NEOShield

A Global Approach to Near-Earth Object Impact Threat Mitigation

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1 Introduction

1.1 Scope

The purpose of this document, as outlined in [AD 1], is to examine and describe the dynamical and physical properties of a NEO that drive the design of a mitigation mission. Design-driving physical properties are identified and where possible limits are imposed and justified, in order to put some bounds on the search for a suitable demonstration mission target NEO.

The requirements presented are mostly not hard requirements, as in each potential case a more detailed analysis of the suitability of the target should be undertaken, but they should aid in narrowing the selection. Also in many cases, the research to be undertaken throughout the NEOShield project may lead to an adjustment of a requirement.

The requirements presented include requirements relating to rendezvous as well as a high speed impact. The rendezvous requirements apply to any mitigation method with rendezvous (kinetic impactor, blast deflection or gravity tractor), whereas the high speed impact derived requirements only apply in case of a kinetic impactor mission with such a high speed impact.

Additionally, the physical and dynamical properties required to be known in order to undertake a mission design are presented.

1.2 List of Abbreviations

AD .... Applicable Document
AU .... Astronomical Unit
MOID .... Minimum Orbit Intersection Distance
NEO .... Near Earth Object
RD .... Reference Document
RTG .... Radioisotopic Thermoelectric Generator

1.3 Applicable Documents

[AD 1] NEOShield: A Global Approach to Near-Earth Object Impact Threat Mitigation Grant Agreement Annex I "Description of Work", Grant agreement no: 282703, Version date: 2011-10-14

1.4 Reference Documents

[RD 1] Astrium and Deimos Space, Impactor Design Report, Phase A of a Near Earth Object Mission Don Quijote, DQPhA-ASG-ENG05, Issue 2 Rev 0, 30.5.2007
[RD 2] Rathke, A and Izzo, D, Keplerian Consequences of an impact on an asteroid an their relevance for a deflection demonstration mission, Near Earth Objects, our Celestial Neighbors: Opportunity and Risk, Proceedings IAU Symposium No. 236, 2006, A. Milani, G. Valsecchi & D. Vokrouhlicky, eds
[RD 3] ESA/ESTEC, NEO Target Selection and Environment Specification, ACT-TN-050916-4210 NEOMAP2, Issue 1 Revision 1, 16-09-2005
[RD 4] Astrium and Deimos Space, Orbiter Design Report, Phase A of a Near Earth Object Mission Don Quijote, DQPhA-ASG-ENG04, Issue 2 Rev 0, 30.5.2007
[RD 5] Deimos Space S.L.U, Typical impact parameters for kinetic impactor missions, NEOSHIELD-DMS-TEC-MEM01, Issue 1.0, 9/3/2012
[RD 6] Larson, WJ and Wertzm JR (eds.), Space Mission Analysis and Design, 3rd edition, 1999, Space Technology Library, El Segundo, California

2 Summary of Requirements for Target NEO

Presented in Table 1 is a summary of the requirements on the target NEO as discussed and justified in detail in section 3 below. The requirements are not hard requirements, and can be discussed and analysed in more detail for specific cases, and may also evolve following the planned research throughout the NEOShield project.

Table 1: Summary of requirements for target NEOs for a demonstration mission

Property	Requirement	Comment
Minimum Size	>>100m	Impactor impact dispersion ellipse semi-major axis 50m 3σ
Maximum Size	~2.4×10^{11}kg	If spherical, diameter ~700m at 1.3g/cm^3 or ~565m at 2.5g/cm^3
Perihelion	~0.72AU	Distance Venus-Sun
Aphelion	~1.52AU	Distance Mars-Sun
MOID	>0.05AU	
Transfer delta-V	<~4km/s	Limited imposed by choice of Soyuz Launch Vehicle in Don Quijote Phase A
Absolute Magnitude	<~20	Limited by visual navigation for Impactor

In addition to the requirements some qualitative guidelines/recommendations were identified, as summarised in Table 2.

Table 2: Summary of qualitative guidelines for target NEOs for a demonstration mission

Property	Guideline	Comment
Inclination	Low	Lower inclinations are easier to reach
Eccentricity	Low	Spherical and low eccentricity orbits are easier to reach
Density	Low	Would learn about the momentum transfer mechanism which is less well understood for low density impacts. Note, however, that the deflection for a high density NEO would be either higher for the same impact or achievable with a lower impact velocity and/or impactor mass.
Shape	Regular	Irregularly shaped NEOs will complicate the GNC
Binarity	Non-Binary	A binary NEO system would complicate the GNC

3 Physical and Dynamical Properties Driving Mission Design

3.1 Size

3.1.1 Minimum Size

The minimum size of a target NEO is limited primarily by the accuracy of the impact in a kinetic impactor concept. In the Don Quijote Phase A study, it was shown that the impact accuracy (semi major axis of the impact ellipse in the B-plane) specification of 50m at 3σ could be met [RD 1]. In fact, an impact performance of 13.7m at 1σ was demonstrated for a generic mission case, which is in fact better than the requirement.

This drives the minimum NEO target size in that the target should be impacted with a given probability. For a demo mission, and definitely for a real mission, a high probability of impact is required. A 3σ accuracy corresponds to a probability of 98.9% for the 2D normal Rayleigh distribution of the impact dispersion ellipse. However, the impact accuracy does not give an exact minimum size, as the effects of an off-nominal impact will depend on the shape of the NEO itself. Certainly the minimum diameter is more than 100m, but in fact a target much larger than this will be required, considering the inefficiency of an impact on the edge of the NEO (a glancing blow), as well as the target NEO's shape.

Note that the impact accuracy will be further investigated in the frame of the NEOShield project. In general, the impact accuracy depends approximately linearly on the time to impact from the last burn, the terminal optical navigation accuracy and the impact arrival velocity. System design decisions will affect the first two parameters, whereas the last is a function of the transfer option chosen to reach the NEO.

As an additional factor driving the minimum size, operations of an orbiter around a very small body become more complex due to the very low gravity attraction which requires very close and dangerous orbits around the asteroid in order to enable in-orbit operations.

3.1.2 Maximum Size

Here the maximum size constraint is clearly different for a demonstration mission or a real hazardous NEO deflection mission. In the latter case, the largest and most powerful launcher available will be chosen. However the maximum size of a target NEO for a demonstration mission is the maximum mass that can be deflected the required amount by a realistic, appropriately priced, launch vehicle. The amount a NEO's orbit is deflected from its potential impact path is given by the following equation, which is the only secular/steady state term in the equation for deflection of a NEO along the velocity direction given in [RD 2].

$$s = -3\Delta V t_c$$

Where s is the deflection from the original, hazardous, orbit, t_c is the cruise time after impact and ΔV is the change in velocity of the NEO.

Using the above as well as the momentum transfer equation for an asteroid impact below, where K is a factor to account for a nonperfectly inelastic collision, i.e. one where ejecta from the impact are removed, increasing somewhat the efficiency of the impact, the maximum mass of the NEO can be calculated.

$$m_{NEO} v_{NEO} + m_{S/C} v_{S/C} = (m_{NEO} + m_{S/C})\left(v_{NEO} + \frac{1}{K}\Delta V\right)$$

Considering the relative velocity of the incoming spacecraft and NEO as:

$$v_{rel} = v_{S/C} - v_{NEO}$$

The delta-V imparted on the asteroid is given by:

$$m_{NEO}v_{NEO} + m_{S/C}(v_{NEO} + v_{rel}) = (m_{NEO} + m_{S/C})\left(v_{NEO} + \frac{1}{K}\Delta V\right)$$

$$\Rightarrow \Delta V = K\frac{m_{S/C}}{m_{NEO} + m_{S/C}}v_{rel}$$

Or solving for the maximum mass of the NEO:

$$m_{NEO} = m_{S/C}\left(\frac{Kv_{rel}}{\Delta V} - 1\right)$$

Considering a typical case to get an order of magnitude limit on the maximum NEO mass, consider a NEO with an orbit that needs to be deflected 10km, 5 years before a given keyhole passage. In this case, the equation above gives a delta-V requirement of 2.1×10^{-3}cm/s. Note that it is this deflection that must be measured, and therefore measurable to confirm deflection success. Even though [RD 3] states that 5×10^{-3}cm/s is minimum limit, the Don Quijote Phase A study confirmed that the RSE requirements given in that study were easily achievable, especially with better knowledge of the NEO [RD 4].

Assuming also a conservative value of K=1, ignoring the benefits of any ejecta removed from the NEO, as well as a spacecraft mass at impact of 500kg and a relative velocity at impact of 10km/s as assumed in Don Quijote and used for the calculation of impact accuracy as discussed above, the maximum size of the target NEO is 2.4×10^{11}kg. For a density of 1.3g/cm^3 or 2.5g/cm^3 the diameter of a spherical NEO would then be 703m or 565m respectively.

The value given here is conservative, but must be adjusted also for the actual deflection distance required and coast time after impact. This result is dependant on the assumptions, and will be updated where possible throughout the NEOShield study. For example, as discussed in [RD 5], the relative impact velocity could be increased with improved GNC technology since the Don Quijote Phase A study (where the limit was 10km/s) allowing perhaps 15km/s relative impact delta-V. The relative velocity and its effect on GNC accuracy will be investigated during the NEOShield project, considering also the dependency on the phase angle. Additionally, a less conservative value for K could be chosen, considering the expected ejecta behaviour when this is better known.

3.2 Orbit

3.2.1 Perihelion and Aphelion

While the perihelion and aphelion of the target NEO does have an impact on reachability in terms of Delta-V, the main design driver from these physical properties is due to spacecraft design constraints.

Particularly for a possible NEO orbiter and/or gravity tractor, the closer the spacecraft must operate to the sun, the more challenging the thermal control system becomes. And at the other end, the further the spacecraft must operate, the larger the solar arrays required to generate the required power (assuming that RTGs will not be used, which in Europe is currently not possible, and will probably not be possible in the time frame of a demo mission.)

For this reason the perihelion of the target NEO should be limited to around the Venus orbit (0.72AU or 108,209,475km) and the aphelion around Mars (1.52AU or 227,943,824km). With these constraints, there is significant heritage in spacecraft design such that it should not be an unnecessary cost or programmatic/schedule driver on the demo mission.

Note that this design driver in fact only applies to the range of Sun-spacecraft distances for which an orbiter and/or gravity tractor spacecraft has to operate, which means that should a target NEO be found for which the mission duration stays within the bounds of Venus and Mars, the target would be in this respect acceptable, however with the orbital period of the great majority of currently known potentially hazardous NEOs less than 4 years, and with the requirement to spend some time at the NEO before and after impact, this is unlikely.

3.2.2 Earth Orbit Crossings

In order to avoid an unsuccessful or unexpected deflection from turning a demo mission target NEO into a potentially hazardous NEO, only NEOs that do not cross Earth's orbit, with a Minimum Orbit Intersection Distance (MOID) greater than 0.05AU, should be chosen for a demo mission. Additionally, no NEOs should be chosen for which the MOID, following collision and considering the evolution of the orbit over the next several centuries, will become below 0.05AU. In fact, an increasing MOID post-impact should be targeted.

3.2.3 General Orbit Considerations

In addition to the requirements above, there are some general considerations regarding NEO orbits that should be considered in the selection of a suitable target. They are not quantitative but should be considered as an aid to ranking if required.

In general, NEOs with high inclinations and high eccentricity are more expensive to reach in terms of energy required and hence delta-V. Targets orbits in or close to the ecliptic and closest to circular should therefore be preferred.

Additionally, targets with a short synodic period allow more frequent mission opportunities, which would relax somewhat the programmatic and schedule constraints on a demonstration mission, however at the cost of a higher delta-V.

3.3 Delta V/Reachability

The limit on the reachability of a target NEO is the energy, expressed in delta-V, required to transfer from the Earth to the target. For a demo mission target, where the cost of such a mission should be considered and therefore a smaller launch vehicle utilised, there is a limit to the amount of fuel that can be carried and therefore the delta-V. For Don Quijote, the orbiter was planned to be launched by a Soyuz, and could reach a NEO with an approximately 4km/s delta-V transfer.

A formula for calculating the transfer delta-V from the orbital elements of the potential target NEOs will be presented here. Note, however, that the method is highly simplified, and is based on the theoretical optimum transfer known as a Hohmann transfer. It is therefore optimistic, as it considers purely impulsive manoeuvres at perigee and apogee of the transfer orbit. In reality, impulsive manoeuvres are not possible, and the orbiter will most probably have long thrust phases with low thrust but highly efficient electric propulsion. Additionally, deep space manoeuvres and/or planetary fly-bys can be utilised during the transfer to reduce the delta-V requirement.

For targets of interest a detailed analysis will need to be performed, however the method here can be used as a comparison between potential targets, and to rule out significantly unreachable NEOs.

The geometry of a Hohmann transfer from Earth orbit to a target NEO is shown in Figure 1, where the standard Hohmann transfer is extended to a transfer to an elliptical orbit, whereby the most efficient transfer is to the aphelion of the target orbit where the velocity is lowest.

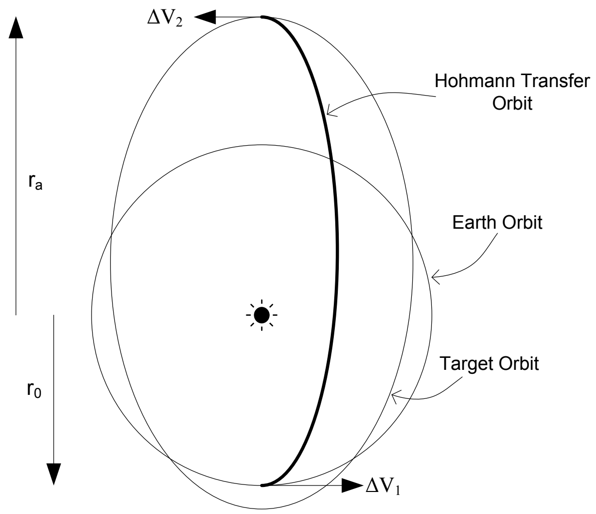

Figure 1:

The delta-V required to begin a transfer is given by the following equation [RD 6], where μ_{Sun} is the gravity parameter of the Sun (the gravitational constant multiplied by the mass, $1.3271\times10^{20} m^3/s^2$), r_0 is the radius of the Earth orbit, a_{tx} is the semi-major axis of the transfer orbit, and r_a is the aphelion radius of the target orbit.

$$\Delta V_1 = \sqrt{\mu_{Sun}}\left(\sqrt{\frac{2}{r_0}-\frac{1}{a_{tx}}}-\sqrt{\frac{1}{r_0}}\right)$$

$$a_{tx} = \frac{r_0 + r_a}{2}$$

The second impulsive manoeuvre is at aphelion and is a combined perihelion raising and inclination change manoeuvre. The inclination change is most efficient at the aphelion of the target orbit as the velocity is lower. The delta-V required for the second manoeuvre is given by the following equation [RD 6], where V_{2i} is the velocity before the manoeuvre at the end of the transfer arc, V_{2f} is the velocity after the manoeuvre at the aphelion of the target orbit, Δi is the inclination change required, and a_{NEO} is the semi-major axis of the target orbit.

$$\Delta V_2 = \sqrt{V_{2i}^2 + V_{2f}^2 - 2V_{2i}V_{2f}\cos\Delta i}$$

Where

$$V_{2i} = \sqrt{\mu_{Sun}\left(\frac{2}{r_a}-\frac{1}{a_{tx}}\right)} \quad \text{and} \quad V_{2f} = \sqrt{\mu_{Sun}\left(\frac{2}{r_a}-\frac{1}{a_{NEO}}\right)}$$

The total delta-V for the rendezvous is given as the sum of the two manoeuvres. Note however that this does not consider additional delta-V for AOCS or insertion manoeuvres, but this will be some orders of magnitude less.

$$\Delta V_{RDV} = \Delta V_1 + \Delta V_2$$

Considering a limit of 4km/s delta-V, as was possible for the Don Quijote orbiter, the delta-V for potential targets can be calculated. Combining the calculations into one formula for rendezvous delta-V, given a target's aphelion radius, semi-major axis and inclination, gives the following.

$$\Delta V_{RDV} = \sqrt{\mu_{Sun}}\left[\sqrt{\frac{2}{r_0} - \frac{2}{r_0 + r_a}} - \sqrt{\frac{1}{r_0}} + \sqrt{\frac{4}{r_a} - \frac{2}{r_0 + r_a} - \frac{1}{a_{NEO}} - 2\sqrt{\left(\frac{2}{r_a} - \frac{2}{r_0 + r_a}\right)\left(\frac{2}{r_a} - \frac{1}{a_{NEO}}\right)}\cos \Delta i}\right]$$

3.4 Absolute Magnitude

The requirement on the faintest absolute magnitude (maximum H) is effectively the faintest magnitude to allow a successful targeting of the NEO by the impactor GNC system, which is highly dependent on visual navigation. The absolute magnitude is related to the diameter and albedo/reflectivity, and so provides some guidance on those.

The impactor navigation camera must be able to acquire the target one day before impact to perform the necessary trajectory correction manoeuvre for a successful autonomous impact (below one day, the communication delay with the Earth starts to become significant and having autonomy implemented is more comfortable). This figure could be between two days and six hours, but one day is a sensible assumption.

The impactor velocity relative to the target NEO could be 15km/s [RD 5], and therefore the target must be acquired 24h×15km/s or 1.3×10^6km. Assuming that the impact occurs when the target NEO is at the largest distance from the Sun (aphelion of 1.52 AU as discussed above), which is the worst case, a phase angle which is less than or equal to 120° (actually ideally it would be closer to 90° close to impact, but depends on the transfer geometry), and a roughly spherical asteroid for phase integral computation, as well as a detection threshold of the NEO of an apparent magnitude of 11, which is the specification of the Rosetta NAC without extended integration time, the NEO absolute magnitude must be brighter than 17.7.

This is a rather pessimistic worst case. Considering less margin on the phase angle (maximum 90° instead of 120°) the absolute magnitude requirement can be relaxed to 18.7. This puts constraints on the anomaly of impact and the eccentricity of the asteroid orbit, but not so strict. The detection threshold of the Rosetta NAC can be extended to 13.5 with 2.5s integration time instead of 0.25s (which is possible when far from the asteroid), thus relaxing the constraint to about 20 with max 120° phase angle or 21 with max 90° phase angle. Additionally, the Rosetta NAC is somewhat old technology, and it is probably possible to do better today, or at least to reduce its mass whilst keeping the same detection threshold. Also the impact at aphelion is a worst case; if impact were to occur at 1 AU the absolute magnitude can also be further relaxed by about 1, with however more constraints on the mission analysis.

Considering the multiple degrees of freedom, with relaxed viewing constraints posing tighter mission analysis constraints, an upper bound for the absolute magnitude of brighter than 20 is an appropriate limit for this stage of the project, with some flexibility if required.

Considering the NEO diameters associated with this absolute magnitude limit, for the minimum NEO diameter of 200m as discussed above, a geometric albedo of 0.44 would be required for detection under the assumptions given in this section, which is somewhat high for the known NEO population. Considering also a dark C taxonomic class asteroid with an albedo of 0.06 the asteroid would have to be 540m to be detected, which is within the upper bounds of what can be deflected, especially considering the relatively lower density of the dark C types.

3.5 Density

Not actually a design driver, however choosing a lower density NEO, such as a rubble pile, will enable better validation of the momentum transfer mechanism for these low density bodies that is less well understood than for a high density rock. This would allow for a better mission design for a real NEO impact mitigation mission.

Seen however from the goal of successfully deflecting and being able to measure the deflection of a NEO, a high density NEO would probably have a higher ejecta factor K and would thus either be deflected further for the same impact or a given deflection would be achievable with a lower impact velocity and/or impactor mass.

3.6 Shape

A NEO target that is not irregularly shaped, i.e. closer to spherical, would ideally be chosen as a target. A demo mission to an irregularly shaped NEO can be designed, however there is an additional level of complication for the GNC, as well as an increased difficulty in successfully transferring the momentum from an impactor to the NEO. That said, the behaviour of such an irregularly shaped NEO after an impact may be a useful research goal of a demo mission.

3.7 Binarity

As for the NEO's shape, although it is technically possible to rendezvous with and impact a binary NEO system, the additional complication for system design and particularly GNC may become a cost and schedule driver, and so a NEO target that is a single body should ideally be chosen.

4 Physical Properties Impacting Mission Design

In addition to the mission design-driving physical properties discussed above, further information is required in order to undertake the mission design. These further physical properties are not as strongly design drivers, however should be determined as accurately as possible.

A list of physical properties that impact mission design is provided below, which is current at this stage, but may be updated throughout the project. All of these properties must be known for mission design, as an input, however not all for all mission designs. The electrostatics information, for example, is mainly for alternative mitigation methods making use of potential charging of the NEO.

An additional input is the expected range of values and/or accuracy of the knowledge, as some of the properties on the list will not be known today, and in fact may only be known accurately following an observation campaign by an in-situ orbiter. The list should however serve as a first guide for the science and research community on the requirements on knowledge of the physical properties to enable mission design.

- Orbit
  - Orbit type (circular, hyperbolic, etc)
  - Accurate orbital parameters (semi major axis, eccentricity, inclination, period, etc)
  - Any keyholes, including date, size, accuracy/uncertainty margins (and criticality?)
  - Reachability
  - Observability
- Physical Properties
  - Mass
  - Material
  - Density
  - Surface material elasticity
  - Surface material strength
  - Surface density (not only bulk density)
  - Surface heat capacity
  - Surface absorptivity (complementary to Bond albedo)
  - Thermal conductivity
  - Asteroid Type (Rock, fine powder, rubble pile, etc)
  - (Asteroid Taxonomy)
  - Shape/Dimensions/Size
  - Albedo (or Absolute magnitude, but actually less useful)
  - Rotation rates or period
  - Rotation axis (or axes if tumbling)
  - Binary or non-binary
- Electrostatics
  - Surface charge density
  - Surface charge distribution
  - Local plasma environment
  - Areas of net charge on the surface or in the asteroid bow or wake

Distribution List

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