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NEOShield Kinetic Impactor Demonstration Mission

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Introduction

This paper outlines a near-term mission concept developed under the NEOShield Project, for the demonstration of deflection capability of Potentially Hazardous Objects (PHOs).

Potentially Hazardous Objects are a subclass of NEOs consisting mostly of asteroids (Potentially Hazardous Asteroids) that have the potential to make close approaches to the earth whilst featuring a size large enough to cause significant regional damage in the event of an impact. The following figure depicts the orbits of the presently known PHOs. It is currently (as of 2012) expected that only 20 - 30 percent of all existing PHOs are already known. This gives an indication that NEOs, in particular PHOs, are likely to pose a real threat to earth on a longer time scale.

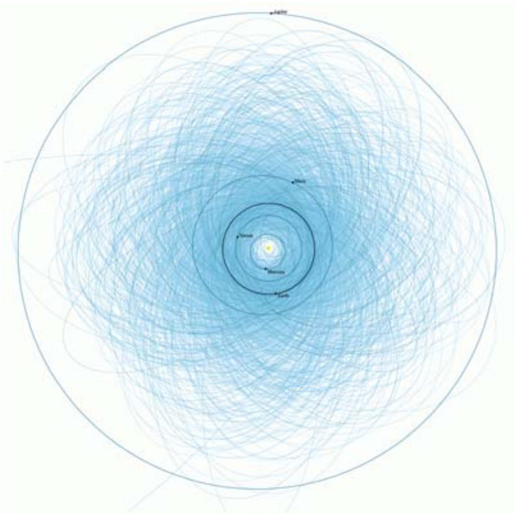

Figure 1: Plot of the orbits of all presently known Potentially Hazardous Asteroids (PHAs), i.e. over 1400 as of early 2013. PHAs are asteroids with a size of at least 140 m and with orbits passing the earth orbit within 7.5 million kilometres. The earth orbit is shown by a bold black nearly circular ellipse. (Credit: Wikipedia Commons)

Among the possible mitigation and deflection options, the mission outlined here seeks to demonstrate NEO deflection by means of a kinetic impactor. Table 1 gives an overview of the objectives that drove the concept development.

Table 1: Kinetic impactor mission objectives

ID	Requirement summary
Primary objectives – Kinetic Impactor demonstration	
MRD-1	Technology demonstration The Kinetic Impactor demonstration mission shall identify uncertainties in the Kinetic Impactor principle in order to eliminate (reduce) them for a real mitigation mission, promote the required technology and demonstrate the overall technical feasibility.
MRD-2	Deflection validation The Kinetic Impactor demonstration mission shall measure and validate the effectively achieved momentum transfer.
MRD-3	β determination The Kinetic Impactor demonstration mission shall quantify the momentum transfer multiplication factor β to a precision of 0.1 (TBC).
Secondary scientific objectives – Enhanced NEO characterization	
MRD-4	Additional scientific characterisation As a goal, the mission shall perform additional measurements of the NEO properties (e.g. near surface properties/mineralogy) to increase scientific outcomes.
Mission extension: Gravity Tractor Experiment	
MRD-5	GT Experiment As a goal and as an optional mission extension based on the already carried equipment, the Kinetic Impactor demonstration mission shall demonstrate the gravity tractor (GT) principle by performing a Gravity Tractor Experiment.

The main objectives of the mission are technology demonstration, deflection validation and beta- determination. This requires a mission that impacts a NEO in a representative velocity regime, allows measurement of the deflection sufficiently accurately to clearly demonstrate the momentum transfer by the impactor. The beta-factor quantifies the additional momentum transfer achieved through ejecta from the asteroid, which can be achieved both through accurate deflection measurement or ejecta observation, ideally through both.

For the development of a fitting mission concept the NEOShield project performed a wide range of trade-offs while taking into consideration a variety of previously developed mission concepts such as Don Quijote.

Mission Architecture

Several different mission architecture concepts were identified. For the different architectures the most relevant conceptual difference is the number of spacecraft. While all precursor studies consider two separate spacecraft, each with complementary mission tasks, there also exist mission concepts fulfilling the mission objectives up to a certain degree with a single spacecraft only. A further defining factor for dual-spacecraft options is whether a shared launch or two dedicated launches are used.

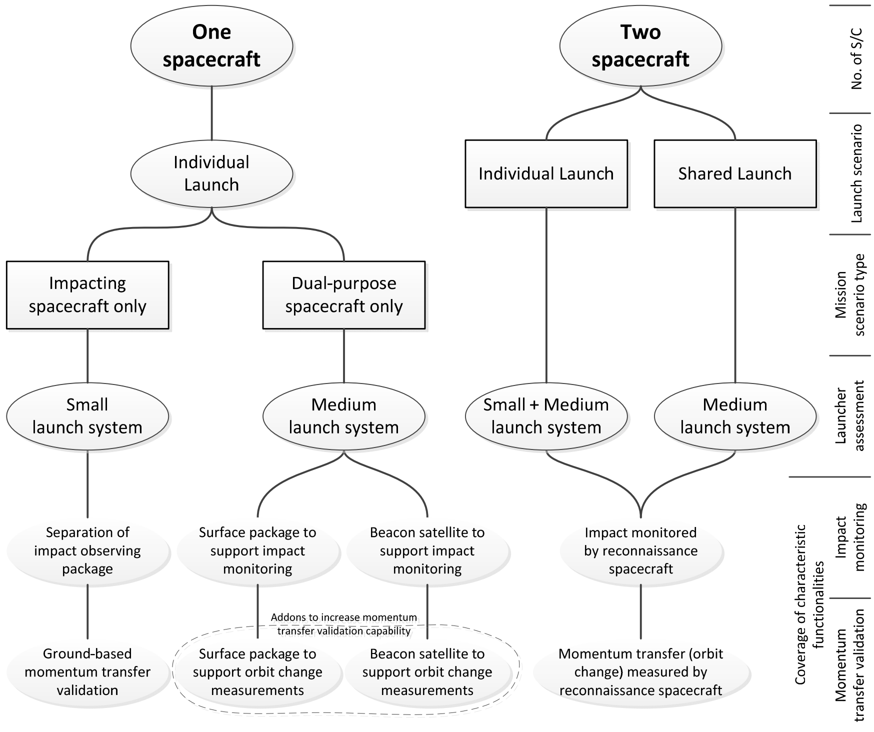

Figure 2: Overview of mission architecture concepts.

The characteristics of the four architecture options shown are further clarified in Table 2.

Table 2: Overview of characteristic mission architecture concepts

Concept identification	Short description	Launch system
Two S/C, Individual launch	A reconnaissance and an impacting spacecraft, launched subsequently by separate launchers. Baseline proposed by all preceding studies.	Small and medium launcher
Two S/C, Shared launch	A reconnaissance and an impacting spacecraft, launched together on a single launcher	Medium launcher
Impacting spacecraft only	Impact an a priori well-characterized target NEO. Deflection effects need to be measured by earth-bound methods. Deflection validation may require years depending on observation opportunities.	Small launcher
Dual-purpose spacecraft only	First characterize target NEO, then gather momentum and hit it. Deflection effects need to be measured by earth-bound methods. Earth-bound deflection validation measurements might require a couple of years, depending on observation opportunities.	Medium launcher

An extensive trade-off of these options was performed. However, the decisive points can be summarized as follows. To be fully representative of a real threat scenario we must assume that the target object is unknown and that time is potentially critical. Examination prior to impact is achieved by dual spacecraft architectures as well as by the impactor dual-purpose spacecraft. However, for the later mission duration is relatively long. Further, only dual-spacecraft options offer good orbit determination before and after the impact and thus direct deflection validation. Earth bound deflection measurement methods are problematic amongst others due to poor knowledge of current NEO orbits, NEO mass, rotational state, and brightness curves (for rotation evaluation).

Trajectory analysis showed that satisfactory transfer trajectories could be found for both shared and individual launches of the impactor and explorer spacecraft. Subsequently, the launch scenario examination favours a shared launch of both spacecraft, mainly due to advantages with regard to impacting mass, mission success probability, and cost.

The selected mission architecture for the Kinetic Impactor Demonstration Mission is as follows:

- Two separate spacecraft: Impactor spacecraft and Explorer spacecraft
- Combined launch on a single Soyuz/Fregat from Kourou
- Launch stack consisting of Explorer spacecraft (top) and Impactor spacecraft (bottom)
- Impactor spacecraft remains connected to the Fregat throughout the mission in order to maximise the momentum at impact
- Separation of Explorer spacecraft from the composite consisting of Impactor spacecraft and Fregat under close supervision from Ground

The selected mission architecture also offers the possibility for a limited Gravity Tractor demonstration.

Mission Timeline

–under review, revision will be provided shortly –

Composite Spacecraft Design

The composite spacecraft consisting of Fregat, Impactor spacecraft and Explorer spacecraft is depicted in the following figure. It can be seen that the Explorer sits on top of the Impactor.

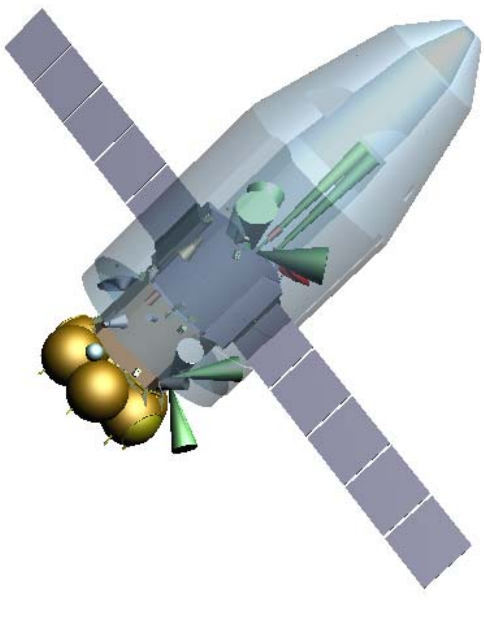

Figure 3: Composite spacecraft consisting of Fregat, Impactor and Explorer with deployed Explorer solar array. The Soyuz fairing envelope is shown transparent.

During launch and Earth escape, GNC/AOCS of Explorer and Impactor spacecraft are inactive. Only after end of this phase, which is under control of the launcher, the Explorer GNC/AOCS is activated and from now on controls attitude and orbit of the composite. GNC/AOCS of the Impactor remains passive until successful separation of the Explorer. Only after this point in time the GNC/AOCS of the Impactor is activated.

During LEOP and cruise in tandem configuration, primarily the Explorer is in charge of communications with ground. This means downlink of HKTM will be done using the Explorer X-Band command and data handling subsystem. To do so, the Explorer OBC gathers the Impactor HKTM and downlinks both Impactor and Explorer HKTM to ground.

Uplink from ground will be achieved during nominal operations also via the Explorer's X-Band communications subsystem. The Explorer OBC will differ between TC for the Explorer and the Impactor and thus distribute accordingly.

In the composite configuration, the Explorer powers the Impactor by its solar array. During that phase, the Impactor requires less than 500 W.

Explorer Spacecraft

The main characteristics of the Explorer spacecraft are shown in the following table.

Table 3: Main characteristics of explorer spacecraft

Mass incl. margins (Dry/Wet)	668kg / 740kg
Solar Array	14.5m², 33% efficiency (BOL)
Power demand (max.)	2720 W
Battery Capacity	3720 Wh (BOL); 31kg
SEP	3x 20mN (QinetiQ T5)
COMS	X/Ka-band HGA & MGA X-band LGA
Navigation Camera	2x Dawn Framing Camera
Payload	VIS/NIR spectrometer (CFI) LIDAR (CFI)
Lifetime	6.7 years

After successful injection into an earth escape orbit the Fregat will be switched off and the Explorer will take over control of the composite until separation from the Impactor, including attitude and orbit control, propulsion, power generation and distribution, communications and data handling.

When close to the target NEO the Explorer spacecraft has to carry out the following top-level tasks:

- Determine mass, CoG position, rotational state, topography and surface properties of 2001 QC34
- Determine the orbit of 2001 QC34 before and after the collision with the Impactor
- Observe the collision from a safe position
- Transmit instrument and housekeeping data to ground
- Relay Impactor telemetry to ground

The deployed configuration of the Explorer spacecraft is depicted in Figure 4. The instruments (not visible) and the two navigation cameras are located on the +Z side and will be oriented towards the NEO once in proximity of it. The equipment for solar electric propulsion is located on the -Z side. The two deployed solar arrays (total area 14.5 m2) are articulated and will be oriented towards sun by rotating them about the Y axis. High gain antenna (HGA) and medium gain antenna (MGA) are shown as well. Each of these two antennas is mounted on a dedicated antenna mount supporting 2-axis pointing. The HGA, for instance, can be rotated about an axis parallel to the Y axis and on top about an axis perpendicular to the first rotation axis. In addition there are two fixed low gain antennas (LGAs) on the +Z and -Z side.

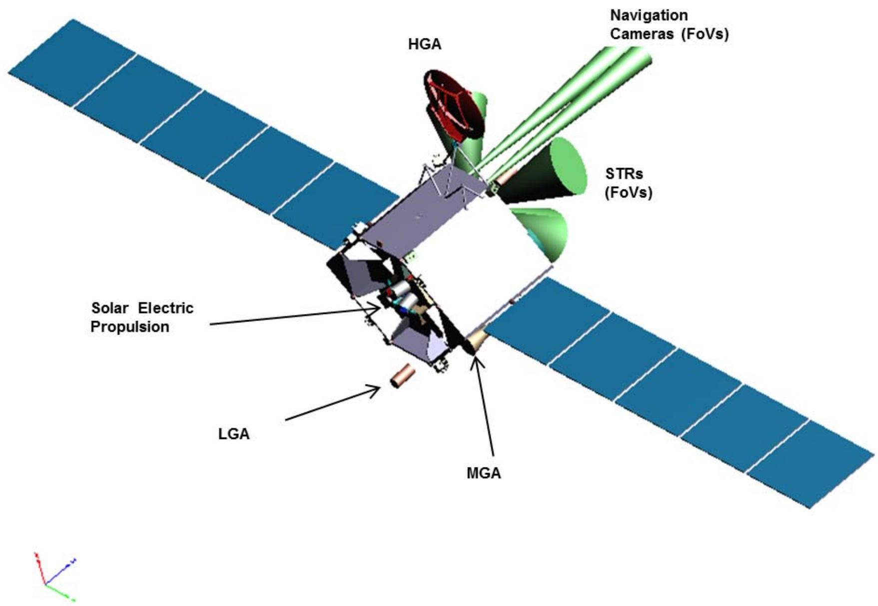

Figure 4: Explorer spacecraft overview in deployed configuration

The payload of the Explorer spacecraft consists of three types of instruments:

- 2 navigation cameras (from Dawn Framing Camera)
- 1 VIS/NIR spectrometer (MaRIS from MarcoPolo-R)
- 1 LIDAR (BELA from BepiColombo)

This suite of instruments has been accommodated on the +Z side of the spacecraft as depicted hereafter. During NEO approach and proximity operations this side will nominally be oriented towards the target NEO.

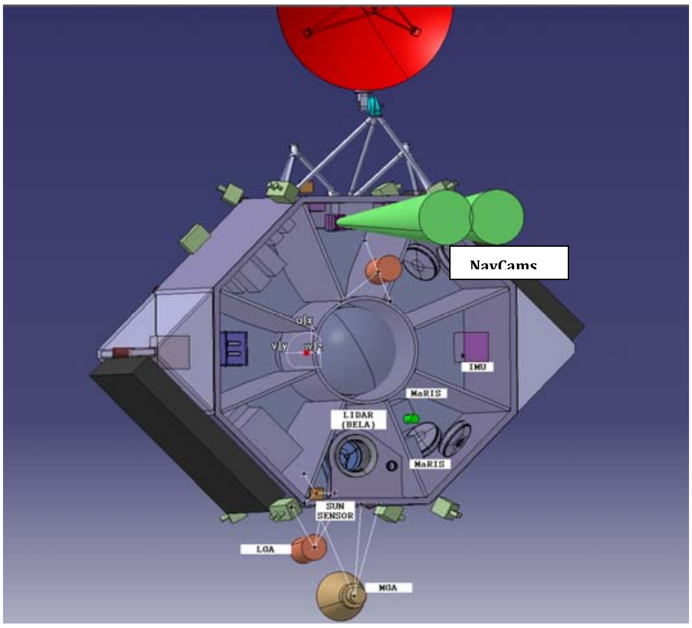

Figure 5: Instruments on the Explorer spacecraft

Impactor Spacecraft

The main characteristics of the Explorer spacecraft are shown in the following table.

Table 4: Main characteristics of impactor spacecraft

Mass incl. margins (Dry/Wet)	407 kg / 498 kg @Impact: 1309kg incl. Fregat
Solar Array	3.1m^2, 33% efficiency (BOL)
Power demand (max.)	785 W
Battery Capacity	3306 Wh (BOL); 28kg
SEP	-
COMS	X-band HGA, MGA & LGA
Navigation Camera	2x LORRI (New Horizon)
Payload	-
Lifetime	6.5 years

The Impactor spacecraft is required to precisely hit the target NEO even under adverse illumination conditions and to transfer a sufficiently high linear momentum (at least 0.02 cm/s) to this celestial body so that its deflection can be quantified by the Explorer. Obviously, the primary factors affecting momentum transfer are mass and relative velocity of the Impactor.

The Impactor consists of the Fregat and of the Impactor S/C that is rigidly mounted on top of the Fregat. This composite is depicted in the following figures. The Impactor S/C is an octagonal prism that is rigidly mounted at its eight lower vertices to eight hardpoints of the Fregat. Intentionally no launcher adapter has been used since there is no need to separate the Impactor S/C from the Fregat. This direct interface between Fregat and spacecraft is customary for Russian space missions and has preliminarily been deemed feasible also European Soyuz launches.

At its top end the prismatic spacecraft body is closed by an upper platform carrying a body-mounted solar array. Each of the upper eight vertices of the prism carries a hold-down and release mechanism for the Explorer spacecraft that is mounted during launch and early cruise phase on top of the Impactor.

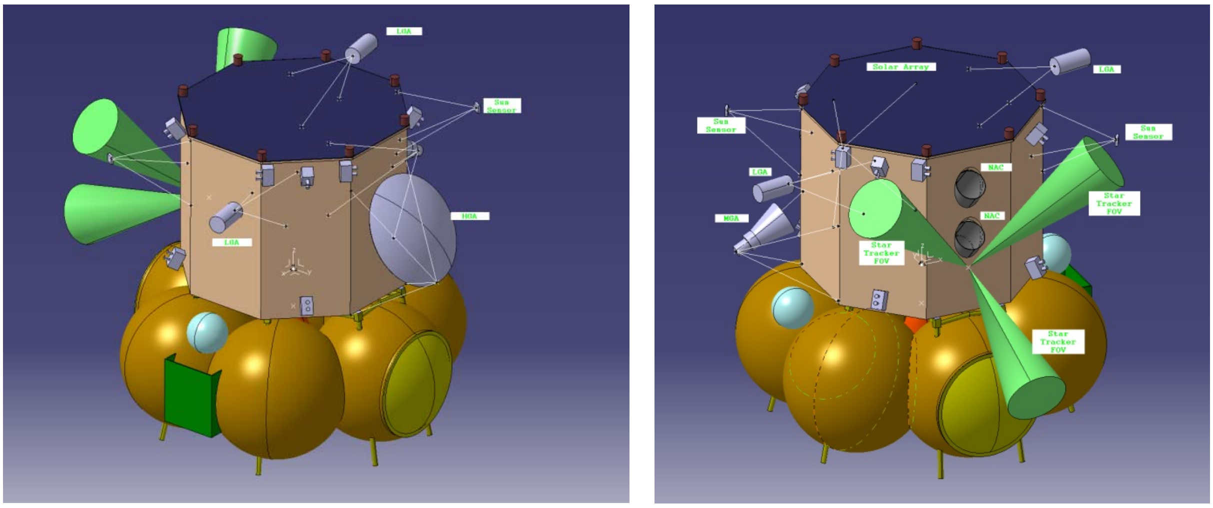

Figure 6: Two views from opposite sides of the Impactor spacecraft together with Fregat

The Impactor spacecraft carries no dedicated payload items. Its two navigation cameras are part of the GNC and AOCS subsystem.

Impactor Terminal Guidance and Control

–under review, revision will be provided shortly –

Alternative Mission Sceanario: Itokawa Spin-Up

–under review, revision will be provided shortly –

Summary and conclusion

The NEOShield study demonstrates the feasibility of a Kinetic Impactor demonstration mission. Such a mission is deemed to be an essential prerequisite for a successful kinetic deflection in case of a real threat.

For this demonstration mission as target the Near Earth Object (NEO) 2001 QC34 has been selected. Driving criteria for this selection were to:

- Avoid any increase in planetary threat, i.e. avoid any reduction in the NEO's Minimum Earth Encounter Distance (MED) due to the deflection action even in view of uncertainties
- Allow for deflection validation with adequate signal-to-noise ratio (SNR ≥ 10)

Both criteria are fulfilled for the selected target which is an Apollo-type asteroid (Earth crosser) that has a diameter of about 240 m.

The mission consists of two spacecraft, an Impactor and an Explorer. What is denoted here *Explorer* is a reconnaissance spacecraft that is to characterise the target NEO prior to the impact in terms of ephemeris data, rotational state, surface geometry and composition. The impact itself and the ejecta produced are observed by the Explorer as well. Finally, after the impact the Explorer will determine the change in ephemeris data of the NEO and thus allows quantification of the momentum transfer and the deflection resulting from the impact. This is important information for a Kinetic Impactor mission in a contingency case.

Both spacecraft, Impactor and Explorer are launched together as a stack on a single Soyuz-Fregat from Kourou. In order to increase the momentum transferred to the selected target NEO, the launcher upper stage (Fregat) remains connected to the Impactor throughout the mission. This means that Impactor (mass 340 kg) and Fregat (mass 902 kg) crash into the NEO as a composite with a total mass of 1242 kg. The impact velocity amounts to 9.6 km/s. The impact accuracy in terms of center of mass offset achievable with the proposed GNC system is only about 12 m and thus excellent bearing in mind that the sun phase angle of the selected target at impact is rather unfavourable so that most of the NEO is in shade when looked at from the approaching Impactor.

The mission design elaborated assumes that the Explorer uses three swing-bys and solar-electric propulsion for the main orbit manoeuvres and ensures that it is reaching the target NEO 5.3 years after launch. The Impactor uses chemical propulsion and as well three swing-bys and will arrive at the NEO more than one year later than the Explorer, thus leaving sufficient time for a detailed characterisation of the NEO prior to the impact. Obviously both spacecraft have to fly on vastly different trajectories to accomplish that. They will remain mated however until shortly prior to their first Earth swing-by manoeuvre occurring roughly one year after launch.

The total wet mass of Impactor (without Fregat) and Explorer including all margins amounts to 1238 kg, whilst the Soyuz-Fregat lift performance allows reaching Earth escape velocity with a payload mass of 1625 kg. There is consequently considerable further room for increasing the Impactor mass and thus its deflection capability.