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HIJACKING A SATELLITE FOR SHORT-WARNING ASTEROID DEFLECTION – FastKD MISSION, DESIGN AND IMPLEMENTATION

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1 Scenario and objectives

The work published in this paper has been elaborated within an activity performed under a program of, and funded by, the European Space Agency. The scenario addressed within this study activity assumes the discovery of an asteroid whose orbit propagation reveals a high probability of Earth impact within a very short warning time of approximately 1-3 years. In such a scenario, one (or multiple) kinetic asteroid deflection missions are identified as a viable mitigation method, but because of the short warning time a significant consequence is an extremely constrained mission preparation time with a "to Launch" requirement of 6 months or less. This results in a build or system adaptation timeframe of 2-3 months.

The activity consequently assesses the feasibility of modifying a commercial spacecraft platform in order to perform asteroid kinetic deflection in the shortest possible time. Moreover, the necessary prerequisites to enable the challenging "build and launch of a Kinetic Impactor (KI) deflection system extremely fast".

The selected approach is outlined by "hijacking" an existing commercial platform with minimal adaptations and the addition of a pre-developed Kinetic Deflection (KD) module, providing in particular GNC impact capabilities, in order to convert it to an asteroid deflection mission.

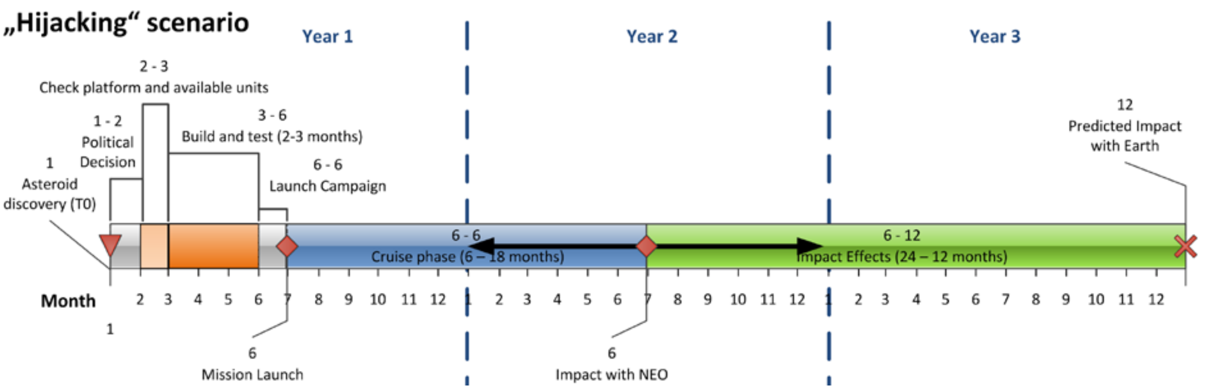


Figure 1: Tentative timeline for the chosen “hijacking" scenario where predicted Earth impact is extremely time constrained (~1-3 years) allowing only minimal build and adaptation time.

With the information of a credible asteroid impact threat political decision makers are expected to push for a rapid deflection attempt using Kinetic Impactor (KI) technology i.e. using a large (massive) spacecraft with maximum possible momentum to deflect the asteroid away from an Earth collision path. The Kinetic Impactor method is currently considered as the most mature option given the existing capabilities and is one of the less complex deflection strategies. In particular, the impact GNC system could be matured by Airbus to a TRL of 5-6 during the NEOShield-2 study in 2016-2017. Because of this extremely short warning time before Earth impact, the timespan to launch a countermeasure mission is also extremely constrained demanding emergency solutions and processes for build and system adaptation activities as well as political decision making.

2 Mission Analysis

To determine the deflection requirements to be met by the KD mission capabilities for kinetic deflection of a 50m asteroid with a short-warning time, more than 250 Near-Earth Asteroids in a size range from 20 to 80 meters (including 45 Potentially Hazardous Asteroids (PHA)) in a dedicated catalogue were analysed with thousands of impact trajectories for all of them. The main findings obtained from the results are:

- Deflection requirements (and thus deflection mission capabilities) depend not only on the transfer time but also on the relative geometry between asteroid and Earth, especially in missions with low warning time. This demonstrates that not only the highest deflection momentum is primarily relevant, but also how early a given momentum can be imparted to allow more time for the deflection effect to accumulate before the predicted Earth impact.
- The arrival mass does not directly relate to the deflection capabilities since for each asteroid (and also the complete set seen as a whole) the full range of deflection efficiency can be achieved for all the considered masses.
- Solar Phase Angle (SPA) is also an important parameter for the study. Higher SPA tends to correspond to higher deflections for the same transfer time. SPA also largely affects the launch opportunities to asteroids: higher allowed SPA result in much more feasible missions and thus increases the mission flexibility & deflection capabilities. Since these are essential to ensure mission success, the SPA cannot be constrained to good illuminations conditions, which has significant implications for the GNC sensors as far as detection and targeting are concerned
- Regarding the asteroid orbit parameters, with the current sample of ~250 asteroids, the greatest level of deflection corresponds to low inclination and/or asteroids with Semi-Major Axis (SMA) closer to 1 AU.
- In terms of distance to Earth and Sun, parametric plots show that the vast majority of missions stay close to Earth orbit.

In conclusion, mission analysis showed that the obtained deflection requirements (and thus the required capabilities) of a kinetic impactor spacecraft are sufficient to deviate an asteroid in a very great number of different conditions and target physical properties. Mission analysis also revealed the limitations of the kinetic deflection capabilities, especially with respect to warning time and arrival conditions such as spacecraft mass, impact velocity and solar phase angle.

3 System Requirements

3.1 European Platforms

A survey of European large platforms that could be suitable for rapid adaptation to meet the needs of a fast Kinetic Impactor mission has been performed using specifications of Airbus and other European large system integrator platforms. It is compiled from discussions and meetings with Airbus telecommunications division experts and publicly available literature sources (manufacturer, ESA Artes programme, technical papers and others).

On subsystem level the applicability of the commercial (telecoms) platform subsystems for an interplanetary asteroid KD mission has been investigated leading to a list of required modifications, replacements and/or additions. The investigation indicates that repurposing an existing platform for such mission objectives is only feasible if key aspects of the KD spacecraft are prepared, developed and tested in advance of the mission need becoming a reality.

3.2 Encompassing System Requirements

The agency selected the proposed shorter "Hijacking" mission scenario to proceed with further investigation and derivation of system requirements.

In this scenario, the necessity to have as pre-requisite a pre-developed “Kinetic Deflection (KD) module” coupled with a suitable available telecommunication satellite was identified. This KD module needs to be available from the beginning of the mission scenario build time, as shown in the timeline (beginning of month 3 after threat discovery, see Figure 1), and needs to contain KI mission specific elements that require longer development time i.e. ahead of the nominal 3 year warning scenario. It would therefore contain elements such as:

- the narrow angle vision sensor set (NAC suite)
- a computer unit running the sensor data (e.g. image) processing
- navigation, guidance and control capabilities
- possible additional thrusters depending on compatibility with the expected repurposed platform existing capability
- a power generation system
- a dedicated communications subsystem
- all necessary thermal, fluidic, mechanical, electrical and data interfaces with telecom satellite platform

In an enveloping design approach, the requirements have been derived in a way that the mission and its systems are generically designed considering the deflection of 5 representative reference target NEO scenarios with specifications obtained from mission analysis, that cover the most relevant proportion of possible targets.

4 Impactor Design

4.1 Impactor system design and approach

The preliminary system design is implemented to be flexible for most sizing cases and applied as far as possible to the range of targets and trajectories in order to avoid different mission architectures for each reference case.

The design is referenced to the most challenging "Hijacking" scenario and considers the key modifications that are necessary to be made to the existing platform and those requiring development, as a minimum, ahead of the six month build time due to their inherent complexity or availability.

It is clear that the time for the spacecraft development does not allow the nominal spacecraft testing period (which can last more than six months) and therefore reuse of an existing platform with minimal adaptations is the priority. Thus, an important design consideration is that every effort is to be made in advance to minimise modifications and reuse the hijacked platform in its developed and "as intended" state. By hijacking a platform that is routinely built however, build errors are minimised.

Conceptually, by considering the KD module as the interface between the launcher and the hijacked spacecraft it should be possible with a well-designed, flexible interface to be compatible with the hijacking of several different large platforms, as launcher interfaces are reasonably generic

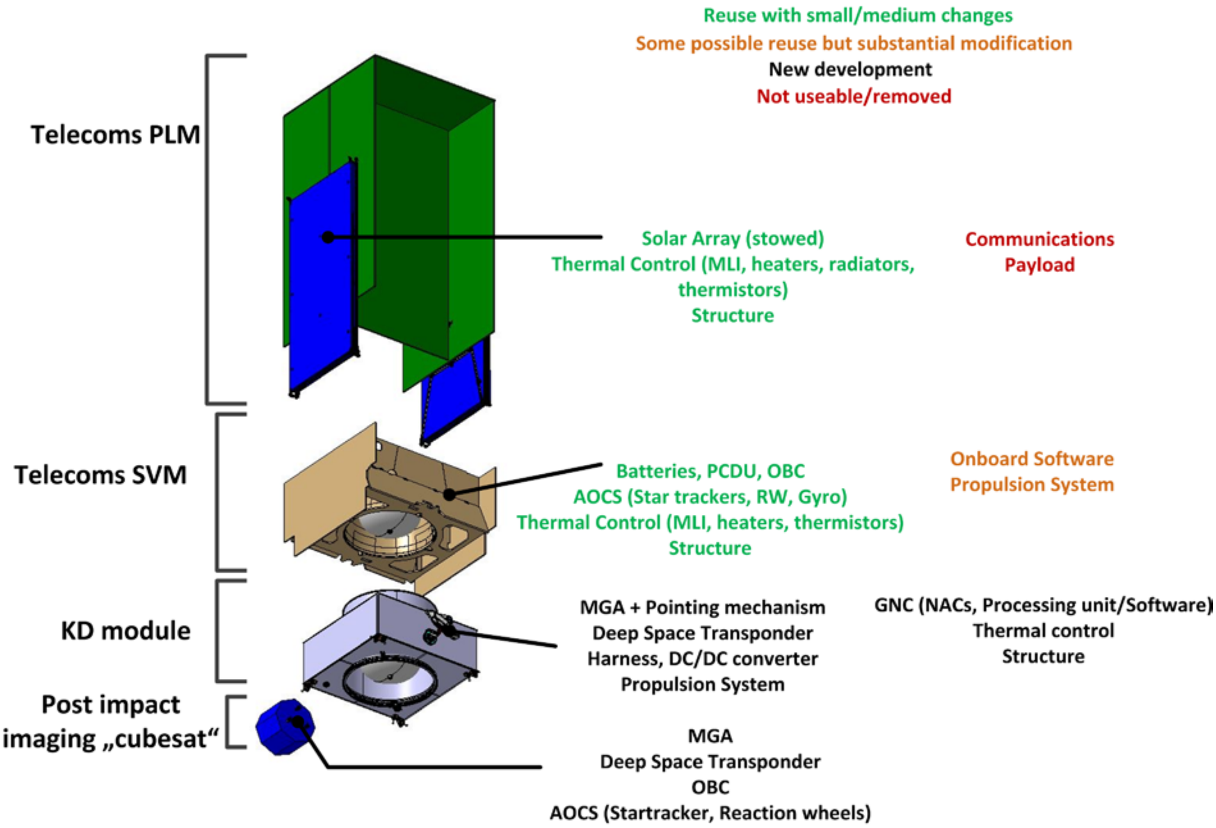


Figure 2: Schematic layout of the complete FastKD spacecraft elements and indications for necessary modifications, new developments or reuse as is

The Fast Kinetic Deflection space segment, as depicted by the schematic illustration in Figure 2, is a spacecraft resulting from the assembly of a complete (i.e. service module and payload module) telecom satellite with the KD module. This latter module contains the hardware elements that are unique to the respective mission profile and is well-tested in advance of the emergency scenario materialising. It consists of the supporting structure, the GNC (sensors and the processing, command and data handling subsystem), the deep-space communications subsystem, the thermal subsystem and redundant propulsion system thrusters in optimised positions used for final targeting manoeuvres. Detailed justification is given in the respective activity deliverables.

4.2 GNC subsystem design

The GNC is the key subsystem of the KD module. Extensive analyses have been undertaken to address the challenging mission profile (target size and approach velocity) and the envisaged S/C repurposing concept with given actuator & sensor hardware specifications. It was found that the repurposing concept is more difficult to address as it requires, beyond optimisation for different impact conditions, the assessment of whether the repurposed S/C assets are usable without modification, with modification, or must be discarded in favour of a specific solution.

This was addressed through sensitivity analysis: starting from the NEOShield-2 developments[1], the parameters were modified one by one to become representative of the FastKD study, to analyse the reusability of the telecom platform assets (the latest Airbus eNEO platform design was taken as main reference) like the propulsion system, to assess alternative solutions and modifications in case of issues (e.g. thruster configuration), to optimize the systems non present on the repurposed S/C (e.g. NAC), and to derive their proper sizing and specification for the new accuracy required.

The considered impact GNC uses LoS vision based navigation, the only technique which can provide sufficient accuracy for the ranges and dynamics considered, and proportional navigation guidance as summarized on Figure 3.

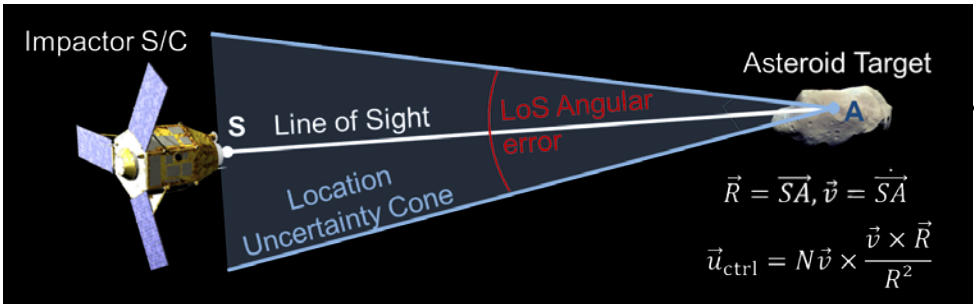


Figure 3: Impact GNC system principles

Through these analyses, the propulsive system available on the eNEO repurposed platform was found compatible with controllability needs of the impactor S/C resulting from the assembly of said platform with the KD module, pending some modifications in configuration allowing sufficient translational authority on cross-track axes. When

[1] See *"NEOShield-2: Desing and End-to-End Validation of an Autonomous Closed-Loop GNC System for Asteroid Kinetic Impactor Missions"*, Chapuy, M. et al., 10th International ESA Conference on Guidance, Navigation & Control Systems, Salzburg, Austria, May 2017.

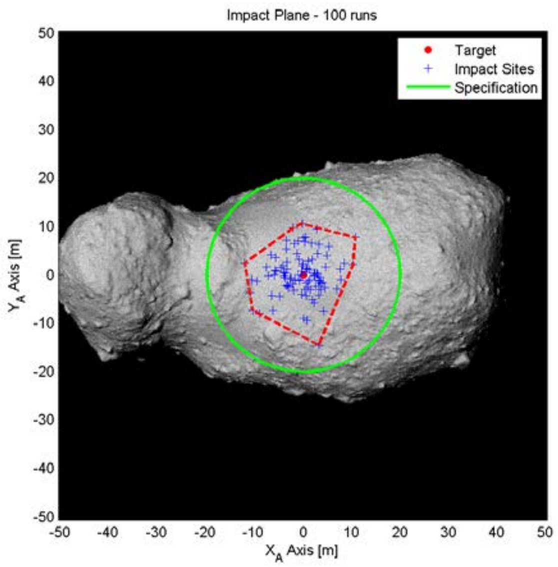
the system is optimized for the desired impact accuracy (below 20m at 99% probability, 95% confidence level), the navigation errors dominate the overall realisation budget, and actuation errors are negligible in comparison.

In the identified and proposed GNC subsystem design the KD module will embark the cameras which form the NAC suite. Two types of camera are foreseen, a Visible Narrow Angle Camera used for asteroid detection at faint magnitude and a TIR Narrow Angle Camera used when the asteroid is resolved.

In fact, considering that the asteroid shape is not known a priori due to limited ground observations, it is only possible to target the part of the asteroid which can be observed during the final approach of the mission itself, and invisible parts cannot be reconstructed contrary to what was done in NEOShield-2 based on template matching image processing and data provided by a reconnaissance orbiter. Furthermore, since the SPA cannot be constrained (in order to maintain a good deflection potential) to values which allow good illumination of the target, the part of the asteroid which can be acquired in the visible domain may be excessively small for the achievable GNC accuracy. This imposes the use of a thermal infrared sensor to acquire the whole asteroid regardless of its illumination state.

The need for Visible Camera is still TBC, depending on TIR sensor capabilities for far range detection to be studied in future activities with suppliers. Both cameras will have to be hot redundant and pointed in the same direction with unobstructed FoV, preferably along a main axis of inertia of the S/C. Given the stringent requirements on magnitude detection and resolution, they are expected to be very heavy and bulky: since the mission can afford the dry mass, the priority is on demonstrating the feasibility of the required sensor design, and mass optimisation is secondary which is unusual in the history of S/C design.

The resulting targeting performance of the proposed GNC subsystem design based on this sensor suite is demonstrated by Monte Carlo campaigns for several reference trajectories to confirm this sizing point. Refer to Figure 3 below, which illustrates the simulated performance for the worst case asteroid 2015 JJ reference trajectory including the applied parameters and statistical performance evaluation.



Parameter	Value
NAC FoV	0.5 degree
Thrust error	3 % (1σ)

Statistical Parameter	Results
Mean Accuracy (m)	5.4
Min Impact Error (m)	0.5
Max Impact Error (m)	14.8
Standard deviation (m)	3.2
Mean +3 sigma (m)	15.0
Control ΔV range (m/s)	5.3 - 8.9

Figure 4: 2015 JJ impact performance, with proposed final GNC system sizing, full Monte Carlo

4.3 General design considerations

In the context of interfacing the KD module with an existing spacecraft platform, and during the later stages of the study, the MetOp-SG platform was also identified as a good possible alternative platform. While not strictly in keeping with the commercial platform aspect of the activity, it is quite a large platform with the required subsystems that can be hijacked and a very capable chemical propulsion system. A further potential advantage of the MetOp-SG platform is the recurring build and storage. MetOp-SG will have six satellites (2 types, A and B, each with three launches) that will span the period 2023 to 2038 such that at any given time from 2024 onward there will be at least 2 satellites available – in a fully tested state – that could be used for the kinetic impactor mission (required adaptations are to be analysed in more detail as this was not possible in the frame of this small activity).

Finally, while highlighting some of the significant complexities of adapting a commercial platform for this unique mission objectives, the work presented in this activity only provides a preliminary design with interesting questions that would considerably benefit from deeper investigation more similar to a Phase A design study.

Finally a “cubesat” or small spacecraft could also be considered as a possible addition to the mission, being attached to the KD module. This would be released before impact and, using a wide angled camera, could provide imagery for the verification of the successful impact.

5 Development and Implementation

The space segment development philosophy and implementation plan follows the driving approach identified in earlier work items: to have a KD module as pre-requisite and rapidly assemble and launch it with a "hijacked" & adapted commercial telecoms satellite, similar to a payload, once a credible asteroid deflection mission becomes necessary. This latter assembly, which then constitutes the KD spacecraft, must be realized within the short 3 months build time, which is a driving requirement.

The testing that can be carried out at this time on the whole spacecraft stack is severely constrained by the available time and therefore consists of electrical and functional tests to check correct operation of the spacecraft and any necessary dynamic acceptance tests on the stack to ensure endurance of the launch. Thermal balance or vacuum tests on the complete spacecraft are excluded due to their duration and are not considered necessary given the tests that will have been carried out on the KD module already in advance.

The extremely challenging schedule constraints do not apply for the KD module as a pre-requisite. Its development approach is thus proposed close to a nominal and more cost efficient spacecraft development procedure. To reduce risk to the mission, a Proto-Flight Model development of the KD module is proposed using a minimum set of models and tests. It shall moreover include extensive (interface) testing with the potentially "hijacked" commercially telecoms satellite model types (because it cannot be done in advance with the actual used S/C, but with that model type) in order to reduce the testing effort required in case of an emergency situation.

6 Conclusion

The activity demonstrates that in an emergency situation, with only a very short warning time, the launch of a fast asteroid kinetic deflection mission is feasible (Targeting for a 6 months launch readiness!), given that certain identified pre-requisites have been prepared well in advance. The capabilities and requirements of "hijacking" and modifying a commercial spacecraft platform in order to perform asteroid kinetic deflection in the shortest possible time have been consequently assessed. A viable preliminary design solution has been proposed compliant to several enveloping mission profiles, advanced GNC subsystem design iterations & performance demonstrations have been accomplished and critical technology developments / long-lead items have been identified and specified within the provided Development and Implementation plan. Most importantly the NAC suite development must be named in this context. With reference to the provided development schedule it is recommended to initiate such developments as soon as possible and at least in parallel to a FastKD Phase A study.

The study scenario is largely driven by the "6 months to launch" requirement and the envisaged approach to "hijack" and re-purpose a commercial spacecraft platform. In this fastest "hijacking" scenario high efforts for preparation of pre-requisites (i.e. KD module completely built and tested) in advance of a threat becoming reality are required. The high pre-development efforts are principally required because of limited compatibility of commercial telecoms P/F (optimized for GEO applications) and the therefore greater modification needs to repurpose such platform for an asteroid deflection mission.

An alternative relevant solution with an even faster "to Launch" requirement could be a dedicated spacecraft completely prepared and kept in stock until a real threat is noticed. With the results of this activity in mind, it appears that "hijacking" an existing platform mated with a prebuild KD module introduces interface complexity and requires more time for integration/adaptation, which could be avoided otherwise. This approach was out-of-scope for the activity which tries to navigate between minimizing a large upfront expenditure and achieving full preparedness for an event whose time horizon is unknown. In view of those programmatic constraints the activity accepted that this approach may not lead to the best technical solution for the problem.

In contrast, with a so called alternative "Cherry-Picking" scenario[2] outlined within the early phases of the study, the "6 months to launch" requirement cannot be fulfilled, but this scenario would offer substantially lower pre-development costs at an adequate level of launch-readiness timescale suitable for slightly longer warning times. This scenario would also allow for additional design optimisations to increase the overall deflection performance. Thus, it could be recommended to keep this scenario in mind for any future Fast Kinetic Asteroid Deflection activity.

In the context of asteroid deflection activities one can generally define two phases: the "preparation" phase, which includes all activities (e.g. study phases, technology development and spacecraft/module manufacturing) until a real asteroid impact is

[2] The “Cherry picking” approach in this scenario is considered to be the emergency reallocation of any suitable platform or hardware units existing in any European integration facility at a given point in time to create a fast-track AIT process for building the KI spacecraft. Here the spacecraft design and fast-track AIT process is to be extensively prepared in advance by corresponding and appropriately detailed Phase A/B1 studies.

discovered; and the subsequently triggered "deflection" phase where actual space missions are being implemented including all necessary development, build and operation phases. While the "Hijacking" scenario aims for the fastest feasible launch readiness, it requires at the same time the highest preparation efforts. The "Cherry-Picking" scenario alternatively comes along with lower preparation efforts (e.g. limited to an appropriate Phase A design study and key technology development only) on the cost of a somewhat longer launch readiness capability in the order 1 to 1.5 years.

Therefore as the following table indicates, if the budget in the preparation phase is limited, it could be reasonable to start with preparations for a "Cherry-Picking" scenario, as these activities (e.g. Phase A study and NAC development) require considerably less preparation efforts and are in parallel, given the inherent synergies, also broadly applicable for the "Hijacking" scenario.

	Stored dedicated spacecraft	"Hijacking" scenario	"Cherry Picking" scenario
Targeted launch readiness	Fastest (≤1 month)	Fast (6 months)	Medium (1-1.5 years)
Preparation efforts (occur even if no threat materializes)	Highest preparation efforts: Full dedicated S/C	High preparation efforts for needed pre-requisites: KD module	Low preparation efforts: Phase A/B1 design study + key technology development
Total implementation efforts	Medium S/C production efforts + storage	Highest S/C production efforts (KD module + Hijacked Platform + emergency adaptations) + storage	Medium S/C production efforts, no storage

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