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Towards Designing a Credible Hazardous NEA Mitigation Campaign of Dual-deflection Act

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Given a limited warning time, an asteroid impact mitigation campaign would hinge on uncertainty-based information consisting of remote observational data of the identified Earth-threatening object, general knowledge on near-Earth asteroids, and engineering judgment. Due to these ambiguities, the campaign credibility could be profoundly compromised. It is therefore imperative to comprehensively evaluate the inherent uncertainty in deflection and plan the campaign accordingly to ensure successful mitigation. This research demonstrates dual-deflection mitigation campaigns consisting of primary and secondary deflection missions, where both deflection performance and campaign credibility are taken into consideration. The results of the dual-deflection campaigns show that there are trade-offs between the competing aspects: the total interceptor mass, interception time, deflection distance, and the confidence in deflection. The design approach is found to be useful for multi-deflection campaign planning, allowing us to select the best possible combination of deflection missions from a catalogue of various mitigation campaign options, without compromising the campaign credibility.

Key Words: Near-Earth asteroid, Deflection technique, Dual-deflection campaign, Uncertainty-based information, Multi-objective optimization

Nomenclature

$\mathbf{p}$: mitigation system design parameters
$\mathbf{x}$: mitigation system design variables
$\mathbf{y}$: mitigation performance indicators
m : mass
t : date
b : deflection distance on b-plane
Bel : Belief; probabilistic measure
v_{imp} : kinetic impact velocity at rendezvous
t_{push} : time period of gravity tractoring
tof : time of flight

Subscripts
0 : initial / Earth departure
1 : primary interceptor
2 : secondary interceptor
$f1$: primary interception completion
$f2$: secondary interception completion
MOID : minimal orbital interception distance
nom : nominal
safe : safety
trim : trim

1. Introduction

Asteroid deflection and retrieval technologies are rapidly becoming of interest amongst scientists, engineers, and politicians particularly after asteroid 2012 DA14 Earth's flyby and the Chelyabinsk meteor event occurred early in 2013. NASA is now planning to send a robotic mission to a 500-ton, <10-metre-wide near-Earth asteroid (NEA), safely redirect it to a lunar orbit, and perform in-situ robotic and human exploration for both planetary defense and resource utilisation purposes. However, asteroid deflection and retrieval initiatives are both still in their infancy and thus abound in scientific, engineering, political, and educational challenges to be addressed at the international level.

As of today, several asteroid deflection concepts have been proposed. Some of these concepts appear to be feasible with the current technology developed through deep space exploration missions, whereas others require certain levels of technological advancement before they can be considered as feasible deflection alternatives. Also, a deflection technique which makes use of nuclear devices for example, involves political issues to be tackled by the international planetary defense community. Nevertheless, we now recognise that it is not unrealistic to prevent an impact event by a modest-sized (<150 metres in diameter) NEA if it can be discovered and identified to be threatening about a decade in advance of the impact event.[1)] Most importantly, even such small asteroids can cause a local devastation far greater than the Tunguska event in 1908 or the recent Chelyabinsk meteor event on February 15th 2013.[2)] Based on the NEA population that has been discovered so far, it is more likely that hazardous NEAs to be mitigated will be in this modest size range, rather than kilometre-sized NEAs which can potentially trigger a global catastrophe such as the K-T boundary impact event. The K-T boundary impact event is believed to be the cause of the mass extinction of dinosaurs approximately 65 million years ago.

Recent work by Sugimoto et al.[3,4] has shown that, for particularly short warning-time impact scenarios (i.e. 10 years), only limited information about the hazardous NEA would be available and that this will most likely come only from ground-based or space-based characterisation approaches. In such cases, the majority of deflection techniques will be subject to epistemic uncertainties and measurement errors in the NEA characteristics, which could lead to compromised outcomes of mitigation.

Fig. 1 shows confidence levels on the outcome of kinetic impactor (KI) subject to different degrees (associated with the ground-based and proximity characterisation scenarios) of uncertainty in NEA mass. There are two probability measures called Belief and Plausibility which represent different confidence levels.[5] In general, Belief represents a confidence level of the truth of an event (i.e. deflection) excluding uncertainty whereas Plausibility represents a confidence level of the truth of the same event including uncertainty. Particularly when the preliminary NEA characterisation is incomplete, the confidence level on the outcome of deflection attempt is substantially jeopardised.

It is therefore essential to investigate mitigation campaign planning that involves design of a reliable and robust NEA mitigation system which guarantees high confidence in successful mitigation campaign even if the preliminary NEA characterisation is incomplete.

The main objective of this research is to demonstrate a mitigation campaign planning approach that results in efficient, reliable, and yet robust NEA mitigation for short warning-time cases. The additional objective is to ensure the flexibility in deflection in order to avoid undesired key-hole passage on the b-plane[6] due to the primary interception.

To fulfil these objectives, we have considered a dual-deflection mitigation approach that makes use of an instantaneous deflection technique (KI) as a primary deflection mission and a slow-push deflection technique (gravity tractor; GT) as a secondary deflection mission. The use of a GT as a secondary deflection mission for the secondary impact keyhole avoidance was suggested in the JPL report by Yeomans et al.[7] in 2008. They also pointed out that tracking of the GT spacecraft would provide precise information about the asteroid orbit before and after the primary deflection mission and also after the GT trim manoeuvre. Their study however, assumed the range of the momentum enhancement factor β of the NEA ($1 < \beta < 5$) in order to evaluate possible outcomes of the primary interception achieved through a KI instead of considering the uncertainties in the NEA characteristics. Such combined mitigation measures have been also investigated as a part of the NEOShield project.[8]

Design of a dual-deflection mitigation campaign involves trade-offs between the competing aspects (the total interceptor mass, interception time, deflection distance, and the confidence in deflection) which are to be optimised in order to minimise the launch cost of NEA mitigation systems and total campaign period while maximising the deflection performance (i.e. deflection distance on the b-plane of the impact epoch) and the confidence in successful mitigation campaign (i.e. Belief of the nominal deflection distance).

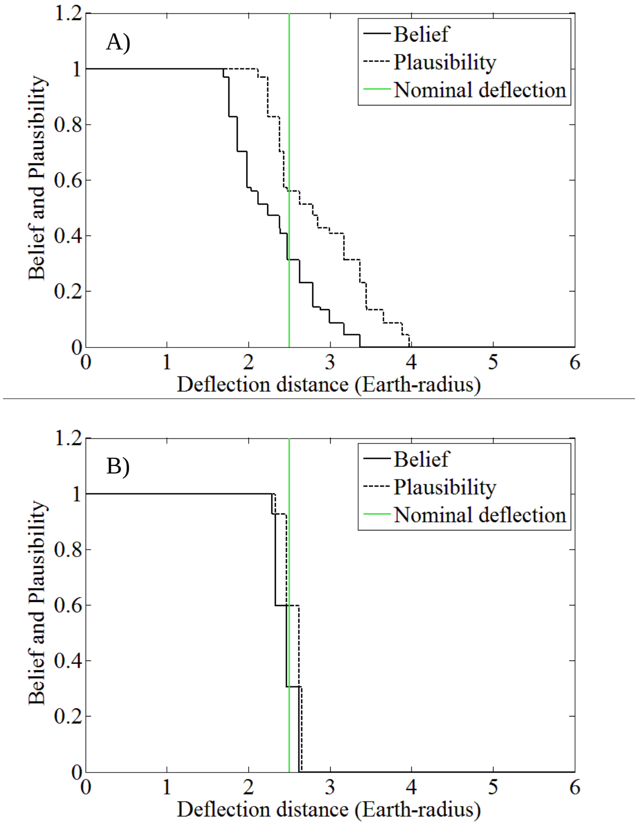

Fig. 1. Uncertainty in deflection by KI. A) Ground-based. B) Proximity. Confidence levels on achieving a given deflection distance on the b-plane are represented by Belief and Plausibility, respectively.

2. Mitigation campaign planning

Mitigation campaigns should be accurately planned in order to provide a successful deflection even if the preliminary NEA characterisation is based on ground-based telescope/radar observation. Sending multiple spacecraft/interceptors of one specific type of deflection technique (e.g. the multiple solar mirror concept of Maddock et al.[9] and the multiple GT concept of Foster et al.[10]) can increase the deflection efficiency as well as the redundancy of a given deflection mission. However, such mitigation campaigns are inevitably subject to the uncertain performance of a specific deflection technique due to not only the epistemic uncertainties in the NEA characteristics but aleatory/practical uncertainties in the technique (e.g. the precision of a KI, the time-variable sublimation efficiency of a SC, etc.).

To overcome the limits imposed on NEA mitigation campaigns of a single type deflection mission and to make the campaigns more reliable and robust, this work focuses on mitigation campaigns consisting of primary and secondary deflection missions (i.e. dual-deflection campaigns). The primary deflection mission makes use of an instantaneous deflection technique whereas the secondary deflection mission makes use of a slow push deflection technique. The final outcome of a dual-deflection campaign is therefore determined by the secondary deflection mission which performs its slow-push interception according to the instantaneous outcome of the primary interception that could be fully successful, partly successful, or at worst, a complete failure. The secondary deflection mission should also be capable of preventing the NEA from undesired keyhole passage on the 2036 b-plane due to the primary deflection mission in order to avoid a subsequent Earth impact.

2.1. Dual-deflection campaign

Dual-deflection campaigns studied here consist of a primary interceptor (KI) and a secondary interceptor (GT). Fig. 2 represents an example of dual-deflection campaign consisting of a KI and a GT (i.e. KI-GT campaign). The hazardous NEA, namely VI_1 is one of the virtual Earth impactors that have been generated from a realistic population of impactors by taking into account the relative impact frequency of each possible trajectory.[11)] VI_1 is an Apollo asteroid and identified as an Earth impactor 10 years before the impact on 2036/4/13. The transfer orbits of the KI and GT are designed by solving a two-body Lambert's problem. A conventional chemical propulsion system of $Isp = 300$ sec is used as a kick stage at Earth departure and to accelerate or decelerate at the final approach to the target NEA. For the case of KI-GT campaign, two interceptors are sent to the NEA separately and hence follow two different trajectories. This is due to the fact that the KI takes advantage of a higher relative velocity at the NEA encounter whereas the GT requires a smaller relative velocity at the NEA rendezvous in order to reduce the total amount of delta-v for the orbital transfers. For this reason, the GT arrival can be, in theory, earlier than the KI's arrival. In this case, we assume that the secondary interception (GT) can be operational before and after the primary interception (KI) takes place according to the proximity characterisation of the target NEA conducted by GT.

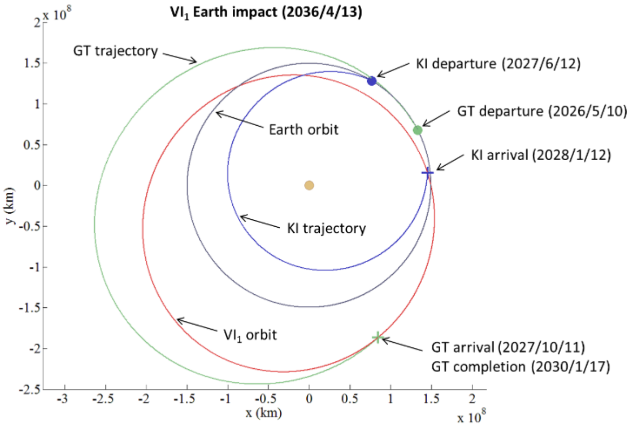

Fig. 2. Example of KI-GT campaign against VI_1.

3. Campaign optimisation

The most notable feature of asteroid deflection mission is that the characteristics (orbital parameters, physical properties, dynamical properties, etc.) of the NEA are deeply embedded into the design as an integral part of the mitigation systems, and influence their deflection performance. Fig. 3 is a schematic diagram that describes such asteroid mitigation system design as multidisciplinary system design. The mitigation system design involves three basic vectors **p**, **x**, and **y** where

- **p** is a vector of design parameters representing fundamental properties of the hazardous NEA (e.g. orbit, physical property, etc.) and environmental parameters (e.g. gravity, solar constant, radiation pressure, etc.).

- **x** is a vector of mitigation system design variables (e.g. mass and impact velocity of KI, mass of nuclear interceptor (NI), mirror size of solar collector (SC), mass and hovering altitude of GT, etc.).

- **y** is a vector of mitigation performance indicators for the campaign (e.g. total mass of mitigation systems, total interception time, deflection distance, confidence in deflection, etc.).

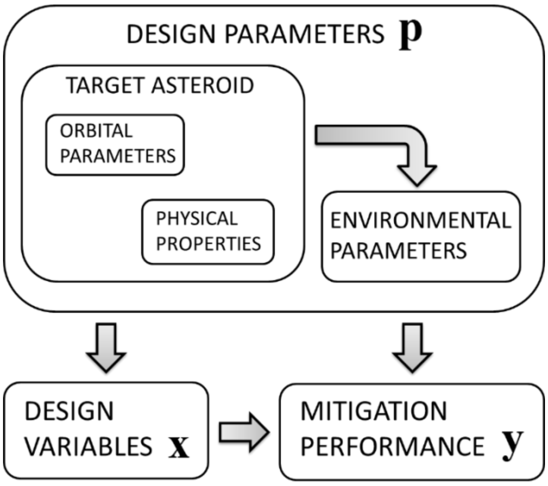

Fig. 3. Hazardous NEA mitigation system design.

The minimum and maximum values of design variables **x** for a KI-GT campaign are given in Table 1. m_1 and m_2 are the masses of primary and secondary mitigation systems at NEA arrival, respectively. t_1 and tof_1 are the Earth departure time and the flight time of the primary interceptor whereas t_2 and tof_2 are the Earth departure time and the flight time of the secondary interceptor. v_{imp} is the relative velocity component of the KI parallel to the flight direction of the NEA. t_{push} is the tractoring/interception period of the GT.

Table 1. Design variables **x** for a KI-GT campaign.

m_1 (kg)	500 – 10000
m_2 (kg)	500 – 20000
t_1	2026/4/13 – 2033/7/11
tof_1 (day)	100 – 1000
t_2	2026/4/13 – 2033/7/11
tof_2 (day)	100 – 1000
v_{imp} (km/s)	0 – 30
t_{push} (day)	0 – 3650

The deflection representation of hazardous NEAs is based on the b-plane concept that is applied to planetary encounter analyses.[6)] The minimum distance of the unperturbed trajectory at the closest approach point on the b-plane is called the impact parameter b. The impact parameter itself does not reveal whether the perturbed trajectory will intersect the Earth sphere; however, it can be available by scaling Earth's radius $\mathrm{R_E}$ as

$$b_{\mathrm{E}} = \mathrm{R_E}\sqrt{1 + \mathrm{v}_{\mathrm{esc}}^2/\mathrm{v}_{\infty}^2} \quad (1)$$

where $\mathrm{R_E}$ is the Earth radius, $\mathrm{v_{esc}}$ is Earth's escape velocity, and v_{∞} is the hyperbolic excess velocity of an Earth encountering object. A given trajectory intersects the Earth sphere if b is smaller than the scaled Earth-radius b_{E}, and not otherwise. The objective of NEA mitigation is therefore to ensure that a given deflection is greater than b_{E} on the b-plane of the impact epoch.

In order to design a dual-deflection campaign, a number of trade-offs between competing aspects must be evaluated and optimised. The campaign optimisation problem requires evaluating the figures of merit (i.e. the mitigation performance indicators vector $\mathbf{y}$) that characterise the performance and the confidence in a successful mitigation campaign. $\mathbf{y}$ consists of m_0, t_{f1}, t_{f2}, b_{nom}, and Bel_{nom} where:

- m_0 is the total mass of two NEA mitigation systems at the Earth departure stage (EDS), which should be as small as possible to reduce the cost of the mitigation campaign.
- t_{f1} is the completion time of the primary deflection mission, which is desirable to be as early as possible such that a longer interception by the secondary deflection mission after the primary interception can be available. In addition, earlier completion of the primary interception is simply preferable for safety reasons.
- t_{f2} is the completion time of the secondary deflection mission (i.e. campaign completion time), which should also be as early as possible such that an additional mitigation campaign can be launched, if necessary.
- b_{nom} is the nominal deflection on the b-plane, which is desired to be as large as possible in the range of $b_{\mathrm{E}} < b_{\mathrm{nom}} < b_{\mathrm{safe}}$.
- Bel_{nom} is Belief of nominal deflection, and thus higher Belief indicates higher confidence in successful mitigation.

In this work, there are a series of constraints that are assumed for demonstration purposes of feasible and desirable hazard mitigation campaigns. m_0 is limited to 200 tons and t_{f1} can be no later than t_{f2} in order to allow the secondary interceptor to conduct a necessary trim manoeuvre for keyhole avoidance after the primary interception. The nominal deflection b_{nom} must be at least b_{E} and can be as large as b_{safe}. The deflection distance b_{trim} that can be provided by the trim manoeuvre of the secondary deflection mission by GT after the primary interception must be greater than 1000 km. This seems to be more than enough to avoid undesired keyhole passage due to the primary deflection mission according to the JPL report.[7)]

The fast and elitist multiobjective genetic algorithm NSGA-II[12)] is used here to compute Pareto optimal design points of dual-deflection mitigation campaigns. A total of 2400 solutions for $\mathbf{y}$ are numerically computed in MATLAB.

3.1. Results and discussion

The results of KI-GT campaigns against $\mathrm{VI_1}$ of S-type asteroid characterised at the ground-based level are presented in Fig. 4. The Pareto-optimal solutions for the campaigns are presented in terms of the campaign completion time (i.e. the completion time t_{f2} of the GT) and the total interceptor mass m_0 at the EDS, which are categorised into eight different levels of the Belief measure of nominal deflection; Bel_{nom}.

One of the notable aspects of dual-deflection campaigns is that Bel_{nom} is highly dependent on both total interceptor mass m_0 at the EDS and the campaign completion time t_{f2}. For the KI-GT campaign scenario, there are quite a few optimal KI-GT campaigns available within 100–150 tons of m_0, given $Bel_{\mathrm{nom}} \leq 0.57$ and 2–4 years of t_{f2}, whereas there are almost no KI-GT campaigns available within 100–150 tons of m_0, given $Bel_{\mathrm{nom}} \geq 0.83$ and <4 years of t_{f2}.

Also, it can be seen that a longer campaign period (>6 years) does not necessarily increases the overall mitigation performance including Bel_{nom} but actually there are many optimal dual-deflection campaigns with a nominal deflection as large as 2.5 Earth-radii within 3–6 years of t_{f2} for $Bel_{\mathrm{nom}} \geq 0.70$ without requiring a significantly large amount of total interceptor mass relative to that for longer-term campaigns. This appears to be simply due to the fact that later asteroid deflection missions are less efficient than earlier ones.

Particularly for the KI-GT campaign scenario against $\mathrm{VI_1}$, the GT rendezvous with the NEA is approximately <2 years before or <1 year after the KI arrival/interception time depending on the respective KI-GT campaign sequences, where the former case is found to be highly beneficial in terms of the proximity characterisation of the NEA as well as of the precise guidance of the KI by GT. The GT might start tractoring immediately after the NEA rendezvous without waiting for the KI arrival/impact, however most importantly, this is not always the case particularly when the true values of the NEA physical properties are in the nominal conditions or much more favourable conditions (e.g. less heavy NEA mass than expected, smaller in size, etc.). If the in-situ NEA physical characteristics result in a favourable outcome, the GT will simply add an extra deflection to the outcome of the primary interception.

In addition, the avoidance of undesired keyhole passage due to the primary interception is fulfilled, counting on the reserved deflection b_{trim} by the GT trim manoeuvre after the primary interception. The period of time to achieve b_{trim} ranges from 107 days to 9.35 years and is, not surprisingly, proportional to the confidence level of each campaign.

Furthermore, the preliminary results of the KI-GT campaign scenario imply that not only the NEA arrival but the Earth departure of the KI could be even later than the GT arrival at the NEA, depending on the availability that is subject to the launch window, warning time, NEA orbit, etc. This would be beneficial for the mitigation system design of KI as a primary interceptor because the GT can conduct preliminary characterisation of the NEA at the proximity level in advance of the Earth departure of the KI, and thus investigating the availability of such a precursor characterisation mission by GT is subject of future work.

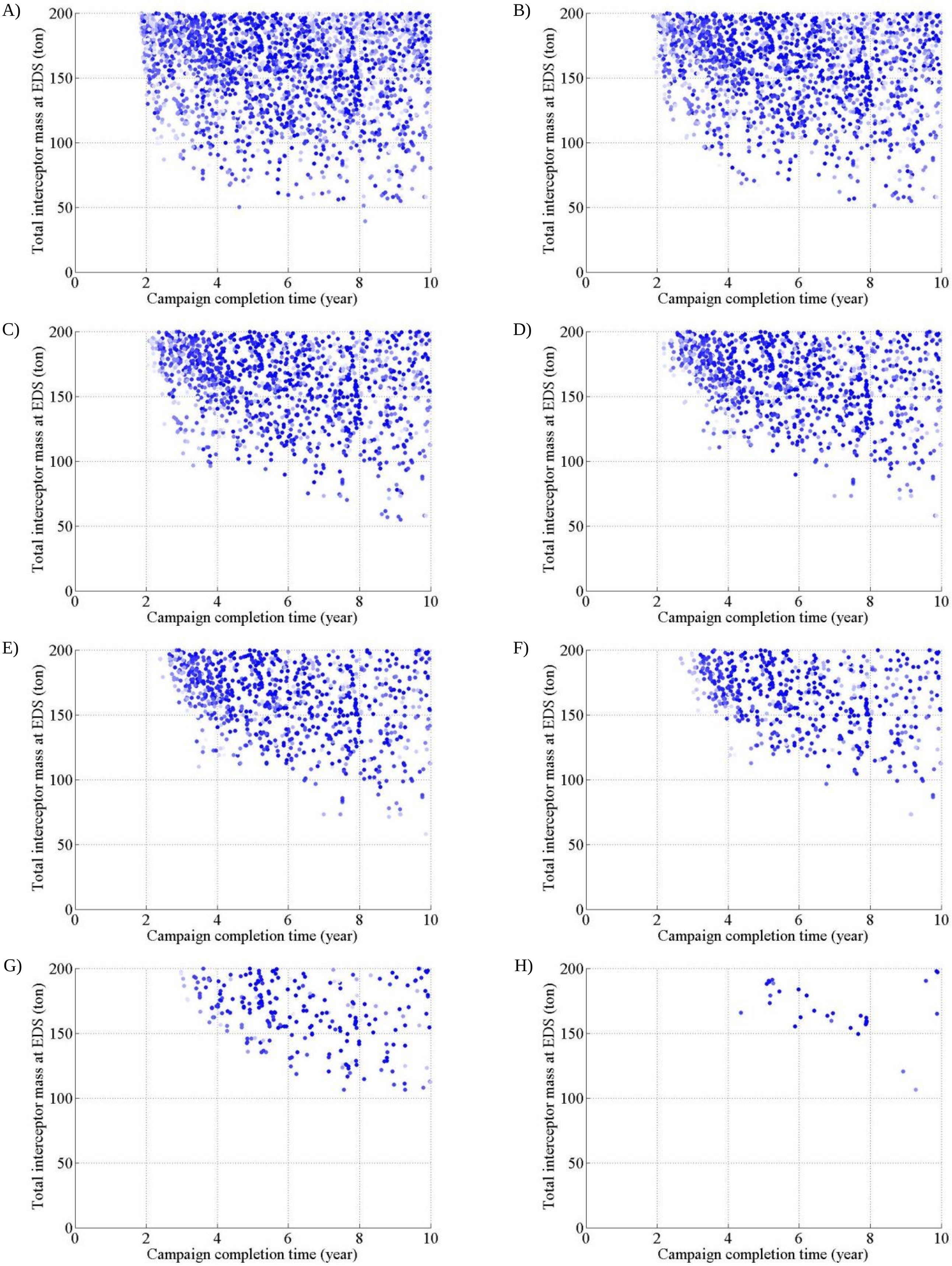

Fig. 4. Optimal solutions for KI-GT campaigns. Darker shades of blue represent higher values of b_{nom} whereas fainter shades represent lower values of b_{nom}. A) $Bel_{\text{nom}} \geq 0.47$. B) $Bel_{\text{nom}} \geq 0.51$. C) $Bel_{\text{nom}} \geq 0.56$. D) $Bel_{\text{nom}} \geq 0.57$. E) $Bel_{\text{nom}} \geq 0.70$. F) $Bel_{\text{nom}} \geq 0.83$. G) $Bel_{\text{nom}} \geq 0.97$. H) $Bel_{\text{nom}} \geq 1.00$.

4. Conclusions

A hazardous NEA mitigation campaign planning based on uncertain information on the fundamental asteroid characteristics has been studied to improve the mitigation campaign credibility, where one of the possible forms of mitigation campaign – dual-deflection campaign – has been investigated in detail. In order to evaluate the confidence level on deflection missions subject to the uncertain NEA characteristics, the uncertainty quantification technique called Evidence Theory is used. The preliminary results of the dual-deflection campaigns consisting of a primary KI and a secondary GT have shown that:

- Dual-deflection campaign planning involves a series of competing aspects that must be assessed and constraints associated with the specific configurations of KI-GT to be satisfied to plan a mitigation campaign with sufficient performance (i.e. deflection) and high confidence in successful deflection (i.e. Belief).
- Given a GT as a secondary deflection mission, Belief of nominal deflection can be improved by years of GT interception manoeuvre before and after a primary deflection mission for the KI-GT campaign scenario. However this does not necessarily means that the GT must always commence its interception immediately after the NEA rendezvous but the actual operation of the GT is subject to the in-situ NEA characteristics.
- Given a 10-year warning time, a mitigation campaign with a completion time of approximately half the warning time seems to be more reasonable than a longer-term mitigation campaign or a mitigation campaign with a heavier total interceptor mass at the EDS. In other words, this appears to be due to the deflection performance decrease with time and increase in the launch cost of necessary mitigation systems for a shorter-term mitigation campaign.
- Possible keyhole passage due to undesired deflection by a primary interception can be avoided by a GT as a secondary deflection mission in a dual-deflection campaign, given the necessary amount of deflection in order to avoid the keyhole passage is 1000km.

Finally, the particular campaign planning approach presented here could be useful for the near-future hazard mitigation campaigns where we might have to tap into our incomplete knowledge on NEAs for mitigation campaign design, allowing us to select the best possible combination of deflection missions from a catalogue of various possible mitigation campaign options, without compromising the campaign credibility. However in the foreseeable future, further knowledge about the NEA population and some specific NEAs will have steadily accumulated and improved through the forthcoming NEA survey and exploration missions such as NEOSSat, Sentinel, Hayabusa2, and OSIRIS-Rex as well as the recently announced NASA's NEA retrieval mission to be launched as soon as the year 2017.

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