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# Don Quijote: An ESA mission for the assessment of the NEO threat

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## ABSTRACT

There is overwhelming scientific evidence that impacts Near-Earth Objects (NEOs) could trigger a catastrophe that might have consequences at a global scale. In July 2002 the General Studies Programme of the European Space Agency (ESA) provided funding for preliminary studies of six space missions that could make significant contributions to our knowledge of the NEOs and the threat the represent to life on Earth. This was the first time ever thatthe full range of NEO space systems were explored and assessed in detail within the scope of a single activity. Following the completion and presentation of these studies, the ESA Near-Earth Object Mission Advisory Panel (NEOMAP) was established in January 2004. NEOMAP was charged with the task of advising ESA on the most effective options for ESA participation in a space mission to contribute to the assessment of the NEO impact hazard and pave the way for the definition of effective impact mitigation strategies. This paper summarizes the final recommendations of the panel and provides an overview of the selected concept, the Don Quijote space mission.

## INTRODUCTION

Near Earth Objects, or NEOs, are not simply a scientific curiosity. In practical terms, if colliding with the Earth, they may originate one of the worst possible natural disasters. There is now overwhelming evidence that large impacts -of objects with dimensions in the order of kilometres- have had catastrophic consequences in the past, in spite of being also extremely infrequent. Objects of various sizes can cause significant damage when they hit the Earth at random intervals of hundreds or thousands of years.

The magnitude of the problem has been recognised in many occasions. The resolution 1080 Council of Europe has provided recommendations on this issue [1] and a task force on the subject was established in the UK [2]. The importance of international initiatives to further our understanding on the NEO has also been highlighted in other international forums at the highest level such as the UN COPUOS [3] and the OECD Global Science Forum [4].

Nevertheless the current level of activity in the area of NEO impact risk assessment, both in Europe and worldwide, is only large among academicians but still very limited at institutional level.

The European Space Agency's long-term space policy [5] identified NEO research as a task that should be actively pursued by the Agency. ESA has as a consequence decided to follow a stepwise approach, assessing European interests and capabilities, and defining a strategy at a European level first as a preparatory step for a framework of international cooperation to be established. This approach is based on several studies and internal assessments that are enabling to elaborate a coherent roadmap of European NEO risk assessment space systems.

As the further step towards this goal, in January 2004 ESA established a NEO Mission Advisory Panel (NEOMAP), having the objective to discuss the results of the NEO mission feasibility studies carried out in the frame of the "NEO Space Mission Preparation" activity and make recommendations on the next actions to be undertaken by ESA. The NEOMAP is composed by recognised European experts on various aspects on the NEOs (detection, orbit determination, physical characterisation) and on the impact threat they pose to our planet.

This paper describes the recommendation resulting from their work and describes the prospects of establishing a cooperative project for the development of a space mission using the selected "Don Quijote" concept as a reference mission.

## THE ROLE OF SPACE MISSIONS FOR THE ASSESSMENT OF THE NEO HAZARD

Up to now, most European efforts on NEOs have concentrated in the theoretical modelling of the NEO population, coordination and improvement of ground-based survey programmes, distribution and analysis of astrometric data, NEO orbit determination, (remote) physical characterisation, and modelling of their physical properties. Some of these activities are supported directly by ESA; as a matter of fact the Spaceguard Central Node (SCN) is hosted by ESA at

ESRIN and is advising ESA in all issues related to the NEOs.

Studies commissioned by ESA to date [6, 7, 8] indicate that a large potential also exists for the utilisation of dedicated space-based assets to further our understanding of the NEO hazard. Thanks to these studies Europe as gained a good understanding of the different existing options.

These have also indicated that a phased approach is necessary so as to assess the threat, a prerequisite for the development of effective mitigation techniques. As a result of these considerations, the "Near Earth Objects Space Mission Preparation" (NEO SMP) parallel pre-phase A mission studies were conducted in the context of ESA´s General Studies Programme with a total budget of 900 KEUR

The studies represented an assessment of six different space mission concepts, all of them dedicated to gather information on several aspects on the NEO hazard so that the most effective countermeasures could be identified. All proposals assumed a financial mission envelope not exceeding that of a ESA Science programme "flexi" mission i.e. 150 MEUR in 1996 economic conditions. These studies have been reviewed elsewhere and will not be described here in detail [9].

Two broad types of space missions were addressed in the activity:

- Survey –type NEO missions. These are missions dedicated to the detection, tracking (i.e. orbit determination) and remote characterisation (e.g. determination of taxonomic type and surface albedo). The main objective of these missions is to improve and expand our catalogue of dangerous objects. Though space borne telescopes cannot be made as large and powerful as their terrestrial counterparts, for these tasks and as a consequence of improved viewing geometry and observation conditions the space option enables an improved access to certain types of objects. These include Inner to Earth Objects (IEOs) and Atens, that due to their proximity to the Sun in the sky are often difficult to observe. These favourable conditions lead to efficient and extensive surveys in which smaller objects down to a few hundred meters in size may also be detected and observed. In addition to this, from space it is also possible to have access to a broader range of wavelengths (e.g. IR) and an improved duty cycle than from the ground.
  The mission concepts in this category include EuNEOS [10], Earthguard-1 [11] and NERO [12]
- In-situ characterisation missions These missions seek precise mass, volume, and internal structure determination, among other physical properties of the objects. Space borne instruments are clearly the best and often only option to obtain these data, which are essential for the assessment of the consequences of an impact and the countermeasures that can be adopted to prevent it. The rendezvous mission concepts that were assessed in the NEO SMP activity were SIMONE [13], ISHTAR [14] and Don Quijote [15].
- Finally, a subset of the second category, the "NEO Precursor missions" was also defined. In addition to gathering data on the physical properties of the objects, these missions would test deflection techniques leading to the demonstration of the ability to move an asteroid. Precursor missions have been identified as having a very high interest, both from the NEO characterization and the technological point of view.

All the missions considered in the "Near Earth Objects Space Mission Preparation" activity represent interesting options and having an overview of all them is necessary. Nevertheless, in practical terms it is not realistic to think that all of them will be implemented and some priorities should be defined.

<u>NEOMAP tasks and objectives</u>

ESA has been supported in the complex task of establishing priorities by an independent group of experts. The NEO Mission Advisory Panel (NEOMAP) has provided the Agency with recommendations on which project should be implemented first in the current context. The NEOMAP tasks were the following:

- Identify advantages and define a solid rationale of the utilisation of space missions for the assessment of the NEO impact hazard. It is not the objective of this task to repeat previous work but to provide a brief summary of their main conclusions.
- Identify which of those advantages associated with the utilisation of space systems can complement ground-based observation and data. This work will also be a summary and update of previous relevant studies.
- Revise and update the scientific priorities for NEO hazard assessment mission concepts entirely in terms of its value in reducing the risk of impact of a NEO - and not e.g. by the value of the results to pure science.

- Judge the value of each mission concept and the potential benefits resulting from the implementation of the missions, considering them in the context of current or future international initiatives, either ground surveys or other planned space missions.
- Produce a set of prioritised recommendations for both each mission category (surveys and rendez-vous) and a proposal for (a) space mission(s) cooperative project(s) at international level.

For six months the panel has carried out work on a set of recommendations that were presented at an event that held at ESRIN (Frascati, Italy) on 9th July 2004.

Panel findings and recommendations

NEOMAP conclusions and final recommendation [16] can be summarised as follows. As far as the observatory concepts are concerned, the Panel felt that improvements in the performance of existing ground-based NEO surveys and, in particular, plans for larger facilities, have led to a dramatic increase over the past few years in expectations for NEO discovery from the ground. Therefore, in the Panel's view, the need for a space-based NEO observatory is not clearly justified in the current conditions, but it should be however reconsidered in 10 – 15 years time, after the residual hazard from NEOs not accessible to the ground-based surveys has become better defined.

In the case of the rendez-vous missions the Panel acknowledged that given the variety of objects already known, it is improbable that any mission will investigate a NEO identical to the next Earth impactor. Nevertheless, in the Panel's opinion such missions would allow to define the techniques we would employ if such a body were discovered, in addition to providing ground-truth for comparison with models based on theory and Earth-based observations. This is the essence of the NEO precursor mission concept, that as opposed to a fully-fledged deflection test mission, could enable a cost effective assessment of capabilities and weakness of different technological solutions.

The Panel thus considered that a rendezvous mission was of significantly higher priority in terms of risk assessment and mitigation than the observatory mission concepts, and it noted in particular that the ability to change the orbit of a NEO has not yet been demonstrated, this being a vital link in the chain from threat identification to threat mitigation that is currently missing. Among the six mission studies under review, the Panel unanimously agreed Don Quijote is the only mission concept that would fill in this knowledge gap in addition to providing valuable information on the physical properties of the target object. Therefore, the Panel made the recommendation to ESA to given the highest priority to this concept and use it as a basis for ESA's participation in a NEO impact-risk assessment and reduction project.

## DON QUIJOTE MISSION

The Don Quijote study, leaded by DEIMOS Space, has designed a mission to a NEO with two correlated but conceptually independent goals:

– To gain a technical experience that would be critical in case there was the need to deflect an asteroid away from a collision course with the Earth.

– To obtain knowledge about the physical properties of Near Earth Objects, which not only has a very high scientific interest by itself, but would also contribute to the characterisation of the NEO threat.

Mission Overview

The mission would contain the following elements:

– Two spacecraft are to launch in separate interplanetary trajectories.

– One spacecraft, which will be referred to as **Hidalgo**, will impact an asteroid of approximately 500 m diameter at a relative speed of at least 10 km/s.

– The other spacecraft, called **Sancho**, will arrive earlier at the same asteroid along a very different route; perform a rendez-vous and remaining in orbit around the asteroid for several months before and after the impact.

– Sancho will also deliver at least four penetrators, to form a seismometer network on the asteroid. Before and after the Hidalgo impact an active seismic experiment (seismic tomography) to study internal structure will be carried out, by means of seismic activators (small explosives) that will be launched from Sancho.

– At the time of the impact, Sancho will retreat to a safe distance to observe the impact without taking unnecessary risk (with an attitude appropriate to its name). It will later return to a close orbit, to observe the changes in the orbit and rotation state of the asteroid, and (optionally) to collect samples from the dust ejected by the crater formation.

Scientific Requirements

Table 1 shows the mission top-level scientific requirements:

| | |
|---|---|
| 1 | To determine the asteroid internal structure, especially the size f the main solid pieces, the average particle size and thickness of regolith and of the debris layers in the space left between the main pieces. This requires seismology, although very useful constraints can also be obtained from the shape changes and rotation dissipation. |
| 2 | To constrain the mechanical properties of the asteroid material. This is measured by the seismic propagation speeds, but also by the penetrators (with an accelerometer). |
| 3 | To measure the orbital deflection of the asteroid as a result of the impact of Hidalgo, with an accuracy of about 10%. This can be achieved with range-rate and/or with range, and also requires that the orbit determinations of the asteroid-centric orbit of Sancho before and after the impact are accurate as necessary: this implies the requirements on the accelerometer performance or altenative options. |
| 4 | To measure the mass of the asteroid, the ratio of the moments of inertia and the low order harmonics of its gravity field. This is needed also to achieve 3., but is a goal in itself. 3. and 4. together measure the transfer of linear momentum achieved with the Hidalgo impact. |
| 5 | To model the asteroid shape before and after the impact, to detect changes (if any). The main problem is that it is very difficult to estimate a priori the size of such changes, thus they may not be detected, apart from the impact crater (delayed changes are possible, and would be very interesting) |
| 6 | To measure the asteroid rotation state before and immediately after the impact; the accuracy must be such that the difference is measured with an accuracy of 10%. This allows determining the absolute value of the moments of inertia. |
| 7 | To detect the dissipation of the non-principal axis rotation after the impact, if possible. The problem is that the dissipation factor Q is very hard to predict, thus we do not know the time-scale of the dissipative changes in the rotation state. Note that the dissipative changes in the rotation state could be associated with delayed shape changes. |
| 8 | To determine the asteroid large scale mineralogical composition. Since such a small asteroid is likely to be rather homogeneous, this suggests low spatial resolution/high spectral resolution IR spectrometry. |
| 9 | To determine the detailed mineralogical composition and texture. Mass spectrometry could be interesting, but may not be top priority. This requires capture and in situ analysis of some particles, e.g., the ones released in orbit around the asteroid by the Hidalgo impact. |
| 10 | To provide a model for non-gravitational forces, such as Yarkovsky effect, acting on the asteroid orbit and rotation. This requires a thermal model. |

**Table 1. Don Quijote Scientific Requirements.**

Of these goals, most refer to the determination of the asteroid internal structure. Only 3. and the mass determination of 4. (and, to some extent, 6.) are directly relevant for the deflection experiment, although the information on the internal structure could be relevant for other deflection methods.

Mission Trajectory

The two spacecraft have to arrive to the same asteroid but with very different conditions:

– The first spacecraft to arrive shall be Sancho. This S/C shall rendezvous the asteroid and remain in orbit until the second spacecraft arrives. The arrival conditions for Sancho are those that:

  - o Maximise the mass reaching the asteroid vicinity
  - o Minimise the ΔV required for orbit insertion.
  - o Result in an arrival date with sufficient anticipation (around 6 months) to allow the proper characterisation of the asteroid prior to Hidalgo arrival.

– The second spacecraft, Hidalgo, shall arrive to the asteroid with:

  - o High relative velocity, impacting the target with a given accuracy
  - o Maximising the mass at impact

Other constraints such as impact geometry for measuring the impact consequences are also considered.

Figure 1 shows the designed trajectory fulfilling these constraints:

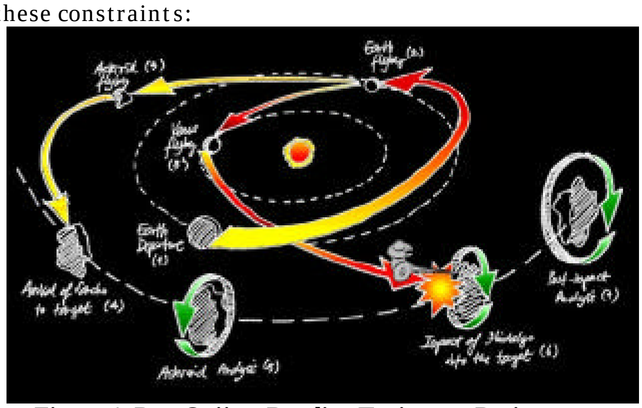

**Figure 1. Don Quijote Baseline Trajectory Design**

– Single launch for both S/C (Soyuz-Fregat like) (see Figure 1, point 1)

– Both S/C in a trajectory that will encounter the Earth 6 months later.

– The Earth swingby (2) is used to separate both spacecraft in two different interplanetary trajectories. Each S/C reach the Earth with a small difference that result in completely different gravity assist manoeuvre, routing Sancho to the target asteroid and directing Hidalgo towards Venus (or Mars).

– Sancho might perform a midcourse asteroid flyby (3) as a scientific add-on to the main mission.

– Sancho rendezvous the asteroid with a small relative ΔV (4) and starts to characterise it (5) (i.e. estimation of its geometrical properties and gravity field), deploying the penetrators.

– Hidalgo performs a Venus (or Mars) swingby that redirects it to the asteroid (3')

– Hidalgo impacts the asteroid with a high relative velocity (6), while Sancho witnesses it.

– Sancho explores the consequences of the impact (7)

A software tool has been created to explore these type of trajectories, and a large number of solutions have been found following this scheme.

A database of NEO has been used as input to the tool, filtering it to keep only bodies of medium size (around 500 meters)

Figure 2 shows the achieved S/C mass at the asteroid when using Venus as intermediate flyby:

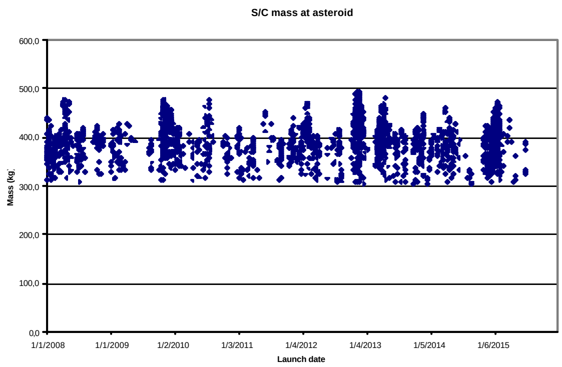


**Figure 2. S/C Mass at asteroid (both Sancho and Hidalgo) (Venus case).**

Results obtained when selecting Mars are shown in Figure 3, with a clear reduction of NEO.

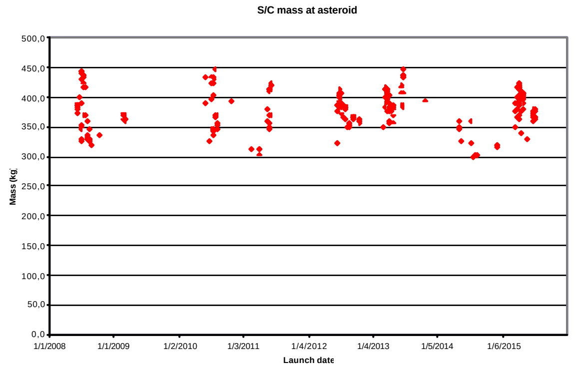


**Figure 3. S/C Mass at asteroid (both Sancho and Hidalgo) (Mars case).**

Figure 4 shows the impact velocity of Hidalgo for the Venus case. Many solutions can be found with velocities higher than 15 m/s.

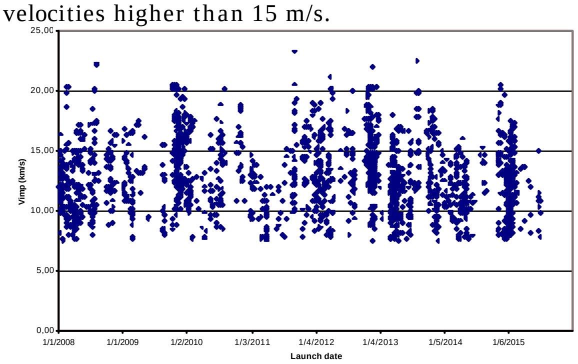


**Figure 4. Impact velocity for Hidalgo (Venus case).**

In the Mars case, Figure 5, the impact velocity is smaller.

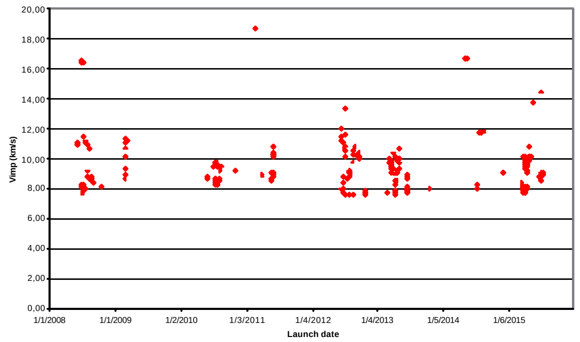


**Figure 5. Impact velocity for Hidalgo (Mars case).**

The following conclusions can be derived:

– Both scenarios offer suitable trajectories.

– Venus offers ten times more opportunities than Mars (2974 vs 298), and a larger list of potential NEO.

– For Venus:

  o The average mass is slightly below 400 kg.

  o The impact velocity is in average around 14 km/s.

– For Mars:

  - The average mass is below that of the Venus case, around 375 kg, with no missions above 450 kg.
  - The impact velocity is much worse than for Venus (this is the most important difference).

Swing-by with Venus was finally selected for further analysis (although the different thermal environment for each S/C should be investigated in more detail).

A pre-selection of targets was made based on Earth-asteroid time, Sancho RV mass, Hidalgo impact velocity and asteroid distance at impact. 13 objects potential targets were identified.

From these pre-selection, 3 asteroid were chosen among them after analysing in detail their physical characteristics: (25143) 1998SF36, 1989 UQ and (10302) 1989 ML.

A figure of merit for the change in asteroid velocity measurement (range and doppler) was defined as an additional selection criteria**:**

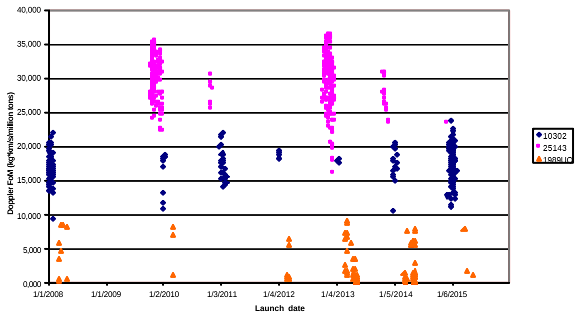


**Figure 6. Doppler Measurements Figure of Merit**

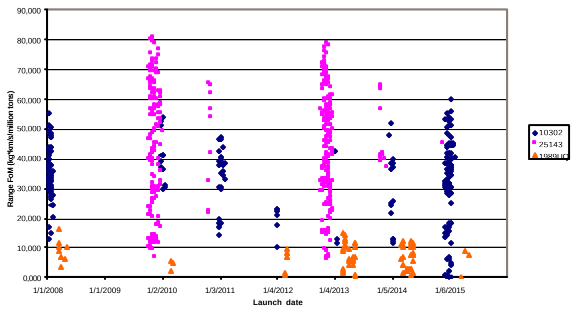


**Figure 7 Range Measurements Figure of Merit**

In view of these results, 1989 UQ is discarded in favour of the other two due to its worst measurement performance. 25143 will be visited by MUSES-C. This could be an advantage as our mission might be designed to complement the other (e.g. no need to duplicate instruments on both, like the IR).

A compromise was reached to select a less than optimal solution that can be used to size the mission, with a considerable amount of backup missions (launch windows):

– Minimum mass at asteroid: ~ 400 kg (this is assuming equal masses, but they could be balanced if needed between the two S/C, e.g increasing Sancho's mass)

– Impact velocity. ~ 13 km/s

Asteroid (10302) 1989 ML is taken as a reference case:

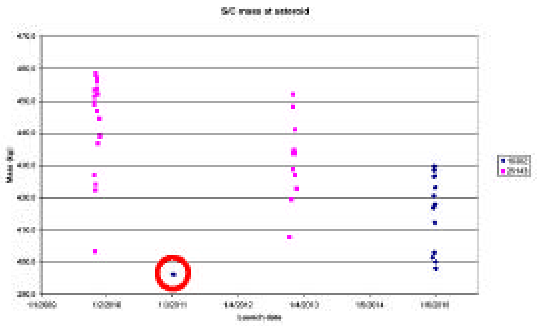


**Figure 8. : S/C Mass at NEO (Sancho & Hidalgo)**

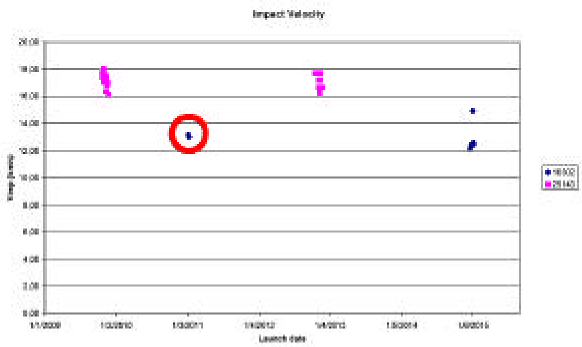


**Figure 9 Impact velocity for Hidalgo**

The reference mission has the following departing and arrival masses and velocities:

| | SANCHO |
|---|---|
| Departure mass (kg) | 582.3 |
| Final injected mass (kg) | 394.0 |
| Relative arrival velocity (km/s) | 1.089 |
| Earth departure date | 2011/ 1/ 6 9:36 |
| | HIDALGO |
| Departure mass (kg) | 388.2 |
| Final injected mass (kg) | 379.1 |
| Relative arrival velocity (km/s) | 13.437 |
| Earth departure date | 2011/ 1/ 6 9:36 |

**Table 2. Departing and arrival mass and velocity.**

The Spacecraft

The Don Quijote mission is divided in four dedicated mission elements. There is the orbiter Sancho that carries the combined camera/TIR-imager, the IR spectrometer, the Penetrators/Surface elements (P/SE), and the seismic sources. The P/SE and the seismic sources (SS) are considered as separate elements, since they perform the "landing" and surface operation on the asteroid, which in itself is a complex "sub-mission" of Don Quijote. The P/SE carry a seismometer, an accelerometer, and a temperature sensor as scientific payload, whereas the seismic sources comprise merely an explosive charge and a timed detonator. The fourth element is Hidalgo, which serves solely as impactor and its main task is to hit the asteroid with a given accuracy and relative velocity.

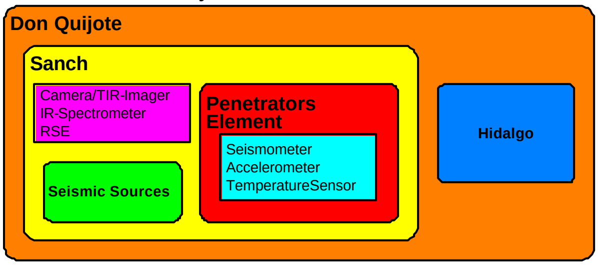


**Figure 10. Mission Elements**

The S/C Sancho is carrying the scientific instruments and will arrive at the asteroid about 6 month before the impact of Hidalgo. While Sancho is orbiting the asteroid, the seismic network is deployed and different scientific measurements are conducted

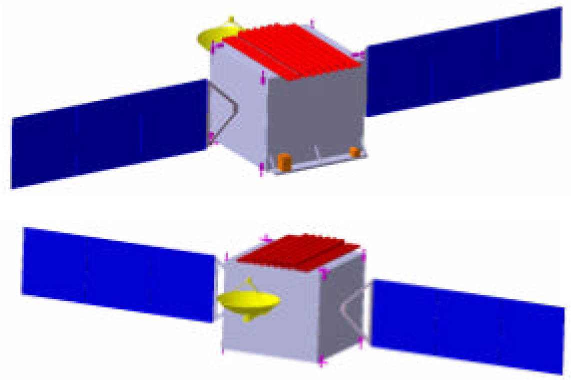

**Figure 11. Sancho Configuration**

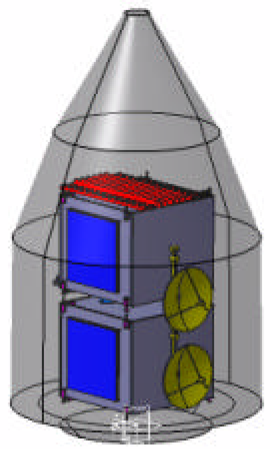

**Figure 12. Launch configuration with Soyuz Fairing**

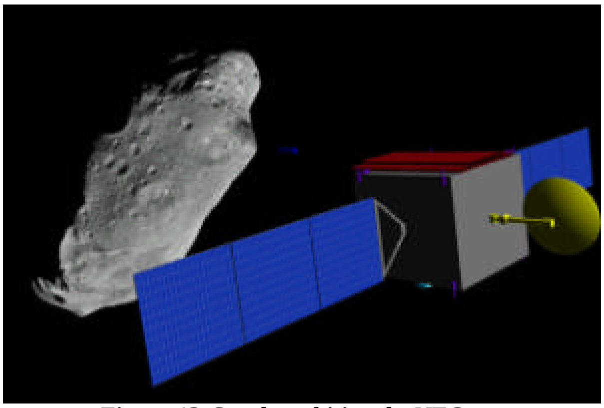

**Figure 13. Sancho orbiting the NEO**

Hidalgo will in principle be a rebuild of the Sancho S/C omitting the instruments, launch mechanisms for the penetrators and seismic sources, and probably the HGA. Due to the reduced power demand the electrical power system, and in particular the solar arrays, may also be reduced in size and mass. The same is true for the propulsion system. For Hidalgo no orbit capture is necessary. Therefore the orbit corrections can be done with thrust vectoring using the AOCS thrusters. Due to these changes, the Hidalgo S/C will be simpler than Sancho except the autonomy/FDIR concept, since it must perform the final targeting prior to the impact without substantial ground support and with a very high reliability.

Strawman payload

The following instrumentation were identified as part of the Don Quijote reference payload:

| Instrument | Mass (kg) | Power (W) | Remarks |
|---|---|---|---|
| Sancho Orbiter | | | |
| Baseline Instruments | | | |
| Compact Camera + comp. TIR Imager | 6.5 | 12 | TIR: micro-bolometer array |
| IR Spectrometer | 8.5 | 2 x 8 | SIR type micro-bolometer based |
| Ka Transponder | 3.5 | 9 | BepiColombo design |
| Design Variation | | | |
| BepiColombo Camera | 3.5 | 4 | BepiColombo design |
| BepiColombo IR spectrometer | 3 | 9 | BepiColombo design (includes TIR) |

| Penetrator/Surface Elements | | | |
|---|---|---|---|
| Seismometer | 0.2 | TBD | Estimated |
| Accelerometer | 0.06 | TBD | Estimated |
| Thermo-Sensor | < .05 | TBD | Estimated |
| Sensor electronics | < .25 | 0.6 | Estimated |

**Table 3. Don Quijote strawman payload.**

The main task for the camera is the imaging of the asteroid at high resolution when Sancho is in orbit around it. In addition, it will be used for navigational purposes during the far and close approach phases. In addition a TIR channel with a micro-bolometer array will be implemented. For the design variation the NAC/WAC design of BepiColombo is considered as possible instrument.

The IR-spectrometer is primarily used for the classification of the asteroid and a high diversity of the soil is not expected. Thus, the requirements with respect to spatial and spectral resolution are moderate. Therefore, a SIR-type micro-spectrometer was selected as baseline. For the design variation the IR spectrometer of BepiColombo was selected, which covers also the TIR region of the spectrum.

The Ka-Transponder is needed for the precise determination of the trajectory and its changes of the asteroid. As a starting assumption exactly the same instruments planned for BepiColombo might be used. Further analysis indicates that the main requirement on the knowledge of non gravitational perturbations can be met without an accelerometer, provided the spacecraft can be kept in a fixed attitude during the Radio Science mission phases. Moreover, the requirements on the range measurements can be met without using a dedicated wide band ranging system, like the one envisaged for BepiColombo. We shall assume performance of the Doppler measurements to be the same of BepiColombo, because they have already been demonstrated with the Cassini Radio Science experiment.

The seismometers and accelerometers carried by the penetrators are dedicated to the seismic experiments conducted in the course of the mission in order to determine the internal structure of the asteroid and determine the feasibility of coupling devices onto its surface under microgravity conditions. This knowledge will be important for the implementation of mitigation strategies relying on a direct contact with the asteroid.

## CONCLUSIONS

The global dimensions of the NEO hazard and the level of awareness of this risk of a large fraction of the general public make it a subject that is especially suitable for international cooperation, even if the project itself i.e. a cooperative space mission or set of missions, could be relatively modest compared to other international cooperation ventures. However, relations among space–fairing nations are complex in nature, and there is a large diversity of interests and possible approaches to the NEO issue. In addition, it should be acknowledged that the level of NEO mission-related activities among space agencies worldwide is currently limited and it is likely that the situation will not change in the near future, as a number of new initiatives in other areas are presently being initiated with strong financial commitments.

Therefore it is important to recognise that the successful implementation of a NEO mission in a cooperative fashion should follow a very pragmatic, stepwise approach. This should encompass a modest initial investment that can however maximise mission return for all the cooperating partners. Having the NEO hazard assessment and mitigation as the driver, the mission payoff should be maximum in terms of technology risk reduction for future missions. The project should also contribute to increase public awareness on the NEO threat, and on the current capabilities that space technology offers to tackle it. Synergies with purely scientific investigations should also be explored to raise the interest and support of the research community.

A mission based on the Don Quijote concept 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 carry out measurements the asteroid mass, density and internal structure. More significantly it would constraint its mechanical properties and determine the feasibility of coupling devices onto its surface. Finally, It would measure the mechanical behaviour of the asteroid as a whole, and estimate the orbital deflection triggered by the impact of the Hidalgo spacecraft at a very high relative speed.

Don Quijote’s modular mission architecture and the clear definition of the interfaces between the mission elements would facilitate independent contributions of the cooperating partners. 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. All these reasons together with the mission’s relatively low cost and complexity make the Don Quijote concept the preferred candidate for implementation by ESA. Suitable schemes for achieving this goal in cooperation with all interested parties will be considered and assessed during the coming months.

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