		Final Report

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Final Report

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PROJECT FINAL REPORT

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Final Report

Please note that the contents of the Final Report can be found in the attachment.

4.1 Final publishable summary report

Executive Summary

NEOShield was conceived to address realistic options for preventing the collision of a naturally occurring celestial body (near-Earth object, NEO) with the Earth. Three deflection techniques, which appeared to be the most realistic and feasible at the time of the European Commission's call in 2010, form the focus of NEOShield efforts: the kinetic impactor, in which a spacecraft transfers momentum to an asteroid by impacting it at a very high velocity; blast deflection, in which an explosive, such as a nuclear device, is detonated near, on, or just beneath the surface of the object; and the gravity tractor, in which a spacecraft hovering under power in close proximity to an asteroid uses the gravitational force between the asteroid and itself to tow the asteroid onto a safe trajectory relative to the Earth.

Detailed test-mission designs are a primary product of the NEOShield project, and are intended to enable rapid development of actual test missions at a later stage.

A prerequisite for the successful deflection of a NEO is relevant knowledge of its physical characteristics. The knowledge required depends on the deflection technique in question, but would include such parameters as mass, shape, spin vector, albedo, and in some cases surface porosity, near-surface structure, and mineralogy. Ideally we wish to know the most likely properties of a future potential impactor that could trigger a space-borne deflection action. Furthermore, by narrowing the range of expected properties, a rational basis for the choice of objects to serve as targets in deflection test missions can be provided. Investigations of the mineralogy and structure of NEOs also aid in predicting the effects of an airburst in the atmosphere or an impact on the ground. Important scientific components of the NEOShield project are: analyses of observational data of NEOs, especially infrared data which provide insight into sizes, albedos, mineralogy, and surface thermal characteristics; laboratory experiments in which projectiles are fired at materials thought to be analogous to those in asteroids; and computer modelling and simulations to incorporate the laboratory results into scaled-up investigations of impulsive NEO deflection techniques. The results of the scientific work provide insight into how asteroids would respond to deflection attempts. Related scientific tasks are studies of the most appropriate observations, instrumentation, and types of space mission to efficiently provide mitigation-relevant information on a threatening NEO, and the identification of potential NEO targets for deflection demonstration missions.

The development and optimisation of some key technologies are essential preparation for a deflection test on a small asteroid. In circumstances in which a kinetic impactor is the technique of choice, it might be necessary to impact a small, only partially illuminated, dark asteroid at high velocity, a challenging task with currently available technology. In order to increase the probability of success, the NEOShield program of work included improvements to spacecraft guidance, navigation and control systems. Likewise, in the case of the gravity tractor, studies have been carried out of complex systems that would allow a spacecraft to manoeuvre and hold its position close to a low-gravity, irregularly-shaped, rotating asteroid, during a deflection attempt that might last years to a decade. In the case of blast deflection, NEOShield work concentrated on theoretical studies of the effects of a nuclear explosion on a typical small asteroid. Obvious military and political issues currently preclude research into optimised explosive devices and tests of this method in space.

Testing deflection techniques, such as the kinetic impactor and gravity tractor, is a vital prerequisite to a reliable international NEO defence system. Results from the type of studies carried out by NEOShield obviously serve to reduce the scientific and technical preparatory work required to bring an appropriate and viable deflection mission to the launch pad in an emergency situation. Two new UN-sanctioned bodies, the International Asteroid Warning Network (IAWN) and the Space Mission Planning Advisory Group (SMPAG), of which NEOShield personnel are members, were established under the auspices of the UN Committee on the Peaceful Uses of Outer Space (COPUOS) during the active lifetime of the NEOShield project. The participation of NEOShield personnel in the most prominent current international efforts addressing the impact hazard, ensures a broad international stage for the dissemination of NEOShield research.

Summary description of project context and objectives

(Note: Figure and table numbers refer to the material uploaded as an attached pdf file.)

Context
Collisions of celestial objects with the Earth have taken place frequently over geological history and major collisions of asteroids and comets with the Earth will continue to occur at irregular, unpredictable intervals in the future. As a result of modern observing techniques and directed efforts thousands of near-Earth objects (NEOs) have been discovered over the past 20 years and the reality of the impact hazard has been laid bare. Even relatively small impactors can cause considerable damage: the asteroid that exploded over the Russian city of Chelyabinsk in February 2013 had a diameter of only 18 m yet produced a blast wave that damaged buildings and caused injuries to some 1500 people (Fig. 1). The potentially devastating effects of an impact of a large asteroid or comet are now well recognized.

Asteroids and comets are considered to be remnant bodies from the epoch of planet formation. Planet embryos formed in the protoplanetary disk about 4.5 billion years ago via the accretion of dust grains and collisions with smaller bodies (planetesimals). A number of planet embryos succeeded in developing into the planets we observe today; the growth of other planet embryos and planetesimals was terminated by catastrophic collisions or a lack of material in their orbital zones to accrete. Most asteroids are thought to be the fragments of bodies that formed in the inner Solar System and were subsequently broken up in collisions.

As a result of collisions, subtle thermal effects and the very strong gravitational field of Jupiter, small main-belt asteroids can drift into certain orbital zones from which they may be ejected under the influence of Jupiter into the inner Solar System. The population of NEOs is thought to consist mainly of such objects, together with an unknown smaller number of old, inactive cometary nuclei. At the time of writing the number of known NEOs exceeds 12000; over 1500 of these are so-called potentially hazardous objects (PHOs), i.e. those having orbits that can bring them within 7.5 million kilometres of the Earth's orbit and are large enough (diameter ≥ 100 m) to destroy a large city or urban area and kill millions of people if they were to impact the Earth. Smaller objects can also present a significant threat: the Chelyabinsk event is a very recent example (see above); a somewhat larger object caused the Tunguska event of 1908 in Siberia, in which an area of over 2000 square km was devastated and some 80 million trees felled. The Tunguska event is thought to have been due to the airburst of an object with a diameter of 30 - 50 m at a height of 5 - 10 km. The estimated impact frequency of NEOs on the Earth depends on size. The impact frequency increases with decreasing size due to the size distribution of the asteroid population: there are many more small objects than large ones. Current, albeit uncertain, statistical knowledge of the NEO size and orbital distributions indicates that NEOs with diameters of 50, 100, 300 m, for example, impact roughly every 1000, 10,000, and 70,000 years, respectively.

The known NEO population contains objects with a confusing variety of physical properties. Some NEOs are thought to be largely metallic, indicative of material of high density and strength, while some others are carbonaceous, of lower density, and less robust. A number of NEOs appear to 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 NEOs range from monolithic slabs to re-accumulated masses of collisional fragments (so-called rubble piles) and binary systems (objects with moons). More than 50 NEOs in the currently known population have been identified as binary or ternary systems and many more are probably awaiting discovery.

The phenomenon of collisions in the history of our Solar System is a fundamental process, having played the major role in forming the planets we observe today. Collisions of asteroids and comets with the Earth have taken place frequently over geological history and probably contributed to the development of life. In contrast, later impacts of asteroids and comets most likely played a role in mass extinctions. NEOs present a scientifically well-founded threat to the future of our civilisation. While past impacts have probably altered the evolutionary course of life on Earth, and paved the way for the dominance of mankind, we would now rather not remain at the mercy of this natural process.

Can we protect our civilisation from the next major impact?

In contrast to other natural disasters, such as earthquakes and tsunamis, the impact of an asteroid discovered early enough can be predicted and prevented. Partners in the NEOShield project (Table 1) are confident the basic technology necessary to prevent an impact is available now. But how do we implement it and what do we need to know about the hazardous object to maximize our chances of success? Preventing a collision with a NEO on course for the Earth would require either total destruction of the object, to the extent that remaining debris posed little hazard to the Earth or, perhaps more realistically, deflecting it slightly from its catastrophic course. 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 highly desirable. Deflection of the object from its course would require the application of an impulse or continuous or periodic thrust, the magnitude and positioning of which may depend on the mass and its distribution throughout the (irregularly-shaped) body, the surface characteristics, and the spin vector, depending on the strategy deployed. It is crucial to ensure that the deflection operation does not simply move the object to another hazardous trajectory. Mitigation planning takes on a higher level of complexity if the Earth-threatening object is a rubble pile or binary system.

In the case of an object with a diameter of about 50 m or less, the best course of action may be to simply evacuate the region around the predicted impact point, assuming there would be sufficient advance warning (however, only a small fraction of the asteroids in this size category have been discovered to date). For objects larger than 50 m a number of mitigation strategies may be considered, depending on circumstances. The NASA Report to Congress, "Near-Earth object survey and deflection. Analysis of alternatives" (http://www.nasa.gov/pdf/171331main_NEO_report_march07.pdf, 2007) on the surveying and deflection of near-Earth objects concluded that nuclear devices offer the most effective means of applying a deflecting force to an asteroid. While they may offer the only feasible solution in desperate circumstances, e.g. in the case of very little advanced warning, it is clear that the geopolitical issues associated with launching nuclear devices and testing them in space seriously compromise the practicability of this technique. The NASA report concluded that the most effective non-nuclear option is the kinetic impactor, which involves applying an impulsive force to the asteroid by means of a large mass in the form of a spacecraft accurately guided to the target at a high relative velocity. The gravity tractor is a "slow-pull" approach that may require a long period of time to achieve the required amount of deflection, but is a promising technique for cases in which there are many years of advance warning, the target NEO is relatively small, and/or a very slight, precise deflection is required to prevent an impact on the Earth.

The report of the National Research Council of the US "Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies: Final Report" (http://www.nap.edu/catalog/12842/defending-planet-earth-near-earth-object-surveys-and-hazard-mitigation, 2010) contains the following findings and recommendation:

"Finding: Mitigation of the threat from NEOs benefits dramatically from in-situ characterization of the NEO prior to mitigation, if there is time to do so."

"Finding: Kinetic impactors are adequate to prevent impacts on Earth by moderately sized NEOs (many hundreds of meters to 1 kilometer) with decades of advance warning. The concept has been demonstrated in space, but the result is sensitive to the properties of the NEO and requires further study."

"Recommendation: If Congress chooses to fund mitigation research at an appropriately high level, the first priority for a space mission in the mitigation area is an experimental test of a kinetic impactor along with a characterization, monitoring and verification system, such as the Don Quijote mission that was previously considered, but not funded, by ESA. This mission would produce the most significant advances in understanding and provide an ideal chance for international collaboration in a realistic mitigation scenario."

Objectives
The objectives of NEOShield broadly reflect the above findings and recommendation. The project work packages are designed around the following tasks: NEO physical characterisation, laboratory experiments to investigate the material properties of asteroid analogue materials, modelling and computer simulations to incorporate the laboratory results into realistic size-scaled investigations of impacts into NEOs, a trade-off study of different deflection techniques, and detailed designs of deflection test missions. In the light of results arising from our research into the feasibility of the various mitigation approaches and the mission design work, a further objective was to formulate a “global response campaign roadmap” that may be implemented when an actual significant impact threat arises. The roadmap considers the necessary international decision-making milestones, required reconnaissance observations, both from the ground and from rendezvous spacecraft, and a space-mission deflection campaign.

Description of main S & T results/foregrounds

The following is a brief description of highlights from the scientific and technical work packages (Table 2) following the logical structure of the project: starting with scientific results from investigations of NEO physical properties, through target selection for deflection test missions, the monitoring of a deflection attempt, post-deflection orbit evolution, to the results from the technical work packages concerned with the design of feasible deflection test missions, and tools for an international strategy or “roadmap” for responding to an impact threat.

A full list of resulting NEOShield scientific and technical documents ("deliverables") is appended to this report.

Hypervelocity gas-gun experiments and associated computer modelling:
An important component of the research into the physical properties of NEOs is laboratory work with hypervelocity gas guns and associated modelling and computer simulations. The gas-gun experiments provide data on the behaviour of asteroid surface analogue materials when impacted by a projectile at high velocity. Modelling and numerical simulations of the impact process required a detailed characterisation of the target materials covering a wide area of strain rates. These material tests, which included determination of porosity, density and chemical composition, were conducted using different types of testing facilities; the tests and results are described in NEOShield Deliverable 4.2.

Following the completion of work to specify the overall strategy and provide detailed requirements for the experiment parameters and the target materials (NEOShield Deliverable 2.4), impact experiments were conducted using a two-stage light-gas accelerator. For NEOShield purposes mm-sized spherical projectiles were fired into four different types of materials: quartzite, sandstone, limestone and aerated concrete. The momentum transfer was measured by means of a ballistic pendulum. A high-speed camera was used to record the highly transient ejection process. Three-dimensional models of the resulting craters were created providing morphological information, and crater volumes were calculated using the digital data. Targets were weighed before and after each experiment to determine the ejected mass.

Experiments were also carried out using an all-angle light-gas gun, which allowed vertical impacts of projectiles into loose material representative of asteroid regolith. The results of the NEOShield experiments (NEOShield Deliverables 4.1 and 4.3; see Figs. 2a and 2b) have provided vivid demonstrations of the dependency of the momentum multiplication factor beta (the ratio between the target momentum change as a result of the impact and the momentum of the projectile) on the target material, especially its density and porosity. An unanticipated, albeit preliminary, finding is that the results for layered targets, with a thin layer of regolith over a high-porosity solid, indicate somewhat higher momentum enhancement than for the bare high-porosity solid material. This can be understood as a result of compaction of the solid material reducing the amount of ejecta, whereas the unconsolidated regolith is more easily released.

The results of the NEOShield gas-gun experiments have demonstrated that knowledge of the physical properties of a potentially hazardous NEO is of fundamental importance for the determination of its response to a kinetic impactor and other impulsive deflection techniques. While the results from the small-scale experiments in Earth gravity cannot be directly applied to large-scale impacts into asteroids with microgravity, they provide useful inferences for impact mitigation:

- For a given material composition, the greatest momentum enhancement is from solid surfaces if the porosity is low, but from deep regolith if the porosity is high.

- The projectile properties (i.e. shape/density of impacting spacecraft) have a larger influence on the momentum enhancement than the regolith particle size/shape.

- The laboratory experiments provide valuable constraints for hydrocode simulations on small scales.

Computer modelling of the effects of various material properties on the beta factor have shown that using a higher tensile strength leads to less ejecta and therefore a smaller beta value. Using a target with a strength corresponding to laboratory scales (cm-sized bodies) leads to a significantly smaller beta value than that found for a target with a strength corresponding to a 300 m diameter object (which is about 20 times smaller). On the other hand, assuming a lower strength against crushing leads to more compaction and therefore also less ejecta and a smaller beta. Decreasing the porosity leads to increased beta.

The modelling and results are described in NEOShield Deliverables 3.2 and 3.3; see Fig. 3.

First main-journal peer-reviewed papers on the NEOShield hypervelocity gas-gun experiments and modelling work have been published:

Jutzi, M., Michel, P. (2014) Hypervelocity impacts on asteroids and momentum transfer I. Numerical simulations using porous targets. Icarus 229:247-253.
Hoerth, T., et al. (2015) Momentum transfer in hypervelocity impact experiments on rock targets. Procedia Engineering 103:197-204.

Investigation of mitigation-relevant properties of NEOs from existing observational data:
Objects with diameters greater than 300 m are relatively rare and impacts of such objects are expected to occur less than once every 70,000 years. Objects with diameters less than 50 m are expected to impact much more frequently (e.g. the Tunguska event of 1908 and the Chelyabinsk superbolide of 2013) but are likely to dissipate the bulk of their energy in the atmosphere causing relatively minor damage on the ground. For the purposes of the NEOShield project we consider the NEO diameter range of interest to be D = 50 – 300 m. Analysis of available observational data suggests that small NEOs can have very irregular shapes, rapid rotation rates of up to 4 rev/min, and, depending on models used, structures ranging from solid monoliths to aggregates (“rubble piles”) with wide ranges of possible bulk densities, porosities, and degrees of cohesion. Realistic ranges of mitigation-relevant NEO parameters have been established to guide the selection of representative targets for demonstration missions, and as an aid to mission planners (see below). We have also shown that there is little danger of a previously benign NEO being deflected onto an Earth-threatening orbit by a deflection test mission, although thorough calculations of all possible outcomes should be carried out in each case.

Observations with infrared telescopes, such as NASA’s Wide-Field Infrared Survey Explorer (WISE), have shown that the sunward surfaces of some asteroids appear cooler than others at similar distances from the Sun, a finding that we have modelled on the basis of enhanced surface thermal conductivity. From comparisons of the emitted heat radiation with radar reflectance measurements, NEOShield research has uncovered a potentially very valuable relationship between a thermal model fitting parameter, related to the surface temperature distribution, and the metal content of asteroids. Our results suggest that values of η (the so-called “beaming parameter”), are a useful indicator of asteroids with high metal content (Fig. 4). It is evident that the peak in the mean-η plot of Fig. 4a coincides with the region occupied by M-type (primarily metallic) asteroids. Comparisons with radar data (Fig. 4b) support the conclusion that η traces metal content. The fact that the peak persists after removal of the currently identified or suspected M types implies that many more asteroids with high metal content are present in the main belt, and therefore probably in the NEO population too. We have provided a list of 18 NEOs, 9 of which are potentially hazardous, for which unusually large η values are suggestive of high metal content (Table 3).

A threatening NEO containing a large amount of metal would presumably be relatively robust and massive, depending on its internal structure, factors that would require careful consideration by deflection-mission planners and/or those mandated to manage mitigation, e.g. evacuation, activities on the ground in advance of a possible impact. Moreover, the identification of NEOs with high metal content is an important task for recently-announced endeavours in the field of planetary resources. The NEOShield results imply that next-generation asteroid surveys, provided they are equipped with sensors operating at multiple thermally-dominated infrared wavelengths, could provide a valuable indication as to which discoveries warrant further investigation regarding possible high metal content.

A first main-journal peer-reviewed paper on NEOShield results in this field has been published:

Harris, A. W. and Drube, L. (2014) How to find metal-rich asteroids. Astrophysical Journal Letters, 785:L4.

The results of NEOShield investigations into the mitigation-relevant properties in the NEO population are described in Deliverable 2.1.

The successful outcome of a deflection attempt would depend on the availability of information on relevant physical parameters of the threatening NEO. While knowledge of the mass, shape, and spin vector could be sufficient for the basic design of a gravity tractor, knowledge of further parameters, such as porosity, mechanical properties, mineralogy, would be a prerequisite for the planning of an effective mitigation strategy involving impulsive options. The observational techniques with which this crucial mitigation-relevant information can be derived, considering both Earth-based facilities and dedicated space missions, have been reviewed in NEOShield Deliverables 2.2 and 2.3. Issues examined include the relevance and accuracy of a variety of observational techniques and data types, how to combine observational techniques to optimise acquisition of the necessary information, the relative merits of rendezvous and flyby missions, and how to optimise the reconnaissance strategy depending on the time available before mitigation actions become necessary. The appropriate instrumentation payloads for a reconnaissance precursor mission in an emergency scenario, and a realistic deflection demonstration mission, were also studied.

An overview of NEOShield results focusing on mitigation-related science, with a brief discussion of technology development and deflection demonstration-mission designs, has been published:

Drube, L., et al. (2015) NEOShield - A global approach to near-Earth object impact threat mitigation. In Handbook of Cosmic Hazards and Planetary Defence, Pelton, J. N. and Allahdadi, F (eds.), Springer-Verlag, Berlin, Heidelberg.

Target selection for deflection demonstration missions:

Physical properties
While the properties of the next seriously hazardous object may turn out to be completely different to those we would expect on the basis of our statistical knowledge of the NEO population, we can attempt to narrow the range of the “expected properties” to provide a rational basis for the choice of objects to serve as targets in deflection demonstration missions. In order for a mitigation demonstration to be convincing, the target object should be as realistic as possible, i.e. typical of the size and type of NEO we are likely to be faced with in the first space-borne deflection campaign.

We used statistical means to investigate the most probable frequency of mitigation-relevant physical properties of objects in the population of NEOs, such as size, albedo, composition, structure, etc. We have combined data from different published catalogues of dynamical, optical, infrared, and radar results, such as DLR EARN, the NASA Planetary Data System Small Bodies Node, the Minor Planet Center, the JPL Small-Body Database, and the new NEOWISE and Spitzer Space Telescope survey data.

Only a small number of the NEOs in the size range relevant for the selection of deflection demonstration mission targets have been physically characterised. Further observing campaigns and surveys of NEOs in the size range 50 - 300 m are essential to improve our knowledge of the mitigation-relevant small NEOs and increase the population from which targets for demonstration missions can be selected. Our results indicate that establishing a realistic probable albedo range for a forthcoming threatening NEO is difficult on the basis of current knowledge. The range observed for NEOs in the size range of interest covers all values observed for asteroids in general (0.03 - 0.7). Our results suggest that a small asteroid may have an albedo significantly higher than the average of all NEOs. However, the analysis presented in this work allows the probable albedo range of a NEO to be constrained if the taxonomic type is available.

NEOs in the size range of interest for mitigation planning may have monolithic structures or be rubble piles with some degree of cohesion provided by dust grains and van der Waals forces. Observational data and modelling results are consistent with rubble-pile structures being common among NEOs. While it would appear likely, it is not yet clear if there is a transition to monolithic structures for diameters below a few hundred metres. Further observations and modelling are required to test the suggestion that very small, elongated, fast-rotating objects are monolithic. In any case the fact that small asteroids can have very high rotation rates (up to around 1 revolution per minute) is a very important consideration for a mitigation mission. Since deflecting a fast-rotating target is likely to be technically challenging, a demo mission targeting a representative relatively fast rotator would provide a revealing test of current NEO deflection capabilities.

While extremely important for mitigation considerations, knowledge of NEO internal characteristics such as structure, density and porosity is still very primitive. A crucial question for future work remains the variety of internal structures possible in the case of very small NEOs and how they influence different deflection options. Another relevant line of investigation would be the exploration of dependencies of structure and porosity on mineralogy. For instance, how might high metal content influence the response of an object to a kinetic impactor or a stand-off blast?

The above work is described in NEOShield Deliverable 5.1.

Dynamical considerations

Simulating the orbit evolution of a target NEO after a potential deflection attempt is not only important from a mission validation perspective. Accidentally turning a previously harmless NEO into a potentially hazardous object (PHO), or increasing the impact risk of a known PHO, should obviously be avoided! Analytic estimates of the changes in an asteroid's minimum orbit intersection distance (MOID, relative to the Earth's orbit) as a result of the deflection attempt can serve as an indicator of increased short-term collision risk with the Earth. However, given the dynamically active environment, minimum encounter distance (MED) and impact probability predictions have to be performed with tools that are capable of accounting for non-linear changes in orbital elements. The fact that knowledge of any NEO orbit has a limited accuracy has to be taken into account, in addition to uncertainties associated with the outcome of the deflection attempt itself. Thus deflection circumstances that may lead to a future collision of the target asteroid with Earth, directly or via a keyhole passage, have to be identified so that they can be avoided in the test mission design. (An asteroid may closely approach the Earth so that the perturbation by the Earth's gravitational field is just the right amount to cause its orbit to enter a resonance condition with the Earth's orbit and impact the Earth on a later approach; the small region of space through which the NEO has to pass to enter a resonance is called a "keyhole"). Naturally, realistic simulations of impact probability changes arising from a planned mitigation can only be performed once the mission details are known.

NEOShield results show that for the kinetic impactor, target NEOs for test-mission purposes should have diameters larger than 100 m in order to minimise GNC targeting issues (it should be possible to reduce this limit depending on progress made with impactor targeting accuracy). An upper diameter limit of around 350 m is set by the need to be able to measure the very small change in the target NEO's orbit as a result of the deflection attempt.

Given the physical and dynamical property constraints, five potential targets for deflection demonstration missions have been identified with the help of the list of realistic targets compiled as described in NEOShield Deliverable 5.2 (see Fig. 5). The list gives known physical properties relevant to deflection test missions and indicates important uncertainties in the data presented. During the course of the project new discoveries were monitored and new results incorporated into the list. The potential target NEOs are: 2000 FJ10, 2001 QC34, 2002 DU3, 2001 JV1, and 1998 VO.

Extensive post-mitigation threat assessments for the proposed targets and deflection scenarios were carried out in order to address potential planetary safety concerns. The results of our work (NEOShield Deliverable 5.3a) demonstrate clearly that risk analysis has to be performed on an individual basis, as the outcome of a deflection attempt can depend strongly on knowledge of target-specific deflection-relevant parameters (the influence of parameter uncertainties on the outcome of deflection attempts is explored further in D9.6c, in which the uncertainty in the target NEO mass is shown to play a vital role).

For the test-mission scenarios investigated the target asteroids 1998 VO, 2000 FJ10 and 2001 QC34 currently appear to be the most suitable candidates for a deflection demonstration mission, where the latter constitutes the "safest" option for which all the test-mission scenarios led to an increase in minimum encounter distance between the NEO and the Earth. However, our results indicate that none of the five proposed mission/target combinations can lead to a significant probability of the target impacting the Earth, compared to the background risk, regardless of the outcome of the deflection attempt.

The work described here is a very good example of how a complex iterative process involving scientific and technical aspects, in this case target NEO selection and space-mission design, can benefit from the close collaboration between scientists and engineers afforded by an international project such as NEOShield, with its diverse scientific and industrial partners.

Kinetic impactor (KI) deflection concept:
A complete demonstration of a KI mission under representative conditions has never been accomplished, although some technological building blocks required to implement a KI mission are already available and well matured through various commercial and scientific satellite projects of the past few decades. However, there are still some technical issues that need to be resolved before we can be confident of being able to successfully implement a real NEO deflection mission on a timescale dictated by nature. Further technology development is necessary, particularly in the field of the impactor GNC and the capabilities (e.g. 3D target reconstruction) of the reconnaissance (orbiter) spacecraft, as well as the high level of autonomy of both spacecraft. A full set of relevant open issues has been identified and analysed for a fully-fledged impactor mission composed of impactor and orbiter spacecraft (NEOShield Deliverable 6.1).

Several kinetic impactor demonstration mission architecture concepts have been identified, evaluated, and traded against each other, and a final mission architecture baseline selected. The final mission design targets the NEO 2001 QC34. Driving criteria for this selection were:

1. Avoid any increase in terrestrial impact threat, i.e. avoid any reduction in the NEO's Minimum Earth Encounter Distance (MED) due to the deflection action, taking account of uncertainties.

2. Allow for deflection validation with adequate signal-to-noise ratio (SNR ≥ 10).

Both criteria are fulfilled for the selected target which is an Apollo-type asteroid (Earth crosser) that has a diameter of about 240 m. The mission consists of two spacecraft, an impactor and a reconnaissance ("explorer") spacecraft to characterise the target NEO prior to the impact in terms of ephemeris data, rotational state, surface geometry and composition. The impact itself and the ejecta produced are also observed by the explorer. Finally after the impact the explorer determines the change in ephemeris data of the NEO and thus allows a quantitative determination of the momentum transfer and the deflection resulting from the impact. Both spacecraft are launched together as a stack on a single Soyuz-Fregat vehicle from Kourou. In order to increase the momentum transferred to the selected target NEO, the launcher upper stage (Fregat) remains connected to the impactor throughout the mission. This means that the impactor (mass 340 kg) and Fregat (mass 902 kg) crash into the NEO as a composite with a total mass of 1242 kg. The impact velocity is 9.6 km/s. The impact accuracy in terms of center-of-mass offset achievable with the proposed GNC system is about 12 m, which is an excellent result considering the solar phase angle of the target NEO at impact is rather unfavourable, so that most of the NEO is in shade as seen from the approaching impactor (Fig. 6). The explorer uses three swing-bys and solar-electric propulsion for the main orbit manoeuvres and reaches the target NEO 5.3 years after launch. The impactor uses three swing-bys and chemical propulsion and reaches the NEO more than one year later than the explorer, thus leaving sufficient time for detailed characterisation of the NEO prior to the impact. The two spacecraft remain mated until shortly prior to their first Earth swing-by manoeuvre, which occurs roughly one year after launch. A detailed mission design is presented in NEOShield Deliverable 8.2.

An alternative low-cost demonstration mission - changing the spin rate of Itokawa:
A kinetic-impactor mission to change the rotation rate of a well-studied asteroid, such as (25143) Itokawa, could be an alternative low-cost approach to obtaining information on momentum transfer. One of the main goals of a kinetic-impactor demonstration mission is to investigate the efficiency of momentum transfer and its dependence on the properties of the target NEO. An option for a low-cost test mission is to target a well-studied NEO with the aim of modifying the spin rate of the asteroid (Fig. 7). A potential target for such a test would be Itokawa, studied by the Japanese Hayabusa rendezvous mission 2005 - 2007. The advantage of this approach is that only one spacecraft, the impactor, is required. A simple calculation (NEOShield Deliverable 5.1) has shown that the change in rotation rate would be measurable by means of lightcurve observations from groundbased telescopes. An accompanying reconnaissance spacecraft would be very desirable to enhance the science return, but may not be necessary if the primary goal were to measure the momentum enhancement due to ejecta. The development of a corresponding mission design ("NEOTWIST") was the subject of a supplementary “mini-project” carried out during the last 3 months of NEOShield (Deliverable 9.6b).

Gravity tractor (GT) concept:
The GT simultaneously serves to make small adjustments to the asteroid orbit and to provide the information needed for very precise tracking of the asteroid from the Earth. In many ways this capability overlaps that of the KI reconnaissance spacecraft, which is required to determine the precise initial orbit of the asteroid, to witness the impact, and then to stay with the asteroid long enough to determine its new, post-deflection orbit. In practice, a GT may be used for fine-tuning the orbit of an asteroid that has already been deflected by other means (this scenario is discussed in NEOShield Deliverable 8.5). However, a standalone GT mission may be the option of choice, depending on the circumstances, e.g. in a scenario in which keyhole avoidance is the goal and the corresponding deflection required relatively small. The mission architecture outlined here refers to a GT standalone mission:

A launch in 2026 on a Falcon-9 to the NEO 2000 FJ10 (diameter 120 - 210 m) is assumed (Deliverable 8.3). The target selection criteria were: maximise the deflection while ensuring minimum threat to Earth due to the deflection taking into account all relevant uncertainties, and deflection validation must be possible with high signal-to-noise. The spacecraft mass is ~1160 kg at launch and ~1100 kg at the beginning of the tractoring phase. Sufficient propellant is available for the GT to operate for 12 years. The approach and rendezvous phase lasts about 2 months and accounts for acquisition and manoeuvre planning in order to zero out the relative velocity between the spacecraft and 2000 FJ10. Trajectory knowledge and successive rendezvous manoeuvres are based on DSN tracking of the spacecraft, space-based tracking of the NEO, and on-board images of the NEO taken by the spacecraft optical detection camera. The spacecraft approaches the sunward side of the asteroid. The GT hovers at a distance of about 125 m from the asteroid’s surface (Fig. 8), assuming the adopted asteroid physical parameters are nominal and a fixed thruster mounting is used with a canting angle of 45°. To maximize the deflection the gravity tractor would be placed such that the NEO is accelerated either along or against its instantaneous velocity vector. It should be possible to detect the deflection on the basis of radio science after 1 - 2 years. The nominal mission duration would be between 4.5 and 6 years.

The GT demonstration mission design work included a detailed post-mitigation risk analysis. Using a state-of-the-art mission design and impact monitoring tools it was shown that deflection actions and their corresponding uncertainties have to be considered on a case by case basis to ensure that the target NEO's threat potential to the Earth is not increased by the mitigation demonstration attempt. It was found that the GT demonstration mission proposed would reduce the risk to the Earth from 2000 FJ10 provided the GT operates in a trailing position with respect to the asteroid. The advantage of the GT lies in the fact that leading or trailing configurations can be chosen in situ. This can ensure planetary safety without changing the general layout of deflection demonstration mission designs. Kinetic impactor concepts are much more rigid in this respect.

Work within the NEOShield project on the GT concept has also investigated how the performance of a GT could be improved by incorporating knowledge of the NEO shape into an algorithm that governs the tilting of the tractor ion engines to direct the ion beams away from the surface of the NEO, while maintaining optimum thrust. The concept uses a realistic asteroid polyhedron model to determine optimum engine tilt angles, instead of assuming a spherical shape. In a modelled scenario based on a fictitious potential impact of the NEO 2011 AG5 in 2040, use of the newly developed algorithm gave 35.2% more deflection of the NEO than that obtained under the assumption of a spherical object (for details see NEOShield Deliverable 7.2 and Ummen, N. and Lappas, V., 2014, Polyhedron tracking and gravity tractor asteroid deflection. Acta Astronautica, 104, 106-124).

Blast deflection concept:
Several interrelated tasks regarding the problem of using nuclear or chemical blasts for the deflection of hazardous asteroids were undertaken, as described in NEOShield Deliverable 7.3. In order to facilitate calculation of the mechanical impulse transmitted to an asteroid by a nuclear or chemical explosion, numerical codes were developed for the calculation of the thermodynamic characteristics of silicates, for solution of the transport problem of x-ray radiation, and for the estimation of the momentum change imparted by stand-off nuclear explosions. The results of past ground explosions were re-analysed to allow estimation of the momentum transfer potential of nuclear and chemical blasts. A complete thermodynamic equation of state is proposed that describes the vaporisation of asteroid analogue material. Example mechanical impulses were calculated for buried and near-surface nuclear explosions of 10 kt and 100 kt of TNT. Results were also calculated for the case of a buried TNT explosion of 0.5 t. The effects of the impulses on an Apophis-type target were calculated. An analysis of the main physical processes associated with stand-off and buried nuclear explosions, and calculations of the mechanical momentum change of an NEO resulting from such explosions, are given by Meshcheryakov et al. (2015) Estimated efficiency of the deflection of a dangerous space object. Technical Physics, 60, 26-30.

A test mission design for the blast deflection concept was carried out to provide insight into the special issues associated with this technique. The objectives of such a mission would be to demonstrate the principle of blast deflection by refining our understanding of the underlying physical processes taking place in a blast near an asteroid, and assessing the efficiency of the technique by accurately measuring the deflection produced by the blast. Asteroid 2001 JV1 was selected as the target asteroid; an analysis of its orbital characteristics and approaches to the Earth in the period 2020 - 2042 was performed and the results used to develop a mission plan and approach trajectory to the asteroid. It was found that the only practical launch window within the coming 20 years occurs around 2021. The optimum mission design, considering fuel requirements and visibility of the asteroid during approach, has a flight duration of 296 days. The scheme of guidance and deceleration on approach to the asteroid is such as to allow a programme of onboard navigation observations and a final stage of precision guidance to the target. Possible schemes of orbiting or hovering near the asteroid were studied, with preference given to the latter. After separation of the explosive charge, the spacecraft performs small manoeuvers in order to achieve a safe distance from the asteroid (~ 100 - 200 km). Analytical solutions were derived for changes to the target’s dynamical parameters depending on the direction of the velocity impulse produced by the blast; the solutions were validated by numerical computations. It was found that in most cases the largest deflection is produced by directing the velocity impulse along the direction of the asteroid orbital motion. A post-deflection period of navigation observations (angular and ranging) is included in the mission design to measure, in the shortest possible time, the change in the target’s orbit resulting from the blast. A detailed test mission design for the blast deflection concept is given in NEOShield deliverable 8.4.

Comparison of NEO deflection concepts:
The feasibility and effectiveness of a number of proposed deflection methods (alternatives to the kinetic impactor) were compared, including the gravity tractor, the ion beam shepherd, laser ablation, and electrostatic deflection. Results show that the gravity tractor, ion beam shepherd, and laser ablation all have potentially useful capability for asteroid deflection (Fig. 9). Multiple gravity tractors improve the performance of the traction and provide redundancy in case of failure of a spacecraft. Analyses of potential manned deflection missions to enable reliable positioning of an explosive device were carried out. The work indicates that such a mission could be conducted with liquid

oxygen/liquid hydrogen propulsion. However, nuclear thermal propulsion could reduce the launch mass significantly. Open issues include life support systems and consumables, and radiation protection, for long duration spaceflight. The deflection concept trade-off study is presented in NEOShield Deliverable 7.5.

Global response campaign roadmap:
NEOShield personnel at DLR, CNRS, and OU have become members of the International Asteroid Warning Network (IAWN) and/or the German, French, and UK delegations, respectively, to the Space Mission Planning Advisory Group (SMPAG); both groups were recently established under the auspices of the United Nations Action Team 14 (COPUOS). We have thereby established an interface between the NEOShield project and the most prominent current international efforts addressing the impact hazard. The SMPAG will help to coordinate the technical know-how of national space agencies and other competent bodies by recommending activities in the field of the impact hazard and mitigation measures in general. Meetings of these groups present an opportunity to highlight and discuss NEOShield work and results, and suggest internationally coordinated efforts based on NEOShield experience. The interface of our work with the activities of the United Nations secures our participation in a truly international coordinated strategy for NEO impact mitigation.

The establishment of the IAWN and of the SMPAG by the United Nations represents an important step forward in the definition of a global response roadmap. The networking of emergency management agencies worldwide seems already active and well developed. However, we identified the following issues requiring further attention (NEOShield Deliverable 9.1):

- An internationally-agreed “decision making protocol” has to be implemented in order to address the asteroid impact risk while minimising the potential for misunderstandings amongst countries involved, either as active partners in a deflection attempt or as possible victims of an impact. Plans, roles and responsibilities have to be defined well in advance of a specific impact threat arising.

- The development of new technologies and the realisation of deflection demonstration missions are fundamental to reducing our reaction time, to enable an effective response even in the case of short warning times.

- NEO research and physical characterisation efforts have to be strengthened in order to fully understand how relevant parameters (e.g. composition, porosity, inner structure, etc.) influence the outcome of deflection attempts and the consequences of impacts on the Earth.

- The asteroid impact hazard should be specifically included in the prevention and preparedness programmes of emergency management agencies.

A suite of three software tools has been developed for NEO impact-risk mitigation within the NEOShield project. These tools serve as an aid in the selection of the most suitable deflection mission given the circumstances of the potential impact scenario. The software tools are:

1. NEO Impact Risk Assessment Tool (NIRAT).
2. NEO Deflection Evaluation Tool (NEODET).
3. Risk Mitigation Strategies Evaluation Tool (RIMISET).

NIRAT, the first tool enables b-plane dispersion ellipses on the date of a possible impact to be evaluated, and the presence of keyholes that could lead to future impacts to be identified. Given knowledge of the relevant NEO physical parameters, NIRAT allows the impact risk in terms of the Palermo Scale and the Torino Scale to be evaluated. The results from NIRAT are required by the following tools.

NEODET calculates the required optimal change in NEO velocity (magnitude and direction) at any given instant prior to the possible impact epoch that would shift the dispersion ellipse out of contact with the Earth. The change in NEO velocity could be achieved by means of an impulsive deflection method (one or several impacts) or by means of a slow-push/pull technique (e.g. the gravity tractor).

RIMISET evaluates how each of the possible impulsive and slow-push techniques could produce the required change in NEO velocity, and the requirements that doing so would impose on the design of the deflection mission. Each solution can be simulated to allow an assessment of its efficiency in achieving the required deflection by any of the proposed methods (kinetic impactor, blast deflection, gravity tractor, and possible combinations of these). Ultimately, it allows a quantitative evaluation of the technical requirements of the chosen deflection space mission.

The software suite has been validated with scenarios based on the NEOs 2011 AG5 and 2007 VK184 that were potential Earth impactors for some time. Both NEOs have recently been removed from the risk list as a consequence of additional observational data. The scenarios were constructed as if these objects still posed a risk for Earth, thus allowing a useful assessment of the three tools in the risk mitigation chain. The three software tools are described in NEOShield Deliverable 9.3.

A detailed NEO threat response campaign based on the 2011 AG5 scenario is developed and discussed in NEOShield Deliverable 9.5.

With regard to practical prerequisites for reconnaissance observations of hazardous objects, current capacities and the shortcomings of ground- and space-based astrometric and radar facilities have been studied. While large ground-based surveys are the most prolific contributors to NEO discovery and asteroid astrometry at the moment, smaller astrometric and radar programmes dominate high precision astrometry. ESA's Gaia mission will have a profound impact on this picture by providing an improved astrometric catalogue and high precision astrometric measurements for about 15% of the known NEO population. In order to quantify the performance of current astrometric and radar facilities in terms of impact risk assessment, we have derived analytic and semi-analytic tools to simulate the achievable orbit quality as a function of data arc and number of observations. Our results confirm that accurate predictions of impact probabilities require either astrometric data arcs of at least half a year, radar observations, space based astrometry (e.g. by Gaia), or a reconnaissance spacecraft. A significant percentage of potential discoveries from large-scale surveys are lost due to the lack of follow-up capabilities. Accurate estimates of orbit uncertainty reduction are essential for successful detection planning and validation. The detection signal-to-noise ratio (DSNR) introduced in Deliverable 5.3a offers a simple framework to quantify the necessary precision for orbit determination before and after a detection attempt. We have provided simple estimates for the observation time requirements to achieve a certain DSNR. In the future it would be desirable to have groundbased observatories located near the Earth's equator in order to increase sky coverage. Since only about 100 NEOs can be observed per year using current radar facilities, new dedicated radar stations would also be valuable assets. The considerable personnel and power requirements to reach out to distances beyond several tenths of an AU, however, would make those extremely costly. (For details see Deliverable 9.2).

Note: The software tools described in the deliverables from work packages 3, 7, and 9 were developed for project internal purposes and are not available at present for open distribution.

Potential impact and main dissemination activities and exploitation results

We consider the main results from the NEOShield project to be:

- Greater insight into the mitigation-relevant physical characteristics of NEOs and how threatening objects may respond to impulsive deflection attempts. Our work has provided an improved understanding of the ranges of relevant physical parameters, and the possible structures and compositions, of objects most representative of those likely to threaten the Earth. The results provide a basis for the selection of targets for realistic, technically and financially feasible, deflection test missions.

- A greater understanding of the importance of post-deflection trajectory analysis. The fact that knowledge of any NEO orbit has a limited accuracy has to be taken into account, in addition to uncertainties associated with the outcome of the deflection attempt itself. Thus deflection circumstances that may, even slightly, increase the probability of a future collision of the target asteroid with Earth, directly or via a keyhole passage, have to be identified so that they can be avoided in the test-mission design.

- Detailed strategies, including the most appropriate instrumentation, for the provision of vital astrometric and physical deflection precursor data from ground- and space-based reconnaissance observations.

- The identification and characterization of suitable target NEOs for deflection test missions.

- Detailed designs of deflection test missions to demonstrate our ability to deflect a threatening NEO with current technology. The results obtained from the detailed mission design studies demonstrate that such missions are feasible and suggest that with current technology the deflection methods investigated should be adequate for the most probable emergency scenarios. In addition, the feasibility and effectiveness of a number of proposed deflection methods (alternatives to the kinetic impactor) were compared, including the gravity tractor, the ion-beam shepherd, laser ablation, and electrostatic deflection. Results showed that the gravity tractor, ion-beam shepherd, and laser ablation all have potentially useful capability for asteroid deflection. Gaining experience with deflection techniques is crucial in order to maximise the probability of success of a space-borne response to a threatening object that may have to be executed at short notice. While the NEOShield project did not have sufficient funding to launch a test mission, we expect that such a mission will be carried out in the framework of a subsequent international initiative with European participation (a current example is AIDA – the “Asteroid Impact and Deflection Assessment” concept, which is under study by NASA and ESA). With the experience gained from the project, NEOShield partners are well-placed for participation in such an initiative.

- A novel low-cost concept and detailed mission study for a kinetic-impactor test mission, based on changing the spin rate of the NEO Itokawa. In its cheapest form, the concept requires only one spacecraft, the impactor, since the change in spin rate of the asteroid, and therefore the momentum transfer efficiency, can be measured via groundbased lightcurve observations.

- The demonstration that a large international team of scientists and engineers, brought together by the European Commission’s research funding programme, can work closely and effectively together to make significant advances in the complex and diverse fields relevant to NEO impact threat mitigation. The efficiency with which the team has tackled the complex issues inherent to this field has increased with time as the partners developed greater mutual understanding and respect. Resources should be made available beyond the horizons of short-term project funding to ensure the momentum built up during the course of NEOShield (and NEOShield-2) does not go to waste, but rather the work of the NEOShield partners can be continued on a long-term basis. The NEO impact hazard is a permanent problem, which can only be tackled by permanent effort.

The events of 15 February, 2013, when a superbolide exploded over Chelyabinsk (Fig. 1) just hours before the predicted close approach of the ~30-m diameter NEO 2012 DA14, have sharpened public awareness of the dangers of NEOs and led to an avalanche of press interest in the work of NEOShield.

A major impact on the project has been the enormous media interest, which has led to extra unforeseen demands on the time of a number of project personnel, in particular the Coordinator. Correspondence and phone calls with journalists, and hosting radio and TV news and documentary teams, have been a seemingly daily occurrence since the Kick-off Meeting (not to mention countless phone calls from interested members of the public). A broad selection of TV, radio, press, and internet items on NEOShield from the beginning of the project is appended to this report. In addition to NEOShield-related queries resulting in press items such as those in the appendix, NEOShield personnel are often approached by the media on related topics (e.g. the origin and nature of asteroids and comets); press items resulting from such related queries are not included in the appendix.

NEOShield’s social media activities are followed with interest by users. The project continues to have a presence on Facebook and Twitter and answers are provided to our followers’ questions and private mails. Our interaction with users organically generates more followers. NEOShield has exchanged website links with the NASA JPL NEO program and the B612 Foundation.

In terms of exploitation of NEOShield results, NEOShield has so far generated around 20 peer-reviewed publications in major international journals, in addition to many conference papers. We comply as far as is reasonable/possible, given the restrictions imposed by many major journals, with the policy of open access. In many cases major refereed journals in our field accept the parallel posting of papers to open online archiving repositories, such as http://arxiv.org/; use has been made of such opportunities, depending on the policies of the partner organisations. The participation of several NEOShield partners in the international UN-sanctioned SMPAG group (see above) is already leading to discussions between SMPAG participants on the use of results from NEOShield deliverables for SMPAG tasks, such as consideration of mitigation mission types and technologies, reference mission design studies for different NEO threat scenarios, instruments and mission requirements for the characterisation of a threatening NEO, and the development of a coordinated strategy for future work on planetary defence.

Finally, the socio-economic impact and the wider societal implications of NEOShield lie in easing public concern over the impact hazard, and demonstrating that the scientific and space-engineering communities are abreast of the problem and have a good chance of successfully deflecting a dangerous NEO should one threaten the Earth in the near future.

Address of project public website and relevant contact details

www.neoshield.net

DLR (NEOShield project Coordinator): Alan Harris [Alan.Harris@dlr.de]
Airbus D&S, Germany (website host, supervisory interface to technical work packages): Albert Falke [Albert.Falke@airbus.com]

4.2 Use and dissemination of foreground

Section A (public)

Publications

LIST OF SCIENTIFIC PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
No.	Title / DOI	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Relevant pages	Is open access provided to this publication ?	Type
1	The European Union funded NEOShield project: A global approach to near-Earth object impact threat mitigation 10.1016/j.act aastro.2012.08.026	A.W. Harris , M.A. Barucci , J.L. Cano , A. Fitzsimm ons , M. Fulc higno ni , S.F. Green , D. Hestroffe r , V . Lappas , W. Lork , P. M ichel , D. Morrison , D. Payson , F. Schäfer	Acta Astronautica	Vol. 90/Is sue 1	Elsevier Limited	United Kingdom	01/09/2013	80-84		Peer revie wed
2	Hypervelocity impacts on asteroids and m omentum transfer I. Numerical simulations using porous targets 10.1016/j.ica rus.2013.11.020	Martin Jutzi , Patrick Mi chel	Icarus	Vol. 229	Academic Press Inc.	United States	01/02/2014	247-253		Peer revie wed
3	HOW TO FIND METAL-RICH ASTEROI DS 10.1088/2041- 8205/785/1/L4	Alan W. Ha rris , Line Dru be	Astrophysical Journal Letters	Vol. 785/I ssu e 1	Institute of Physics Publishing	United Kingdom	10/04/2014	L4		Peer revie wed
4	The near-Earth objects and their potential threat to our planet	D. Perna , M. A. Barucci , M. Fulchign	Astronomy and Astrophysics Review	Vol. 21/Is sue 1	Springer Verlag	Germany	01/11/2013	id.65		Peer revie wed

	10.1007/s0015 9-013-0065-4	oni								
5	Ultraviolet to near-infrare d spectroscopy of the potentially hazardous, low delta-V a steroid (175706) 1996 FG3 10.1051/0004- 6361/201321677	D. Perna , E. Dotto , M. A. Barucci , S. Fornasier , A. Alvarez-C andal , F. Gourgeot , J. R. Brucato , A. Rossi	Astronomy and Astrophysics	Vol. 555	EDP Sciences	France	01/07/2013	A62		Peer revie wed
6	Rotational spectra of (162173) 1999 JU3, the target of the Hayabusa2 mission 10.1051/0004- 6361/201220629	D. Lazzaro , M. A. Barucci , D. Perna , F. L. Jasmim , M. Yoshikaw a , J. M. F. C arvano	Astronomy and Astrophysics	Vol. 549	EDP Sciences	France	01/01/2013	L2		Peer revie wed
7	The triple near-Earth asteroid (153591) 2001 SN263: an ultra-blue, primitive target for the Aster space mission 10.1051/0004- 6361/201424447	D. Perna , A. Alvarez- Can dal , S. Fornas ie r , Z. K a#uchov á , S. M. Giuliatti Winter , E. V ieira Neto , O. C. Winter	Astronomy and Astrophysics	Vol. 568	EDP Sciences	France	01/08/2014	L6		Peer revie wed
8	Low delta-V near-Earth asteroids: A survey of suitable targets for space missions 10.1051/0004- 6361/201322283	S. Ieva , E. Do tto , D. Perna , M. A. Barucci , F. Bernardi , S. Fornasie r , F. De Luise , E. Perozzi , A. Rossi , J. R. Brucato	Astronomy and Astrophysics	Vol. 569	EDP Sciences	France	01/09/2014	A59		Peer revie wed
9	Polyhedron tracking and gravity tractor asteroid deflection 10.1016/j.act aastro.2014.07.024	N. Ummen , V. Lappas	Acta Astronautica	Vol. 104/I ssu e 1	Elsevier Limited	United Kingdom	01/11/2014	106-124		Peer revie wed
10	Estimated efficiency of the deflection of a dangerous space object using an explosion or impact 10.1134/S1063 784215010181	S. A. Mesh chery akov , Yu. M. Lipnit sk ii	Technical Physics	Vol. 60/Is sue 1	Maik Nauka-Interp eri odica Publishing	Russian Federation	01/01/2015	26-30	No	Peer revie wed

11	ROTATION-DEPE NDENT CATAST ROPHIC DISRUPTION OF GRAVITATI ONAL AGGREGATES 10.1088/0004- 637X/789/2/158	Ronald-Lo uis Ballouz , De rek C. Ric hardson , Patri ck Michel , Stephen R. Sc hwartz	Astrophysical Journal	Vol. 789/I ssu e 2	Institute of Physics Publishing	United Kingdom	10/07/2014	158		Peer revie wed
12	Low-speed impact simulations into regolith in support of asteroid sampling mechanism design I: Comparison with 1-g experiments 10.1016/j.pss .2014.07.013	Stephen R. Schwartz , Pat rick Michel , Derek C. Ri chards on , Hajime Yano	Planetary and Space Science	Vol. 103	Elsevier Limited	United Kingdom	01/11/2014	174-183		Peer revie wed
13	Numerical simulations of collisional dis ruption of rotating gravitationa l aggreg ates: Dependence on material properties 10.1016/j.pss .2014.06.003	R.-L. Ballouz , D.C. Rich ardso n , P. Michel , S.R. Schwartz , Y. Yu	Planetary and Space Science	Vol. 107	Elsevier Limited	United Kingdom	01/03/2015	29-35		Peer revie wed
14	NEOShield - A global approach to NEO Impact Threat Mitigation 10.1017/S1743 921314011843	Patrick Mi chel	Proceedings of the Internationa l Astrono mical Union	Vol. 10/Is sue H16	Cambridge University Press	United Kingdom	01/08/2012	478-479		Peer revie wed
15	The potentially hazardous Asteroid (2148 69) 2007 PA8: An unweathered L chon drite analog surface 10.1016/j.ica rus.2014.12.015	S. Fornasie r , I.N. Belskaya , D. Perna	Icarus	Vol. 250	Academic Press Inc.	United States	01/04/2015	280-286		Peer revie wed
16	Nongravitatio nal perturbations and virtual impactors: the case of asteroid (410777) 2 009 FD 10.1051/0004- 6361/201424743	Federica S poto , Andrea Milani , Da vide Farnocch ia , Steven R. Chesley , Ma rco Micheli , Giovanni B. Valsecchi , Da vide Perna , Olivier Hain aut	Astronomy and Astrophysics	Vol. 572	EDP Sciences	France	01/12/2014	A100		Peer revie wed
17	Momentum Transfer in Hypervelocity Impact Experiments on Rock Targets 10.1016/j.pro eng.2015.04.027	Tobias Hoerth , Frank Sch äfer , Jan Hupfer , Olive	Procedia Engineering	Vol. 103	Elsevier BV	Netherlands	01/01/2015	197-204		Peer revie wed

		r Millon , Matthias Wickert								
	Near-Earth Objects 10.1016/B978- 0-12-415845-0.00027-X	Alan W. Ha rris , Line Dru be , Lucy A. McFadden , R ichard P. Binzel	Encyclopedia of the Solar System		Elsevier	Amsterdam	06/06/2014	603-623	No	Article
	NEOSHIELD - A Global Approach to Ne ar-earth ObjectNEAR-E ARTH OBJECT Impact ThreatIMPACT THREAT Mitig ation 10.1007/978-3 -319-03952-7_61	L. Drube , A. W. Harris , T. Hoerth , P. Michel , D. Pe rna , F. Schäfe r	Handbook of Cosmic Hazards and Plan etary Defense		Springer Internationa l Publishing	Cham	01/01/2015	763	No	Article
	Integrated End-To-End NEO Threat Mi tigation Software Suite	Juan L. Cano, Gabriele Be llei, Javier Ma rtín	64th Internationa l Astronautica l Congress		International Astron autica l Federation		23/09/2013		Yes	Conference
	Mission Architectures and Technologies to Enable NEOshield, a Global Approach to NEO Impact Threat Mitigation	Noah Saks, Alan Harris, C raig Brown, Marc Chapuy, Noela Despre, Juan L. Cano, Gabriele Bel lei	63rd Internationa l Astronautica l Congress		International Astron autica l Federation		01/10/2012		Yes	Conference
	NEOShield Study of Hypervelocit y Im pacts into Small Bodies: Simulating the Fate of Ejecta	S. R. Schw artz, P. M ichel	45th Lunar and Planetary Science Confere nce (2014)		Lunar and Planetary Institute	Houston, Texas, USA	20/03/2014	2415	Yes	Conference
	High Precision Astrometry in Asteroid Mi tigation - the NEOShield Perspective	S. Eggl, A. Ivantsov, D. Hestroff er, D. Perna, D. Bancelin , W. Thuillot	SF2A-2013: Proceedings of the Annual meeting of the French Society of Astro nomy and Astrophysics . Eds.: L. Cam bresy, F. Martins, E. Nuss, A. Palacios, pp.169-176		French Society of As tronomy & Astro physics		07/06/2013	169-176	Yes	Conference
	Are we producing PHAs? On the target sel ection for a proposed mitigation demo-mi ssion within the NEO-Shield project	S. Eggl, D. Hestroffer, W .Thuill ot	European Planetary Science Congress 2013 , held 8-13 September in London, UK		European Planetary S cience Congress		12/09/2013	EPSC2013- 9 36	Yes	Conference
	GNC Design and Performance of a Liq uid-Fuelle d Asteroid Kinetic Impactor	M. Chapuy, P. Vernis, N.	GNC 2014: 9th Internationa l ESA Con ference on Guidance, Navigation, and Con		ESA		05/06/2014		Yes	Conference

		Despre', F. Capolupo	trol Systems, Porto, Portugal							
	Metallic asteroids in the IRAS minor planet survey — a NEOShield study	L. Drube, A.W. Harris	ACM 2014		The ACM Conference		01/07/2014		Yes	Conference
	How to find metal-rich asteroids — a NEO Shield study	A.W. Harris, L. Drube	ACM 2014		The ACM Conference		01/07/2014		Yes	Conference
	Physical Property Requirements of a Target Asteroid for a Mitigation Demonstratio n Mission	L. Drube, A.W. Harris, A. Barucci, M. Fulchign oni, D. Perna	DPS 2012		Division for Planetary Sciences of the A merican Astronomical Society		14/10/2012		Yes	Conference
	The NEOShield Project: Understanding the Mitigation-Re levant Physical Properties of Potentially Hazardous Asteroids	A.W. Harris, L. Drube	DPS 2012		Division for Planetary Sciences of the A merican Astronomical Society		14/10/2012		Yes	Conference
	Numerical Simulations of Granular Proces ses	Richardso n, D.C, Michel, P., Schwartz , S.R., Ballouz, R.L., Yu, Y., Matsumar a, S .	DPS 2014		Division for Planetary Sciences of the A merican Astronomical Society		10/11/2014		Yes	Conference
	Analysis of ejecta fate from proposed ma n-made impactors into near-Earth objects --- a NEOShield study	Schwartz, S.R., Michel, P., Jutzi, M.	ACM 2014		The ACM conference		01/07/2014		Yes	Conference
	Eccentricity estimates in hierarchical triple systems	Georgakar a kos, N. & Eggl, S.	International Astronomical Union Symposi um 310		Cambridge Univ. Pres s		05/01/2015	88-89		Conference
	Close encounters of Near Earth Objects w ith large asteroids	Ivantsov, A., Eggl, S., H estroff er, D., Thuillot , W., & Gurfil, P.	International Astronomical Union Symposi um 310		Cambridge Univ. Pres s		05/01/2015	164-165		Conference
	PôDET : A Centre for Earth Dynamical Environment	Hestroffe r, D.; Deleflie, F.	SF2A-2013: Proceedings of the Annual meeting of the French Society of Astro nomy and Astrophysics . Eds.: L. Cam bresy, F. Martins, E. Nuss, A. Palacios		French Society of As tronomy & Astro physics		01/11/2013	183-188		Conference
	GNC Design for Asteroid Orbit Modificati on Missions	M. Hagenfel dt, J.L. Cano,	AIAA Guidance, Navigation, and Control Conference		AIAA		19/08/2013		Yes	Conference

		L.F. Peñín, C. Bombardel li, J. Peláez, E. Luraschi , A. Gálvez								
	NEO Threat Mitigation Software Tools wit hin the NEOShield Project and Application to 2015 PDC	J.L. Cano, J. Martín, G. Bellei	IAA Planetary Defense Conference 2015		IAA		16/04/2015		Yes	Conference

LIST OF DISSEMINATION ACTIVITIES								
No.	Type of activities	Main Leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
1	Press releases	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Project NEOShield: Asteroid defence systems	03/02/2012	DLR, Cologne, G ermany	Medias		All
2	Articles published in the popular press	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	When things get too close for comfort	01/04/2013	DLR magaz#ne 136 · 137	Civil society		Germany, DLR in ternational partners
3	Interviews	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Stopping asteroid st rikes: Defenders of the Earth	29/06/2013	The Economist	Civil society		All
4	Interviews	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	NEOShield to assess Earth defence	20/01/2012	BBC	Civil society		All
5	Interviews	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Europe is devel oping an asteroid sh ield	27/01/2012	Daily Mail, UK	Civil society		UK
6	Interviews	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Scientists race to b uild asteroid shield	28/01/2012	Daily Mirror, UK	Civil society		UK
7	Interviews	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	"NEOShield": De utsche Raumfahr tagentur will Astero iden abwehren	30/01/2012	German.China.Or g.CN	Civil society		Germany, China
8	Interviews	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	NASA: Asteroid flyby next week will be closest for a sp ace rock so large	07/02/2013	The Washington Post	Civil society		USA, world
9	Interviews	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Abwehr von Aste roiden: Globale Antworten auf eine globale Bedrohung	14/02/2013	Neue Zuercher Z eitung, Switzerland	Civil society		Switzerland, Ge rmany, Austria

10	Interviews	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Rendezvous mit einem kosmischen Besucher	15/02/2013	Frankfurter All gemeine Zeitung	Civil society		Germany
11	Interviews	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Der Asteroidenjäger	15/02/2013	Frankfurter All gemeine Zeitung	Civil society		Germany
12	Interviews	THE QUEEN'S UNI VERSITY OF BELFAST	Asteroids and how to deflect them	18/02/2013	The Guardian, UK	Civil society		UK
13	Interviews	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Wenn sie uns zu nahe kommen	20/02/2013	Frankfurter All gemeine Zeitung	Civil society		Germany
14	Interviews	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	The Odds of an Asteroid Strike	27/03/2013	PBS Nova Next, USA	Civil society		USA, world
15	Interviews	CENTRE NAT IONAL DE LA RECHERCHE SCI ENTIFIQUE	Risque d'astéroïde : "On est loin de sav oir quoi faire et qu elle décision prendr e"	23/04/2013	TF1 News, France	Civil society		France
16	Interviews	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Kosmische Bomben – Strategien gegen eine tödliche Gefahr	25/07/2013	Mannheimer Morg en, German news paper	Civil society		Germany
17	Interviews	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Gefahr aus dem All	01/02/2014	Terra Mater Mag azine, Austria	Civil society		Austria, Germany, Switzerland
18	TV clips	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Dara O Briain's Scie nce Club: "Life, Dea th and Extinction"	12/01/2013	BBC Television, UK	Civil society		UK
19	TV clips	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Planetary Defense	01/07/2013	NASA Edge Telev ision, USA	Civil society		All
20	TV clips	DEUTSCHES	Gefahr aus dem All:	03/12/2013	WDR German Tele	Civil society		Germany

		ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Wenn Asteroiden das Leben auslösche n		vision			
21	TV clips	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Erde an Zukunft: Von Asteroiden, Me teoriden und Sternsc hnuppen	28/09/2013	KIKA TV (A RD/ZDF) German children's television	Civil society		Germany
22	TV clips	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Accidents and astero ids: Addressing the threat	21/02/2014	Euronews Televi sion	Civil society		Europe
23	Films	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Meteorite - Boten au s dem All	20/12/2012	Servus TV, Aust rian Television	Civil society		Austria, Germany, Switzerland
24	Videos	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Gefahr aus dem All	05/11/2012	WQ-TV (internet)	Civil society		Germany
25	Press releases	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	The tell-tale radiat ion from metallic as teroids	02/04/2014	DLR, Cologne, G ermany	Civil society		Germany, all
26	Web sites/Appli cations	ASTRIUM GMBH	www.NEOShield.n et	26/01/2012	www.NEOShield.n et	Scientific comm unity (higher educat ion, Research) - Ind ustry - Civil society - Policy makers - Medias		Worldwide
27	Web sites/Appli cations	ASTRIUM GMBH	NEOShield Faceb ook profile	20/06/2012	www.facebook.co m/NEOShield	Scientific comm unity (higher educat ion, Research) - Ind ustry - Civil society - Policy makers - Medias		Worldwide
28	Web sites/Appli cations	ASTRIUM GMBH	NEOSHield Twitter Tweets	15/10/2012	www.twitter.com /NEOShieldTeam	Scientific comm unity (higher educat ion, Research) - Ind ustry - Civil society - Policy makers - Medias		Worldwide

29	Articles published in the popular press	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Metallische Asteroid en sind kälter	01/07/2014	Sterne und Welt raum	Civil society		German-speaking
30	Oral presentation to a scientific event	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	NEOShield – ein europäisches Projekt zur Asteroidenabwe hr	14/03/2013	Heidelberg, Ger many	Scientific comm unity (higher educat ion, Research)		Germany
31	Oral presentation to a scientific event	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	NEOShield: prog ress towards an inte rnational near-Earth object mitigation p rogram	15/04/2013	Planetary Defense Conf., Flagstaff, Arizona, USA	Scientific comm unity (higher educat ion, Research)		All
32	Posters	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	NEOShield: the physical properties of the most frequent impactors	15/04/2013	Planetary Defense Conf., Flagstaff, Arizona, USA	Scientific comm unity (higher educat ion, Research)		All
33	Posters	THE QUEEN'S UNI VERSITY OF BELFAST	Choosing NEO mi ssion targets: current knowledge and fut ure Earth-based obse rvation opportunities	15/04/2013	Planetary Defense Conf., Flagstaff, Arizona, USA	Scientific comm unity (higher educat ion, Research)		All
34	Posters	OBSERVATOIRE DE PARIS	Requirements for mitigation precursor reconnaissance, a study from the NEOShield project	15/04/2013	Planetary Defense Conf., Flagstaff, Arizona, USA	Scientific comm unity (higher educat ion, Research)		All
35	Oral presentation to a scientific event	OBSERVATOIRE DE PARIS	The asteroid impact threat: instrumentat ion for mitigation p recursor and demo missions, a study from the NEOShield project	09/09/2013	European Planetary Science Congress, London, UK	Scientific comm unity (higher educat ion, Research)		All
36	Oral presentation to a scientific event	OBSERVATOIRE DE PARIS	The asteroid impact threat and the Europ ean NEOShield p roject	19/11/2013	University of S cience and Tech nology, Hanoi, Vietnam	Scientific comm unity (higher educat ion, Research)		Vietnam, France
37	Oral presentation to a scientific event	OBSERVATOIRE DE PARIS	The asteroid impact threat, the European NEOShield project, and beyond	12/03/2014	INAF - Rome Obs ervatory, Italy	Scientific comm unity (higher educat ion, Research)		Italy

38	Oral presentation to a scientific event	OBSERVATOIRE DE PARIS	On the post mitigati on impact risk asses sment of possible ta rgets for an asteroid deflection demonst ration mission in the NEOShield project	29/04/2014	AAS/DDA Meeting , Philadelphia, USA	Scientific comm unity (higher educat ion, Research)		USA, all
39	Oral presentation to a scientific event	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Beyond NEOShield: A roadmap for nea r-Earth object impac t mitigation	08/05/2014	Glasgow, Scotland, UK	Scientific comm unity (higher educat ion, Research)		All
40	Oral presentation to a wider public	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	From dust to dust – a cosmic cycle	12/05/2014	Leeds, UK	Civil society		UK
41	Oral presentation to a scientific event	OBSERVATOIRE DE PARIS	Propriétés physiques des astéroïdes géoc roiseurs : le point de vue de NEOShield	27/05/2014	3rd ESEP Day, O rléans, France	Scientific comm unity (higher educat ion, Research)		France
42	Oral presentation to a scientific event	OBSERVATOIRE DE PARIS	NEOShield: une approche globale vis ant à atténuer le ri sque d'impact des as téroïdes	27/05/2014	3rd ESEP Day, O rléans, France	Scientific comm unity (higher educat ion, Research)		France
43	Organisation of Workshops	OBSERVATOIRE DE PARIS	STRATEGICAL AND SCIENTIFIC ASPECTS OF THE ASTEROID IMPA CT THREAT: The NEOShield persp ective	03/07/2014	Marina Congress Center, Helsinki, F inland	Scientific comm unity (higher educat ion, Research) - Ind ustry - Policy makers		All
44	Oral presentation to a scientific event	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Asteroid impacts and modern civilis ation - can we preve nt a catastrophe?	04/03/2015	Queen's University Belfast	Scientific comm unity (higher educat ion, Research)	30	UK
45	Oral presentation to a scientific event	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	The achievements of the NEOShield P roject and the promi se of NEOShield#2	13/04/2015	Planetary Defense Conf., ESRIN, Fra scati, Italy	Scientific comm unity (higher educat ion, Research) - Ind ustry		All
46	Oral presentation to a scientific event	DEUTSCHES ZENTRUM FUER LUFT - UND R	A kinetic-impactor d emonstration mi ssion to change the	16/04/2015	Planetary Defense Conf., ESRIN, Fra scati, Italy	Scientific comm unity (higher educat ion, Research) - Ind		All

		AUMFAHRT EV	spin of an asteroid			ustry			
47	Oral presentation to a scientific event	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE	NEOShield - A global approach to NEO Impact Threat Mitigation	29/08/2012	General Assembly of the IAU, Special Session 7, Beijing (China)	Scientific community (higher education, Research)			All
48	Oral presentation to a wider public	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE	Les astéroïdes: amis ou ennemis	29/11/2013	Conservatoire National des Arts et Métiers (CNAM), Paris, France	Civil society			France
49	Oral presentation to a wider public	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE	Astéroïdes: conquête spatiale et risques d'impact	12/10/2013	Nice, France	Civil society			France
50	Oral presentation to a wider public	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE	A la conquête spatiale des astéroïdes	16/05/2014	Gassin, France	Civil society			France
51	Oral presentation to a wider public	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE	Astéroïdes: conquête spatiale et risques d'impact	13/12/2013	Saint-Tropez	Civil society			France
52	Interviews	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE	Radio France Inter: Emission "On verra ça demain", sujet "Le jour où le ciel nous tombera sur la tête"	03/07/2012	Paris, Radio France	Civil society - Medias			France
53	Interviews	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE	Radio France Inter: Emission "3D, Le Journal", sujet "Les astéroïdes"	16/03/2014	Paris, Radio France	Civil society - Medias			France
54	Oral presentation to a wider public	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE	Collisions dans le Système Solaire	24/04/2015	Lycée Carnot, Cannes	Civil society			France
55	Oral presentation to a scientific event	OBSERVATOIRE DE PARIS	Characterizing the near#Earth asteroid population in the framework of the NEOShield project	14/04/2015	Planetary Defense Conf., ESA-ESRIN, Frascati, Italy	Scientific community (higher education, Research)			All
56	Posters	OBSERVATOIRE	Les astéroïdes géocr	02/10/2014	COLLOQUE DU	Scientific comm			France

		DE PARIS	oiseurs : des origines du système solaire à l'atténuation du risque d'impact		PROGRAMME NATIONAL DE PLANETOLOGIE, Paris	unity (higher education, Research)		
57	Oral presentation to a scientific event	OBSERVATOIRE DE PARIS	STRATEGICAL AND SCIENTIFIC ASPECTS OF THE ASTEROID IMPACT THREAT: The NEOShield perspective	28/11/2014	Assemblée Générale ESTERS, Paris	Scientific community (higher education, Research)		France
58	Oral presentation to a scientific event	OBSERVATOIRE DE PARIS	NEOShield: Post Mitigation Impact Risk Assessment For Asteroid Deflection Demonstration Missions	15/04/2015	Planetary Defense Conf., ESA-ESRIN, Frascati, Italy	Scientific community (higher education, Research)		All
59	Posters	OBSERVATOIRE DE PARIS	NEOShield: Finding safe harbors in asteroid deflection missions	15/04/2015	Planetary Defense Conf., ESA-ESRIN, Frascati, Italy	Scientific community (higher education, Research)		All
60	Oral presentation to a scientific event	OBSERVATOIRE DE PARIS	Strategies For Secure And Recovery Near#Earth Objects	13/04/2015	Planetary Defense Conf., ESA-ESRIN, Frascati, Italy	Scientific community (higher education, Research)		All
61	Interviews	OBSERVATOIRE DE PARIS	Konferenz der Weltretter: Ein Besuch bei der Planetary Defense Conference	24/04/2015	Scienceblogs.de	Civil society		Germany
62	Interviews	OBSERVATOIRE DE PARIS	Un cargo spatial hors de contrôle entame sa chute vers la Terre	29/04/2015	francetvinfo.fr	Civil society		France
63	Oral presentation to a scientific event	OBSERVATOIRE DE PARIS	Asteroid deflection test mission concepts - a European perspective	23/03/2015	NASA - Jet Propulsion Laboratory, Pasadena, California, USA	Scientific community (higher education, Research)		USA
64	Oral presentation to a scientific event	OBSERVATOIRE DE PARIS	Post mitigation impact risk analysis for Kinetic Impactors and Gravity Tractors	16/03/2015	NASA - Ames Research Institute, Mountain View, California, USA	Scientific community (higher education, Research)		USA

65	Oral presentation to a scientific event	OBSERVATOIRE DE PARIS	PoDET: A Hub For Dedicated Orbits A nd Ephemerides Computations And General Predictions	13/04/2015	Planetary Defense Conf., ESA-E SRIN, Frascati, Ital y	Scientific comm unity (higher educat ion, Research)		All
66	Oral presentation to a scientific event	OBSERVATOIRE DE PARIS	On the post mitigati on impact risk asses sment of possible ta rgets for an asteroid deflection demonst ration mission in the NEOShield project	29/04/2014	American Astron omical Society, Division of Dy namical Astronomy meeting #45, Phil adelphia, USA	Scientific comm unity (higher educat ion, Research)		USA, All
67	Oral presentation to a scientific event	OBSERVATOIRE DE PARIS	Increasing Space Sit uational Awareness for NEOs	06/05/2015	American Astron omical Society, Division of Dy namical Astronomy meeting #46, Pasa dena, USA	Scientific comm unity (higher educat ion, Research)		USA, All
68	Posters	OBSERVATOIRE DE PARIS	Triangulation of nea r earth objects by e arth based observers	16/09/2013	Planetary Defense Conf., Flagstaff, Arizona, USA	Scientific comm unity (higher educat ion, Research)		All
69	Oral presentation to a wider public	OBSERVATOIRE DE PARIS	NEOshield: aste roides geocroiseurs voisins de la Terre	02/11/2012	Rencontres de C &E, La Villette, Par is	Civil society		France
70	Oral presentation to a scientific event	OBSERVATOIRE DE PARIS	Quantifying low NEO impact pro babilities in the NE OShield project	27/05/2014	3rd ESEP Day, O rléans, France	Scientific comm unity (higher educat ion, Research)		France
71	Interviews	DEUTSCHES ZENTRUM FUER LUFT - UND R AUMFAHRT EV	Wie man Himmels körper ablenken könnte	29/05/2015	Deutsche Welle Podcast: Wissen schaft	Civil society		German-speaking
72	Flyers	AIRBUS DS GMBH	NEOShield Promo tional Material	13/04/2015	Frascati, Italy	Scientific comm unity (higher educat ion, Research)		All
73	Oral presentation to a wider public	AIRBUS DS GMBH	SpaceUp Paris U nconference: Present ation of NEOShield	25/05/2013	Paris, France	Civil society		All
74	Oral presentation to a wider public	AIRBUS DS GMBH	Family Day Frie drichshafen: Present ation of NEOShield	20/07/2013	Friedrichshafen, Germany	Civil society		Germany

75	Oral presentation to a scientific event	AIRBUS DS GMBH	International S PACE World 2013: Presentation of NE OShield	05/11/2013	Frankfurt/Main, Germany	Scientific comm unity (higher educat ion, Research)		Germany, All
76	Oral presentation to a scientific event	AIRBUS DS GMBH	DoDDs-Europe ST EMposium: Prese ntation of NEOS hield	18/11/2013	Germany	Scientific comm unity (higher educat ion, Research)		Germany, All
77	Oral presentation to a scientific event	AIRBUS DS GMBH	50th session of UN COPUOS: Presenta tion of NEOShield	11/02/2014	Vienna, Austria	Scientific comm unity (higher educat ion, Research)		All
78	Oral presentation to a wider public	AIRBUS DS GMBH	SpaceUp UK Unco nference: Presentati on of NEOShield	05/07/2014	London, UK	Civil society		UK, All
79	Oral presentation to a scientific event	AIRBUS DS GMBH	Presentation of the NEOShield Public Outreach	15/04/2015	Planetary Defense Conference, Rome/ Frascati, Italy	Scientific comm unity (higher educat ion, Research)		All
80	Web sites/Appli cations	AIRBUS DS GMBH	Comic Contest and Twitter Q&A sessi on	04/10/2013	World Space Week ; www.NEOShie ld.net ; www.twitter .com/NEOShieldT eam	Civil society - Medi as		All
81	Web sites/Appli cations	AIRBUS DS GMBH	NEOShield Catch ing Comets Contest	16/05/2014	www.NEOShield.n et	Civil society		All
82	Oral presentation to a wider public	AIRBUS DS GMBH	Presentation of NEOShield with film at Dornier Mus eum	01/10/2013	Friedrichshafen, Germany	Civil society		Germany
83	Organisation of Workshops	AIRBUS DS GMBH	Mission Zukunft	01/10/2012	Baden-Württembe rg, Germany	Civil society		Germany
84	Web sites/Appli cations	AIRBUS DS GMBH	NEOShield Noël	10/12/2012	www.NEOShield.n et	Civil society		All
85	Oral presentation to a wider public	AIRBUS DS GMBH	Presentation of NEOShield at the EU Open Doors 201 3	04/05/2013	Brussels, Belgium	Civil society		Europe, All
86	Oral presentation to a wider public	AIRBUS DS GMBH	SpaceUp Stuttgart U nconference	27/10/2012	Stuttgart, Germany	Civil society		Germany, All
87	Oral presentation to	AIRBUS DS	Presentation of	05/12/2012	Toulouse, France	Scientific comm		France, All

	a wider public	GMBH	NEOShield at the ENS Innovation Show			unity (higher education, Research) - Civil society		
88	Press releases	AIRBUS DS GMBH	Launching of the NEOShield project	09/01/2012	Online	Scientific community (higher education, Research) - Civil society		All

4.3 Report on societal implications

B. Ethics

1. Did your project undergo an Ethics Review (and/or Screening)?	Yes
If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final reports?	Yes

2. Please indicate whether your project involved any of the following issues :

RESEARCH ON HUMANS	
Did the project involve children?	No
Did the project involve patients?	No
Did the project involve persons not able to consent?	No
Did the project involve adult healthy volunteers?	No
Did the project involve Human genetic material?	No
Did the project involve Human biological samples?	No
Did the project involve Human data collection?	No
RESEARCH ON HUMAN EMBRYO/FOETUS	
Did the project involve Human Embryos?	No
Did the project involve Human Foetal Tissue / Cells?	No
Did the project involve Human Embryonic Stem Cells (hESCs)?	No
Did the project on human Embryonic Stem Cells involve cells in culture?	No
Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	No
PRIVACY	
Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	No
Did the project involve tracking the location or observation of people?	No
RESEARCH ON ANIMALS	

Did the project involve research on animals?	No
Were those animals transgenic small laboratory animals?	No
Were those animals transgenic farm animals?	No
Were those animals cloned farm animals?	No
Were those animals non-human primates?	No
RESEARCH INVOLVING DEVELOPING COUNTRIES	
Did the project involve the use of local resources (genetic, animal, plant etc)?	No
Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	No
DUAL USE	
Research having direct military use	Yes
Research having potential for terrorist abuse	No

C. Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator	0	1
Work package leaders	2	15
Experienced researchers (i.e. PhD holders)	4	31
PhD student	0	5
Other	14	44

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	11
Of which, indicate the number of men:	4

D. Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project ?	No

6. Which of the following actions did you carry out and how effective were they?	
Design and implement an equal opportunity policy	Not Applicable
Set targets to achieve a gender balance in the workforce	Not Applicable
Organise conferences and workshops on gender	Not Applicable
Actions to improve work-life balance	Not Applicable
Other:	

7. Was there a gender dimension associated with the research content - i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?	No
If yes, please specify:	

E. Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?	Yes
If yes, please specify:	open days, prizes, lectures, etc.

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?	Yes
If yes, please specify:	public website, flyers, on-line videos, articles in the popular literature, etc.

F. Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?	
Main discipline:	
Associated discipline:	1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]
Associated discipline:	1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)

G. Engaging with Civil society and policy makers

11a. Did your project engage with societal actors beyond the research community? (if 'No', go to Question 14)	Yes
11b. If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?	Yes, in communicating /disseminating / using the results of the project
11c. In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	No
12. Did you engage with government / public bodies or policy makers (including international organisations)	Yes, in communicating /disseminating / using the results of the project
13a. Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?	Yes - as a primary objective (please indicate areas below multiple answers possible)
13b. If Yes, in which fields?	
Agriculture	No
Audiovisual and Media	No
Budget	No
Competition	No
Consumers	No
Culture	No
Customs	No
Development Economic and Monetary Affairs	No
Education, Training, Youth	No
Employment and Social Affairs	No
Energy	No
Enlargement	No
Enterprise	No
Environment	No
External Relations	No
External Trade	No
Fisheries and Maritime Affairs	No
Food Safety	No
Foreign and Security Policy	Yes
Fraud	No

Humanitarian aid	No
Human rightsd	No
Information Society	No
Institutional affairs	No
Internal Market	No
Justice, freedom and security	No
Public Health	No
Regional Policy	No
Research and Innovation	Yes
Space	Yes
Taxation	No
Transport	No
13c. If Yes, at which level?	International level

H. Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	36
To how many of these is open access provided?	14
How many of these are published in open access journals?	0
How many of these are published in open repositories?	5
To how many of these is open access not provided?	3
Please check all applicable reasons for not providing open access:	
publisher's licensing agreement would not permit publishing in a repository	Yes
no suitable repository available	No
no suitable open access journal available	Yes
no funds available to publish in an open access journal	No
lack of time and resources	No
lack of information on open access	No
If other - please specify	
15. How many new patent applications ('priority filings') have been made? ("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).	0

16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	
Trademark	0
Registered design	0
Other	0

17. How many spin-off companies were created / are planned as a direct result of the project?	0
Indicate the approximate number of additional jobs in these companies:	0

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:	Increase in employment, In large companies

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (FTE = one person working fulltime for a year) jobs:	0Difficult to estimate / not possible to quantify

I. Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?	Yes

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?	No

22. Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?	
Press Release	Yes
Media briefing	Yes
TV coverage / report	Yes
Radio coverage / report	Yes
Brochures /posters / flyers	Yes
DVD /Film /Multimedia	Yes
Coverage in specialist press	Yes
Coverage in general (non-specialist) press	Yes
Coverage in national press	Yes
Coverage in international press	Yes
Website for the general public / internet	Yes

Event targeting general public (festival, conference, exhibition, science café)	Yes

23. In which languages are the information products for the general public produced?	
Language of the coordinator	Yes
Other language(s)	Yes
English	Yes

Attachments	NEOShield_Aug_2015_Attachment_Final_Report.pdf
Grant Agreement number:	282703
Project acronym:	NEOShield
Project title:	A Global Approach to Near-Earth Object Impact Threat Mitigation
Funding Scheme:	FP7-CP-FP
Project starting date:	01/01/2012
Project end date:	31/05/2015
Name of the scientific representative of the project's coordinator and organisation:	Prof. Alan Harris DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV
Name	
Date	05/08/2015

This declaration was visaed electronically by Alan HARRIS (ECAS user name nharriaa) on 05/08/2015

NEOShield Final Report: Figures, Tables, Appendices 1 and 2

Figure 1. The trail left by the Chelyabinsk bolide. The left part of the image shows two contrarotating vortices formed by heating and buoyancy effects in the horizontal cylinder of air in which kinetic energy of the asteroid was deposited. The asteroid had a diameter of only 18 m yet produced a blast wave in the atmosphere that damaged thousands of buildings and caused injuries to some 1500 people. The high altitude of the airburst (> 20 km) and the shallow entry angle (about 17° from the horizon) combined to prevent a potentially far worse outcome. (Credit: Nikita Plekhanov; Wikimedia Commons.)

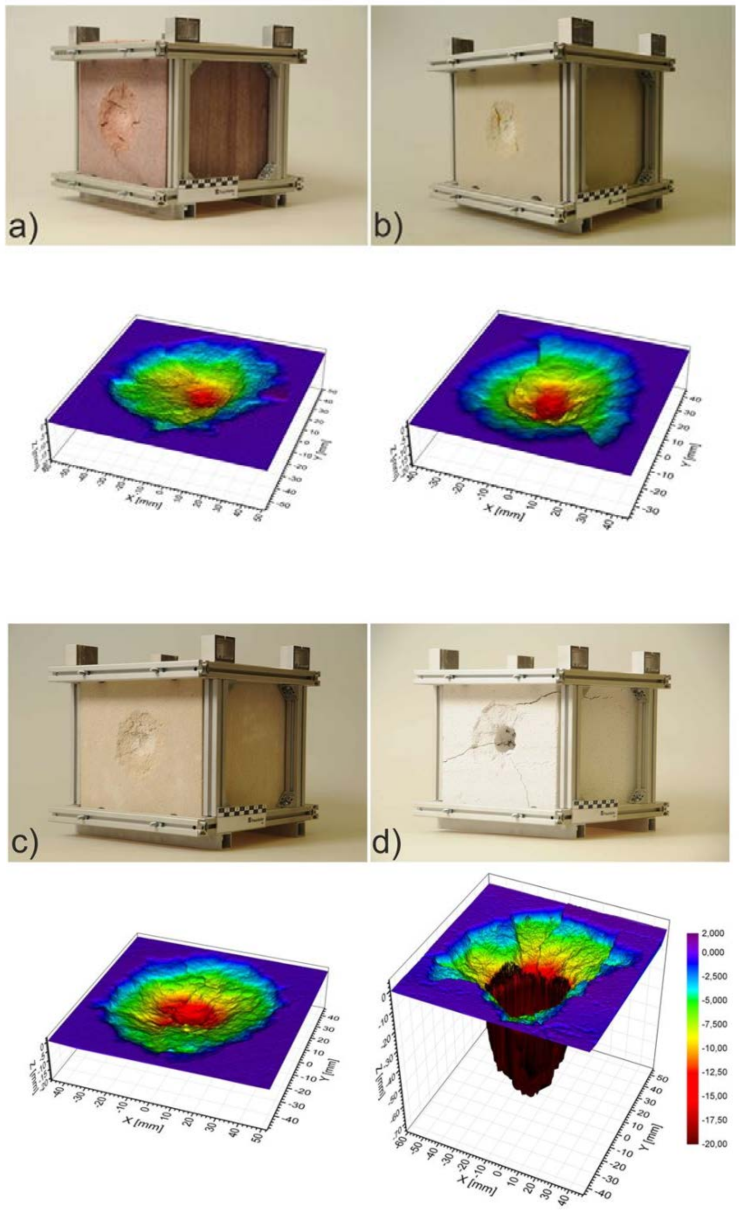

Figure 2a. Examples of the results of gas-gun experiments on asteroid surface analog materials carried out by NEOShield partner Fraunhofer Ernst Mach Institute, Freiburg, Germany. The impact craters in different target materials with porosities, ϕ, were formed by projectiles with approximately the same impact velocity: a. Quartzite (ϕ ~ 3 %); b. sandstone (ϕ ~ 25 %); c. limestone (ϕ ~ 31 %); d. aerated concrete (ϕ ~ 87 %). In each case a photograph of the target after the impact is shown above a three-dimensional model of the crater morphology. The colour code shown adjacent to the bottom right crater model applies to all four models. The experiments demonstrate that large craters are formed in highly porous material but in contrast, the ejected mass is small. (Credit: Fraunhofer EMI.)

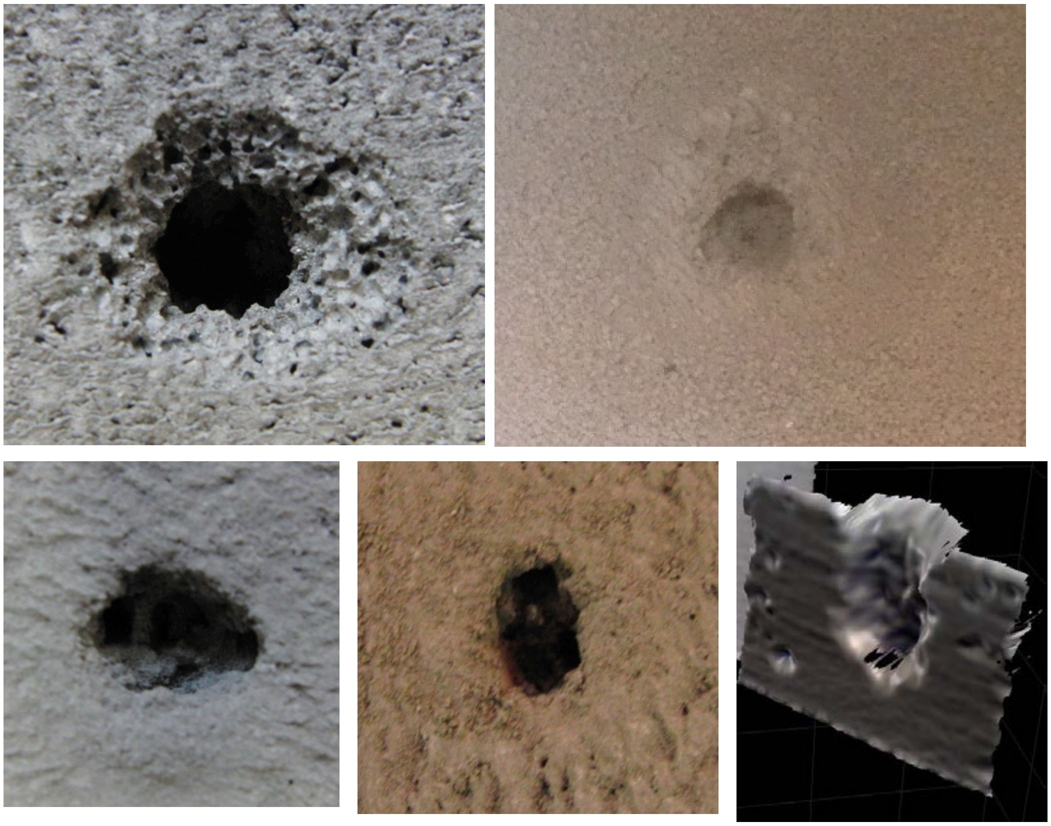

Figure 2b. Examples of the results of experiments with the all-angle gas gun operated by NEOShield partner Open University. The frames show craters in solid aerated concrete (top left), and with 5 mm (top right), 10 mm (lower left) and 20 mm (lower centre) overlying layers of regolith. Lower right: scan of the cross-section of the top left hand crater showing large depth/diameter ratio. The depth of the core crater is smaller for impacts with a regolith layer present but, for the small data set available, does not change with increasing regolith layer depth. This is true for regolith layers at least as thick as the crater depth in the solid target, indicating that particles penetrate much deeper in the regolith than they do in the solid. (Credit: Open University.)

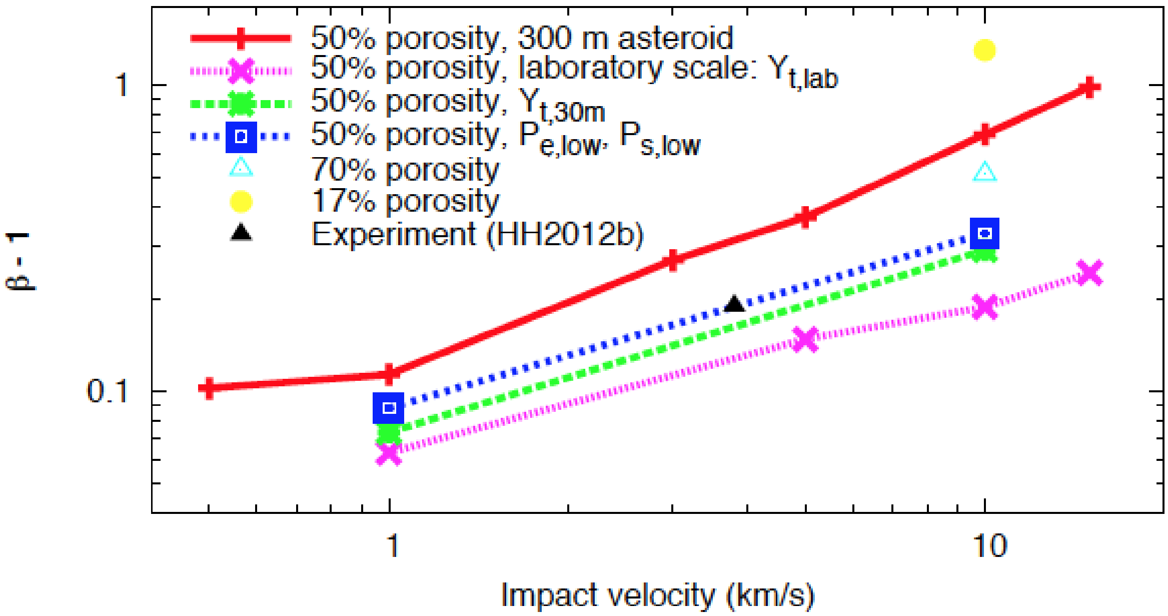

Figure 3. Momentum multiplication factor β-1 as a function of impact velocity, considering various strengths and porosities. The result of an impact experiment using a pumice target (Housen and Holsapple, 2012) is also shown. High tensile strengths, Y_t, corresponding to a 30 m ($Y_{t,30m}$) and a 3 cm ($Y_{t,lab}$) sized body, lead to less ejecta and therefore a smaller β. On the other hand, using a lower crushing strength (i.e., smaller crush-curve parameters Pe, Ps) leads to more compaction and therefore also less ejecta and smaller β. Increasing the porosity, while keeping the strength parameters constant, leads to a decreased β. Overall, our results are in reasonable agreement with the laboratory measurements of β in the case of a porous pumice target (Housen and Holsapple, 2012, 43rd LPSC, LPI Contribution No. 1659). Figure from Jutzi and Michel, 2014, Icarus 229:247-253.

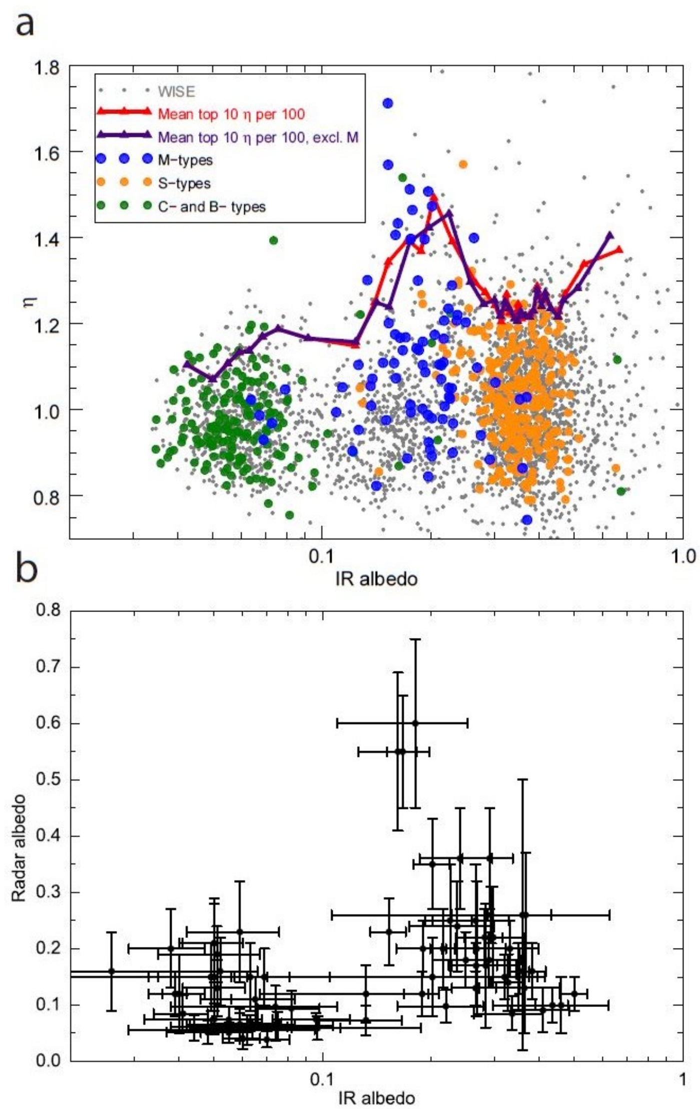

Figure 4.

a. WISE η values versus infrared albedo. η is a model fitting parameter derived by finding the model thermal continuum that best fits the measured infrared fluxes of a NEO; in general, η increases with thermal conductivity. Basic taxonomic types are shown as coloured bullets. The red curve is a plot of the mean of the highest 10 η values in bins of 100 data points; the purple curve is the same after removal of all the currently identified and suspected M (metallic) types from the dataset. The fact that the peak persists implies that many more metallic asteroids exist but remain unidentified to date.

b. Radar albedo versus WISE near-infrared albedo for main-belt asteroids. The broad clustering into 3 groups seen in (a) is also evident here, whereby the central group here corresponds to high radar albedo, and in (a) to a peak in η and the location of the M types.

Figure from Harris and Drube, 2014, Ap.J. Letters, 785:L4.

NEOShield mission target selection lists

Rendezvous targets			Fly-by targets		
Selected	All (Delta-v)	All (Name)	Selected	All (Delta-v)	All (Name)

All NEOs with Rendezvous delta-v < 6 km/sec, ordered by delta-v

Colour	MPC Orbital Uncertainty Code
White	0 - 1
Green	2 - 3
Orange	4 - 6

Warnings: CEU is an RMS uncertainty, the error ellipse may be significantly larger along the major axis.
Numbers in brackets () are inferred from other parameters and have not been directly measured.

	Number	Name	H	delta-v (km/s)	U (MPC)	CEU (")	D (km)	a/b	Albedo	Taxonomy	Period (hr)	Tumbling?	Binary?	PHA?
1		2006RH120	29.5	3.94	1	8.4		3.0			0.0458;0.03			
2		2012TF79	27.4	3.94	3	165								
3		2009BD	28.1	3.95	0	1.65	0.004		.45					
4		2010UE51	28.3	4.00	2	96								
5		2007UN12	28.7	4.00	3	246								
6		2008HU4	28.2	4.02	3	570								
7		2010VQ98	28.2	4.09	3	129								
8		2013XY20	25.5	4.12	3	60								
9		2012EC	23.4	4.13	2	39								
10		2013DA1	27.3	4.13	6	1470								
11		2008EA9	27.7	4.13	5	810								
12		1991VG	28.5	4.18	2	273								
13		2013EC20	29.0	4.20	5	135								
14		2012WR10	28.7	4.24	5	510								
15		2013BS45	25.9	4.25	0	2.4								
16		2014SU1	25.0	4.26	4	87								
17		2010AN61	27.0	4.26	5	14700								

Figure 5. Screenshot of the first 17 entries in the target selection list, here in order of increasing rendezvous dv for NEOs likely to be in the size range ~100 m to ~600 m. The total number of entries at the time of writing was 1163. The online list, which was updated regularly during the course of the project with new NEO discoveries and measurements of physical parameters, is currently located at http://star.pst.qub.ac.uk/~af/lowdv_neos/. (Credit: Queen's University, Belfast).

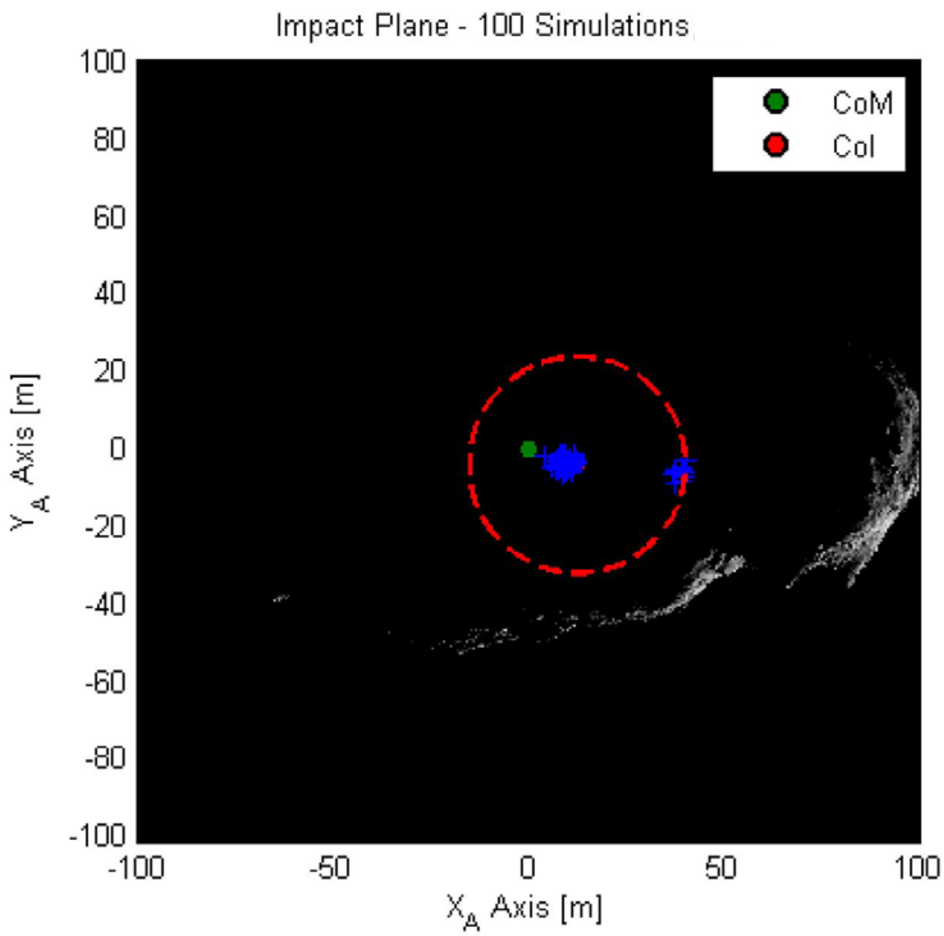

Figure 6. The results of 100 simulated impacts of a kinetic impactor into the NEO 2001 QC_{34}. Note that due to the very high phase angle at impact (roughly 140 degrees), only a very small sunlit horizon of the asteroid is visible. The last measurement and manoeuvre were 100 s prior to impact. The shape of the NEO Itokawa was assumed since the shape of 2001 QC_{34} is unknown. The largest diameter of the ellipsoid was taken to be 190 m, which was computed to be the smallest possible value given current knowledge and pessimistic uncertainty assumptions. The smallest diameter of the ellipsoid is around 100 m. A larger area would reduce the risk of missing the target and enhance the quality of the information provided by the vision-based navigation. The green bullet is the center of mass (CoM) of the asteroid, chosen as the reference target point. The red-dashed circle is a projection onto the image of the navigation error standard deviation envelope. The blue crosses are the individual points of impact of each of the 100 Monte Carlo runs. The red dot (just visible at the edge of the main cluster of blue crosses) is the averaged point of impact (centre of Impact, CoI). For most (~ 85%) of the impacts the performance is very good (within 12 m), with only a very small bias of some 5 - 7 m in the direction of the centre of brightness (CoB). The remaining 15% of impacts fell in a tight cluster 40 m away in the direction of the CoB, suggesting that the timing of the final measurement and manoeuvre (100 s before impact) may require revision. A preliminary investigation considered a last manoeuvre at 50 s prior to impact instead of 100 s which increased the performance by a factor of 2 and reduced the number of offset points from 15% to 3%. The overall performance of the system is well within the goal and commensurate with analytical expectations. See Deliverable 8.2 for further details.

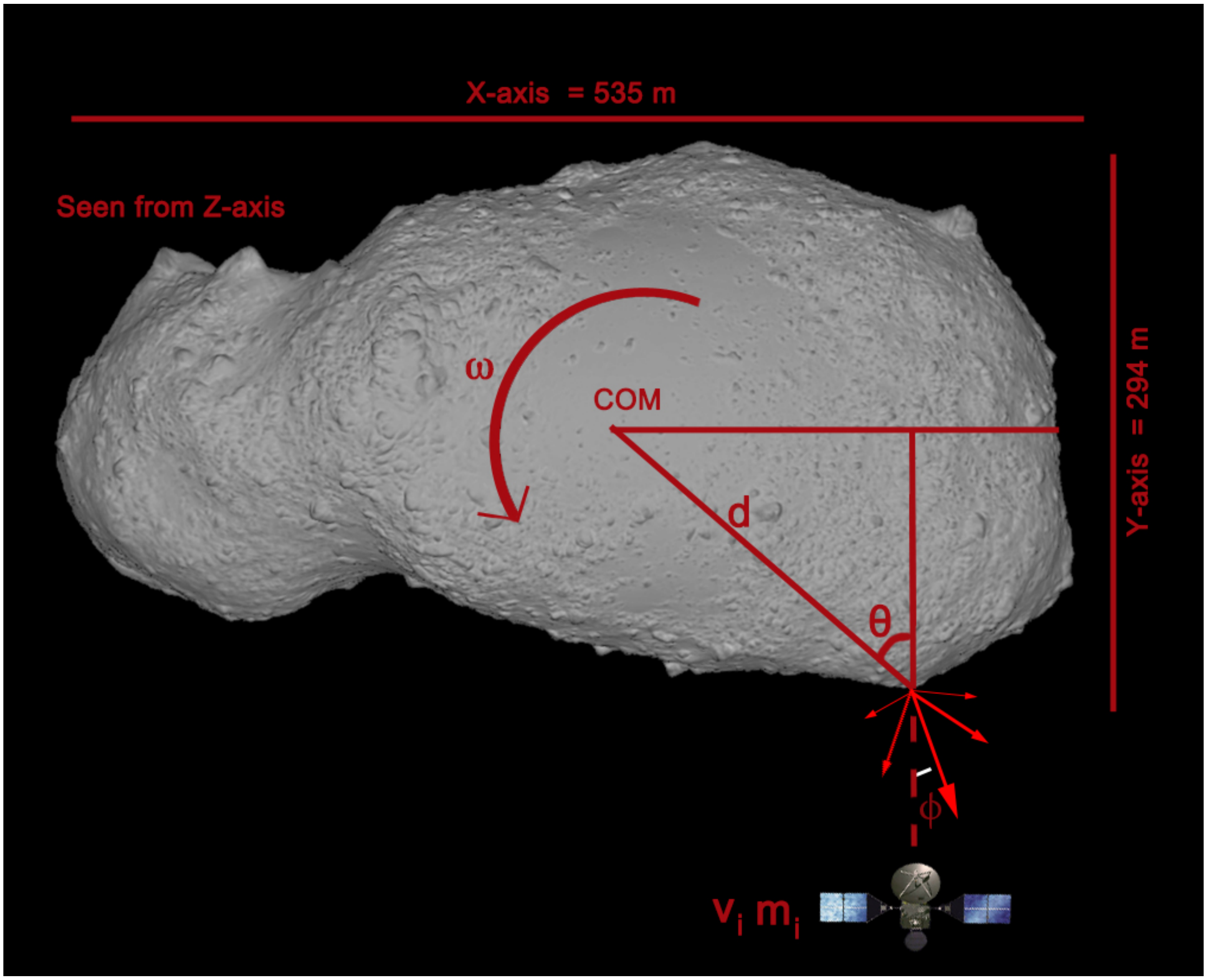

Figure 7. A kinetic impactor impacts off-center on Itokawa thereby changing its rotational period. Itokawa's dimensions are 535 x 294 x 209 m and it rotates around the Z-axis, which is perpendicular to the image. See Deliverable 9.6b for further details. Credit: Robert Gaskell produced the shape-model of Itokawa used.

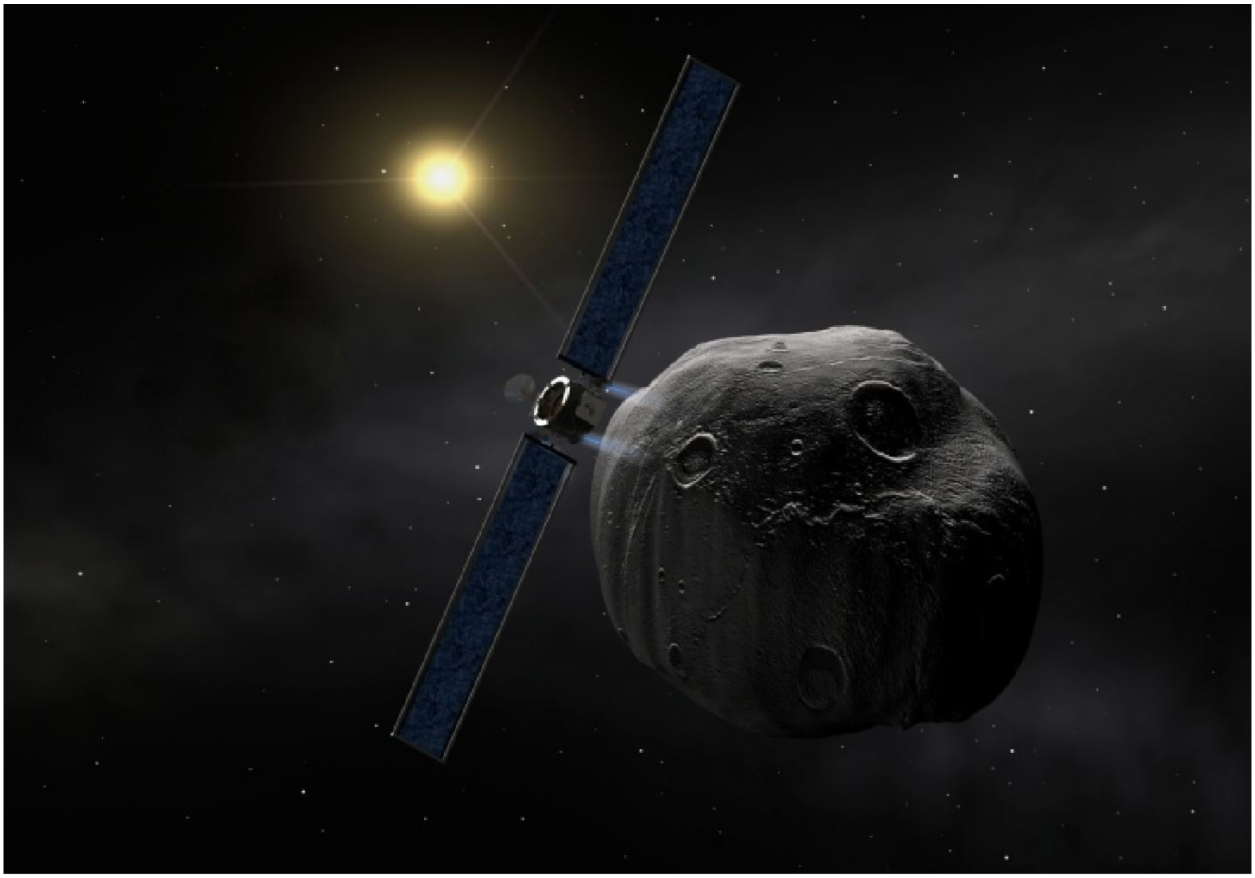

Figure 8. Artist’s impression of NEO deflection by means of a gravity tractor (from Deliverable 8.3, background image credit: ESO).

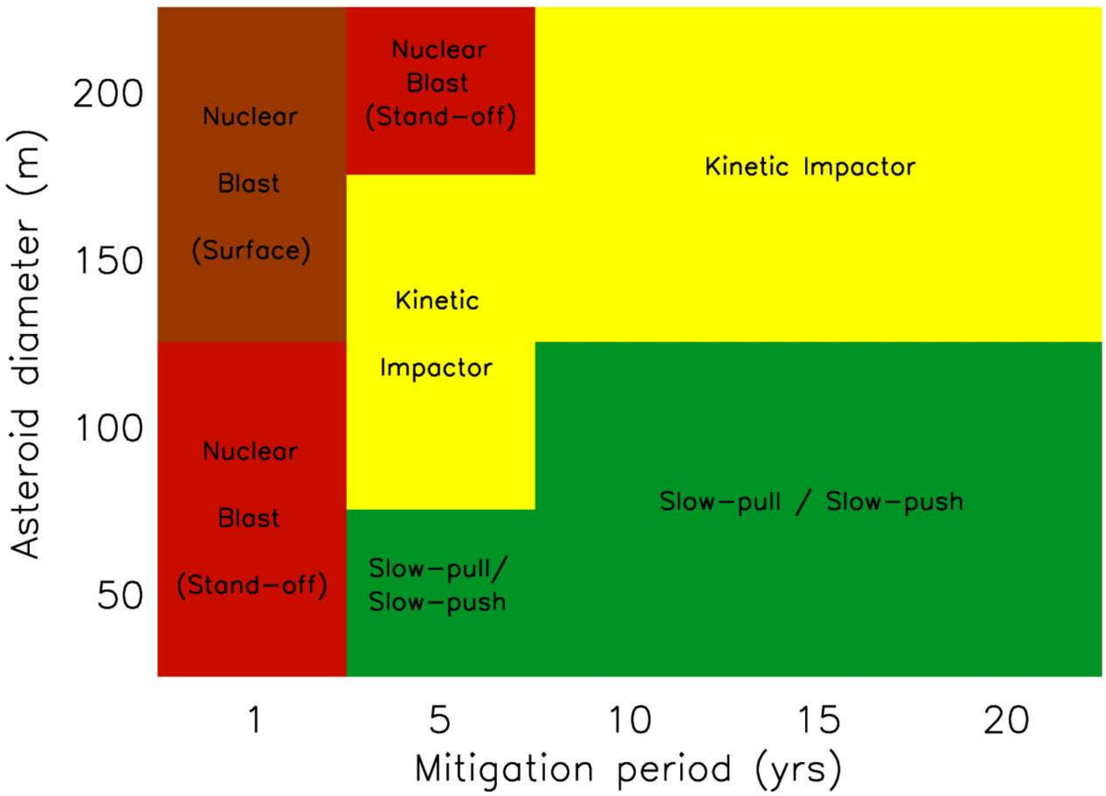

Figure 9. The best choice of space-mission deflection method, according to the results of the NEOShield trade-off study (Deliverable 7.5), is shown for realistic ranges of potential impactor size and time available for deflection of the NEO. "Mitigation period" is defined as the time between the start of the spacecraft's interaction with the asteroid and the predicted date of the impact of the NEO on the Earth. Accurately controllable slow-pull and slow-push techniques include the gravity tractor in addition to alternative approaches studied in less detail within NEOShield, such as the ion-beam shepherd and laser ablation. For very rare threatening NEOs much larger than 200 m, or mitigation periods shorter than a few years, nuclear blast deflection is deemed the best option. For objects smaller than 50 m, no space missions are foreseen, and "civil defence" actions (i.e., sheltering and evacuation measures) would probably be most appropriate. For intermediate scenarios, given current technology, the kinetic impactor appears to be the most viable deflection option. Figure credit: S. Eckersley (NEOShield, Airbus DS Limited, UK) and D. Perna (NEOShield, Observatoire de Paris, LESIA).

Table 1. NEOShield partner organisations

Partner name	Country	Role/main contributions WP = work package involvement (see Table 2)
German Aerospace Center (DLR) Institute of Planetary Research, Berlin	Germany	NEOShield project coordinator; NEO science: data analysis, modeling; global mitigation strategy; public outreach. WP 1, 2, 5, 9, 10
Airbus Defence & Space	Germany	Supervision of technical work; space mission design; public outreach. WP 1, 7, 8, 9, 10
Paris Observatory	France	NEO science: orbital dynamics, space-mission instrumentation; global mitigation strategy. WP 2, 5, 9
Centre National de la Recherche Scientifique (CNRS), Côte d'Azur Observatory	France	NEO science: computer modeling of NEO material and structural properties. WP 2, 3
The Open University	UK	NEO science: all-angle gas-gun experiments. WP 4
Fraunhofer Ernst Mach Institute, Freiburg	Germany	NEO science: horizontal gas-gun experiments, computer modeling of NEO material properties. WP 2, 3, 4
Queen's University Belfast	UK	NEO science: observations, data analysis, deflection test-mission target selection. WP 2, 5
Airbus Defence & Space	UK	NEO deflection techniques trade-off study; global mitigation strategy. WP 7, 8, 9
Airbus Defence & Space	France	Kinetic-impactor concept; space mission design. WP 6, 8
Elecnor Deimos	Spain	Kinetic-impactor concept; space mission design; global mitigation strategy. WP 6, 8, 9
Carl Sagan Center, SETI Institute, Mountain View, California	USA	Gravity tractor concept; space mission design. WP 7, 8, 9
TsNIIMash, Russian Federal Space Agency	Russia	Blast deflection concept; space mission design; global mitigation strategy. WP 7, 8, 9
University of Surrey	UK	Gravity tractor concept. WP 7

Table 2. NEOShield work packages

Work package no.	Description	Type of activity MGT = management RTD = Research/ technological development	Lead partner	Person-months
1	Consortium administrative and financial management.	MGT	DLR	30
2	NEO Physical properties.	RTD	Obs. Paris	76
3	Modelling/numerical simulations.	RTD	CNRS	73
4	Laboratory experiments.	RTD	Open University	57
5	Deflection demonstration mission target NEOs.	RTD	DLR	48
6	Kinetic impactor concept.	RTD	Elecnor Deimos	45
7	Alternative mitigation approaches.	RTD	Airbus DS UK	68
8	Design of appropriate demonstration missions for realistic scenarios.	RTD	Airbus DS Germany	63.5
9	Global response campaign roadmap.	RTD	Obs. Paris	51.5
10	Dissemination of results/Public outreach.	OTHER	DLR	21

Table 3. NEOShield results suggest that the listed NEOs, half of which are categorised as potentially hazardous, are relatively metal rich (from Harris and Drube, 2014, Ap.J. Letters, 785:L4)

THE ASTROPHYSICAL JOURNAL LETTERS, 785:L4 (5pp), 2014 April 10

Table 1
Candidate High Metal Content NEOs Passing the Filter $0.15 < p_{IR} \leqslant 0.3$; $\eta > 2.0$

NEO	Tax.	PHA?	D (km)	p_v	η	η_{err}	p_{IR}
138359		N	1.09	0.10	2.931	0.105	0.19
1865	S	N	1.61	0.14	2.902	0.036	0.27
152931	Q	N	1.65	0.24	2.884	0.138	0.24
152978	S:	Y	0.53	0.11	2.641	0.116	0.19
365071		Y	0.87	0.15	2.559	0.117	0.28
3554	X, M, D	N	3.05	0.09	2.411	0.072	0.19
215442		N	0.79	0.15	2.328	0.325	0.17
152558	S	N	1.36	0.18	2.284	0.051	0.28
366774	AS	Y	0.86	0.20	2.284	0.059	0.29
250680		Y	0.40	0.15	2.279	0.075	0.30
7822	S	Y	1.21	0.13	2.261	0.049	0.30
163243	S, Q	Y	1.68	0.17	2.191	0.061	0.23
263976	L	Y	0.79	0.13	2.165	0.043	0.18
142464		N	0.89	0.12	2.139	0.044	0.22
2002 NW16		N	0.85	0.16	2.118	0.066	0.26
103067	S	Y	1.28	0.25	2.114	0.056	0.29
363024		Y	0.56	0.10	2.055	0.067	0.24
325102		N	0.36	0.12	2.048	0.063	0.18

Notes. Taxonomic classifications are taken from the EARN database (http://earn.dlr.de/). A colon following the taxonomic class signifies an uncertain classification. All *WISE* sightings in the catalog, including multiple sightings of the same object, have been considered for the purposes of this table; due to measurement errors or different observational circumstances one record in the *WISE* catalog may pass the filter while another for the same object may not. The uncertainties in values of diameter and albedo derived from NEATM fitting are of the order of 15% and 30%, respectively (Mainzer et al. 2011a; Delbo' et al. 2003). For details of the NEO*WISE* data see Mainzer et al. (2011a).

NEOShield Final Report: Appendix 1

A Selection of NEOShield Public Outreach Items

Newspapers, internet (selection)

http://www.bbc.co.uk/news/science-environment-16651642 20 Jan. 2012

http://www.allesoversterrenkunde.nl/artikelen/1194-Europa-wil-voorbereid-zijn-als-de-hemel-omlaagvalt.html 21 Jan. 2012

http://www.lefigaro.fr/sciences/2012/01/24/01008-20120124ARTFIG00690-proteger-la-terre-contre-la-chute-d-un-asteroide.php 24 Jan. 2012

http://www.dw-world.de/dw/article/0,,6703710,00.html 25 Jan. 2012

http://www.francetv.fr/info/des-scientifiques-planchent-sur-la-deviation-d-asteroides-au-cas-ou_54551.html 25 Jan. 2012

http://www.spiegel.de/wissenschaft/weltall/0,1518,811368,00.html 26 Jan. 2012

http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10081/151_read-2536/ 26 Jan. 2012

http://www.space.com/14370-asteroid-shield-earth-threat-protection-meeting.html 27 Jan. 2012

http://www.sueddeutsche.de/wissen/asteroidenabwehr-vorbild-armageddon-1.1268537 27 Jan. 2012

http://www.dailymail.co.uk/sciencetech/article-2092626/Asteroid-shield-wont-time-19-mile-wide-monster-hurtling-past-Earth-week.html 27 Jan. 2012

http://news.yahoo.com/asteroid-threat-earth-sparks-global-neoshield-project-155016535.html

27 Jan. 2012

http://www.mirror.co.uk/news/technology-science/scientists-race-to-build-asteroid-shield-304366 28 Jan. 2012

http://www.nrk.no/vitenskap-og-teknologi/1.7965575 28 Jan. 2012

http://www.francesoir.fr/actualite/scienceecologie/asteroides-des-solutions-a-l-etude-pour-eviter-la-collision-178970.html 29 Jan. 2012

http://www.24heures.ch/savoirs/sciences/Bientot-un-bouclier-antiasteroides-pour-proteger-la-Terre/story/13281508 30 Jan. 2012

http://german.china.org.cn/international/2012-01/30/content_24508259.htm 31 Jan. 2012 http://www.astrium.eads.net/node.php?articleid=8210 31 Jan. 2012

http://www.lexpress.fr/actualite/sciences/comment-detourner-un-asteroide-qui-menace-la-terre_1076349.html 31 Jan. 2012

http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10081/151_read-2640/ 3 Feb. 2012

http://www.welt.de/wissenschaft/weltraum/article13849960/NEO-Shield-als-Abwehr-gegen-kosmische-Bomben.html 4 Feb. 2012

http://www.augsburger-allgemeine.de/wissenschaft/Schutzschild-gegen-den-Gott-der-Zerstoerung-id18634306.html 4 Feb. 2012

http://www.franceinfo.fr/sciences-sante/du-cote-des-etoiles/comment-se-proteger-des-asteroides-511667-2012-02-04 4 Feb. 2012

http://www.raumfahrer.net/news/astronomie/05022012181158.shtml 5 Feb. 2012

http://www.bild.de/news/ausland/asteroiden/forscher-wollen-asteroiden-sprengen-neu-22454458.bild.html 6 Feb. 2012

http://www.rp-online.de/wissen/weltraum/schutzschild-gegen-bomben-aus-dem-all-1.2701621

6 Feb. 2012

http://www.sciencepresse.qc.ca/blogue/2012/02/06/projet-neoshield-pour-ne-finir-dinosaures

6 Feb. 2012

http://www.spacedaily.com/reports/Project_NEOShield_Asteroid_defence_systems_999.html

7 Feb. 2012

http://www.sanfinna.com/?p=52685 7 Feb. 2012

http://www.morgenpost.de/web-wissen/article1903270/Wie-die-Erde-vor-Asteroiden-geschuetzt-werden-soll.html 11 Feb. 2012

http://www.welt.de/print/wams/vermischtes/article13863879/Rettung-vor-dem-grossen-Crash.html

12 Feb. 2012

http://www.universetoday.com/93595/neoshield-a-preemptive-strike-against-asteroids/

15 Feb. 2012

http://www.dw.de/dw/article/0,,15751387,00.html 19 Feb. 2012 http://www.news.ch/Forscher+Netzwerk+untersucht+Asteroidenabwehr/530515/detail.htm

21 Feb. 2012

http://www.rp-online.de/digitales/rp-plus/die-angst-vor-dem-einschlag-1.2733312 28 Feb. 2012

http://www.faz.net/aktuell/feuilleton/debatten/asteroidenabwehr-vom-ende-her-11709851.html

24 Apr. 2012

http://www.badische-zeitung.de/nachrichten/panorama/die-kosmische-bombe-aus-der-bahn-werfen

7 Jul. 2012

http://www.oberbipp.ch/documents/NZZ_2.pdf 26 Aug. 2012

http://www.welt.de/print/wams/article112043724/Davon-geht-die-Welt-nicht-unter.html

16 Dec. 2012

http://www.washingtonpost.com/national/health-science/nasa-asteroid-fly-by-next-week-closest-ever-of-its-size/2013/02/07/ff47b876-714d-11e2-ac36-3d8d9dcaa2e2_story_1.html 8 Feb. 2013

http://www.berliner-zeitung.de/raumfahrt/begegnung-im-weltall-asteroid-kommt-der-erde-extrem-nah,10808910,21685052.html 8 Feb. 2013

http://www.fr-online.de/raumfahrt/begegnung-im-weltall-asteroid-kommt-der-erde-extrem-nah,1473248,21685052.html 8 Feb. 2013

http://www.nzz.ch/wissen/wissenschaft/globale-antworten-auf-eine-globale-bedrohung-1.17997976

14 Feb. 2013

http://www.faz.net/aktuell/wissen/weltraum/asteroid-2012-da14-rendezvous-mit-einem-kosmischen-besucher-12080808.html 15 Feb. 2013

http://www.faz.net/aktuell/wissen/weltraum/weltraum-forschung-der-asteroidenjaeger-12081900.html 15 Feb. 2013

[Countless TV, radio, and newspaper reports cited NEOShield on the occasion of the close approach of 2012 DA14 and the Russian fireball over Chelyabinsk. 15 Feb. 2013]

http://www.guardian.co.uk/science/across-the-universe/2013/feb/18/asteroids-how-deflect-dangerous

18 Feb. 2013

http://www.faz.net/aktuell/wissen/weltraum/interview-ueber-asteroidenabwehr-wenn-sie-uns-zu-nahe-kommen-12085485.html 20 Feb. 2013 http://www.dw.de/meteorite-explosion-puts-space-on-un-agenda/a-16622302 22 Feb. 2013

http://www.pbs.org/wgbh/nova/next/space/risk-of-an-asteroid-strike/ 27 Mar. 2013

http://lci.tf1.fr/science/nouvelles-technologies/risque-d-asteroide-on-est-loin-de-savoir-quoi-faire-et-quelle-decision-7934438.html 23 Apr. 2013

http://www.morgenweb.de/nachrichten/welt-und-wissen/kosmische-bomben-strategien-gegen-eine-todliche-gefahr-1.1131111 25 Jul. 2013

http://www.spiegel.de/wissenschaft/weltall/tscheljabinsk-meteorit-anatomie-einer-beinahe-katastrophe-a-932197.html 6 Nov. 2013

http://www.berliner-zeitung.de/wissen/glueck-im-unglueck-meteorit-von-tscheljabinsk-hatte-gewaltige-wucht,10808894,24921716.html 6 Nov. 2013

http://www.tagesspiegel.de/wissen/asteroiden-sie-koennten-eine-ganzestadt-zerstoeren/9050734.html 9 Nov. 2013

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NEOShield Final Report: Appendix 2. Tables of Deliverables and Milestones

Del. no.	Deliverable name	Version	WP no.	Lead beneficiary	Nature	Dissemination level	Delivery date from Annex I (proj month)	Actual / Forecast delivery date	Status	Comments
1	Initial progress repo rt to the REA.	1.0	1	DEUTSCHES ZENTRUM FU ER LUFT - UND RAUMFAHRT E V	Report	CO	6	06/07/2012	Submitted	
2	Periodic progress rep ort to the REA.	1.0	1	DEUTSCHES ZENTRUM FU ER LUFT - UND RAUMFAHRT E V	Report	CO	16	30/05/2013	Submitted	
3	Periodic progress rep ort to the REA.	2.0	1	DEUTSCHES ZENTRUM FU ER LUFT - UND RAUMFAHRT E V	Report	CO	32	21/10/2014	Submitted	
4	Final project report to the REA.	1.0	1	DEUTSCHES ZENTRUM FU ER LUFT - UND RAUMFAHRT E V	Report	CO	41	31/05/2015	Submitted	
1	Report on frequency o f mitigation-relevant pr operties.	1.0	2	DEUTSCHES ZENTRUM FU ER LUFT - UND RAUMFAHRT E V	Report	PU	24	10/01/2014	Submitted	
2	requirements for miti gati on precursor reco nna issance.	1.0	2	OBSERVATOI RE DE PARIS	Report	CO	31	08/08/2014	Submitted	
3	Instrumentation design s.	1.0	2	OBSERVATOI RE DE PARIS	Report	CO	24	10/01/2014	Submitted	
4	Requirements modellin g/simulation work and la b. experiments.	1.0	2	CENTRE NAT IONAL DE LA RECHERCHE SCIENTIFIQUE	Report	CO	2	21/03/2012	Submitted	

1	Experiments requireme nts.	1.0	3	CENTRE NAT IONAL DE LA RECHERCHE SCIENTIFIQUE	Report	CO	5	03/07/2012	Submitted	
2	Modeling/simulations o f laboratory results.	1.0	3	CENTRE NAT IONAL DE LA RECHERCHE SCIENTIFIQUE	Report	CO	24	13/01/2014	Submitted	
3	Scaled-up modelling: m omentum gain and NEO deflection efficiency .	2.0	3	CENTRE NAT IONAL DE LA RECHERCHE SCIENTIFIQUE	Report	CO	31	19/05/2015	Submitted	
4	Potential for re-accu mula tion of hazardous large b odies from impa ct ejecta.	2.0	3	CENTRE NAT IONAL DE LA RECHERCHE SCIENTIFIQUE	Report	PU	31	05/06/2015	Submitted	
1	Results of momentum-tr ansfer experiments on u nconsolidated materi als.	2.0	4	THE OPEN U NIVERSITY	Report	CO	27	09/06/2015	Submitted	
2	Material properties o f the regolith analogu e sampl es.	1.0	4	FRAUNHOFER -GESELLSCH AFT ZUR FO ERDERUNG D ER ANGEWAN DTEN FORSC HUNG E.V	Report	CO	12	28/06/2013	Submitted	
3	Results of impact expe riments on consolidat ed samples.	1.0	4	FRAUNHOFER -GESELLSCH AFT ZUR FO ERDERUNG D ER ANGEWAN DTEN FORSC HUNG E.V	Report	CO	27	10/04/2014	Submitted	
1	Dynam.- and phys.-pro perty requirements fo r N EOs as targets in mitigat ion demo missi ons.	1.0	5	DEUTSCHES ZENTRUM FU ER LUFT - UND RAUMFAHRT E V	Report	CO	15	21/05/2013	Submitted	
2	List of potential tar get NEOs and their pr ope rties relevant to m itigat ion demo missio ns.	1.0	5	THE QUEEN'S UNIVERSITY OF BELFAST	Report	PU	11	10/12/2012	Submitted	

3	Prioritized demo-miss ion target suggestion s.	1.0	5	THE QUEEN'S UNIVERSITY OF BELFAST	Report	PU	15	31/05/2013	Submitted	
4	Orbit refinement and re connaissance observati ons as required.	1.0	5	THE QUEEN'S UNIVERSITY OF BELFAST	Report	PU	31	18/09/2014	Submitted	
1	Significant open issu es w ith regard to the kinetic -impactor conc ept.	1.0	6	DEIMOS SPACE SOCIEDAD LIM ITADA UNIP ERSONAL	Report	CO	5	18/06/2012	Submitted	
2	Impactor GNC technolo gies.	1.0	6	AIRBUS DEF ENCE AND S PACE SAS	Report	RE	31	22/09/2014	Submitted	
3	Orbitor GNC technolog ies.	2.0	6	DEIMOS SPACE SOCIEDAD LIM ITADA UNIP ERSONAL	Report	CO	31	21/01/2015	Submitted	
1	Assessment of gravity tra ctor and other mit igation concepts.	1.0	7	SETI INSTI TUTE CORPO RATION	Report	PU	15	06/05/2013	Submitted	
2	Assessment of gravity tra ctor with multiple -spacec raft tractors.	1.0	7	UNIVERSITY OF SURREY	Report	PU	15	22/05/2013	Submitted	
3	Assessment of blast de fle ction and other miti gatio n concepts.	3.0	7	FEDERALNOE GOSUDARST VENNOE UNI TARNOPREDP RIYATIE TS ENTRALNY N AUCHNO- IS SLEDOVATEL SKY INSTITUT MACHINO STROENIYA	Report	PU	15	05/05/2014	Submitted	
4	Potential benefits of hum an missions for mi tigatio n strategies.	1.0	7	AIRBUS DS GMBH	Report	PU	15	03/04/2013	Submitted	
5	Trade-offs of viable al te rnative mitigation concep ts.	1.0	7	AIRBUS DEF ENCE AND S PACE LTD	Report	PU	18	24/09/2013	Submitted	
1	Requirements on NEO ta	1.0	8	AIRBUS DS	Report	PU	4	28/06/2012	Submitted	

	rget selection.			GMBH						
2	Detailed demo-mission design, kinetic impa ctor.	1.0	8	AIRBUS DS GMBH	Report	CO	36	25/02/2015	Submitted	
3	Detailed demo-mission design, gravity trac tor.	1.0	8	SETI INSTI TUTE CORPO RATION	Report	CO	36	29/05/2015	Submitted	
4	Detailed demo-mission design, blast deflect ion.	1.0	8	FEDERALNOE GOSUDARST VENNOE UNI TARNOPREDP RIYATIE TS ENTRALNY N AUCHNO- IS SLEDOVATEL SKY INSTITUT MACHINO STROENIYA	Report	CO	36	16/03/2015	Submitted	
5	Assessment of demo-mis sion variants.	1.0	8	AIRBUS DEF ENCE AND S PACE LTD	Report	PU	36	07/04/2015	Submitted	
1	Preliminary roadmap o utline.	1.0	9	OBSERVATOI RE DE PARIS	Report	CO	31	08/08/2014	Submitted	
2	Required reconnaissan ce observations.	1.0	9	OBSERVATOI RE DE PARIS	Report	PU	36	08/06/2015	Submitted	
3	Description of decisi on-making tool.	1.0	9	DEIMOS SPACE SOCIEDAD LIM ITADA UNIP ERSONAL	Report	CO	36	19/01/2015	Submitted	
4	Atmospheric trajector y analysis and ground- da mage limitation.	1.0	9	FEDERALNOE GOSUDARST VENNOE UNI TARNOPREDP RIYATIE TS ENTRALNY N AUCHNO- IS SLEDOVATEL SKY INSTITUT MACHINO STROENIYA	Report	PU	31	18/09/2014	Submitted	
5	Final roadmap, includi ng political decision -making	1.0	9	AIRBUS DEF ENCE AND S	Report	PU	36	24/04/2015	Submitted	

	, reconnaissan ce, decisio n tool.			PACE LTD						
6	Options for future im plementation of propo sed demo missions.	1.0	9	AIRBUS DS GMBH	Report	CO	41	31/05/2015	Submitted	
1	Presentation of web de sig ns to project.	1.0	10	AIRBUS DS GMBH	Report	CO	3	30/04/2013	Submitted	
2	Public web site online.	1.0	10	AIRBUS DS GMBH	Other	PU	6	29/05/2015	Submitted	
3	Project web site.	1.0	10	AIRBUS DS GMBH	Other	CO	6	29/05/2015	Submitted	
4	Outreach events.	1.0	10	DEUTSCHES ZENTRUM FU ER LUFT - UND RAUMFAHRT E V	Other	PU	41	27/05/2015	Submitted	

Milestones

Milestone no.	Milestone name	Work package no	Lead beneficiary	Delivery date from Annex I	Achieved Yes/No	Actual / Forecast achievement date	Comments
1	Kick-Off meeting.	All	DLR	16/01/2012	Yes	16/01/2012	
2	Initial progress assessme nt.	1,2,3,4,5,6,7,8,10	DLR	31/05/2012	Yes	31/05/2012	
3	Preparation for mission designs complete.	1,2,4,5,6,7	DLR	31/03/2013	Yes	30/06/2013	Delays in submission of s ome deliverables have only minor impact on ov erall schedule.
4	Outline designs of demo missions complete.	1,2,3,4,7,8	Astrium-DE	31/12/2013	Yes	31/12/2013	
5	Research work packages wrap up.	1,2,3,4,5,6,9	DLR	31/07/2014	Yes	31/07/2014	Delays in submission of s ome deliverables have only minor impact on ov erall schedule.
6	Final presentation.	All	DLR	31/05/2015	Yes	25/06/2015	