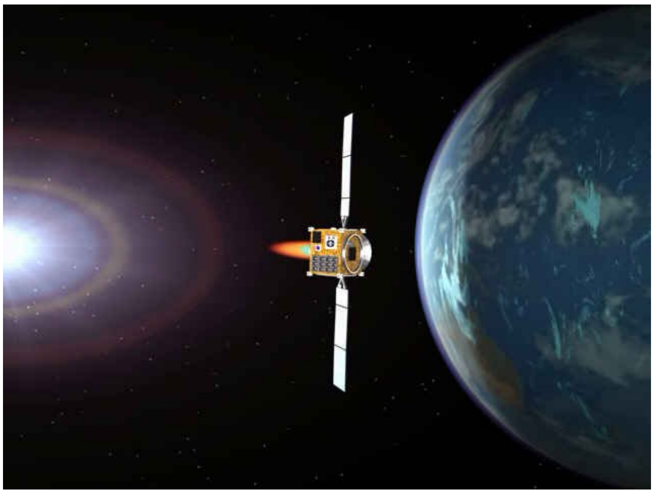
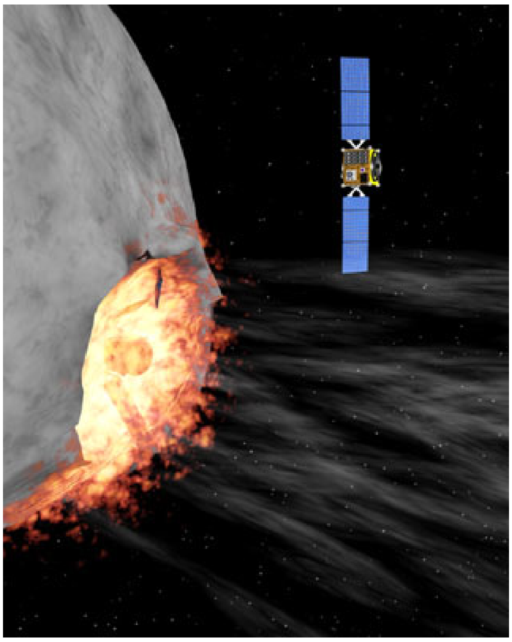
Target Selection for the Don Quijote Mission

Near-Earth Object Mission Advisory Panel
Report to ESA

23 February, 2005





The Near-Earth Object Mission Advisory Panel (NEOMAP)

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Glossary of Frequently Used Technical Terms and Acronyms

Albedo	Measure of the reflectivity of an object’s surface.
Amor	Near-Earth asteroid with orbit having perihelion distance in the range 1.017 – 1.3 AU that therefore does not cross the Earth’s orbit at the present time.
Apollo	Near-Earth asteroid with orbit having perihelion distance less than the Earth’s aphelion distance (1.017 AU) and semi-major axis greater than 1.0 AU.
Aten	Near-Earth asteroid having semi-major axis less than 1.0 AU and aphelion distance greater than the Earth’s perihelion distance (0.983 AU).
AU	Astronomical Unit: mean Earth – Sun distance.
H magnitude	Absolute magnitude: the visual (V) magnitude an observer would record if the asteroid were at a distance of 1 AU from the observer and the Sun, and at zero phase angle (note: H is measured on a logarithmic scale such that the numerical value of H decreases with increasing brightness. H can be used as a rough indicator of the size of an asteroid).
IEO	Inner-Earth Object: has an orbit entirely within the Earth’s.
MOID	Minimum Orbit Intersection Distance (with respect to the Earth’s orbit in the context of near-Earth objects).
NEA	Near-Earth Asteroid: see NEO.
NEO	Near-Earth Object: asteroid or comet in an orbit with perihelion distance less than 1.3 AU, i.e., that allows it to enter the Earth's neighbourhood.
Phase angle	The angle between the directions to the observer and the Sun, as measured from the object being observed (e.g. 0º, 90º, 180º for the full, half, new Moon, respectively).
PHO	Potentially Hazardous Object: asteroids and comets with a MOID of 0.05 AU or less and an absolute magnitude of H = 22.0 or less (i.e. diameter ~ 150 m or more).
Regolith	Surface layer of fragmented rocky debris**.**
V magnitude	Measure of the visual brightness of a celestial object. The magnitude scale is logarithmic: a factor of 100 in brightness is equivalent to a magnitude difference of 5. The numerical value of the V magnitude decreases with increasing brightness. The letter V refers to a standard photometric filter centred at a wavelength of 0.55 μm.

1. Introduction

The primary source of near-Earth objects (NEOs) is the main asteroid belt between the orbits of Mars and Jupiter. Since the epoch of planetary formation collisions between objects in the main belt have given rise to a very broad distribution of sizes. The largest asteroid in the main belt is (1) Ceres with a diameter of about 950 km. Ceres is probably an example of a primordial body that has remained largely unaltered since the time of planet formation 4.5 billion years ago. However, most bodies in the main belt are thought to be collisional fragments with sizes ranging from hundreds of kilometres down to pebble-sized objects and dust grains.

The strong gravitational fields of Jupiter and Saturn can perturb the orbits of small asteroids in the main belt and increase their eccentricity until they cross the orbits of one or more of the inner planets. Asteroids that can come close to the Earth's orbit are called near-Earth asteroids (NEAs) and are traditionally classed by astronomers in three groups according to their orbital parameters, named after the archetypal members of each group (Table 1.1).

Table 1.1. Categories of near-Earth asteroids

Name	Description
Amor **1260** known as of 23 Feb. 05	Objects with orbits having perihelion distances in the range 1.017 – 1.3 AU and therefore do not cross the Earth's orbit at the present time. Current members of this class could, however, become hazardous to the Earth in the future as their orbits evolve.
Apollo **1676** known as of 23 Feb. 05	Objects with orbits having perihelion distances less than the Earth's aphelion distance (1.017 AU) and semi-major axes greater than 1.0 AU.
Aten **263** known as of 23 Feb. 05	Objects with orbits having semi-major axes less than 1.0 AU and aphelion distances greater than the Earth's perihelion distance (0.983 AU).
IEOs **3** known as of 23 Feb. 05	Objects with orbits having semi-major axes less than 1AU and aphelion distances less than 0.983 AU.

Note: Potentially hazardous objects (PHOs) are asteroids and comets with a Minimum Orbit Intersection Distance (MOID) with the Earth of 0.05 AU or less and an absolute magnitude of H = 22.0 or brighter (i.e. diameter of ~150 m or more). The number of known PHOs as of 23 Feb. 05 was 672.

The Apollo and Aten asteroids are on so-called "Earth-crossing orbits" which do not necessarily actually intersect the Earth's orbit at the present time but have the potential to enter the Earth's capture cross-section as a result of gravitational interactions with the Earth and other planets.

Inner-Earth Objects (IEOs) are a largely undiscovered population of objects that have orbits with aphelia less than 0.983 AU, i.e. that lie entirely within the orbit of the Earth. As in the case of Amors, members of this group could become hazardous to the Earth in the future as their orbits evolve. IEOs are very difficult to detect from the ground and very little is known about their number and sizes. Confirmed detections of only a few IEOs have been made to date.

Comets can also collide with the Earth. Due to their porous and fragile structure, the short warning times of long-period comets, and the relatively large potential impact velocities, mitigating against them is generally beyond the capability of current technology. However, observations and dynamical computation (for a summary see Stokes et al. 2003) show that far fewer comets than asteroids make close approaches to the Earth, and near-Earth asteroids appear to be responsible for 99% of the impact hazard.

Which physical parameters of near-Earth asteroids are most relevant for mitigation considerations? The known NEA population contains a confusing variety of objects: a few NEAs are thought to be largely metallic, indicative of material of high density and strength, while many are carbonaceous with lower densities and are less robust. A number of carbonaceous NEAs may be evolved cometary nuclei that are presumably porous and of low density but otherwise with essentially unknown physical characteristics. In terms of large-scale structure NEAs range from monolithic slabs to "rubble piles" and binary systems. An asteroid that has been shattered by collisions with other objects may survive under the collective weak gravitational attraction of the resulting fragments as a cohesionless, consolidated rubble pile. A rubble pile may become a binary system if it makes a close approach to a planet and becomes partially disrupted by the gravitational perturbation. More than 20 NEAs in the currently known population are thought to be binary systems and many more are probably awaiting discovery (current estimates indicate that some 15% - 20% of NEAs are binary).

Preventing a collision with a NEA on course for the Earth would require total destruction of the object, to the extent that the resulting debris poses no hazard to the Earth or, perhaps more realistically, slightly modifying its orbit. In either case accurate knowledge of the object's mass would be of prime importance. In order to mount an effective mission to destroy the object knowledge of its density, internal structure, and strength would also be required. Deflection of the object from its course would require the application of an impulse, or of a continuous or periodic thrust, the magnitude and positioning of which would depend on the mass and its distribution throughout the (irregularly shaped) body and on the spin vector. In either case mitigation planning takes on a higher level of complexity if the Earth-threatening object is a rubble pile or binary system.

Much mitigation-relevant information on the physical characteristics of NEAs can be obtained from astronomical observations. Accurate rotation periods and some information on shapes can be derived from observations of rotation-induced lightcurves. The rotation periods of NEAs generally lie in the range 2 – 10 hr but there are examples of objects with periods well outside this range. For example, the NEA 1999 SF_{10} with a diameter of ~ 60 m has a period of only 2.5 min, whereas 1989 ML, with a diameter of ~ 500 m, has a rotation period of 19 hr. The sizes and optical albedos of asteroids can be derived from radiometric, polarimetric and radar observations. The albedos of NEAs reflect the albedo distribution of main-belt asteroids and are loosely correlated with taxonomic type (Table 1.2). Radiometric observations can also reveal information about the regolith and thermal inertia of NEAs and the temperature distribution around their surfaces, which is relevant to the operation of lander or penetrator instruments. Small NEAs (diameters < 1 km) may lack insulating regolith and have a higher thermal inertia than larger objects; this would lead to smoother temperature distributions around their surfaces with less contrast between day-side and night-side temperatures. However, such statements must be treated with caution since our knowledge of the thermal characteristics of asteroids is still very rudimentary.

Table 1.2. Albedos and probable mineralogies of taxonomic types identified in the NEA population.

Taxonomic Type	Typical Albedo	Probable Mineral Composition
D, P	0.03-0.06	Carbon, organics, silicates
C, B, F, G	0.03-0.10	Carbon, organics, hydrated silicates
M	0.1-0.2	Metals, enstatite
S	0.1-0.3	Silicates, metals
Q	0.2-0.5	Silicates, metals
V	0.2-0.5	Silicates (pyroxene, feldspar)
E	0.3-0.6	Enstatite + other iron-poor silicates
X	0.03-0.6	Unknown

2. Mission-Relevant NEO Characteristics

2.1. Asteroid orbit characteristics

2.1.1. Rendezvous delta-V

Of primary importance is the accessibility of the target, which is given by the delta-V necessary to have a rendezvous with it. Sancho requires a low delta-V; in contrast it is necessary to find trajectories for Hidalgo that *maximize* the arrival velocity at the target asteroid, which can be achieved by exploiting a planetary fly by (e.g. with Venus). The delta-V budgets for rendezvous missions to NEAs have been conveniently tabulated by Binzel et al. (2004).

2.1.2. Orbit type and MOID

Of the known types of NEAs, Atens and Apollos have orbits with perihelia within the Earth's orbit and aphelia outside it, but only for a small fraction of them is a very close encounter with the Earth (i.e. within the distance of the Moon) currently possible. However, the secular orbital evolution induced by planetary perturbations, while leaving the semi-major axis unchanged, does in fact change the perihelion and aphelion distances of the orbits, even in the absence of close planetary encounters, and over a time scale of tens of thousands of years some Aten orbits can become IEO orbits and vice-versa; the same thing can occur for Apollos and Amors.

The Minimum Orbit Intersection Distance (MOID) is the minimum distance between the orbit of the small body and that of the Earth. In many cases of interest, the function giving the distance between two generic points on the two orbits has two local minima, located close to the points at which the small body's orbit crosses the ecliptic (the so-called node crossing points). We have therefore to consider the corresponding two local MOIDs, of which the smaller one is, at any time, the actual MOID.

Another important effect of the secular orbital evolution is that, in addition to the changes in perihelion and aphelion distances mentioned above, it induces a rotation of the orbit of the NEA within its orbital plane, with the consequence that the heliocentric distance of the node crossing points varies with time. This in turn means that the two associated local MOIDs vary with time, and in particular that they can pass through 0 (i.e., the orbits of the NEA and of the Earth actually intersect) at particular epochs. It is close to these epochs that an impact with the Earth becomes possible, and can actually happen if the two bodies come close to the local MOID-nearly-equal-to-0 condition simultaneously.

2.1.3. Orbit determination accuracy

A final issue to consider is the accuracy with which the orbital elements of the target are known. The orbits of NEOs observed at one opposition only are in general too poorly determined to allow the planning of a space mission.

2.2. Physical characteristics

2.2.1. Asteroid's size, mass, and shape

Deflection measurement

The goal of the Don Quijote mission of measuring the orbital deflection of the asteroid as a result of the impact of Hidalgo with an accuracy of about 10% poses an upper limit on the mass of the target asteroid. Taking nominal values of the Hidalgo mass and impact speed of 400 kg and 10 km/s, respectively, and assuming low porosity so that the momentum change of the asteroid is enhanced by substantial ejecta, a delta-V of 5×10^{-3} cm/s measured to an accuracy of 0.5×10^{-3} cm/s (feasible with current radio-science systems but requiring a long integration time of 1000 s) constrains the asteroid mass to less than about 1.7×10^{11} kg. For densities of 1.3 gm/cm^3 and 2.5 gm/cm^3, the corresponding constraints on the diameter are 630 m and 500 m, respectively, assuming a spherical shape. Note, however, that a spherical shape is likely to be a rare case amongst small asteroids. If the NEA is significantly more massive, then the deflection would be measured with a correspondingly lower precision.

Navigation around a small body

To facilitate the navigation of the orbiting satellite around the asteroid, and to prevent its escape or an impact onto the asteroid’s surface, it is important to choose an asteroid for which we have some knowledge of its physical properties, such as its shape and mass. Indeed, the design of a mission and spacecraft to a body with unknown characteristics is very difficult and this is especially true concerning the robust implementation of close proximity dynamics. Ground-based physical characterization can play an important role in target selection and initial mission and spacecraft design. In particular, some prior indications of the shape, density, size, gravity field or density distribution, and spin vector are required to define stable orbits around the small body and the minimum radius for stable motion. For instance, it is known that an orbit at high inclination with respect to the equator of the asteroid decreases the minimum radius for stable motion. Some computations of orbital motion around the asteroid Eros show that an orbital motion in the equatorial plane and opposite to the sense of rotation, i.e. retrograde, is quite stable. On the other hand, orbital motion close to the body with low velocity relative to the surface is in general to be avoided. A retrograde orbit allows very low altitudes relative to the long ends of the body but results in relatively high velocities and places strict constraints on the geometry of the close orbits.

To properly assess what may be feasible in terms of orbit mechanics some specific information is required. For example, some indications of the size, mass and shape of the asteroid must be available together with a nominal model of the orbiting spacecraft, including its total mass (at the asteroid) and total projected area. Depending on the satellite mass-to-area ratio the solar radiation pressure may destabilize the satellite's orbital motion in some regimes. Having these parameters in hand, some orbital constraints can then be defined for an implementation of close proximity dynamics (see Section 3.3.1 for the final requirements).

2.2.2. Taxonomic type and albedo

Spectroscopy is the main source of information on the mineralogy of asteroid surfaces. Analysis of asteroid spectra of modest resolution in terms of absorption band depth, spectral slopes, positions of maxima and minima, etc., reveals details of mineralogical composition and allows asteroids to be classed into taxonomic types according to their spectral features. The taxonomic type of an asteroid can be used as a rough indicator of the reflectivity or albedo of its surface (see Table 1.2). Broadly speaking, carbonaceous asteroids such as D, P and C types have dark surfaces with albedos typically in the range 0.03 – 0.1. Most asteroids with spectra dominated by silicates or metals have intermediate albedos, although certain minerals, e.g. enstatite, can give rise to remarkably high albedos of 0.5 or above. In general the mineralogy of NEAs appears to reflect that of main-belt asteroids so it is not surprising that a broad range of albedos is observed amongst NEAs.

2.2.3. Rotation period

Rotation periods are derived through measurements of the photometric lightcurves of asteroids. It is the synodic rotation period that is measured, however at the accuracies normally achieved (seconds or minutes) this is essentially the same as the sidereal period. The distribution of rotation periods depends on the absolute magnitude. For asteroids brighter than $H = 22.0$ (roughly equivalent to diameters of 150 m), NEOs have a non-maxwellian distribution of spin rates; the mean rotation period is approximately 6 hours. The truncation occurs at approximately 2.2 hours for all NEOs, with only one or two exceptions. As this is approximately the limit at which a strengthless rotating ellipsoid will disrupt due to centrifugal forces, this strongly suggests that most NEOs are either heavily fractured or rubble piles.

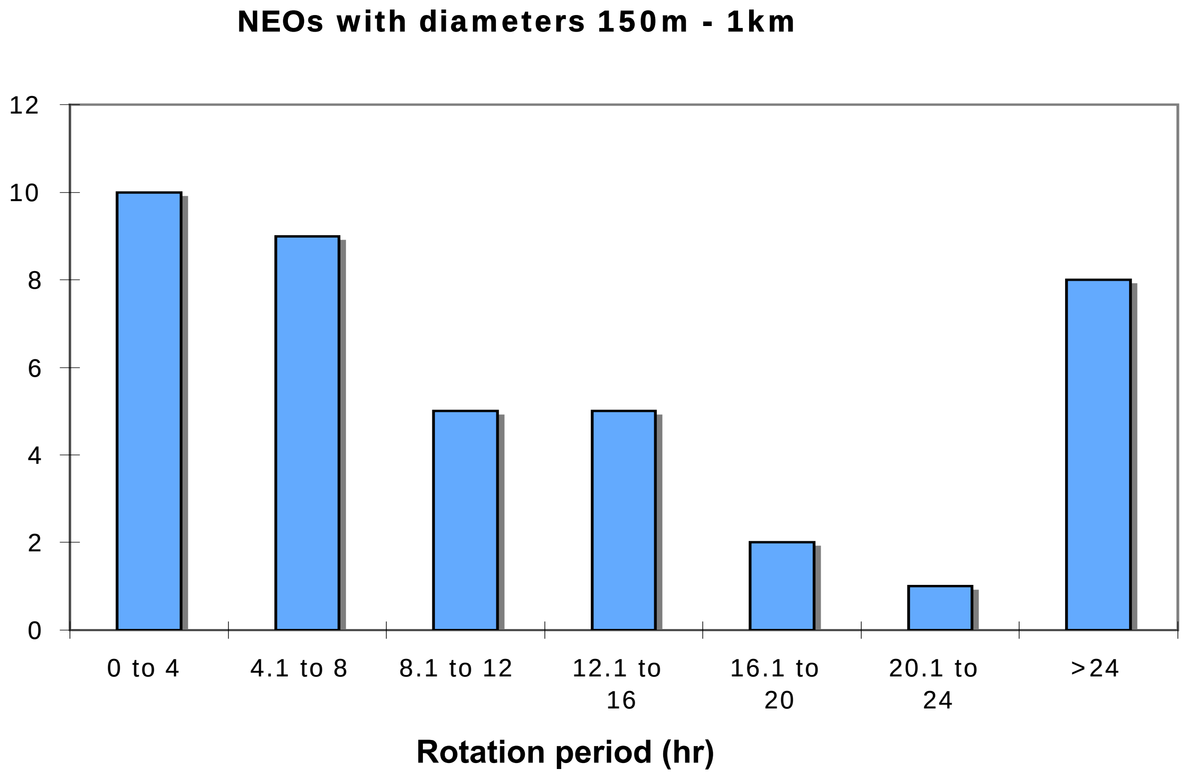

Fig 2.1. Rotation periods measured for 40 NEOs with approximate diameters between 150 m and 1 km. Data obtained from the database maintained by P. Pravec (Ondrejov Observatory).

The distribution of rotation rates shows a large excess of slowly rotating NEOs (see Fig. 2.1). An important aspect for rendezvous missions is the presence of tumbling NEOs. These are objects that simultaneously rotate around two independent spin axes, giving rise to an apparent tumbling state. Put simply, these can be viewed as objects where there exists a precessional period of the same order of magnitude as the normal spin period (although this is not the actual case). A famous example is the NEA (4179) Toutatis, with spin periods of 176 hours and 130 hours. Recent studies imply that the probability of encountering a tumbling NEO increases as one moves to smaller sizes and longer rotation periods.

2.2.4. Non-binarity

As the database of radar images of NEOs has increased, so has the number of binary objects discovered. The separation and relative size of the components show a wide range, although in many cases the primary body is rotating near the centrifugal disruption threshold of 10-11 rotations per day. Both radar and photometric surveys show roughly 15% of NEOs are binary. It is currently unknown whether there is any dependence on spectral type. The prevailing hypothesis is that binaries are created during close approaches to planets. Coupled with the aforementioned likelihood of negligible internal strength for all NEOs more than 150m across, this might imply there should be no dependence on composition. However this remains to be shown.

3. NEO Characteristics: Requirements/Preferences for the Don Quijote Target

3.1. Criteria for target selection

The relevant criteria for target selection, including delta-V, orbit type and accuracy, mass, taxonomic type, albedo, rotation period, binarity, and surface and internal structure, are discussed in the following sections.

3.2. Asteroid orbit characteristics

3.2.1. Rendezvous delta-V

For the present purposes, we consider targets with delta-V up to 7 km/s although targets with lower values of delta-V (say, less than 5 km/s) are preferable, since they allow the use of less expensive launchers and/or larger masses for the spacecraft on arrival.

3.2.2. Orbit type and MOID

It is very important that, in selecting the target for the Don Quijote mission, the behaviour of the two local MOIDs in the coming decades and centuries be closely examined. A deflection manoeuver resulting in unpredicted changes in the orbit of the target NEA could initiate a dangerous situation. It is therefore advisable to choose as mission target either a NEO in an Amor orbit, with perihelion distance well in excess of 1 AU, or a NEO whose MOID is not too small, and will increase in the coming centuries, so that the next epoch in which collisions with the Earth become possible is in the distant future.

3.2.3. Orbit determination accuracy

Only numbered or unnumbered asteroids with orbits sufficiently well determined to enable future recovery should be considered. Targets whose orbits are not known well enough to perform the planned mission based on knowledge current at that time could be recovered telescopically at their subsequent apparition, which might be, say, one or two years later. At that point, still well before the launch, the uncertainty with which their orbital elements are known would decrease by orders of magnitude down to satisfactory levels.

3.3. Physical characteristics

3.3.1. Asteroid's size, mass, and shape

Deflection measurement

In order to determine the appropriate target size to produce a measurable deflection from the impact of Hidalgo, we need to understand the efficiency of momentum transfer to the target. Numerical simulations of this impact have been performed using a state-of-the-art numerical code. This so-called hydrocode allows the computation of the shock wave propagation in elastic solids, utilizing a plastic yield criterion for intense deformation along with an explicit fracture and dynamic fragmentation model to handle brittle solids. Despite this high level of sophistication, the simulations are still limited to impacts that do not involve micro-porosity effects (e.g. crushing of pores), such as those expected during an impact on a porous C-type asteroid.

At present, the momentum transfer in impacts involving bodies of such types cannot be explicitly computed. Consequently we have to resort to simple analytical parameterization in order to estimate the effect on such a structure. The total amount of momentum transferred by an impact can exceed by a large fraction the momentum carried by the projectile, since the mass of the slower moving ejecta is generally much larger than the mass of the projectile. On the other hand, laboratory experiments on porous targets have shown that the amount of ejecta from such targets can be significantly less. Hence we expect that momentum transfer could be significantly reduced in impacts involving highly porous targets. In the absence of detailed numerical models we define a momentum transfer efficiency factor K (K>1), which contains the unknown physics.

In the case of a projectile with mass m_{proj} travelling at velocity v_{imp} and impacting head-on a spherical body of diameter D and bulk density ρ, we can compute the expected change of velocity of the target using the law of conservation of momentum to obtain: $\Delta V = K\, m_{proj}\, v_{imp} / (4/3\, \pi\, \rho\, (D/2)^3)$. Using the nominal values given for the Don Quijote mission, namely m_{proj} = 400 kg, v_{imp} = 10 km/s, we can compute the change in velocity of the target asteroid as a function of its diameter, transfer efficiency factor, and bulk density. The latter can either be the actual bulk density or the density taking into account the porosity, i.e. $\rho = \rho_0$ (1-porosity), where ρ_0 = bulk density with zero porosity.

Figure 3.1 shows the deflection of an asteroid as a function of its size, bulk density and momentum transfer efficiency factor K. The impact conditions are an impactor, Hidalgo, of 400 kg hitting at a velocity of 10 km/s exactly at the centre of mass of the target. The velocity change of the target has been computed for three different bulk densities (black, blue, and red curves) and for three different values of the momentum transfer efficiency, K, of 1, 5 and 10 (from bottom to top). A porous asteroid will have a low bulk density and, as explained above, probably a low transfer efficiency, i.e. a value of K near unity. A rocky body will have a density closer to 3 g/cm^3 and, as shown by numerical simulations, a value of K in the range 3 - 5. Hence, we expect the lower red curve to be more representative for porous objects, while the intermediate black curve would apply to non-porous bodies. If this assumption is correct, the deflection of a porous asteroid would then be smaller than that of a non-porous one. For instance, the deflection of a 500 m-sized non-porous body would be around 10^{-2} cm/s, while the deflection of a porous body of similar size would be around 4 x 10^{-3} cm/s, i.e. a factor 2.5 smaller for the same impact energy. Note however that these results have to be treated with a great deal of caution as the impact response of a porous asteroid is not well understood and is currently based on badly constrained assumptions (which is, after all, part of the motivation of making this deflection experiment on a real asteroid).

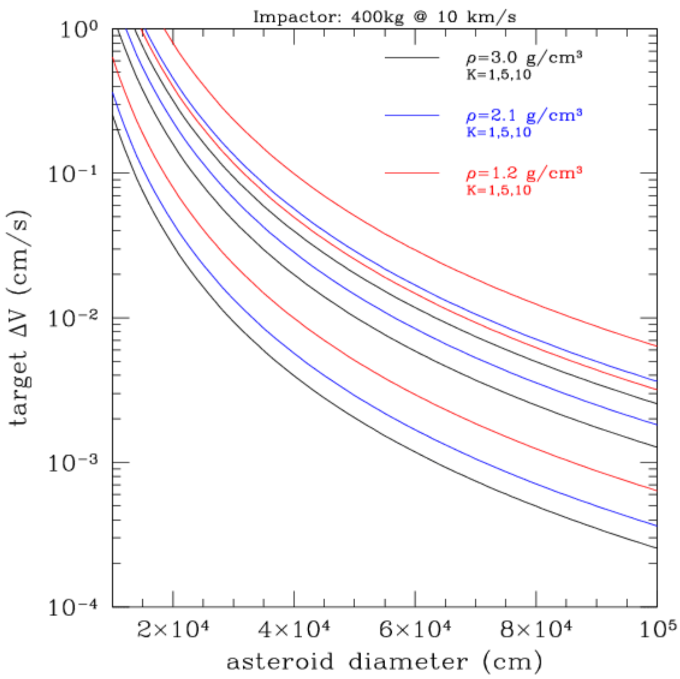

Fig. 3.1. Target deflection (cm/s) as a function of the target's diameter (cm) for different values of the bulk density and efficiency factor K (see text for details).

Even taking into account the possibility that the density of the current potential target asteroids (see Table 4.1) could be rather low, i.e. around 1.3 gm/cm^3, the requirement on the accuracy of the deflection measurement does not allow the target diameter to be much more than about 500 m. Given the uncertainties in converting from the observed absolute magnitudes to diameters (due to lack of knowledge of the albedos) appropriate margins in H should be adopted in candidate target selection. A size of 500 m corresponds to an H-value of about 20.4, 19.6, assuming albedos of 0.05, 0.1, respectively.

For maximum transfer of linear momentum the impulse vector should pass through the center of mass. The difficulty in achieving such an impact increases for highly elongated or irregular shapes. Therefore less irregularly shaped objects are preferred.

Navigation around a small body

The analysis of the limits for stable orbital motion about the chosen "generic" target for the mission presented here has benefited from the expertise of Dan Scheeres of the Department of Aerospace Engineering, University of Michigan, USA. It is still an approximate characterization, as the limits are all derived from approximate analytical theories of motion about rotating small bodies, and a more in-depth analysis would require more precise models or information on the real target. In order to calculate the limits for orbital stability, we consider1989 ML as it has H = 19.6, which is compatible with the deflection measurement requirement discussed above. The known (or assumed) physical parameters of this asteroid are used as a starting point. Table 3.1 lists the quantities of interest.

Table 3.1. Assumed quantities.

Name	Value	Notes
Perihelion distance	1.1 AU	
Mean radius	0.25 km	
Shape (a:b:c)	2:1:1	
Bulk density	2 g/cm^3	C-type asteroid
Rotation period (P)	6 hr, 19 hr	P = 19 hr for 1989 ML
Satellite mass/area	20 to 40 kg/m^2	Rosetta and NEAR

Given the assumed quantities listed in Table 3.1, several relevant parameters can be computed for the asteroid and orbiting satellite (Table 3.2). With all these data in hand, constraints for stable motion about the chosen asteroid can be estimated.

Table 3.2. Computed quantities.

Name	Value	Notes
Gravitational parameter	8.7×10^{-9} km^3 / s^2	
Asteroid semi-major axis (a)	0.4 km	
Asteroid semi-minor axes (b, c)	0.2 km	
Synchronous orbit radius	0.47 km	For P = 6 hr
Synchronous orbit radius	1.0 km	For P = 19 hr
Hill radius	46 km	At perihelion

Minimum orbit radius: Ignoring perturbations from solar radiation pressure (SRP), the minimum orbit radius for a prograde equatorial orbit should be around 0.9 km. Orbits within this limit will be subject to strong, destabilizing perturbations from the rotating gravity field. As indicated in Section 2.2.1, when higher inclination orbits are considered, this minimum radius shrinks in general, reaching its minimum for retrograde orbits. (Note that the asteroid 1989 ML has a rotation period of 19 hours, but a more “usual” rotation period of 6 hours is adopted in order to study a more probable scenario.) Fortunately, in this particular case, the limit on the orbit radius is the same for the two values of the rotation period (although in general this limit is not invariant with respect to the period). This illustrates an important point: while a more slowly rotating asteroid may more weakly perturb an orbiting body, its larger synchronous orbit radius works against this effect. In this case it becomes difficult to characterize how the “safe” radius decreases with increasing inclination, as the role of higher-order resonances between the orbit and the asteroid rotation becomes quite important. However, it is usually true that a retrograde orbit will be stable down to the surface of the asteroid, although there are exceptions to this statement.

Maximum orbit radius: If SRP effects are ignored again, the maximum safe orbit is 20 km or more. However, for an orbiting satellite about a small body, SRP has to be considered. Incorporating this effect into the model leads to a maximum orbit radius of 1.75 to 2.5 km, depending on the mass to area ratio of the satellite. For either case, this provides a range of orbit radii within which a satellite can safely orbit.

Orbit orientation: It is very important to note that not all orientations will be stable for a satellite orbit with a radius within the limits outlined above. In general, the effect of SRP is to cause orbit eccentricity to periodically fluctuate with a relatively large amplitude. This can lead to stronger interactions with the rotating asteroid and can lead to impact with the surface over a relatively short time scale. To minimize these fluctuations in eccentricity, the satellite orbit should be circular and in the terminator plane of the asteroid. This is also a very convenient orbit, as the dynamics of the system will force the satellite orbit to be sun-synchronous, meaning that the satellite will remain in the sun-terminator plane naturally, even if the asteroid has an elliptic orbit.

Summary of requirements: Taking all the above considerations into account, we can recommend the following constraints on the orbit design. *The nominal mapping orbit should be near circular and have a semi-major axis in the range 0.9 km to 2.5 km. The orbit plane should be oriented so that it lies close to the Sun-terminator plane.* Orbits at different inclinations will be subject to destabilization from SRP, although if carefully designed, a satellite could be in a non-terminator orbit for a few weeks. Orbits at smaller radii will be subject to destabilization from the gravity field, except at low-altitude retrograde inclinations. Orbits at larger radii run the risk of the satellite separating from the asteroid.

We note that highly elongated objects would pose more severe constraints for orbital stability.

3.3.2. Taxonomic type and albedo

Our rudimentary knowledge of the abundance of asteroids of different taxonomic types in the NEA population indicates that the probability of the next hazardous asteroid having a dark surface with a carbonaceous spectral signature is roughly equal to the probability of it having a brighter surface with the spectral signature of silicates. We should be prepared for every eventuality. The surface brightness of the target asteroid is a critical factor in the final phase of the navigation of the Hidalgo spacecraft. A dark object viewed at a large solar phase angle represents the most challenging case for a spacecraft with a high relative velocity dependent on visual acquisition for navigation purposes. Research to date indicates that a carbonaceous asteroid is likely to be less dense and more porous than asteroids with more reflective surface materials. In other respects our knowledge of the physical properties of carbonaceous asteroids is lacking. A carbonaceous asteroid would therefore represent a very interesting target from the point of view of mitigation-relevant scientific return, in particular seismology and the dynamical effects of the Hidalgo impact. Given that a target with a dark surface would also represent a more challenging case for spacecraft operations, the choice of a carbonaceous, e.g. C-type, target is considered to be most desirable for the proof of concept of Don Quijote as a pre-cursor to a mitigation mission.

3.3.3. Rotation period

The rotation period is important for both the orbital dynamics of spacecraft around a NEO (due to the changing gravitational field) and for the implementation of surface operations. It is highly unlikely that a NEO considered for Don Quijote will have a rotation period of less than 2.2 hours. Hence this can be considered as the limiting case for a mitigation mission at the current time. However another factor here is that slow rotators such as 1989 ML are likely to be tumbling. This could cause additional problems in maintaining a close orbit due to the non-repeating fluctuations in the near-surface gravitational field. NEOs with diameters of 400 m are likely to be tumbling if they have rotation periods of 15 hours or longer. Therefore we suggest that this is the longest rotation period that should be deemed acceptable for the Don Quijote mission. Finally, for objects of this size, the mean rotation period is near 6 hours. We conclude that a target with a rotation period near this value would be appropriate.

3.3.4. Non-binarity

Approximately 15% of NEOs are binary. A close or contact binary NEO might cause significant problems in achieving a stable orbit due to the fluctuations in the gravitational field. It would also pose problems for Don Quijote due to possible confusion in the targeting of Hidalgo, i.e. we require Hidalgo to impact on the primary body. Furthermore, it may significantly increase the difficulty of placing surface instruments on the NEO, and in interpreting the dynamical effects of the Hidalgo impact. On the other hand, a wide binary would presumably impose significant constraints on the orbit of Sancho in terms of avoiding a close encounter or even a collision with the orbiting secondary. Given all of these problems, we suggest that the target NEO should not be binary.

3.3.5. Thermal surface properties: estimate of thermal inertia.

Our knowledge of the physical properties of the surfaces of small asteroids is almost non-existent. It is not clear that asteroids with diameters below about 1 km possess a significant regolith because their weak gravity may not be sufficient to retain the debris created by impacts on their surfaces. On the other hand, the small amount of observational data available for NEAs suggests that objects with very high values of thermal inertia, such as would be expected for a surface of bare, dust-free rock, are rare in the NEA population, at least in the size range 0.3 – 10 km (Delbó et al., 2003). In general, an object with a surface covered in a thermally insulating layer of dusty debris, i.e. possessing a mature regolith, would have a low thermal inertia and its surface temperature distribution would have a prominent maximum at the sub-solar point and very low temperatures on the night side. On the other hand, an object with a bare, dust-free surface would have a relatively high thermal inertia (perhaps up to 2500 J m^{-2} s^{-1} K^{-1}, or 50 times the thermal inertia of the Moon's surface which has a substantial, mature regolith) and its surface temperature distribution, assuming a normal rotation rate, would be smooth in comparison, with relatively little difference between the day and night sides. The temperature distributions around the equator of a smooth spherical object with visual albedo = 0.1, rotation period = 6 hr, emissivity = 0.9, at 1 AU from the Sun, assuming sub-solar latitude = 0, are plotted for various values of thermal inertia in Fig. 3.2. Preliminary results for one or two NEAs are indicative of thermal inertia values in the range 5 – 10 times the lunar value, i.e. 250 – 500 J m^{-2} s^{-1} K^{-1} (e.g. Müller et al., 2005). The actual temperature distribution on the surface of an asteroid would also depend on its shape and the roughness and topography of the surface. Observational data obtained so far are inadequate for studies of the dependence of thermal inertia on asteroid properties such as size, taxonomic type, etc.

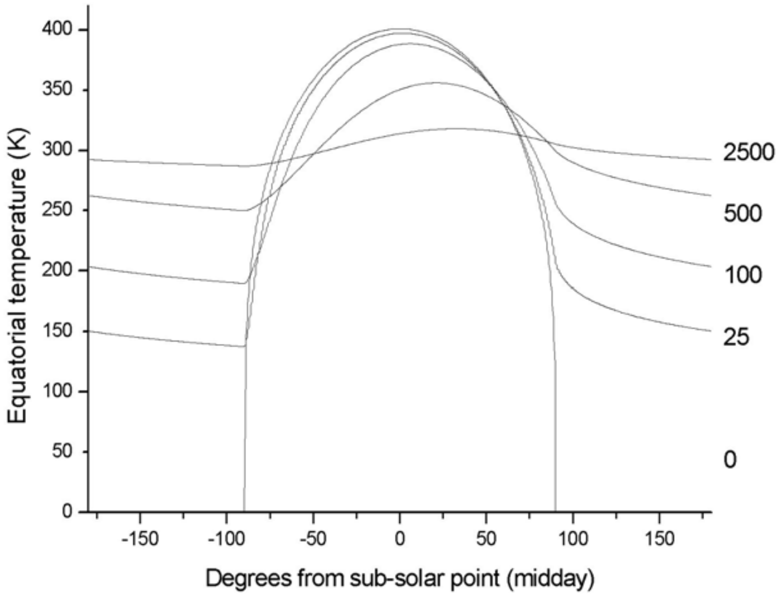

Fig. 3.2. Equatorial temperature profiles for a smooth, spherical asteroid at a heliocentric distance of 1 AU, with a rotation period of 6 hr, geometric albedo p_v = 0.1, emissivity = 0.9, sub-solar latitude = 0º. Profiles are plotted for thermal inertia = 0, 25, 100, 500 and 2500 J m^{-2} s^{-1} K^{-1}. Thermal inertia = $(\kappa\rho c)^{1/2}$, where κ is the thermal conductivity, ρ the density, and c the specific heat capacity. The thermal inertia of the surface of the Moon is about 50 J m^{-2} s^{-1} K^{-1}, that of bare rock about 2500 J m^{-2} s^{-1} K^{-1}.

3.3.6. Surface mechanical properties

The mechanical properties of the surface of a particular NEO will be dictated largely by the surface structure. Although the properties of the surface materials can be reasonably estimated from our understanding of the composition from spectral types and meteorite parent body materials, the structure of the surface is more difficult to determine. The near surface structures may range from an extreme of monolithic solid metal or rock, through fractured materials, to compacted or loose regolith, or even localized regions of fine powdered material.

It is possible to gain some insight into surface strength and structure from a range of ground-based data:

- solid vs. regolith from thermal-infrared spectrophotomety (see Section 3.3.5)
- limits on cohesive strength from rotation period,
- indications of surface roughness (regolith indicator?) from photometric phase curves,
- presence of regolith from local slopes derived from high resolution radar data,
- indications of porosity from radar albedo.

Mitigation techniques may involve either low or high strain rate operations. Examples of low strain rate operations are landing, drilling, hammering (e.g. to attach low impulse propulsion mechanisms), in which case the parameters of interest are from soil and rock mechanics, such as shear and compressive strength, cohesion, angle of internal friction, bulk density, porosity, grain-size distribution and microstructural texture. For high strain rate operations, as in the case of the Hidalgo impact, parameters more appropriate to large-scale shock physics are of interest, e.g. Young's modulus, Poisson ratio, shock Hugoniots etc. Such properties can only be inferred from the supposed surface composition and structure.

Although there may be a large range of possible surface mechanical properties among the NEO population (and even distributed across a single object), there is little clear preference for target selection. This is because, with the exception of a monolithic target, the response of the NEO to the impact is highly uncertain and is the primary objective of the mission. It is vital, however, that the Don Quijote payload is capable of determining the near-surface structure and properties so that the impact response can be placed in context. For most NEOs the surface is not constrained, so target selection should be based on maximizing the probability of a non-monolithic target by excluding any object with thermal-IR or radar data indicative of such a surface and selecting a primitive object, such as the spectral type P, D, C, B, F or G which are believed to be more likely to have complex structures.

3.3.7. Internal structure, seismology

In order to develop adapted mitigation strategies, it is important to have some knowledge of the internal structure and surface properties of the target asteroid. Indeed, according to our current understanding, most NEOs are probably fragments of larger bodies that have been disrupted during their evolution in the asteroid main belt. Recent simulations of catastrophic disruptions of asteroids have demonstrated that most large fragments of a disrupted asteroid should be formed by gravitational reaccumulation of smaller fragments during the collisional event (Michel et al. 2001). Therefore, each of these fragments should consist of a gravitational aggregate or a rubble pile, i.e. a group of several boulders bound together by gravity. If most NEOs are produced by this process, we can expect their internal structure to be highly non-homogeneous, probably filled with macroscopic fractures and/or voids. It has also been shown (Michel et al. 2003, 2004) that the properties of the internal structure of an asteroid greatly influence the impact energy that is required to achieve a fixed degree of disruption (or change of the orbit), since the efficiency of the shock wave propagation within the body (and thus the momentum transfer efficiency) directly depend on these properties.

For these reasons measurements that provide information on the internal structure of the target asteroid, such as seismology, should be accorded high priority. With the placement of several seismometers around the surface, it should be possible to record seismic signals that allow the determination of the seismic wave velocities and provide information on internal structure. This technique has already proven useful in the study of the internal structure of the Earth and Moon. However in the case of a small asteroid, the requirement to discriminate between different kinds of internal structure, such as monolithic, fractured, or fragmented (rubble pile), sets challenging constraints on the necessary spatial resolution.

Taking already qualified technology, the current baseline considers four penetrators and four seismic sources. However, the spatial resolution achievable with this network would certainly be relatively poor, of the order of 100 m for a 500 m-sized asteroid (about ¼ of the body's diameter). If the asteroid is a rubble pile, depending on the size of its components (of which we would have no advance knowledge) this resolution may well be insufficient to give a useful picture of its structure. To allow unambiguous interpretation of the seismic data in terms of internal structure a spatial resolution of at most several meters may be necessary, which could only be achieved using low-mass seismic sensors based on new technologies. However, more development work and space qualification would be required before such sensors could be considered for Don Quijote.

A compromise solution may be to aim for a spatial resolution of some 10% of the object's diameter, which could be achieved using 10 high-frequency sensors and would significantly increase the probability of obtaining useful information on the asteroid's internal structure. A higher operational frequency (of the order of 100 - 500 Hz) would allow the mass of the sensors to be reduced and would therefore increase the number that could be carried.

In summary, large uncertainties remain regarding the internal structure of small asteroids and consequently the spatial resolution required of a seismic network. However, it is important to emphasize that the aim of the mission is to test the applicability and efficiency of the overall Don Quijote "mitigation pre-cursor" strategy in providing exactly the information required for the design and implementation of a successful mitigation mission. In this sense, the aim is not to learn about the internal structure of the particular NEO chosen as the target, but rather to learn how well seismology could be performed on an actual hazardous asteroid. So the question to be asked is: *what is the minimum scale of seismic network that will enable us to decide if seismology presents a practical and effective method of obtaining the required mitigation-relevant information on internal structure?* (We can assume that in the event of a real mitigation pre-cursor mission to a threatening NEO the current financial constraints would not apply!) On the basis of the discussion presented here the answer probably lies in the region of 5 – 10 seismic sensors and a similar number of sources. This should at least allow the sizes of the largest individual structural units of the asteroid to be estimated.

3.4. Ground-based supporting observations

There are three periods during which Earth-based supporting observations might be considered: pre-launch, impact epoch and post-impact.

Pre-launch: This period would involve observations with the aim of providing physical information on the target. Minimum requirements would be compositional information and a zeroth-order estimate of the albedo from optical-IR spectroscopy or high SNR multi-filter photometry, plus lightcurve measurements using CCD photometry to obtain the rotational state. More accurate albedo and size measurements might be feasible using thermal-IR observations and/or radar imaging.

Impact epoch: Although Sancho will be performing *in-situ* observations of the impact, it may also be possible to observe the impact flash and heating of the impact site from Earth if the geometry is favourable. An estimate of the thermal energy released by the impact would aid in the calculation of the kinetic energy of the ejecta and the overall momentum transfer. The rate of cooling of the impact site may provide valuable information on the thermal properties of the surface and near-surface material. This would require high-time-resolution observations in the optical, near-IR and thermal-IR.

Post-impact: Ejecta created by the impact may be visible using Earth-based optical telescopes, given favourable viewing geometry. Finally, but most importantly, optical astrometry and, if possible, radar observations pre- and post-impact could act as a backup to the Sancho measurement of the orbital change caused by the Hidalgo impact.

4. Target Selection

Table 4.1 lists the candidate targets which satisfy the constraints discussed above, namely:

- Delta-V below 7 km/s. The most accessible are (65679) 1989 UQ, (10302) 1989 ML, and 1999 JU_3, all with delta-V less than 5 km/s. The least accessible, with values of delta-V in excess of 6 km/s are 2002 AT_4, 1988 TA and 2001 SG_{286}.

- H = 19 – 21.

- Taxonomic type consistent with low density (essentially D, P, C, B, F, G; some objects currently classified as X may also satisfy this criterion).

The taxonomic types and delta-V values (for Hohmann-like transfer trajectories) are from Binzel et al. (2004).

Among the targets considered, (10302) 1989 ML and 2002 AT_4 are Amors, with perihelion distances of about 1.1 AU and 1.03 AU, respectively. The other possible targets include 3 Atens, 1992 BF, (65679) 1989 UQ, and 2000 EW_{70}, and 3 Apollos, 1999JU_3, 1988 TA, and 2001 SG_{286}.

The two Amors represent by far the best choice as far as the future behaviour of the MOID is concerned. Their secular evolution, as computed by Gronchi and Milani (2001), whose results are shown in the relevant pages of NEODyS (http://newton.dm.unipi.it/cgi-bin/neodys/neoibo), shows that no crossing of the Earth's orbit will take place for a long time in the future. As far as the other possible targets are concerned, the MOIDs of (65679) 1989 UQ, 1999 JU_3 and 1988 TA are all decreasing in the near future, so these NEAs should therefore be excluded; those of 2000 EW_{70} and 1992 BF are increasing. Finally, the MOID of 2001 SG_{286} is currently very small, which also excludes this object from the list of preferred targets.

The orbits of (10302) 1989 ML, (65679) 1989 UQ, 1999 JU_3, and 1992 BF are all well determined, while those of 2000 EW_{70}, 2002 AT_4, 1988 TA, and 2001 SG_{286} are poorly determined. In the next two years 2000 EW_{70} and 2002 AT_4 could be recovered, thus enabling much better determination of their orbits.

Depending on actual absolute magnitudes (H-values) and values of albedo, which are very uncertain for the targets considered here, some of the objects listed in Table 4.1 may breach the size constraint. In particular, with an H-value of 19.23 1999 JU_3 would be too massive by a factor ~5 if its albedo turned out to be very low. However, given the current large uncertainties in the H-values and albedos, the assumption of a diameter of 500 m for the high priority targets is not unreasonable (for instance, taking albedo = 0.1, and H = 19.5 for 1989 ML from the Minor Planet Center web service, instead of H = 19.35 from the NEODyS service as given in Table 4.1, the diameter of 1989 ML is reduced from 570 m to 530 m). It is, however, clear that more accurate physical data on potential targets is required for final mission planning. For the purposes of this study, 1989 ML has been taken as the nominal target. The taxonomic type of 1989 ML, does not constrain the mineralogy and albedo of this object. Moreover since the rotation period of 1989 ML (19 hr) is much longer than is typical for NEAs in this size category, we recommend that for study purposes a more typical rotation period is assumed, e.g. 6 hr.

Ground-based observations of the candidate targets to constrain the albedos, spectral types, shapes and rotation vectors will be necessary before a final selection is made. New candidate targets in the appropriate delta-V and H ranges may arise as a result of future discoveries and/or physical characterisation.

Table 4.1. Relevant characteristics of potential Don Quijote targets.

Number	Name	P (yr)	e	i (deg)	H (mag)	Del-V (km/s)	Taxon. type	D (m) for Pv=0.05,0.1	Orb. type	MOID
10302	1989 ML	1.436	0.137	4.4	19.35	4.46	X	800, 570	Amor	Large
65679	1989 UQ	0.875	0.265	1.3	19.3	4.04	B	820, 580	Aten	Decr.
	1988 TA	1.915	0.479	2.5	20.81	6.67	C	400, 290	Apollo	Decr.
	1992 BF	0.865	0.272	7.3	19.62	5.47	Xc	710, 500	Aten	Incr.
	1999 JU_3	1.297	0.190	5.9	19.23	4.80	Cg	850, 600	Apollo	Decr.
	2000 EW_{70}	0.908	0.321	5.4	21.20	5.47	F	340, 240	Aten	Incr.
	2001 SG_{286}	1.588	0.348	7.8	20.93	6.67	D	390, 275	Apollo	V. low!
	2002 AT_4	2.549	0.447	1.5	20.96	6.58	D	380, 270	Amor	Large

Notes: Orbital parameters and H values were taken from the NEODyS web site: http://newton.dm.unipi.it/cgi-bin/neodys/neoibo. The H-values have typical uncertainties of several tenths of a magnitude.

5. Mitigation-Relevant Science Return

We would expect the results from the Don Quijote mission to address the following questions:

1. *How effective is a kinetic impact on a relatively porous, low-density body for orbit modification?*

Don Quijote will provide direct observational evidence of the effects of a kinetic impact. The dynamical response of the NEO to Hidalgo's impact will be assessed by long-term observations from Sancho and ground-based facilities to detect the change in orbital motion (or provide a meaningful upper limit) and any change in spin vector. Imaging by Sancho of the impact process will provide the volume and speeds of ejecta to aid in the determination of the momentum change of the asteroid.

2. *Surface properties of a small asteroid: How much and what type of regolith is present? Does the surface present a stable, robust base for the attachment of structures?*

The physical effects on the target of the Hidalgo impact (i.e. the impact cratering process itself) will be observed by Sancho. The crater formation process and resultant morphology will provide valuable information to help determine the near surface structure. Remote sensing of the Hidalgo impact site from Sancho will also provide clues on interior structure from crater morphology and the depth of regolith at the crater site. The following information on near-surface structure and physical properties can be obtained from images of the surface in general:

- the extent of regolith coverage,
- regolith cohesiveness from evidence of downslope movement,
- indications of particle sizes from the scattering phase function,
- surface strength from the nature and maximum angle of surface relief,
- indications of subsurface structure from surface morphology (e.g. exposed bedrock, boulders etc),
- possible compositional heterogeneity from multicolour imaging or spectroscopy.

The penetrator deployment will provide information on the surface and subsurface properties, depending on what sensors are incorporated. The deceleration profile on entry will yield clues on regolith cohesion, texture and layering.

3. *Internal structure of a small C-type asteroid: monolith, fractured body, rubble pile?*

A seismometer network is complementary to both radar tomography and gravity field measurements. Radar tomography (not baselined for Don Quijote because of resource constraints) is more effective for determining the macroscopic structure of loose or porous material, while seismic studies are more suitable for examining variations in mechanical properties of consolidated material. Gravity field measurements from orbit, together with the object's shape, can provide an indication of any large-scale internal variations in bulk density. For many mitigation scenarios the response of the NEO's material to the technique employed depends on both the material's small-scale mechanical properties and, perhaps more critically, its larger-scale structure. This is the case at least for impulsive techniques, which involve mechanical failure of the material at high strain rate. Low-force techniques depend on the lower strain rate mechanical properties of only the near-surface material. While the limited seismometer network baselined for Don Quijote may not give sufficient resolution to derive the internal structure on the desired spatial scales, it will provide a test bed for the technique (see Section 3.2.7). Signals are provided by deployed seismic sources. Accelerometers will operate during the Hidalgo impact when the seismometers will be saturated.

4. *Thermal properties: Thermal cycling of penetrator or lander instruments? Magnitude of the Yarkovsky effect for highly accurate computations of an object's orbital evolution and impact predictions?*

Information on the thermal properties of the target asteroid's surface is important for a number of reasons: 1. The insulating properties of the surface layer determine the surface thermal inertia. High values of thermal inertia are indicative of a bare rocky surface or a coarse regolith dominated by particles larger than a few centimetres. Low values of thermal inertia are associated with an insulating dusty regolith (see Section 3.2.5). Therefore measurements of thermal inertia provide information on the physical properties of the surface layer. 2. The question of what amount of thermal cycling penetrator or lander instruments will undergo is of particular relevance to seismometer operations since thermal creak in the penetrator itself may be a significant source of noise. 3. Due to the momentum of the thermal photons, there is a net reactive force associated with asymmetric thermal emission that can significantly influence the long-term evolution of a small asteroid's orbit. This phenomenon has become known as the Yarkovsky effect. The magnitude of the effect depends on the object's thermal inertia, albedo and size. For accurate calculation of the long-term orbital evolution of a NEO the Yarkovsky effect has to be taken into account.

Spatially resolved thermal-IR spectrometry would:

- measure the spatially resolved temperature distribution to derive surface thermal inertia, diagnostic of surface structure,
- assist in evaluation of the magnitude of the Yarkovsky effect for highly accurate computations of an object's orbital evolution and impact predictions.

Measurements of the subsurface temperature and its temporal variation by thermometers in the penetrators would complement the surface thermal radiometry for derivation of the asteroid thermal properties.

5. *How feasible are the required/proposed operational and measurement techniques?*

Don Quijote has an important role to play as a feasibility demonstrator for some of the special operational and measurement techniques required or proposed for a future mitigation pre-cursor mission or a mitigation mission per se. It will address such questions as:

- What are the hazards of operating a spacecraft in orbit around a small, irregular body?
- How feasible would it be to attach structures (e.g. a propulsion system) to the surface?
- How effective are the penetrators?
  - depth of penetration in a given material?
  - orientation relative to surface?
  - coupling with medium for seismic, thermal and other measurements?
- How effective are the seismic detectors? What scale of seismic network will be required?

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