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# ESA'S DON QUIJOTE MISSION: AN OPPORTUNITY FOR THE INVESTIGATION OF AN ARTIFICIAL IMPACT CRATER ON AN ASTEROID

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**Abstract**

The European Space Agency (ESA) in recent years has been investigating the implications of using the space segment as a NEO impact mitigation asset. Through the General Studies Program several mission concepts were studied and, in particular, the attention has been focused on the Don Quijote mission. This mission would demonstrate our ability to perturb the trajectory of a small near-Earth asteroid by a measurable amount. Also, as a secondary objective, it would deploy an autonomous surface package that would provide an unprecedented opportunity to investigate in-situ primitive, unexposed subsurface material uncovered as a result of the impact. This paper describes the Don Quijote mission and, in particular, the opportunity for the investigation of the artificial impact crater on the target asteroid by means of the autonomous surface package.

## 1 Introduction

In recent years the European Space Agency has conducted both industrial and internal feasibility mission studies on the Don Quijote space mission concept [1][2][3]. This mission would try to demonstrate our ability to perturb the trajectory of a relatively small near-Earth asteroid (the pre-selected targets being about 500 meters in diameter) by a measurable amount. Therefore the mission's primary objective is to impact a given NEA and to be able to determine the momentum transfer resulting from the impact, by measuring (a) the asteroid mass, size, shape and bulk density, (b) the variation of both the asteroid's Centre of Mass (CoM) orbital parameters, and (c) the modification, if any, of the asteroid's rotation state.

As secondary objectives, the mission would carry out the so-called Autonomous Surface Package Deployment Engineering eXperiment (ASP-DEX) – discussed below – and perform multi-spectral mapping of the asteroid. The mission would thus involve a hypervelocity impact by a spacecraft, called Hidalgo, and a monitoring campaign by a second one, called Sancho. The latter would observe the impact and investigate its consequences. These investigations could be carried out either remotely from Sancho's operational orbit or possibly at closer range (i.e. at the surface of the asteroid), either by the Orbiter spacecraft itself or by a deployed surface device.

This second possibility is in line with the hardware and operations foreseen for the implementation of the 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 while the spacecraft is placed in an orbit about the asteroid. For the experiment to have a successful outcome, the device, called Autonomous Surface Package (ASP), would passively free-fall towards the asteroid surface after its release, and should touchdown within a certain distance of a target landmark. The latter would most likely be the artificial crater produced by the impact of the Hidalgo spacecraft. This approach has been baselined as it is in line with the stringent constraints – especially regarding technical complexity and cost – considered for the implementation of the Don Quijote mission.

## 2 Don Quijote Mission

The objectives of the Don Quijote NEO mission are the following [3]:

- 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 multispectral mapping of the asteroid. An optional

extension of this secondary objective is the characterization 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 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.

## 3 Mission Overview

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 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 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 engineering GNC data and images of the target to the G/S and Orbiter spacecraft, and impact 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.

## 4 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 Don Quijote mission design. These were defined by ESA's NEOMAP and are summarized in table 1. As a result of this analysis two targets have been pre-selected for the purposes of the phase-A studies [4]. These are asteroids 2002AT$_4$ and 1989ML, the latter is heavier but more accessible than 2002AT$_4$. Thus it is more favorable from a mission and Orbiter spacecraft design point of view. However, perturbing its trajectory would be more challenging. Therefore the 2002AT$_4$ scenario is the sizing case for the Orbiter; while in the case of the Impactor design the sizing scenario is 1989ML. 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 or if a similar mission had to be used to asses a real NEO threat.

| **Orbit characteristics** | **preferred range** |
|---|---|
| Rendezvous $\Delta$ V | $<$ 7 Km/s |
| Orbit type | Amor |
| MOID | large and increasing |
| Orbit accuracy | well determined orbits |
| **Physical characteristics** | **preferred range** |
| Size | $<$ 800 m |
| Density | $\sim 1.3$ g/cm$^3$ |
| Absolute magnitude | 20.4 – 19.6 |
| Shape | not irregular |
| Taxonomic type | C-type |
| Rotation period | $<$ 20 hours |
| Binarity | not binary |

Table 1: Target selection criteria

Relevant orbital and physical characteristics of 2002AT$_4$ and 1989ML are summarized in table 2 ($^\S$based on the results presented in [5]).

| | **2002AT$_4$** | **1989ML** |
|---|---|---|
| Orbital period [yr] | 2.549 | 1.463 |
| e | 0.447 | 0.137 |
| i [deg] | 1.5 | 4.4 |
| $\Delta$ V [km/s] | 6.58 | 4.46 |
| Orbit type | Amor | Amor |
| MOID | large | large |
| Absolute magnitude | 20.96 | 19.35 |
| Taxonomic type | D-type | E-type$^\S$ |
| Diameter [m] | 380 | 800 |
| Rotational period [h] | 6 (assumed) | 19 |

Table 2: Selected targets' main properties

## 5 Impact Analysis

Simulations were carried out during the initial pre-phase A studies in order to have a preliminary assessment of the possible outcome of hypervelocity impact on a small asteroid. The studies analyzed the propagation of the shock wave inside the target body, the consequences in terms of affected ("damaged") region and the resulting ejecta velocity distribution and crater sizes.

The Smooth Particle Hydrodynamics (SPH) method was used, and simulations assumed a simple scenario in which a small spherical projectile 0.5 m in diameter having a density of 5.5 g/cm3 impacting on an object 500 m in diameter at 10 km/s. Different types of asteroids such as monolithic, pre-fractured or porous objects were also considered. Although full high resolution (demanding) simulations of the excavation stage have not been carried out at this stage, they are planned in future studies in support of the mission phase B definition. Still a good estimation of the size of an impact crater can be achieved using so-called scaling laws [6]. A crater diameter of 8.81 m for the 10 km/s impact has been derived using an actual model [7] for a non porous target. Crater diameters can be in the range of roughly 10-20 m for increasingly fractured and porous bodies. The depth of the excavated crater can be estimated as roughly a tenth of its diameter.

As mentioned before, one of the important aspects that were addressed was the variation of velocity distribution of the ejecta as a function of the porosity of the target body. The studies concluded that when the porosity is small or close to 0%, the bulk of the momentum of the ejecta is carried by matter traveling at slow velocities - between 1 m/s and 100 m/s. With increasing porosity the relative contribution of the slow moving material is decreasing so that by 50% most of the momentum is carried almost exclusively by ejecta traveling near 100 m/s. This result has important consequences in terms of the selection of the mission target, and seems to support the choice of a primitive – possibly porous – body to maximize momentum transfer to the ejecta and to provide a safer post-impact operational environment close to the asteroid.

## 6 Autonomous Surface Package Deployment Engineering eXperiment (ASP-DEX)

The DQ+ system option includes an Autonomous Surface Package Deployment Engineering eXperiment (ASP-DEX). The experiment would consist in demonstrating the simplest possible spacecraft operations required for the release and de-orbit of a small device while the spacecraft it is placed in an orbit about the asteroid. For the experiment to have a successful outcome, the ASP would passively free-fall towards the asteroid surface after its release, and should touchdown within a certain distance of a target landmark. This simple design approach has been taken to minimize the uncertainties related to the Orbiter operations during the deployment of this payload.

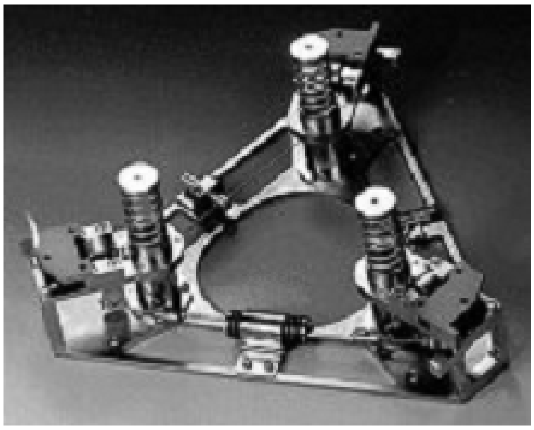

Fig. 1: Release mechanism **A**

Deploying a package on the surface implies imparting a manoeuvre that stops the package's orbital motion and then a second manoeuvre that sends it down to the surface. Considering the baseline scenario in ESA's Concurrent Design Facility (CDF) internal study [2], where the Orbiter would deploy the ASP from its 1 km radius operational orbit around asteroid $2002AT_4$, the first maneuver requires a velocity change of only 4 cm/s. The second instead depends on the allowed drift period and impact velocity. Assuming this period to be 2 hours, the required change in velocity would be 10 cm/s. The inertial impact velocity is around 16 cm/s. The actual impact velocity depends on the asteroid rotation rate and the target location. Assuming a rotation period of 6 hours and a mean radius of 160 m, the impact velocity may vary between 11 and 21 cm/s, which actually corresponds to a very soft touchdown and would not become the driver for the design of the ASP [2].

In terms of the attitude and stabilization at deployment, two possible approaches summarized in table 3 have been assessed considering their applicability to the near-zero-g environment in the asteroid's vicinity. One concept (**A**) would be simple to implement at spacecraft level while the other (**B**) imposes far more demanding system functional requirements on the Orbiter design and operations. Based on existing low mass separation system for micro satellites by Swedish Space Corporation, the total mass impact for concept **A** (see figure 1) is:

- mass on the Orbiter: 1.2 kg
- mass on the ASP: 0.3 kg

For concept **B** (see figure 2), based on a scaled-down version of the Beagle-2 SUEM lander deployment system (this approach would indeed require a specific development), the total mass impact on the system is:

| Concept | Description | Pro | Cons |
|---|---|---|---|
| **A** | Spring release<br>No anchoring<br>No spinning | Simple | Possible re-bouncing (low-energy)<br>Unknown ASP orientation<br>Accurate targeting is complex |
| **B** | Spring driven<br>With anchoring<br>Spinning | Known ASP orientation<br>Simpler targeted<br>deployment | Significant implications on<br>Orbiter's design<br>Complex ASP design |

Table 3: ASP release concepts

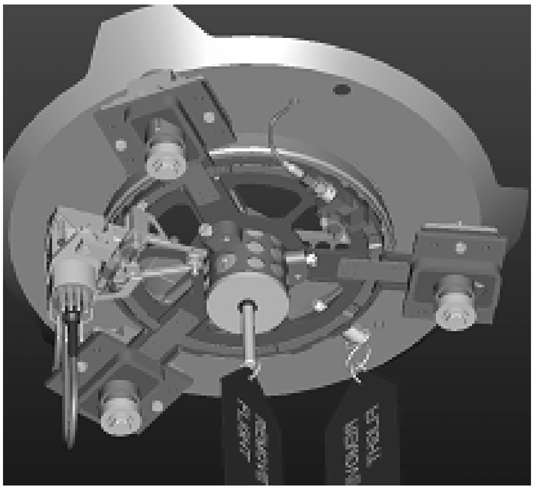

Fig. 2: Release mechanism **B**

- scaled mass estimate: 3.5 kg (including spin-up and eject mechanisms)
- mass on the Orbiter: 80% (assumed)
- mass on the ASP: 20% (assumed)
- current system: 0.3 m/s velocity<br>12 rpm rotation rate<br>would need modification

For the sake of completeness, landing devices based on Rosetta anchors activated by accelerometers have also been considered. In the case the estimated mass impact is as follows:

- mass on the Orbiter: 3 kg
- mass on the ASP: 1 kg

## 7 Autonomous Surface Package (ASP)

The ASP is thus part of the payload of the Orbiter, carried and delivered, from an orbit about the asteroid, on the surface at the end of the mission. After deployment the ASP shall 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. In particular, the ASP would carry communications equipment enabling data and telemetry to be relayed to the Orbiter. The ASP chassis would most likely include the hopping mechanism (or other simple system providing autonomous mobility) in addition to housing all subsystems required for the nominal operation of the device.

Even if in the baseline scenario the ASP addresses objectives directly related to the Deployment Engineering eXperiment, the deployment of the ASP clearly provides an excellent opportunity for the investigation of the asteroid's structural make-up and the consequences of the hypervelocity impact by performing in-situ measurement of both the surface regolith and the subsurface material exposed by the impact.

Thus the ASP could support a set of scientific instruments supplied by PI institutes. With this possibility in mind, a strawman payload has been considered in order to understand possible mass and resource impacts on the ASP. The experiments could include [8]:

- a micro-camera, both for scientific investigations and for navigation. To measure asteroid topography and sampling context information;
- an environmental package made up by: (1) a triaxial accelerometer used to detect touchdown, the asteroid surface's mechanical properties, and any seismic activity (resulting from the impact); (2) a thermal sensor for the characterization of the thermal conductivity of the surface material;
- a laser mass spectrometer (LMS) for measuring the surface elemental composition, rock dating and isotopic information;
- a Mössbauer Spectrometer (MS) for phase state information, Fe content and mineralogical context;
- a device providing subsurface analysis capabilities (temperature, elemental and structural composition) e.g. a mole has also been considered, though it is clear this element might drive in excess the complexity of the ASP design due to the need of some type of anchoring and/or attitude control for its operation.

It should be borne in mind however that if the mission of the ASP includes scientific investigations, the ASP design might need to be considerably more sophisticated to ensure autonomy of operations, mobility and sufficient lifetime to meet its mission objectives.

The extension of the ASP mission for it to characterize the thermal and mechanical properties of the asteroid surface would be very much in line with the top level objectives of the Don Quijote mission. This knowledge will be important in order to determine the feasibility of coupling devices onto the surface of an asteroid under microgravity conditions. This would be required for the implementation of mitigation strategies relying on a direct contact with the asteroid. The in-situ determination of the thermal properties of the surface material would be very useful to determine the relative contribution of the Yarkowsky effect in the long term evolution of the dynamics of the asteroid, especially when combined with thermal IR imager data.

## 8 Conclusions

In addition to addressing technology requirements for future asteroid deflection missions a kinetic Impactor experiment like that foreseen in the frame of the Don Quijote mission would provide an unprecedented opportunity to investigate in detail and over an extended period of time the physical properties of an impact crater in a small body. Even more scientifically meaningful would be the possibility to analyze in-situ primitive, unexposed subsurface material uncovered as a result of the impact.

In principle it would be interesting to perform all type of experiments involving energy and momentum transfer to the asteroid surface material in order to better understand its dynamics in the microgravity environment and the consequences on the evolution of the asteroid topography. However most likely only the artificial hypervelocity impact method can provide the required directed delivery of energy onto the asteroid surface that would result in the excavation of a crater of a considerable size, and maybe in other changes in the asteroid surface topography or even internal structure that could be detected by an spacecraft in orbit about the object.

This direct investigation of the unweathered material inside a recently created crater could be carried out by using a relatively inexpensive and almost independent addition to the payload of a spacecraft operating in the vicinity of the target object. A small Autonomous Surface Package could be deployed in the interior of the impact crate or its vicinity by the Orbiter spacecraft. This element would have the important advantage of not imposing significant constraints on the design of the spacecraft itself, and it could be thus procured totally independently.

For all these reasons an asteroid Autonomous Surface Package is currently being considered as part of a possible extended payload of Sancho, Don Quijote's Orbiter spacecraft. In the ongoing mission phase A studies, only the ASP interfaces with the rest of the system will be addressed from the technical standpoint; technical, industrial and scientific interest and possible hardware procurement schemes are being explored in parallel. If suitable scenarios for the implementation of this element are identified after the project mid-term review (mid-October 2006) dedicated design activities will then be considered.

Full high resolution simulations the all stages of the impact (compression, excavation and modification) will be required in order to have more accurate estimations of the physical characteristics of the impact crater, on any impact-induced changes to the target body physical properties. A better understanding of the short and medium term evolution of the impact ejecta is also mandatory.

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