NEOShield-2

Science and Technology for Near-Earth Object Impact Prevention

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WP 9.2 **Deliverable D9.2**	**List of potential target NEOs**		
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i1.2	17/07/2017		Initial final document for consortium review
i1.3	25/07/2017		Updated FINAL document incorporating comments from consortium

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1 Introduction

1.1 Scope

This document reports on work carried out under Work Package 9.2 of the NEOShield-2 project. The exact deliverable of task 9.2 as specified in the GA:

Compile and maintain a list of potential target NEOs for this project (special emphasis for NEOs in 50-300m diameter range and with low delta-v) by means of priority criteria definition in respect to the objects' physical properties and accessibility. Critically review their known properties and measurement uncertainties relevant to reconnaissance, sample return and mitigation demonstration missions.

Identify further observations needed to increase the physical characterisation quality for NEOs of special interest and insert these requests into the web-interface provided by Task 10.5.

The dynamical- and physical-property requirements for NEOs to be used as targets in mitigation demonstration missions shall be based on NEOShield-1 deliverable D5.1.

Monitor new discoveries and regularly incorporate new results on relevant physical properties from this project and results from external observational programmes.

Access available on-line surveys and databases to provide new astrometry of potential mission targets to assist observations carried out under WP10.

The potential target NEOs listing shall contain the accessibility of these objects for reconnaissance, sample return or mitigation demonstration missions.

In summary, the objective of task 9.2 is to assess the currently known NEO population in terms of orbital parameters and physical knowledge, and provide a prioritized target list for demonstration mission designs. At the start of April 2016 at mid-term review, there were over 14,199 NEOs catalogued. By July 2017, due to the current discovery rate of > 1800 per year, there were 16,387 NEOs catalogued, including 1816 PHAs.

The primary goal is therefore to select the best targets for a NEO mission from the continuously growing NEO catalogue and their published physical properties.

1.2 List of Abbreviations

AD	Applicable Document
AU	Astronomical Unit
GA	Grant Agreement
MOID	Minimum Orbit Intersection Distance
NEO	Near Earth Object
RD	Reference Document
WP	Work Package

1.3 Applicable Documents

[AD1] NEOShield-2: “Science and Technology for Near-Earth Object Impact Prevention”, Grant Agreement no. 640351, 28.10.2014.

1.4 Reference Documents

[RD1] NEOShield-2 D11.2: "*Report on data analyses and mitigation-relevant NEO physical properties*", Issue 1.6, 13/07/2017.

[RD2] NEOShield-2 D9.1: "*Dynamical web interface tool and User Manual*", Issue 1.5, 06/07/2017.

[RD3] Harris, A.W., 1998. *A Thermal Model for Near-Earth Asteroids*. Icarus 131, p291.

[RD4] Mainzer, A. et al., 2014. *“The population of tiny Near-Earth Objects observed by NEOWISE.”* Astrophys J. 784:110.

[RD5] Mueller M. et al., 2011. *“ExploreNEOs. III. Physical characterization of 65 potential spacecraft target asteroids.”* Astron. J. 141:109.

[RD6] Mainzer, A. et al., 2011. *“NEOWISE studies of spectrophotometrically classified asteroids: preliminary results*. Astrophys J. 741:90.

[RD7] NEOShield-2 D10.2: "*Intermediate observations and analysis progress report*", Issue 1.0, 30/03/2016.

[RD8] Perna, D. et al., 2016. *Grasping the nature of potentially hazardous asteroids*. Astron. J. 151:11.

[RD9] Margot, J.L. et al., 2002. *Binary Asteroids in the Near-Earth Object Population*. Science 296, p1445.

[RD10] NEOShield-2 D10.4: *“Report on Photometric Observations I (Colours, and Phase Functions)”*, Issue 1.0, 30/06/2017

[RD11] NEOShield-2 D11.4: *“NEO Physical Properties Database User Manual*”, Issue 1.4, 06/07/2017

[RD12] NEOShield-2 D10.7: *“Report on spectroscopic observations ”*, Issue 0.1, 30/06/2017

[RD13] NEOShield-2 D10.5: *“Report on Photometric Observations II (lightcurves and rotational properties)*”, Issue 1.0, 12/07/2017

[RD14] Mommert M. et al., 2016. *“First Results from the Rapid-Response Spectrophotometric Characterization of Near-Earth Objects Using UKIRT.”* AJ 151: 98.

[RD15] Nugent C.R. et al., 2016. *“NEOWISE Reactivation Mission Year Two: Asteroid Diameters and Albedos “*. AJ 152:63.

[RD16] Trilling D.E. et al., 2016. *“NEOSURVEY 1: Initial Results from the Warm Spitzer Exploration Science Survey of Near-Earth Object Properties*”. AJ 152:172

[RD17] Thirouin T. et al. 2016. *“The Mission Accessible Near-Earth Objects Survey (MANOS): First Photometric Results*”. AJ 152:163

[RD18] Kikwaya Eluo J.B. and Hergenrother, C.W., 2015. “*Physical characterization of fast rotator NEOs*”. EPSC Abstracts 10, EPSC2015-843.

[RD19] Mueller M. et al., 2011. *“ExploreNEOs. III. Physical Characterization of 65 Potential Spacecraft Target Asteroids*”. AJ 141, p.109.

[RD20] Perna D. et al. 2017. *“An investigation of the low-DeltaV near-Earth asteroids (341843) 2008 EV5 and (52381) 1993 HA. Two suitable targets for the ARM and MarcoPolo-M5 space missions.”* MNRAS Astron. Astrophys. 597, A57.

2 Background

2.1 NEO Orbital and Physical Parameters

For planning any mitigation demonstration mission, it will be important to have concise knowledge of the potential targets. Like any space mission the target selection will depend on several factors. Uppermost in selection criteria is the energy required for a spacecraft reach the NEO, given as the delta-v. However, this is only one of a number of parameters that can be used as selection criteria for which NEO to visit.

For example, high priority must be given to the current knowledge of their orbits, as many NEOs have only been observed once during their discovery apparition as seen from Earth. These objects can have orbital uncertainties which means that although they may be dynamically suitable for the proposed mission, we currently cannot state their position with certainty.

Another important factor is knowledge of their physical properties as relevant to the mission profile, described in NEOShield-2 Deliverable D11.2 [RD1]. Only a small fraction of the discovered NEO population have any additional study beyond the initial orbital determination; even the absolute magnitude of the NEO (a rough indication of size) may be uncertain by tens of percent for recently discovered NEOs.

The known population at sizes below a diameter of ~5 km is incomplete, with the fraction known decreasing as the size decreases. This is reflected in the current discovery statistics, with over 1,800 new NEOs now being discovered per year. Therefore it is important in the mission planning and design stages to monitor and identify new potential mission targets. This identification process can direct remote observations from Earth to both ensure improvement in orbital knowledge, and physical characterization relevant to the mission.

Previously, two on-line resources existed concerned with potential spacecraft targets. First, the delta-v for all NEOs for both flyby and rendezvous missions is maintained by Lance Benner at JPL (http://echo.jpl.nasa.gov/~lance/delta_v/delta_v.rendezvous.html). While up to date, this list contains only the absolute magnitude and primary orbital elements (a,e,i) of the NEOs, and no other physical information. Second, the Near-Earth Object Human Space Flight Accessible Targets (NHATS), also maintained at JPL (http://neo.jpl.nasa.gov/cgi-bin/nhats). Although this contains click-through links to physical properties where measured, the selection criteria are based on a manned return space mission, with the length of time heavily dictated by astronaut survivability. Therefore neither of these two lists are suitable for the assessment of NEOs for a robotic mitigation test.

The objective of WP9.2 is to compile and maintain a list of potential target NEOs to aid in the design of a mitigation test mission. Their known properties have been reviewed and their measurement uncertainties relevant to mitigation demo missions have been incorporated into the list.

2.2 Parameter envelope

The requirements for the potential targets were given in NEOShield-1 deliverable D5.1. To summarize:

- Diameter of 50m – 300m.
- A common taxonomic type, either S-class (silicate) or C-class (carbonaceous).
- A density of 1-2 gm cm^{-3}. This is extremely difficult to measure remotely, except in binary systems. However existing data imply S/C-class NEOs should span this range.
- Avoidance of the fastest rotating NEOs with spin periods P<2.2 hours.

3 Selection criteria

Orbital Catalogues

The fundamental resource for this project is a catalogue of all NEOs discovered to date. There are many possible sources for this catalogue, including the MPC, NEODyS, JPL and Lowell Observatory. For the initial creation of this list we have used the list of al NEOs in the MPCORB database as maintained at the Minor Planet Centre (http://www.minorplanetcenter.net) in the MPCORB/NEA.txt file. For the original NEOShield project the ASTORB database maintained by Lowell Observatory (http://asteroid.lowell.edu) and served by the Centre de Données astronomiques de Strasbourg (http://cdsweb.u-strasbg.fr) was used. These catalogues are effectively interchangeable. Importantly, there are no significant differences for NEOs with long observation arcs and therefore good orbits.

Orbital Accuracy

This is an important criterion for selection of mission candidates, and was assessed using the two most straightforward criteria. First the MPC orbit uncertainty code indicates the relatively uncertainty of the orbit. This spans values from 0-9, with 0 indicating a highly accurate orbit and 9 effectively implying the NEO is lost (http://www.minorplanetcenter.net/iau/info/UValue.html). For this Task, NEOs with orbital uncertainty codes of greater than 5 were rejected. Second, we also use the current sky-plane positional uncertainties contained within the ASTORB database. This gives a clear indication of the possibility of observing the NEO using an Earth-based telescope and is an excellent proxy for the total orbital uncertainty.

Delta-v

Calculating the ability of a spacecraft to reach a NEO requires significant effort to optimising all possible flight trajectories to any given NEO, as all NEOS have different orbital elements. Additionally, the trajectory will be different depending on whether a flyby, rendezvous or sample-return is required. Such work is beyond the scope of this task. Therefore we have used the simple approximation of Hohmann transfer orbits to calculate an indicative delta-v for flyby or rendezvous. These are being made available through the NEO Properties Portal [RD2]. Mission planning beyond this work would require at least a preliminary trajectory analysis for each individual target. Our maximum delta-v assumed was 6 km/sec.

Absolute magnitude

This gives the apparent magnitude in the V-band of the NEO if it was at 1 au from Earth and Sun, and simultaneously at zero phase angle. Although this geometry is impossible, the absolute magnitude gives the intrinsic brightness of the NEO which is a combination of the size and albedo. For silicate NEOs with a geometric albedo of ~0.2, the required diameter of 300m-50m implies an absolute magnitude in the range 20.0-24.0

Diameter

The physical size of a NEO may be directly measured either through a spacecraft mission or, more likely, via Earth-based radar. The only facilities currently providing these measurements are the US-run Arecibo and Goldstone-based programme (http://echo.jpl.nasa.gov/). While these return Doppler and ranging information that immediately improve the accuracy of the NEO orbits, obtaining accurate sizes for the NEOs observed is a more involved process. The majority of diameter determinations are made through the measurement of mid-IR thermal fluxes and application of the standard Near-Earth Asteroid Thermal Model (NEATM) [RD3]. Historically performed by thermal IR measurements from the ground, a growing number of NEOs have albedos measured through the NEOWISE [RD4] and ExploreNEOs [RD5] programmes. If a spectroscopic classification is available, the mean visual geometric albedo for that spectroscopic class [RD6] can be used to estimate the diameter.

Visual Albedo

This can be directly measured by combining the absolute magnitude with a direct radar/spacecraft measurement of the diameter with the absolute magnitude, or through application of the NEATM to thermal measurements.

Spectral Classification

This is the fundamental method by which the composition of the NEO is known. Historically this was only known via optical spectroscopy, however in the past decade significant numbers of NEOS have been observed with near-infrared spectrographs. This is important as the main silicate diagnostic features are at wavelengths of ~ 1 micron and longer, and hence near-infrared spectroscopy can provide precise information on the surface composition of a NEO [RD7, RD8].

Spin Period and State

Towards the lower diameter of 100m suitable for demonstration missions, there exists a large number of fast rotating NEOs with spin periods < 2.2 hours. Additionally, a small number of NEOs have been shown to have a tumbling spin-state i.e. they spin around two axes simultaneously. Fast rotating NEOS are unlikely to have regolith, and fast rotating or tumbling NEOs may be too technically demanding for close-proximity operations by a spacecraft. Therefore, a minimum spin period of 3 hours has been used here for target selection, and NEOs with known tumbling states are rejected. However, we note that few NEOs have sufficiently accurate lightcurve or radar data to allow tumbling states to be recognized.

Binarity

Approximately 15% of NEOs are binary systems [RD9] and previously these have been ignored as potential mission targets. The advancement of the AIDA mission concept now implies such systems should be considered. For many binaries the approximate relative or absolute size of the secondary is known and the orbital period. This is the only method the bulk density of an NEO system can be remotely determined unless it is a rubble-pile object rotating at critical break-up spin period. But it must be remembered that few binary NEOs have mutual orbits that are precisely measured.

Other Criteria

There are other potential selection criteria that have not been used in the current Task. For example, the thermal beaming parameter and thermal inertia can be used to infer surface structure and metal content [RD1]. Phase curves of NEOs are correlated with taxonomy, which can also be used to indicate composition [RD10]. Finally, the value and rate of change of the MOID may be important in considering a mitigation demonstration mission at a specific NEO. These factors are not considered here.

4 Data Sources for Physical Properties

As before, the baseline source of physical properties of NEOs remains the European Asteroid Research Node (EARN) NEO database, maintained by Gerhard Hahn at the Institute of Planetary Research of the German Aerospace Center (DLR-Berlin), and sponsored by the ESA-SSA. From now on the NEO Physical Properties Database produced under NEOShield-2 WP 11.4 [RD11] will be another baseline source of information. However, the updating of this resource is not automatic, requiring manual input of data due to varied nature of published results (peer-reviewed journals, Minor Planet Centre Bulletins etc.). This means that the database is not always completely up to date. During this task the following additional sources of physical information were included in this study:

NEOShield-2 Spectroscopy. Reported in deliverable 10.7 [RD12] this work led by D. Perna and M. A Barucci reports new visible and NIR spectroscopy of 162 NEOs, leading to good taxonomic classifications of 137 objects and less certain classifications of a further 27.

NEOShield-2 photometric spectral classes. Reported in deliverable 10.4 [RD10] this work led by D. Ieva and E. Dotto reports BVRI photometry of 113 individual NEOs, leading to taxonomic classifications. As photometric colours are generally less accurate than spectroscopy for establishing composition, all these taxonomic classifications are regarded as more uncertain than those obtained by spectroscopy, although this is not always the case.

SDSS Photometric spectral classes. As reported in deliverable 10.5 [RD13], Carry et al. (2016) have performed a new analysis of SDSS data. They obtain 4-colour taxonomic classifications for 944 NEOs and Mars-crossing asteroids, plus 3-colour taxonomic classifications for another 209 NEOs. In these totals, NEOs with a “U=Uncertain” classification have been ignored. Again, these taxonomic classifications are more uncertain than spectroscopic classifications.

The UKIRT Rapid Response Spectrophotometric Characterization programme. Mommert et al. (2016) [RD14] report the first results of ZJHK photometry, observing mostly sub-km asteroids soon after discovery. They assign probabilities to the likely broad taxonomic types. As before, these taxonomic classifications are more uncertain than spectroscopic classifications.

NEOWISE extension year-2 results. The Near-Earth Object Wide-Field Infrared Survey Explorer (NEOWISE) mission led by A. Mainzer continues to detect, track, and characterize NEOs via detection of mid-infrared thermal emission. C.R.Nugent et al. (2016) [RD15] reported new diameters and albedos of 207 NEOs measured via NEATM.

The Spitzer NEOSurvey programmes. These programmes led by D. Trilling uses the warm Spitzer Space Telescope mission to observe NEOs at 3.6μm and 4.5μm [RD16]. A total of 545 NEOs diameters and albedos were included in this database. While these measurements are at shorter wavelengths than NEOWISE and at only two wavelengths, comparison of the reported diameters with other measurements of the same NEOs shows good agreement.

NEOShield-2 Photometric Lightcurves. Reported in deliverable 10.5 [RD13] this work led by D. Hestroffer and S. Eggl reports spin periods for 49 NEOs, plus lower limits to the spin periods for another 7 NEOs.

MANOS Survey lightcurves. Due to the interest in small NEOs as potential destinations for cis-lunar manned missions, Thirouin et al. 2016 [RD17] obtained lightcurves for 86 sub-km NEOs with low delta-v’s. Of these, 62 showed distinct periods and amplitudes, 12 targets only allowed measurement of a lower limit for the spin period, and for another 12 no period information could be determined.

5 Sample Return/Mitigation/Rendezvous Target Lists with delta-v<6 km/sec

The task requires targets for reconnaissance and sample return missions. As described above, a full trajectory analysis required for both these types of mission is beyond the remit for this Task. Therefore, we use the delta-v calculations for a simple rendezvous as the first approximation in this selection. As sample return generally has more stringent delta-v requirements than simple rendezvous, we restrict our selection to dv < 6 km/sec.

Selection for the target lists requires a measurement of the spectral type, and a measurement of the diameter. The diameter may either be directly measured through radar/thermal observations, or it may be inferred through assuming the mean albedo for the NEO spectral type. The effects of applying all of these criteria is graphically demonstrated in figure 1, where the 16,000 NEOs are down-selected to 461 with an absolute magnitude in the range requested and then further sifted to require a silicate taxonomy.

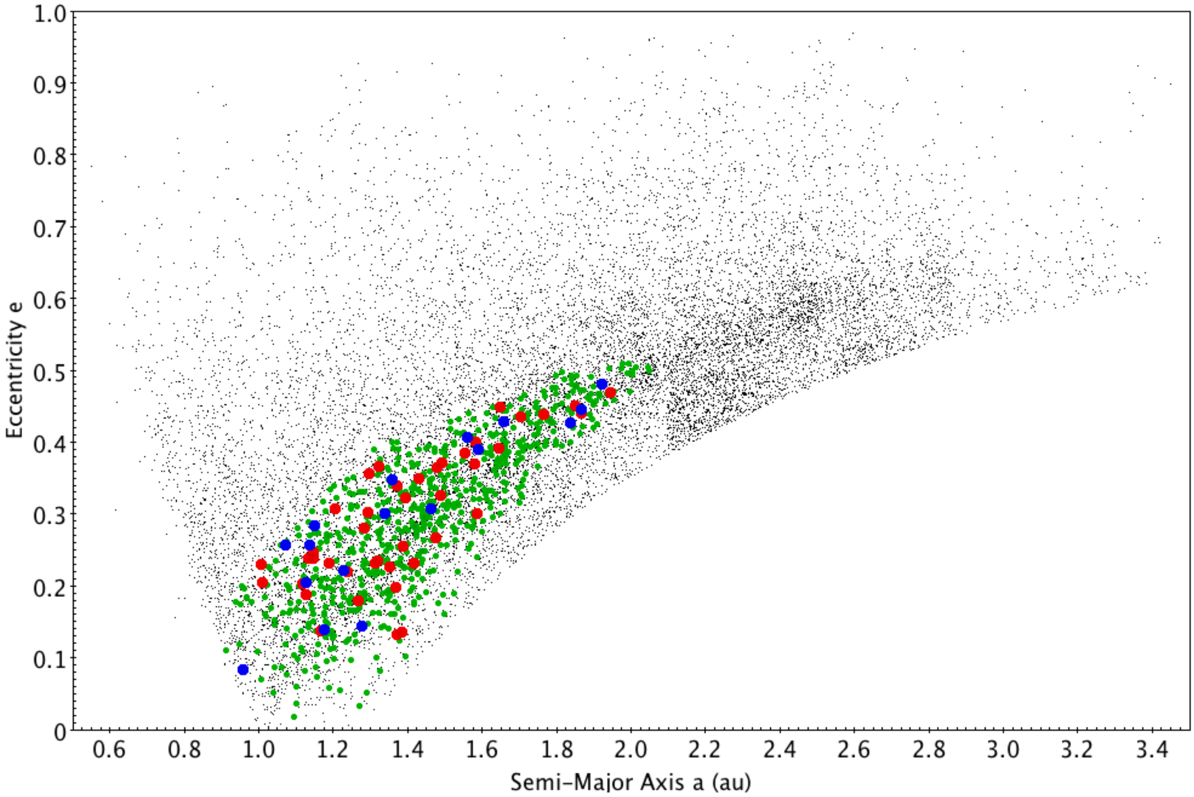

Figure 5-1 Selection of silicate NEOs. Grey dots - all 16153 NEOs. Green dots - subset of 678 NEOs with dv < 6 km/sec and suitable absolute magnitude H. Red dots - subset of 60 NEOs with known silicate taxonomy. Blue dots – subset exhibiting C-type or D-type spectra.

Given the long lead-time for space missions and the ongoing efforts to observe and characterise NEOs such as those in Work Package 10 [RD11], it is important to take into account future Earth-based opportunities to study potential mission targets. However, it is impossible to predict which NEOs might be observed, as this will be dependent on both the availability of observing facilities and weather.

The only “certainty” we have is that currently funded Earth-based NEO surveys, which are projected to continue until the early 2030’s. NEOs with uncertain orbits may be recoverable within the next decade by continuing NEO survey efforts at no “extra cost”, and therefore can be considered as second ranked-targets. The ongoing PS1+2/CSS surveys cover much of the visible sky each lunation down to V~21.5-22.0. A NEO that gets brighter than this at a reasonable elongation has a good chance to be automatically recovered with a significant improvement in the orbit. Second, the Large Synoptic Survey Telescope (LSST) is due to start regular survey operations in the year 2022. It will have an equivalent limiting magnitude in the r filter of V~24.6 and will be able to survey the visible sky within 3-4 nights at this depth. Therefore, if a NEO requires orbital refinement and will be visible to LSST within the first few years of operation, it can also be considered as a second ranked potential mission target.

Imposing an additional restriction of a measured rotation period results in the tables listed in below and in section 6.

5.1 Silicate S-class Targets

Below we list the best silicate targets for a demonstration reconnaissance or sample-return mission, in order or nominal delta-v for rendezvous. All of these NEOs have (or will have) precisely known orbits and known physical properties.

5.1.1 First ranked silicate NEO targets

Table 5-1: First ranked S-class targets for sample return/mitigation/rendezvous.

Number	Name	H	delta-v (km/s)	U (MPC)	CEU (ASTORB)	D (km)	a/b	Albedo	Taxonomy	Period (hr)	Binary?
363305	2002 DU3	20.7	5.80	2	0.06	(0.20)	1.2	(0.23)	Sq	4.4	No
423321	2005 ED318	20.8	5.65	0	0.03	0.202	1.2	0.212	Q	17.157	No
451157	2009 SQ104	21.0	5.05	1	0.12	(0.17)	4.0	(0.23)	Sq	6.8532	No
	1999 FN19	22.5	5.22	2	7.5	(0.09)	1.1	(0.23)	Sq/S:	3.5	No
	2001QC34	20.1	5.15	1	0.03	(0.28)	1.3	(0.21)	Q/O/Q:	3.65	No
	2004 RQ10	20.9	5.95	4	20.8	(0.18)	1.9	(0.23)	Sq	5.16	No
	2008UE7	20.4	5.81	2	1.98	0.204	1.3	0.22	Sq/Q	3.25146	No

(363305) 2002 DU3 This object has an excellent orbit, known spectral type and precise spin period. The albedo has not been measured but using the mean value for Sq-type asteroids it is likely to have a diameter of 200m.

(423321) 2005 ED318 This potential target as a directly measured albedo and therefore diameter measurement of 200m. It has a particularly slow rotation period of 17.2 hours which might simplify spacecraft reconnaissance operations.

(451157) 2009 SQ104 This object has an excellent orbit, known spectral type and precise spin period. The albedo has not been measured but using the mean value for Sq-type asteroids it is likely to have a diameter of 170m. The lightcurve amplitude of 1.5 magnitudes implies an extremely elongated object, but the lightcurve [RD18] does not show the cusp-like morphology that normally indicates a contact binary. Hence it is listed as a first-ranked target.

1999 FN19 This is a highly suitable 180-m S-class NEO with a relatively short rotation period. It was noted that the ASTORB database contains an incorrect positional uncertainty, possibly due to not included radar observations. Both NEODyS and JPL Horizons give a current orbital uncertainty < 10 arcsec, the NEODyS 3-sigma uncertainty semi major axis is used here.

2001 QC34 This NEO was the primary target selected during the original NEOShield project. It remains a first ranked target.

2008 UE7 Again the albedo has not been measured, but using the mean value for Sq-type asteroids this NEO is likely to have a diameter of 230m. It has a relatively short rotation period of 3.25 hours.

5.1.2 Second ranked silicate NEO targets

Table 5-2: Second ranked silicate targets for sample return/mitigation/rendezvous.

Number	Name	H	delta-v (km/s)	U (MPC)	CEU (ASTORB)	D (km)	a/b	Albedo	Taxonomy	Period (hr)	Binary?
190491	2000 FJ10	20.9	4.66	0	0.03	(0.14)	1.4	(0.23)	S	>2	No
136617	1994 CC	17.7	5.57	0	0.03	0.64	1.0	0.42	Sq/Sa/S:	2.39	Binary
	1994 CJ1	21.4	4.88	0	0.03	(0.15)	1.0	(0.23)	A	30	Binary
	2004 RQ10	20.9	5.95	4	20.8	(0.18)	1.9	(0.23)	Sq	5.16	No

(190491) 2000 FJ10 With an S-class taxonomy this NEO has a relatively small diameter of 140m. Unfortunately only a lower limit to the spin period of 2 hours is available. However, it will have a reasonably good apparition in July 2017, when it will reach V=20.6 near opposition, allowing lightcurve studies.

1994 CC This is a triple system detected by radar, with the three components of 690m, 110m and 80m. The "Beta" secondary has an orbital period of 1.24 days, and so if it is tidally locked it would provide a similar but slightly smaller target to the secondary of Didymos. It is possible that the added complication of the outermost "Gamma" component may render this system as too complex for a mitigation demonstration.

1994 CJ1 This is only the second-known equal mass binary in the NEO population and hence would have significant additional scientific benefits from a mission. Radar shows the two components have approximately equal sizes of 125m and an orbital period of approximately 30 hours.

2004 RQ10 This is a highly suitable 180-m S-class NEO, which similar to 1999 FN19 has an incorrect positional uncertainty within the ASTORB database. Instead the NEODyS 3-sigma uncertainty semi major axis is used here. It is listed as a second-ranked target due to the relatively high orbital uncertainty, and it will not be detectable by the current NEO surveys for the next 10 years. However it should be detected by LSST (if operational) in early-2024 at V=23.8, or earlier with a directed recovery effort.

5.2 Carbonaceous C-class and primitive targets

To provide this list, we have assumed that low albedo is synonymous with a primitive composition. Relative to silicate targets, the number of low albedo NEOs with good physical characterization is far lower. The reason is that low-albedo objects are fainter and therefore more difficult to both detect and characterize from Earth with a given telescope. Assuming the upper limit to the diameter of a primitive NEO can be larger than for a silicate NEO, below we list the only three suitable NEOs with complete or near-complete physical characterization the currently meet the selection criteria.

5.2.1 First ranked primitive NEO targets

(64803) Didymos This NEO has been extensively studied and is the target of the proposed ESA/NASA AIDA mission concept. Although the primary is larger than considered suitable for a mitigation demonstration mission, its secondary has a diameter of 150m and is the primary target for the mission. We note that it will_reach V<21 when at opposition in early 2017, allowing further remote characterisation of the binary system.

Table 5-3: First ranked C-class or primitive NEOs for sample return/mitigation/rendezvous.

Number	Name	H	delta-v (km/s)	U (MPC)	CEU (ASTORB)	D (km)	a/b	Albedo	Taxonomy	Period (hr)	Binary?
65803	Didymos	18.0	5.27	0	0.21	(1.10)	1.1	(0.08)	Xk	2.2593	Binary
101955	Bennu	20.9	5.26	0	0.12	0.484	1.2	0.046	B/C	4.2905	No

(101955) Bennu This NEO has been extensively studied and is the destination of the NASA OSIRIS-REx sample-return mission. While significantly larger than the nominal 300-m diameter upper limit, OSIRIS-Rex will fully characterize this object, removing the need for much of this phase of any mitigation test mission.

5.2.2 Second ranked primitive NEO targets

Table 5-4: Second ranked C-class or primitive NEOs for sample return/mitigation/rendezvous.

Number	Name	H	delta-v (km/s)	U (MPC)	CEU (ASTORB)	D (km)	a/b	Albedo	Taxonomy	Period (hr)	Binary?
52381	1993 HA	20.0	5.47	1	0.03	0.337	1.7	0.140	T/D	4.107	No
341843	2008 EV5	20.0	5.80	1	0.48	0.400	1.0	0.104	C/X	3.725	No
388945	2008 TZ3	20.4	5.79	0	0.03	(0.45)	1.7	(0.06)	C	44.2	No
	2009 DL46	22.0	5.23	0	0.03	(0.20)	2.7	(0.07)	D	42.46	No
	2011 HP	22.1	5.84	3	252	(0.23)	1.5	(0.09)	Xc	3.95	No

(52381) 1993 HA This NEO was a target characterized by both spectroscopy within WP10.7 [RD12] and photometry within WP10.5 [RD13]. This is now a fully characterized T/D-type NEO. The NEATM derived albedo of 0.14 from the ExploreNEOs Spitzer programme as reported by Mueller et al. (2011) [RD19] is high compared to the average value for this class of 0.09. However, the authors report a relatively large uncertainty for this measurement at 0.14/+0.11/-0.08, and this is compatible with the expected albedo.

(341843) 2008 EV5 This is a fully characterised C/X-type NEO, with spectroscopic observations carried out externally to WP10 due to its special nature as the prime target of the proposed ARM mission [RD20], but its relatively large diameter of 400m may rule it out for some designs of mitigation test missions.

388945 2008 TZ3 is a relatively large C-type NEO with a spectroscopic classification from WP10 [RD12]. The probable large diameter makes this a second-ranked target.

2009 DL46 is a relatively accessible D-type NEO. The provisional D-type nature from photometry reported in D10.4 [RD10] was confirmed via spectroscopy in D10.7. [RD12]. The reported amplitude indicates a highly elongated object, which makes it second ranked.

2011 HP is a well characterised Xc-type NEO, but with a currently poor orbit. It will make a close approach to Earth in early 2019 when it will reach V=18, and therefore should easily be picked up by the ongoing PS1+2/CSS surveys.

6 Mitigation/Rendezvous Target Lists with 6<delta-v<7 km/sec

In these tables we list the NEOs with relatively complete physical information and with delta-v between 6 km/sec and 7 km/sec, making them more suitable for operations at the NEO rather than sample return.

6.1 Silicate S-class Targets

6.1.1 First ranked silicate NEO targets

Table 6-1: First ranked silicate NEOs for mitigation/rendezvous.

Number	Name	H	delta-v (km/s)	U (MPC)	CEU (ASTORB)	D (km)	a/b	Albedo	Taxonomy	Period (hr)	Binary?
277475	2005 WK4	20.1	6.80	0	0.24	(0.27)	1.4	(0.23)	Sk/S:	2.595	No
474158	1999 FA	20.7	6.37	1	0.51	0.3	3.0	(0.10)	S	10.092	No
	2014 SS1	21.7	6.05	0	0.15	(0.13)	1.5	(0.23)	S	16.63	No
	2015 JY1	20.8	6.60	3	0.72	(0.24)	2.9	(0.15)	R	6.442	No

All of the above targets have excellent orbits, known silicate compositions and lie in the size range required. 2001FE90, 1999 FA and 2015 JY1 are moderately elongated, but remain excellent targets. 2015 JY1 was partially characterised within WP10 [RD12]

6.1.2 Second ranked silicate NEO targets

Table 6-2: Second ranked silicate NEOs for mitigation/rendezvous.

Number	Name	H	delta-v (km/s)	U (MPC)	CEU (ASTORB)	D (km)	a/b	Albedo	Taxonomy	Period (hr)	Binary?
89136	2001 US16	20.2	4.57	0	0.03	(0.29)	2.3	(0.16)	K/Xe	14.39	No
208023	1999 AQ10	20.4	6.49	1	0.06	0.148	1.2	0.46	S	2.79	No
	2013 RH74	20.9	6.71	3	180	(0.24)	1.2	(0.23)	Sq	5.346	No

(208023) 1999 AQ10 appears to be fully characterised, but its derived albedo is significantly higher than expected for an S-type, implying some uncertainty in either the spectroscopy or thermal observations.

2013 RH74 has a relatively uncertain orbit, but should be observed by LSST at the start of 2024.

(89136) 2001 US16 appears to be a suitable silicate NEO, but there is currently some uncertainty in its precise mineralogy.

6.2 Carbonaceous C-class and primitive targets

6.2.1 First ranked primitive NEO targets

Table 6-3: First ranked C-class or primitive NEOs for mitigation/rendezvous.

Number	Name	H	delta-v (km/s)	U (MPC)	CEU (ASTORB)	D (km)	a/b	Albedo	Taxonomy	Period (hr)	Binary?
281375	2008 JV19	20.8	6.64	2	0.12	(0.38)	1.3	(0.06)	C	3.500	No

(281375) 2008 JV19 is the only fully characterised C-type NEO in this range of delta-v that meets all the criteria for a first-ranked target. Its spectrum was obtained within WP10 [RD12].

6.2.2 Second ranked primitive NEO targets

Table 6-4: Second ranked C-class or primitive NEOs for mitigation/rendezvous.

Number	Name	H	delta-v (km/s)	U (MPC)	CEU (ASTORB)	D (km)	a/b	Albedo	Taxonomy	Period (hr)	Binary?
	2005 TF	20.3	6.05	0	0.03	(0.47)	1.3	(0.06)	C:	2.57	No
	2014 CR	22.5	6.61	6	26400	(0.15)	2.1	(0.09)	Xc	6.35	No
	2014 OT111	21.7	6.70	4	510	(0.25)	1.5	(0.06)	C	19.41	No

2005 TF has a taxonomy only derived through broad-band photometry within WP10 [RD10], and requires spectroscopy to considered as first ranked targets.

2014 CR is effectively lost. It will only occasionally be near the specified detection limit of LSST during its 10-year survey, meaning recovery of this object is uncertain.

2014 OT111 also has a very poorly known orbit. It may be detected again during the LSST 10-year survey in 2024, or again require directed recovery.

6.3 D-type primitive targets

There are currently 2 sample–return missions flying to B/C-class asteroids (*Hayabusa-2* to Ryugu; *OSIRIS-Rex* to Bennu). While it will be extremely interesting to compare and contrast the composition, structure and regolith properties of different NEOs with similar compositions, it is plausible that scientific considerations pushes the next NEO mission towards a different class. The most interesting are arguably the D-type asteroids, as these objects are normally found in the outer main-belt and Trojan clouds, and are believed to hold substantial amounts of volatiles and organics dating from the formation of the Solar system. NASA has recently approved the *Lucy* mission to fly-by 6 Trojan asteroids. However, a rendezvous mission would bring significant increases in knowledge about these primitive bodies.

Recognising this, WP10 [RD12] has listed 8 D-types in the NEO population which would be potential targets for a low delta-v mission. 2 of these are already listed above in Table 5-4 as potential sample-return targets. The rest are not included in the above tables as they do not possess known spin periods as yet and/or do not meet the size criteria adopted in this analysis. That said, below we repeat the table from NEOShield-2 D10.7 for completeness.

Table 6-5 Potential D-type targets for a rendezvous mission as identified in NEOShield-2 D10.7.

Name	Orbit	ΔV(km/s)	H(mag)	Diam. (m)	a (AU)	e	i (°)
2016 WZ8	AP	4.81	28.4	13	1.502	0.34	4.1
2017 DL34	AM	4.96	25.9	40	1.346	0.25	8.2
2009 DL46	AM	5.08	22.0	242	1.461	0.31	7.9
(52381) 1993 HA	AM	5.30	20.0	607	1.278	0.14	7.7
2016 WL7	AP	6.05	24.3	84	1.057	0.19	10.0
2015 LN21	AM	6.35	23.0	152	2.092	0.49	8.6
2016 PN38	AP	6.61	21.2	349	2.456	0.62	3.6
2016 UU80	AM	6.69	21.1	366	2.439	0.56	7.9

7 Summary

The current knowledge of the physical characteristics of low delta-v NEOs have been reviewed. Since the start of the original NEOShield project, and even since the commencement of NEOShield-2, there has been a significant increase in the amount of physical follow-up observations, due to both NEOShield-2 WP10 observations and external projects. This has resulted in a commensurate increase in the number of sub-km NEOs that may be considered for missions.

Overall, there now exists a good selection of well characterized sub-km silicate NEOs which could be used for impact mitigation tests or other in-situ missions. The number of suitable carbonaceous/primitive NEOs remains small. This is probably due to the factor of ~3-4 flux decrease from these NEOs compared to silicate bodies that results in the well-known bias towards the discovery of silicate NEOs, plus the increased difficulty in obtaining physical observations.

Restricting selection to NEOs with delta-v < 6 km/sec and good physical characterization, there are 7 silicate NEOs and 2 carbonaceous/primitive NEOs suitable for all classes of proposed missions. Extending the required delta-v to 7 km/sec. adds another 4 silicate NEOs and 1 carbonaceous/primitive NEO. Another 7 silicate and 8 carbonaceous/primitive NEOs have been identified but with relatively uncertain orbits, taxonomies, or that are known to have a binary nature.