# Don Quijote: a NEO deflection precursor mission

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## Abstract

There is general agreement that Near-Earth Objects (NEOs) impacts may be the origin of the worse possible natural disaster. Although impacts of large objects with catastrophic consequences are extremely infrequent, impacts of smaller bodies have higher rates of occurrence and can cause severe damage at local or regional level. Furthermore a direct ground impact is not the sole threat since NEOs might trigger Tsunamis affecting much larger areas.

The Don Quijote (DQ) mission has been proposed by the European Space Agency as an asteroid-deflecting experiment with both a scientific and a practical perspective in the context of the NEOs impact hazard management. The primary objective of the DQ mission is to impact a given NEO with a spacecraft (Impactor) and to measure the resulting variations of the orbital parameters and of the rotation states by means of a second spacecraft (Orbiter) previously operating in the proximity of the asteroid. A radio science instrument carried by the Orbiter will be used for the precise measurement of the asteroid orbit and of its gravity field. The Orbiter will also perform measurements to determine the asteroid mass, size and surface properties. Secondary mission goals have also been defined, which would involve the deployment of an autonomous surface package and several other experiments and measurements.

This paper describes the mission and provides a short analysis on the possibility to use the mission to assess specific Near Earth Asteroids for which close Earth approaches have been predicted.

## 1. Background

The mission was proposed in response to a call for Mission and Instrument Ideas issued by ESA in 2002 [1]. It was later given the highest priority of implementation by ESA's NEO Advisory Panel (NEOMAP), an independent panel of experts set up by ESA to provide advice on this preparatory phase.

Don Quijote was the only mission concept addressing an aspect that the experts of NEOMAP considered particularly interesting. That is, the mission not only would gather knowledge on a particular object, but would also demonstrate the capability to modify the trajectory of an asteroid in a measurable way.

Using these recommendations as the starting point, ESA conducted a first assessment in the context of the Concurrent Design Facility (CDF) [2]. This study was carried out by a multidisciplinary team of spacecraft engineers and had the objective of assessing the feasibility of several mission scenarios based on the Don Quijote concept while understanding their cost and technical risk implications. This analysis was then used as the basis for a second assessment [3] in which the goal was to prepare for the industrial phases A studies, as it was used to help define the scope of these studies and derive the system requirements and their priority.

Three parallel industrial phase-A studies have now started, that involve all major European aerospace companies. These studies, which will end in the beginning of 2007, are assessing the designs and trade-offs performed by ESA and putting forward alternative design solutions for DQ. They are also focusing on the design of both spacecraft, together with the equipment and operations needed for the characterization of the deflection. The whole mission operations scenario, including the ground segment, will also be defined.

This paper describes the main results of the second ESA-CDF study [3].

## 2. DON QUIJOTE MISSION

Don Quijote is a deflection precursor mission intended to assess, design and test technologies to deflect an asteroid in a measurable way. Hence, both systems requirements and target selection (see section 3) have been defined so that the obtained information is useful in other types of deflection scenarios (e.g. non-kinetic).

The objectives of the Don Quijote NEO mission are the following:

- primary objective: to impact a given NEA and to be able to determine the momentum transfer resulting from the impact, by measuring the asteroid mass, size, bulk density, and the variation of both the asteroid's CoM orbital parameters and its rotation state.
- Secondary objective: to carry out an Autonomous Surface Package Deployment Engineering eXperiment (ASP-DEX) and perform multi-spectral mapping of the asteroid. An optional extension of this secondary objective is the characterisation of the thermal and mechanical properties of the asteroid surface.

As a result, two system options have been defined:

- Option 1: DQ+ mission, addressing both the primary and the secondary objectives. In this option the system comprises an Impactor and an Orbiter spacecraft. The Orbiter spacecraft would carry a simple suite of engineering and scientific payloads, including the ASP-DEX (see section 5.2).
- Option 2: DQ "Light" mission that would address the primary mission objective only. The system also comprises an Impactor and an Orbiter, however the Orbiter would carry only the minimum payload needed to accomplish the mission primary objective (i.e. to measure the linear momentum transfer resulting from a hypervelocity impact on the target asteroid).

The mission will contain the following elements. In both system options, the Orbiter spacecraft (called Sancho) is the vehicle that performs rendezvous with the target asteroid. It is inserted into an orbit about the asteroid and measures its orbital parameters, the mass, size, gravity field and shape, before and after impact in order to assess the momentum transfer. In addition, the Orbiter shall operate as a backup data relay for transferring the collected Impactor Guidance and Navigation Control (GNC) engineering data, and image the impact from a safe parking position. In parallel to attaining this primary objective the Orbiter, in the DQ+ mission option, pursues scientific investigations of the asteroid, addressing part of the mission secondary goals. Finally, after completion of the primary mission, the DQ+ Orbiter will carry out the ASP-DEX and act as data relay for the surface package.

The Impactor (called Hidalgo) is the vehicle that, after an interplanetary cruise with minimum ground segment (G/S) support, will perform completely autonomous terminal guidance and navigation manoeuvres towards the target asteroid. It relays GNC engineering data and images of the target to the G/S and Orbiter spacecraft, and impact at very high relative speed (~10 km/s) against the asteroid's surface. This spacecraft will demonstrate the autonomous GNC capability based on optical navigation. As NASA's Deep Impact mission already proved, vision-based autonomous guidance navigation and control is feasible, however DQ will be facing additional challenges linked to the target's reduced dimensions (e.g. a very elongated small asteroid could even pose serious concerns to the autonomous navigation system from a visibility point of view).

## 3. TARGET SELECTION

The selection of an appropriate target for the internal pre-phase A and industrial phase A studies was based on a set of NEO characteristics that are most relevant for the DQ mission design. These were defined by NEOMAP and are summarized in Table 1.

| **Asteroid orbit characteristics** | **Preferred range** | **Remarks** |
|---|---|---|
| Rendezvous ΔV | < 7 km/s | Targets with ΔV < 5km are preferable |
| Orbit type and MOID | AMOR or large and increasing MOID | To rule out perturbing a PHO |
| Orbit determination accuracy | Well determined orbits | |

| **Physical characteristics** | **Preferred range** | **Remarks** |
|---|---|---|
| Size | < 500 m diameter | Or slightly larger; driven by the need to measure a deflection |
| Density | 1.3 gm/cm3 | |
| Absolute magnitude H | 20.4 - 19.6 | For albedo between 0.05 and 0.1 |
| Shape | Not irregularly shaped | To guarantee a maximum transfer of linear momentum |
| Taxonomic type | C-Type | Worst-case albedo for visual navigation. Might also maximize the generation of ejecta |
| Rotation period | Around 6h | Average rotation period value for given diameter |
| Binarity | Not binary | For ease of operations |

**Table 1 Preferences for the mission target**

As a result of this analysis two targets have been pre-selected for the purposes of the phase A studies [4]. These are asteroids 2002 $AT_4$ (baseline) and 1989 ML (backup). 1989ML is heavier bur more accessible than 2002 $AT_4$, and thus more favourable from a mission and Orbiter spacecraft design point of view. However, perturbing its trajectory would be more challenging. Therefore the 2002 $AT_4$ scenario is the sizing case for the Orbiter; while in the case of the Impactor design the sizing scenario is 1989 ML. As a result of adopting this approach based on two different target bodies, the system design will be able to cope with a wide range of possible targets. This could be beneficial in case other interesting target candidates are identified in later phases of the mission or if a similar mission had to be used to asses a real NEO threat (see section 6).

## 4. MISSION ANALYSIS

### 4.1 ORBITER TRANSFER

In the reference mission scenario to 2002 $AT_4$ of the CDF study [3], the Orbiter's Earth escape will take place in mid-March 2011 (see Figure 2) with an escape velocity of 3.5 km/s. This will be preceded by a typically lengthy escape sequence, which might take 3 weeks or more. Arrival will occur in early January 2015, almost 2.5 years prior to impact.

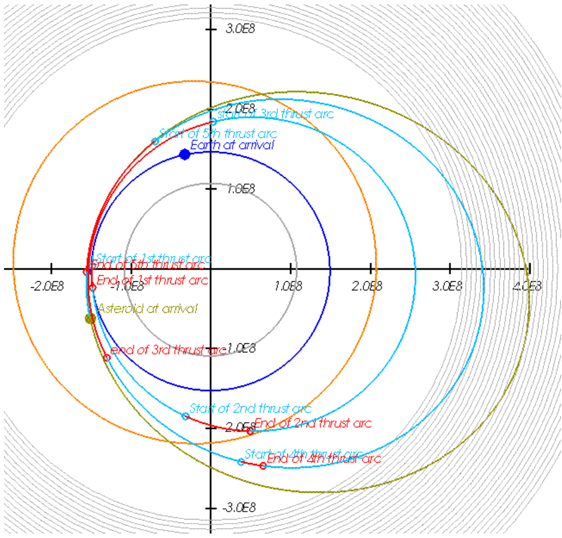


**Figure 2 Orbiter Transfer to 2002 $AT_4$ using SPT**

Sancho, after a series of short drift-bys for initial target mass estimation, will be inserted into orbit around it. This will happen at the latest in mid-November 2016, when the asteroid is still at over 2 AU from the Sun. It is more than 6 months prior to impact, which in this scenario would take place on 1 June 2017. In total, the Orbiter will perform three revolutions around the sun. Its mission will last until around 6 months after impact in order to complete the second Radio Science Experiment (RSE) and measure the change in the target's semi-major axis. Hence, the total mission duration is almost 7 years. The overall Orbiter mission is summarized in Table 3.

The Solar Electric Propulsion system (SEP), as explained later in section 5, is chosen from the SMART-1 spacecraft. It is a Stationary Plasma Thruster (SPT) with input power at 1 AU of 1.78 kW[1]. Due to the large heliocentric distance values, the SEP cannot be operated throughout the whole orbit. Two heliocentric revolutions are therefore required in order to complete the transfer. These contain five thrust arcs, mostly around the perihelion. The total propellant consumption is 76 kg, which is still within the SMART-1 tank capacity, allowing for some margin.

| | |
|---|---|
| Launch vehicle | Dnepr |
| Initial parking orbit | 300 km |
| Earth escape date | 2011/3/4 |
| Hyperbolic departure velocity | 3.5 km/s |
| Spacecraft mass at separation | 450 kg |
| Arrival date | 2015/1/4 |
| Transfer duration | 3.8 years |
| Xenon consumption | 76 kg |
| Thrust time | 6312 h |

**Table 3 Summary of Orbiter transfer to 2002 $AT_4$ using SPT**

Figure 4 shows some geometrical aspects of the transfer as function of the epoch: the Earth and asteroid range, as well as the thrust level history. As it can be seen, the most relevant thrust arcs take place at low heliocentric ranges where the available power, specific impulse, and thrust levels are higher. Following arrival, the Orbiter spacecraft will remain in the vicinity of the asteroid.

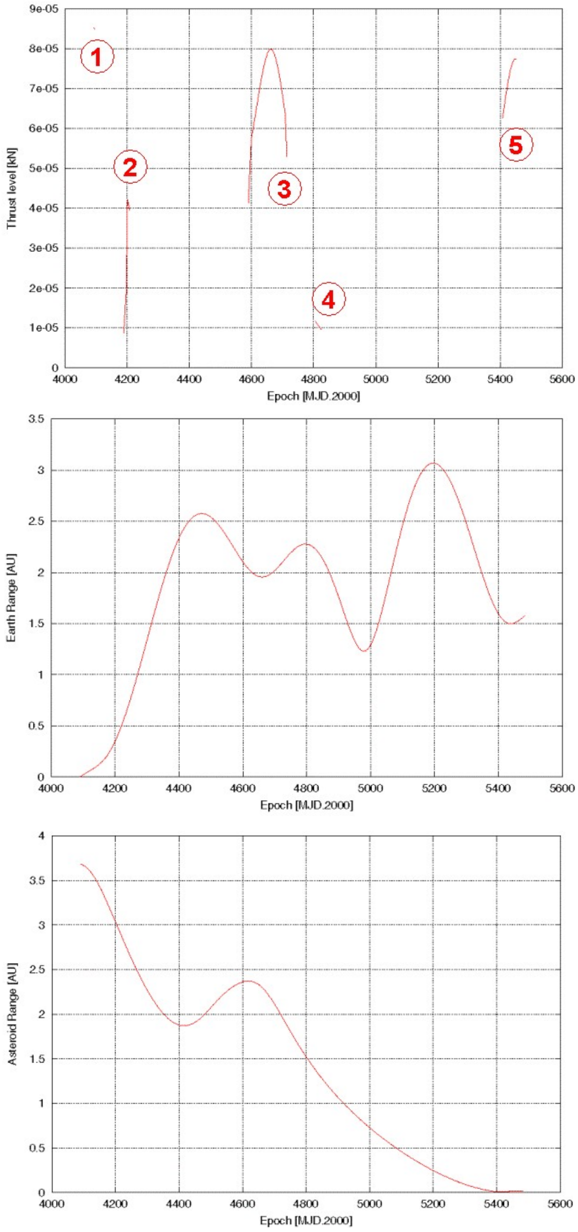


**Figure 4: Geometry of Orbiter Transfer to 2002 $AT_4$ Using SPT**

## 4.2 IMPACTOR TRANSFER

Due to the orbital properties of the target asteroid, a high-velocity impact does not require a Venus swing-by, as it is the case for the mission to 1989 ML, which is not discussed here. The impactor is launched in late December 2015 that is after the Orbiter's arrival. It performs one complete heliocentric revolution and, on the outbound arc of the second one, it hits the asteroid on

[1] as opposed to 1.42 kW in the case of SMART-1

1 June 2017 with a relative velocity of over 9 Km/s, see Figure 5.

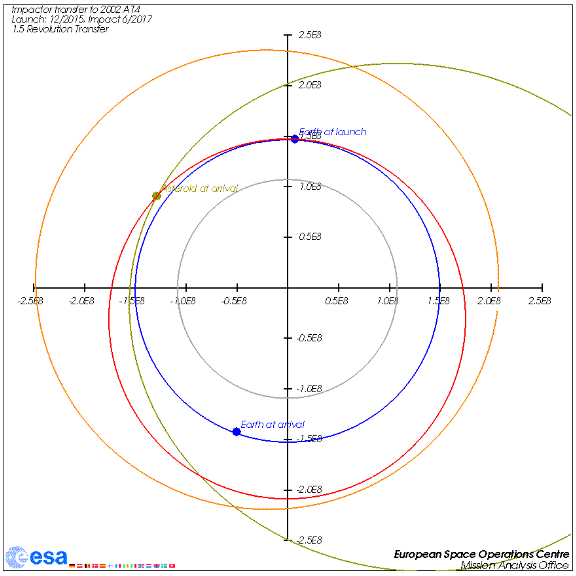


**Figure 5 Hidalgo transfer to target asteroid 2002AT$_4$**

Earlier launches would also enable possible transfers, starting in September 2015 and arriving as early as April 2017 at 13 km/s. However, a mission scenario in which the impact would take place around perihelion was favoured in the studies due to the reduced Sun and Earth ranges and the possibility to perform Earth-based observation campaigns of the event. With an escape velocity of 2.26 km/s, no deep space manoeuvres or swing-bys are required. Finally the total transfer duration is less than 18 months, which is quite efficient, simple and fast. Table 7 summarizes the transfer properties.

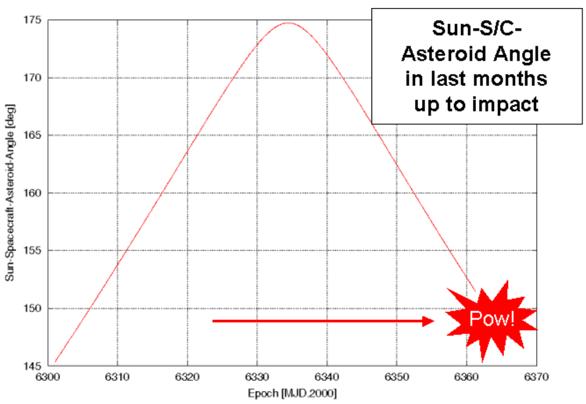


**Figure 6 Hidalgo pre-impact Sun aspect angle**

Figure 6 shows some aspects of the asteroid approach geometry in the two months prior to impact. Impact takes place at an Earth range of 1.64 AU and the sun-spacecraft-asteroid angle describes the viewing conditions of the asteroid. For a value of 180°, the spacecraft "sees" the asteroid fully illuminated. Thanks to the final approach on the outbound arc, the value for this angle remains large throughout the final approach, facilitating autonomous navigation during the final approach. Thus, a major requirement for the mission design is fulfilled.

| | |
|---|---|
| Launch vehicle | Dnepr |
| Initial parking orbit | 300 km |
| Earth escape date | 2015/12/20 |
| Hyperbolic departure velocity | 2.26 km/s |
| Total s/c mass into escape | 790 kg |
| Max. s/c mass without CPS | 560 kg |
| Impact date | 2017/6/1 |
| Impact velocity | 9 km/s |
| Transfer duration | 1.45 years |
| DSMs | none |

**Table 7: Impactor transfer to asteroid 2002 AT$_4$**

## 5. SYSTEM DESIGN

### 5.1 ORBITER SPACECRAFT

During the internal mission feasibility analysis, a re-use of the SMART-1 bus has been considered. Though this approach provides a good reference case to assess mission costs reduction and the maturity of the technologies compatible with TRL ≥ 8, there are some limitations. These are mainly given by the availability of a single PPS-1350 engine, a fixed Xenon tank capacity that limits the propellant mass to 84 kg (at 50°C)[2], and finally the given bus structure. In order to accomplish the mission, the input power to the SEP requires an increased solar array surface consisting in an extra panel per wing. Also a completely different communication subsystem consisting of two-degree-of-freedom (DOF) steerable 70 cm high gain antenna (HGA), medium and low gain antennas and a UHF antenna for the communication with the Impactor during

[2] Or 91 Kg of Xenon at 40°C

targeting phase and the ASP are required. Another modification is the replacement of the SMART-1 payload by the set of instruments described in section 5.2.

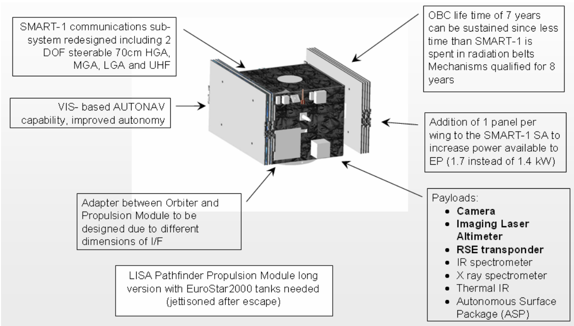


**Figure 8 Sancho's design in launch configuration (main differences with SMART-1 are highlighted)**

Considering the extended payload set (i.e. the DQ+ version), the Orbiter's system mass budget can be summarized as follows:

- Total dry 395 kg
- Payload 20.6 kg
- Total propellant 96 kg
- Total wet 491 kg
- Power 1.7 kW

The seven years required mission lifetime is far longer than the one of SMART-1 (2.5 years by design). However, an analysis showed that the SMART-1 design is compatible with the extended required lifetime considering the encountered radiation dose levels and the thrusters' lifetime.

## 5.2 ORBITER PAYLOAD

Sancho's payload can be considered to be quite basic [5]. It is defined by the navigation camera, the RSE and a LIDAR addressing the primary objective. DQ+ is however complemented by a set of scientific instruments dedicated to the secondary mission goal, see Figure 9.

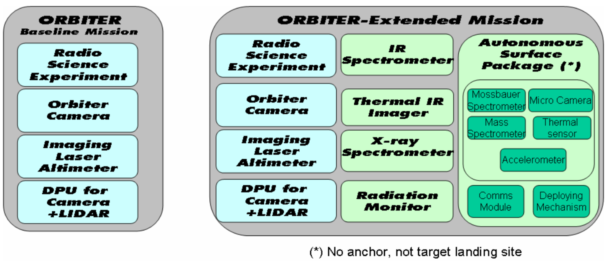


**Figure 9 Sancho's strawman payload**

Also being part as this secondary objective, the Autonomous Surface Packaged Deployment Engineering eXperiment, or ASP-DEX, will also enable to investigate the mechanical properties of a small asteroid's surface. This knowledge will be important in order to determine the feasibility of coupling devices onto the surface of an asteroid under microgravity conditions, which would be required for the implementation of mitigation strategies relying on a direct contact with the asteroid.

The Autonomous Surface Package (ASP) would thus be part of the payload of the Orbiter, which would carry and deliver it to the surface at the end of the mission, from an orbit about the asteroid. This approach has been taken to minimize the uncertainties related to the Orbiter operations during the deployment of this payload. In the 2002 $AT_4$ asteroid scenario, deployment would take place from an orbit of 1 km in radius, a $\Delta V$ of 16 cm/s being required for the release and deorbit of the ASP. The duration of the drift towards the asteroid surface would be of around 2 hours and the impact velocity would range between 11 and 21 cm/s. After deployment the ASP will reach autonomously its preferred location, which would most likely be the interior of impact crater.

Though the ASP has not been investigated in detail, in the frame of the internal ESA studies a minimum functionality has been assumed and a preliminary assessment of its payload has been conducted. The ASP would carry communications equipment enabling data and telemetry to be relayed to the Orbiter. The ASP chassis would most likely include a hopping mechanism in addition to housing all subsystems required for the nominal operation of the device.

In addition to this the ASP would most likely carry a set of scientific instruments, including at least the a micro-camera, both for scientific investigations and for navigation, an environmental package made up by a tri-axial accelerometer (used to detect touchdown and analyse the mechanical properties of the asteroid surface) and a thermal sensor (for the characterisation of the thermal conductivity of the surface material).

### 5.3 IMPACTOR SPACECRAFT

The mission of the Impactor spacecraft is a peculiar one: the spacecraft should remain in a dormant state during most of its lifetime until the last days of asteroid approach where the autonomous guidance takes over and targets it toward the asteroid. During the cruise phase only minimum functions are required but before the impact all the sub-systems have to be up and functional with high level of reliability. A major system design constraint is also on the spacecraft mass that (contrarily to what is normally required) shall be above a certain threshold to achieve the required asteroid orbit deflection and lower than the launch system escape performance. This implies that the DQ approach is applicable only to relatively small target asteroids.

Its function is to perform the impact with the target asteroid by means of autonomous GNC. Navigation from Earth will in fact be available only up to a few hours before the impact. In the baseline mission scenario, the propulsion module (derived from the Lisa Pathfinder mission to reduce costs) is not jettisoned at escape but kept attached during the whole Impactor mission duration as ballast. Clearly this strategy would impose specific constraints in the GNC subsystem design. But it would have the advantage of increasing the total momentum transferred to the target, thus maximising the chances to achieve the required 100 m variation in the target semi-major axis.

The major design drivers for the Impactor are:

- The optical autonomous navigation system based on advanced on-board computer and high resolution camera.
- Low-cost requirements able to match TRL ≥ 6
- No moving appendages (solar arrays and antennas) to achieve stringent AOCS pointing accuracies.

A summary of the Impactor's main design features is shown in Figure 10. It is based on a large re-use of the octagonal LPF science module structure and body mounted solar arrays. The spacecraft mass budget can be summarized as follows:

- Total dry 523 kg
- Payload 9 kg
- Total propellant 1162 kg
- Total wet 1694 kg

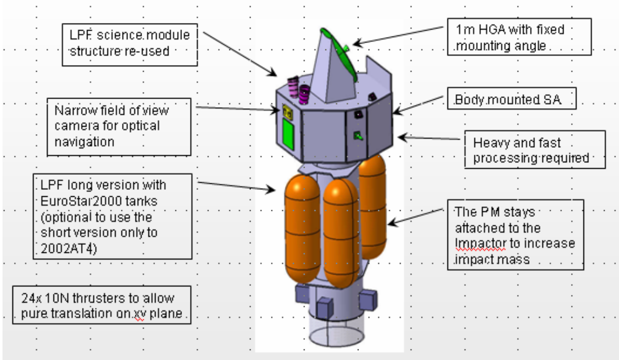


**Figure 10 Hidalgo's design**

### 5.4 IMPACTOR PAYLOAD

No specific scientific objectives are assigned to the Impactor [5]. Only the camera to support autonomous navigation is considered as payload. It is accommodated on one lateral panel of Hidalgo, together with the relevant electronics. A second lateral panel, this time internal, is dedicated to the accommodation of the COMM equipment.

## 6. THE CASE OF APOPHIS

In the early days of its detection an astonishing 1/37 chance was predicted for the catastrophic event of an impact with the Earth during its 2029 close approach. Such an enormous risk focused the attention of many astronomers on the small rock (roughly 400m of diameter). Further data were made available and served to exclude, a few months after the asteroid discovery, the 2029 impact. With the current knowledge, it still may not be excluded that the close Earth encounter will change the asteroid orbit and make a resonant return in 2036, thus impacting the Earth. Although the

chance currently foreseen is quite low and comparable to the background probability level of possible impacts with the NEO population, the case of Apophis is interesting as it may teach us about when decisions should be taken to design and build an asteroid deflection mission.
The current uncertainty of Apophis hitting a keyhole and putting it on a 6/7 resonance could be assessed by a flexible mission like DQ. It is in fact within Sancho's capabilities to reach Apophis and carry out a RSE campaign which would precisely determine (taking also into account the Yarkowski effect) its heliocentric position, in time for a deflection mission to be planned. Also, as demonstrated by Izzo and al. in [6], the achievable deflection by actually using the Hidalgo spacecraft would be more than enough to prevent any risk of a resonant return for the April 2029 encounter. As summarized in Table 11, global optimum trajectories are such that a launch can be planned as late as 2026. In this case, it is still possible to obtain a 10 km deflection on the b-plane that is well above the keyhole thickness (i.e. about 1 km).

| Launch | Impact | Deflection |
|---|---|---|
| 16.04.2001 | 12.06.2012 | 87.8 km |
| 25.04.2012 | 04.05.2013 | 63 km |
| 25.09.2013 | 27.03.2014 | 43.5 km |
| 03.06.2014 | 26.02.2015 | 18 km |
| 16.04.2018 | 12.07.2019 | 57.58 km |
| 17.04.2019 | 31.05.2020 | 43.37 km |
| 29.12.2020 | 09.03.2021 | 47.4 km |
| 08.09.2021 | 25.03.2022 | 17.23 km |
| 02.03.2026 | 02.03.2027 | 10.05 km |
| 01.04.2027 | 02.12.2027 | 3.96 km |
| 05.02.2028 | 18.11.2028 | 0.45 km |

**Table 11 Possible DQ Impactor (Hidalgo) launches for Apophis 2029-keyhole deflection**

The Impactor's trajectory is showed in Figure 12 for the 2018 launch opportunity. It is worth noticing that this scenario is well within the DQ development programmatics.

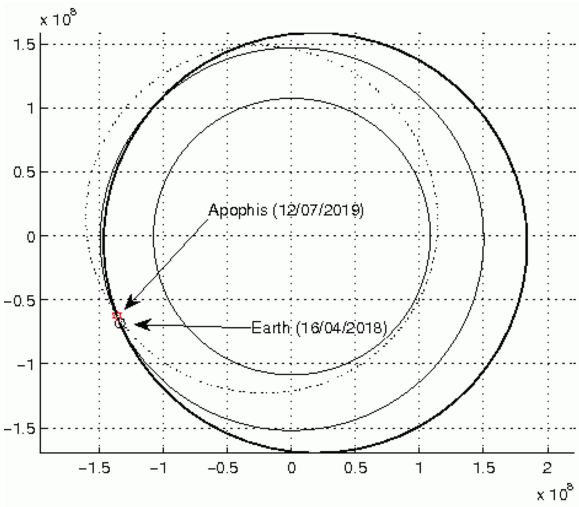


**Figure 12 Globally optimal solution for the DQ kinetic impactor**

## 7. Conclusions

The Don Quijote mission will address essential technology and system needs. It therefore represents an excellent example of a "NEO precursor mission" that could pave the way for an effective NEO deflection mission, independently of the deflection strategy finally being considered.
Don Quijote will measure the mechanical behaviour of the asteroid as a whole, and determine the orbital deflection triggered by the impact of the Hidalgo spacecraft at a very high relative speed. It would also carry out measurements the asteroid mass and bulk density and constrain its mechanical properties.
In addition to this, investigations in the close proximity and the surface of a NEO would provide excellent opportunities for scientific research to be carried out.
Finally, having independent mission elements, Don Quijote is a mission concept enabling a flexible implementation strategy from the perspective of ESA. Furthermore, the large reuse of existing technology (already flight-qualified) and associated high TRLs ensure a low-cost and high reliability approach of the design.

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