scenario is illustrated in Fig. 1 where an Explorer S/

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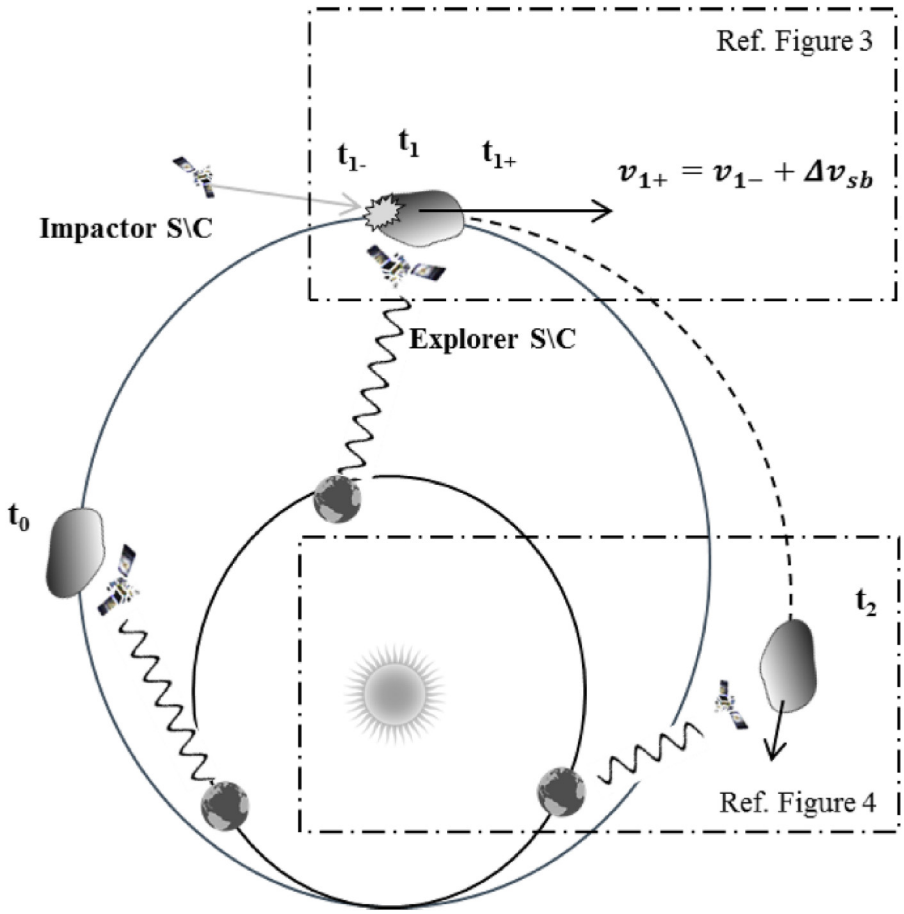

Fig. 1. Kinetic Impactor scenario and observation strategy involving an Explorer S/C.

C assists in determining the SB orbit before (t_0 till t_{1-}) and after (t_{1+} till t_2) impact with a high precision. In between, it will monitor the deflection by the Impactor S/C that transfers its momentum onto the object and therewith changes its orbit. The momentum transfer from Impactor S/C to object is aided by ejecta escaping the SB surface where the effect is mathematically described by the momentum enhancement factor, often called β-factor. The SB momentum gain $M\Delta\boldsymbol{v_{sb}}$ is related to the spacecraft linear momentum ($m\boldsymbol{u_{sc}}$) and the ejecta momentum ($\boldsymbol{p_{ej}}$) through a matrix formulation [11]:

$$M\Delta\boldsymbol{v_{sb}} = \boldsymbol{\beta_{lin}} m\boldsymbol{u_{sc}} = -\boldsymbol{p_{ej}} + m\Delta\boldsymbol{v_{sc}} \tag{1}$$

With the SB mass M, the Impactor S/C mass m, the total SB delta-v $\Delta\boldsymbol{v_{sb}}$ and relative impactor velocity $\boldsymbol{u_{sc}}$ where the **linear enhancement matrix** is defined as:

$$\boldsymbol{\beta_{lin}} = \begin{pmatrix} \beta_{lin,x} & \beta_{lin,xy} & \beta_{lin,xz} \\ \beta_{lin,yx} & \beta_{lin,y} & \beta_{lin,yz} \\ \beta_{lin,zx} & \beta_{lin,zy} & \beta_{lin,z} \end{pmatrix} \tag{2}$$

Where this matrix can be rewritten as:

$$\boldsymbol{\beta_{lin}} = \beta_{lin}\,\mathbf{R}_{\beta} \tag{3}$$

With the scalar momentum enhancement gain β_{lin} (also called "*β-factor*"):

$$\beta_{lin} = \frac{M|\Delta\boldsymbol{v_{sb}}|}{m|\boldsymbol{u_{sc}}|} \tag{4}$$

With $\mathbf{R}_{\beta}$, the direct cosine matrix that relates the momentum vector $\beta_{lin} m\boldsymbol{u_{sc}}$ and $M\Delta\boldsymbol{v_{sb}}$ directions. The SB velocity change $\Delta\boldsymbol{v_{sb}}$ can be written as:

$$\Delta\boldsymbol{v_{sb}} = \Delta\boldsymbol{v_{sc}} + \Delta\boldsymbol{v_{ej}} \tag{5}$$

Where $\Delta\boldsymbol{v_{sc}}$ is the SB velocity change due to the Impactor S/C and $\Delta\boldsymbol{v_{ej}}$ the SB velocity change caused by the ejecta. Is the collision perfectly plastic, no ejecta is generated and thus $\Delta\boldsymbol{v_{ej}} = 0$, $\beta_{lin} = 1$ and $\mathbf{R}_{\beta}$ the unity matrix.

2. Material and methods

The overall aim of this work is (1) to present a β-factor estimation technique with the focus on a SB orbit determination (OD) filter where radioscience tracking data of an Explorer S/C at the close proximity is fused with optical navigation information and (2) to present an extensive error analysis where the major drivers of the β-factor error budget are identified based on a breakdown tree. Based on the β-factor expression (ref. Eq. (4)), the necessary parameters to be estimated are described and are used to establish an error budget using a linear error analysis assuming all parameters being uncorrelated. The knowledge uncertainties for the first three parameters, SB mass σ_M, Impactor S/C mass σ_m and impact velocity $\sigma_{\boldsymbol{u_{sc}}}$ have been considered stochastic, normal distributed with the variances taken from the literature and previous mission data. The total SB velocity change uncertainty $\sigma_{|\Delta\boldsymbol{v_{sb}}|}$ will be shown to drive the β-factor knowledge $\sigma_{\beta_{lin}}$ and is therefore the focus of this work. An iterative least square estimation technique including a covariance analysis and a high-fidelity simulation framework are setup to assess and verify the β-factor estimation technique.

3. Theory

The measurement strategy of the momentum enhancement gain β_{lin} will be elaborated in this section. Based on the definition given by Eq.