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ESA studies on the Don Quijote NEO mission: dealing with impact uncertainties

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ABSTRACT

There is overwhelming scientific evidence that impacts of Near-Earth Objects (NEOs) could trigger a catastrophe that might have consequences at a regional or even global scale. In July 2004 ESA's Near-Earth Object Mission Advisory Panel (NEOMAP) recommended to give Don Quijote implementation priority over other NEO mission concepts. Using these recommendations as the starting point, ESA conducted two assessments in the context of the Concurrent Design Facility with 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 paper describes the main results of these internal studies. In addition to this, it provides a short analysis on the possibility to use the mission or some of its elements not only to perform a validation of technologies but cope with impact certainties of actual NEO threats.

INTRODUCTION

There is general agreement that Near-Earth Objects, or NEOs, do not represent merely a scientific curiosity but may be the origin of one of the worse possible natural disaster. Although impacts of large objects with catastrophic consequences are extremely infrequent, impacts of smaller bodies –with sizes of few tens or hundreds of meters in diameter- have higher rates of occurrence and can cause severe damage at local or regional scale. A direct ground impact is not the sole threat; NEOs might be the origin to a large scale Tsunamis affecting much larger areas.

In this paper, an asteroid-deflecting mission studied by the European Space Agency's Advanced Concepts Team is described. The mission was proposed in response to a Call for mission and instrument ideas issued by the Agency in 2002 [1]. It was later given the highest priority of implementation by NEOMAP [4], 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: The mission not only would gather knowledge on a particular object, but would also demonstrate a capability i.e. prove our ability to modify the trajectory of an asteroid in a way that can be measured.

Using these recommendations as the starting point, ESA conducted a first assessment in the context of the Concurrent Design Facility [2]. This study was carried out by a multidisciplinary team of spacecraft engineers with the objective of assessing the feasibility of several mission scenarios. These were all based on the Don Quijote concept but provided a thorough understanding of their cost and technical risk implications. Such analysis was then used as the basis for a second assessment in which the goal was to prepare for the industrial phase-A studies [3],

as it was used to help define the design envelops of these studies and derive the system requirements and their priority.
This paper describes the main results of this second study. In addition to this, it provides a short analysis on the possibility to use the mission -or some of its elements- not only to perform a validation of technologies but cope with impact certainties of actual NEO threats.

DON QUIJOTE MISSION

Mission Objectives and system options

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 and 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 below).
- Option 2: DQ "Light" mission, addressing the primary mission objective only. Again the system comprises an Impactor and an Orbiter; however the latter 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.

Mission Overview

The mission would contain the following elements: In both system options, the *Orbiter* spacecraft, called Sancho, is the vehicle that rendezvous with the target asteroid. It is inserted into an orbit about the NEO and measures its orbital parameters, the mass, size, gravity field, and shape before and after impact to assess the momentum transfer. In addition, the Orbiter operates as a backup data relay for transferring the collected Impactor's guidance, navigation and 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, shall pursue scientific investigations of the asteroid, addressing part of the mission secondary goals. Finally, after completion of the primary mission, the DQ+ Orbiter carries out the ASP-DEX and acts as data relay for the surface package.

The *Impactor* is the vehicle that after an interplanetary cruise with minimum ground segment (G/S) support would perform completely autonomous terminal guidance and navigation manoeuvres towards the target asteroid. It transmits engineering GNC data and images of the target both to the G/S and to the Orbiter spacecraft while impacting at very high relative speed (in the order of 10 km/s) against the asteroid's surface. This spacecraft will demonstrate the autonomous GNC capability based on optical navigation.

The DQ+ mission includes in addition an Autonomous Surface Package Deployment Engineering eXperiment (ASP-DEX). The experiment would consist of a demonstration of the simplest possible spacecraft operations required for the release and de-orbit of a small device on the NEO surface while the spacecraft is placed in an orbit around it. For the experiment's successful outcome, the device, called Autonomous Surface Package or ASP, should passively free-fall towards the asteroid surface after its release, and touchdown within a certain distance of a target landmark.

Target Selection

The selection of an appropriate target for the pre-phase-A and phase-A studies was based on a set of NEO characteristics that are most relevant for the Don Quijote mission design, see Table 1. These were defined by NEOMAP as well as their range acceptable for attaining a feasible mission.

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 Mission Target Preferences

As a result two targets have been pre-selected for the purposes of the phase-A studies; these are asteroids 2002 AT_4 and 1989 ML. 1989ML is heavier bur more accessible than 2002 AT_4, and thus more favourable from a mission and Orbiter spacecraft design point of view but perturbing its trajectory would be more challenging. Therefore the 2002 AT_4 scenario was the sizing case for the Orbiter, while 1989 ML was the sizing case for the Impactor designs. By adopting the above approach based on two different target bodies the system design would be able to cope with a wide range of possible targets. Such design philosophy could be strongly beneficial in case other interesting target candidates are identified or if a similar mission had to be used to asses a real NEO threat.

Relevant orbital and physical characteristics of 2002 AT_4 and 1989 ML are summarized in Table 2 and Table 3.

Name	P (yr)	e	i (deg)	ΔV (km/s)	Orb. type	MOID
2002 AT_4	2.549	0.447	1.5	6.58	Amor	Large
1989 ML	1.436	0.137	4.4	4.46	Amor	Large

Table 2 Relevant Orbital Characteristics of Selected Don Quijote Targets

H (mag)	Taxon. type	D (m) for Pv=0.05,0.1	Rotation Period (h)
20.96	D	380, 270	Unknown, assumed 6
19.35	X	800, 570	19

Table 3 Values of Relevant Physical Characteristics assumed for the pre-selected Don Quijote NEA targets

Mission Analysis

Orbiter Transfer

In the CDF study's reference mission scenario to 2002 AT_4 the Orbiter's Earth escape would take place in mid-March 2011. This would be preceded by a typically lengthy escape sequence, which might take 3 weeks or more. Therefore the actual launch date would have to be chosen accordingly. The arrival takes place in early January 2015, almost 2.5 years prior to impact. The orbiter would either be inserted into orbit around the asteroid at that time or remain in a heliocentric orbit in proximity to the body, following it.
The final orbit insertion would happen at the latest in mid-November 2016, when the asteroid is at over 2 AU from the Sun. This is more than 6 months prior to impact, which in this scenario would take place on 1st June 2017. In total, the orbiter would perform three revolutions around the sun. Its mission would last until around 6 months after impact (i.e. the end of 2017) to complete the post-impact NEO orbit determination, leading to a total mission duration of almost 7 years.

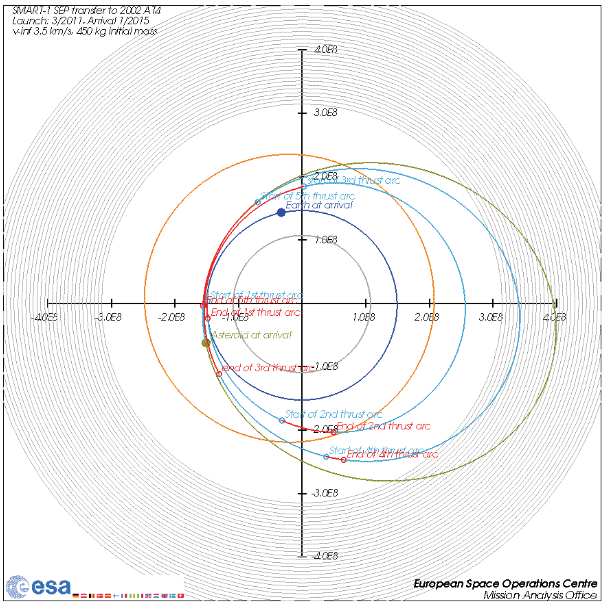

Figure 1 Orbiter Transfer to 2002 AT_4 Using SPT

Sancho would have an initial mass of 450 kg and leave the Earth with an escape velocity of 3.5 km/s.

Launch vehicle Upper stage	Dnepr CPS
Initial parking orbit [km]	300
Earth escape date	2011/3/4
Escape velocity [km/s]	3.5
Spacecraft mass at separation [kg]	450
Arrival date	2015/1/4
Transfer duration [years]	3.8
Xenon consumption [kg]	76
Thruster on time [h]	6312

Table 4 Summary of Orbiter Transfer to 2002 AT_4 Using SPT

The Solar Electric Propulsion system (SEP) is a Stationary Plasma Thruster (SPT) with input power at 1 AU of 1.78 kW (as opposed to 1.42 kW in the case of SMART-1). Due to the large heliocentric distance values, the SEP cannot be operated throughout the whole orbit. Therefore, two heliocentric revolutions are required 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.

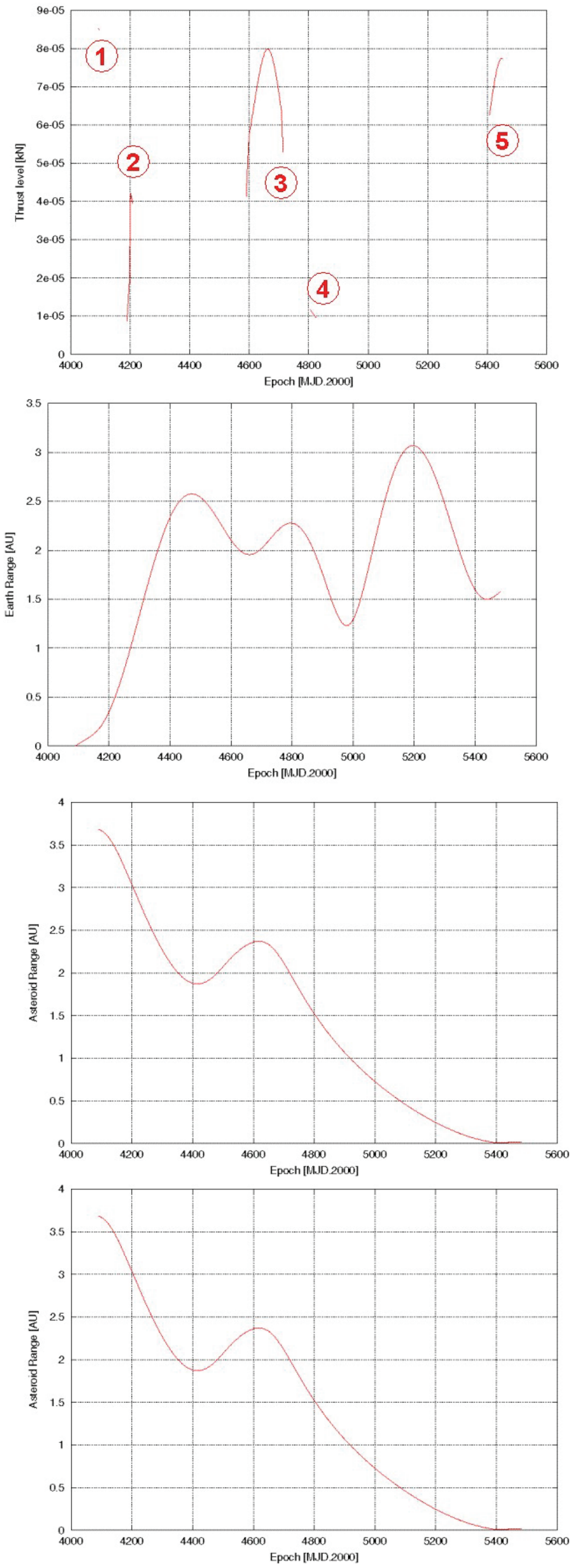

Figure 2 Geometry of Orbiter Transfer to $2002AT_4$ Using SPT

Figure 2 shows some geometrical aspects of the transfer as function of the epoch: the Earth and asteroid range as well as the heliocentric range, with the perihelion and aphelion radii superimposed and the temporal locations of the thrust arcs are highlighted. Additionally, the thrust level over time is shown. As it can be seen, the most relevant thrust arcs take place at low heliocentric ranges where the available power, specific impulse, and consequently thrust levels are highest. Following arrival, the orbiter spacecraft will remain in the vicinity of the asteroid.

Impactor Transfer

Due to the orbital properties of the target asteroid, a high-velocity impact does not require a Venus swing-by, as is the case for the mission to 1989 ML (not discussed here). The impactor is launched in late December 2015. It performs one complete heliocentric revolution and on the outbound arc of the second, it hits the asteroid on 1st June 2017 at a relative velocity of approximately 9 km/s. Earlier possible launch windows were also identified starting in September 2015 and arriving as early as April 2017. This would yield an impact velocity close to 13 km/s.

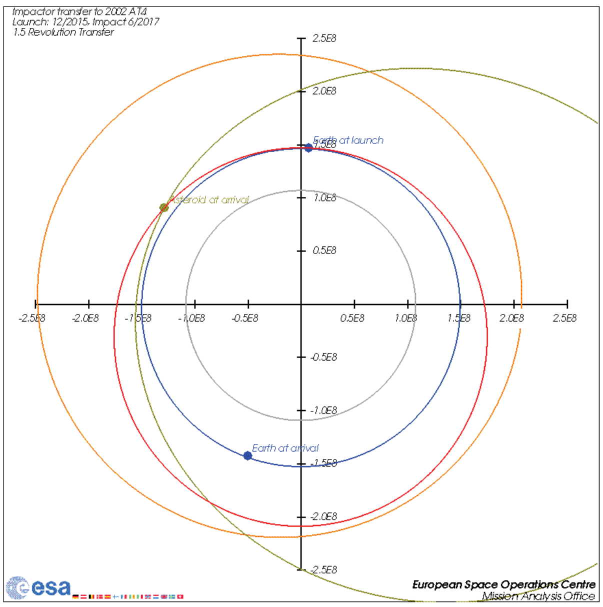

Figure 3 Impactor Transfer to 2002 AT_4

However, the former mission scenario was favoured in the study due to the impact close to perihelion where the Sun and Earth ranges are minimized and Earth-based observation campaigns of the event are an interesting possibility.

Table 5 summarizes the Impactor's transfer properties. Thanks to an escape velocity of 2.26 km/s, no deep-space manoeuvres or swing-bys are required. The total mission duration of less than 18 months proves that the transfer is efficient, simple and fast.

Launch vehicle upper stage	Dnepr CPS
Initial parking orbit [km]	300
Earth escape date	2015/12/20
Escape velocity [km/s]	2.26
S/C mass into escape [kg]	790
Max. s/c mass without CPS [kg]	560
Impact date	2017/6/1
Impact velocity [km/s]	9
Transfer duration [years]	1.45
DSMs	none

Table 5 Impactor Transfer to Asteroid 2002AT$_4$

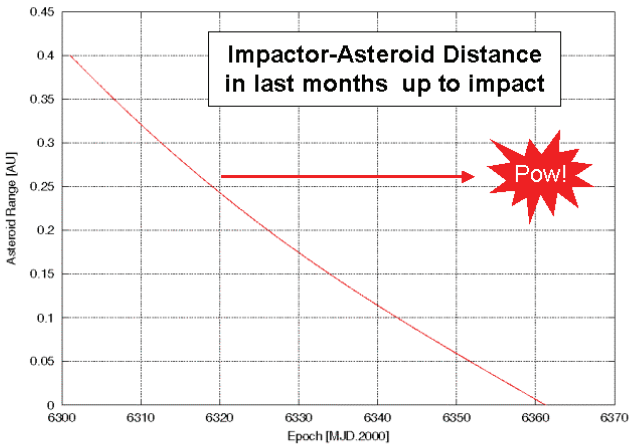

Figure 4 2017 Impactor Pre-Impact Distances

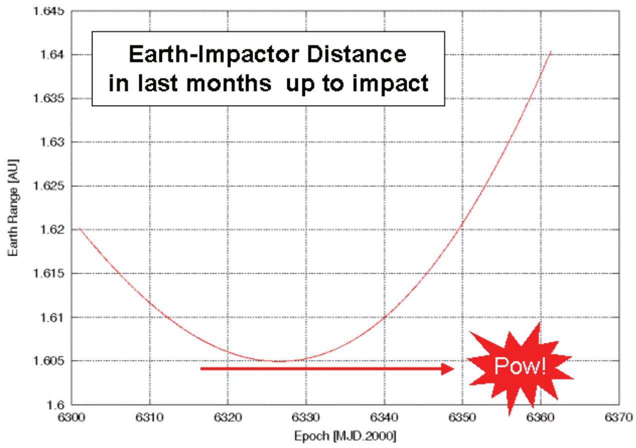

Figure 5 Impactor-Earth Distance

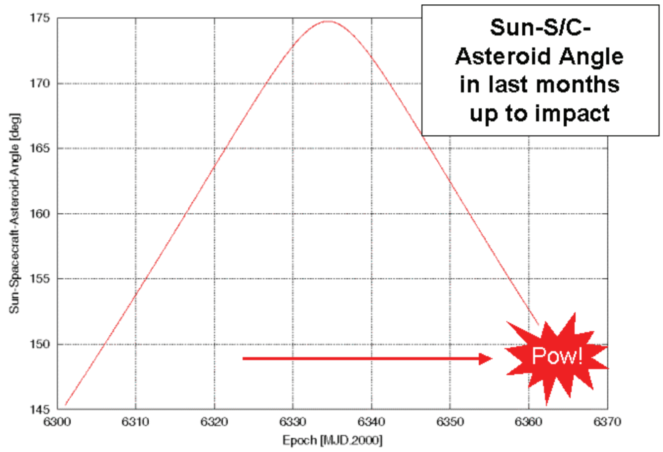

Figure 6 Sun-Spacecraft-Asteroid Angle Prior to Impact

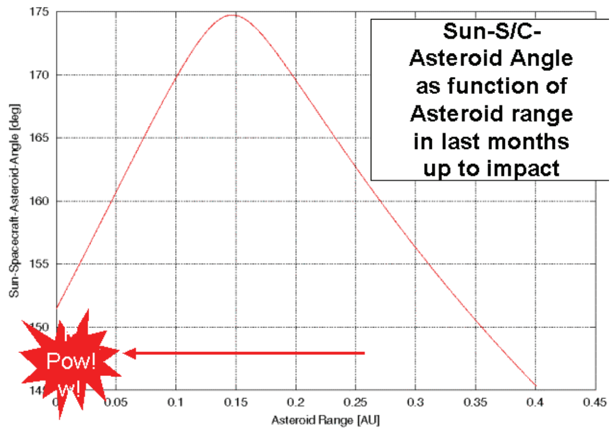

Figure 7 Impactor Pre-Impact Sun Aspect Angle

Figure 4 to Figure 7 show some aspects of the asteroid approach geometry in the two months prior to impact. This takes place at an Earth range of 1.64 AU. The Sun-Spacecraft-

Asteroid angle was maximized as it describes the viewing conditions of the asteroid therefore allowing for a simpler onboard camera design. For a value of 180°, the spacecraft would image 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.

SYSTEM DESIGN

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 and the maturity of the technologies, there are some limitations. These are mainly given by the availability of a single PPS-1350 engine, a fixed Xenon tank capacity limiting the propellant mass to 84 kg (at 50°C)[1], and finally a given bus structure. In order to accomplish the mission, the necessary 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 a 70 cm two-degree-of-freedom steerable high gain antenna (HGA), medium and low gain antennas and a UHF antenna for the Impactor communication link during the targeting phase and the ASP release are required. Finally, the SMART-1 payload was replaced by the set of instruments described in the following section.

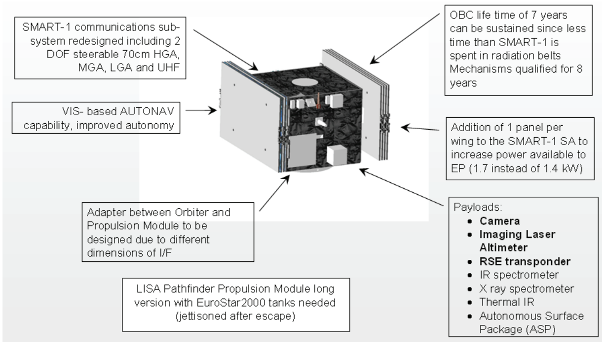

Figure 8 Sancho Launch Configuration

Sancho's main budgets with the extended payload set are:

- Total dry 395 kg
- Payload 20.6 kg
- Total propellant 96 kg
- Total wet 491 kg
- Power 1.7 kW at 1 AU

The required seven years mission lifetime is far longer than SMART-1's (2.5 years by design). However, the analysis showed that the SMART-1 design can in principle be compatible with the lifetime extension considering the encountered radiation dose levels and the thrusters' lifetime.

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 Hidalgo 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 (e.g. hot redundant). A major system design constraint is set on the spacecraft's mass that (contrarily to usual designs) shall be above a certain threshold in order to achieve the required asteroid orbit deflection and lower than the launcher's escape performance.

[1] Or 91 Kg of Xenon at 40°C

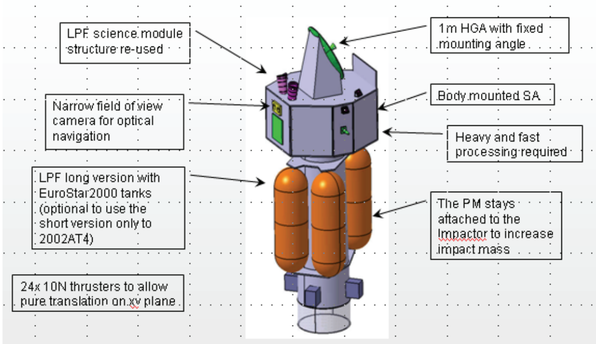

Figure 9 Hidalgo Launch Configuration

Sancho's strawman payload

The Orbiter instrumentation identified as part of the Don Quijote reference payload is shown in the following diagram:

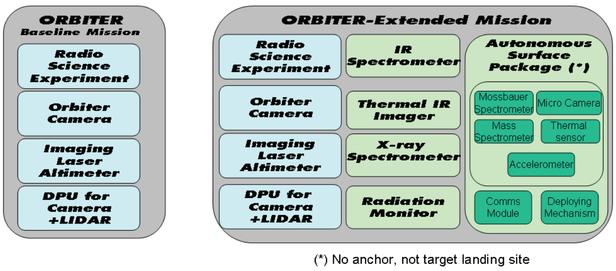

Figure 10 Don Quijote Strawman Payload

A basic payload (made up by the navigation camera, the Radio Science Experiment and a LIDAR) addressing the primary objective would be complemented by a set of scientific instruments [5] dedicated to the secondary mission goal[2].

Also, as part of the secondary objective, the ASP-DEX would 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 under microgravity conditions. This would be required for the implementation of mitigation strategies relying on a direct contact with the asteroid.

The ASP would be carried and delivered by Sancho to the target's 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 phase. In particular, in the 2002 AT_4 asteroid scenario the ASP deployment would take place from a 1 km radius orbit. In this case a 16 cm/s Δv would be required to successfully release and deorbit of the package. The duration of the drift towards the asteroid's surface would be approximately 2 hours and the touch-down velocity would range between 11 and 21 cm/s. After deployment the ASP should reach autonomously its preferred location, which would most likely be the interior of impact crater.

Though the ASP design itself 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 device operations.

In addition to this, the ASP would most likely carry a set of scientific instruments including at least the following:

- A micro-camera, both for scientific investigations and for navigation
- An environmental package made up by:
  - A tri-axial accelerometer used to detect the touch-down and analyse the mechanical properties of the asteroid surface
  - A thermal sensor for the characterisation of the thermal conductivity of the surface material.

[2] The assessment of the scientific payload was carried out by NEOMAP.

THE CASE OF 99942 APOPHIS

The Apophis impact probability was initially estimated to be 2.6%. This impact was calculated to occur in 2029. Additional observations allowed ruling out this possibility with great confidence, however the closest NEO-Earth encounter ever will be observed. Such close encounter will put Apophis on a return trajectory leading to a non-negligible collision in 2036 (such impact probability is still lower than general "background" risk).

Still, accurate orbit determination in cases like this could be performed by a tracking spacecraft like Don Quijote's Sancho orbiter.

A "cheap" orbit transfer for a DQ-like spacecraft to 99942 Apophis exists: The characteristics of this sample transfer are summarized in Figure 11. The propellant consumption is well within the SMART-1 tank capacity, so an increase of the initial mass could be envisaged even using a spacecraft design based on the SMART-1 architecture. If the launch takes place one year earlier and a 2012 Earth swing-by is added, the Earth escape velocity can be reduced significantly. The main characteristics of the transfer are depicted in Figure 11 and summarized hereafter:

- Initial Mass = 396 Kg
- Final Mass = 351 Kg
- Xenon Mass Consumed = 45 Kg
- Departure date: 2012/5/5
- Arrival date 99942: 2013/6/6
- Transfer duration: 397 days
- Hyperbolic Escape Velocity = 3.5 km/s
- Thrust Time = 2574 hrs

Incidentally, as described by Izzo and al. [6] a spacecraft system identical to the one designed for the Don Quijote mission is capable of deflecting the asteroid Apophis *if this was necessary,* due to the very small Δv required to be imparted to the object. This small modification of Apophis' trajectory would be enough not hit a keyhole during the 2029 Earth flyby avoiding an impact during the 2036 returning encounter. In principle impactor launch dates as late as 2026 would enable the required deflection. This demonstrates the flexibility of the design, not only as a precursor but even as an initial mitigation in case this was required.

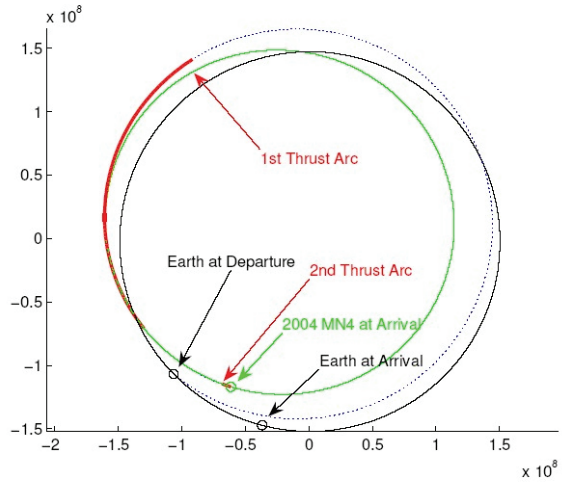

Figure 11 Obiter Rendezvous Trajectory to Apophis

P (yr)	e	i (deg)	Del-V (km/s)	Orb. type	MOID
0.889	0.191	3.3	3.38	Aten	V. low

Table 6

H (mag)	Taxon. type	D (m) for Pv=0.05,0.1	Rotation Period (h)
19.20	-	610, 870	6

Table 7 Physical characteristics of Apophis

CONCLUSIONS

The Don Quijote mission would address essential technology and system needs. It therefore represent 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 would 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 high relative speed. It would also carry out measurements the asteroid mass and bulk density and constrain its mechanical properties

In addition to all this, investigations in the close proximity and surface of a NEO would provide excellent opportunities for scientific research to be carried out.

Having independent mission elements Don Quijote is a mission concept enabling a flexible implementation strategy from the perspective of ESA but also in terms of possible contributions by ESA's international cooperating partners. The industrial Phase-A studies starting early next year will provide a solid foundation for a successful mission.

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