Space Mission Planning Advisory Group (SMPAG)

Roadmap of Relevant Research for Planetary Defense

Work plan activity: 5

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Executive Summary

This document is intended to be a regularly updated “roadmap”, or strategy, for international mitigation-related scientific and technical activities, to serve as a guide to future efforts. The aim of the work is to monitor worldwide activity in the field of the impact hazard and highlight areas in which further scientific research and technical development work is necessary. The areas covered by this work include space-mission-related research relevant to the deflection or destruction of a threatening NEO in the light of improving scientific understanding and technological capabilities, and efforts to facilitate accurate predictions of the possible consequences of a deflection attempt and/or an impact on the Earth. Efforts relating to NEO discovery and follow-up observations are not covered here as they fall under the remit of the International Asteroid Warning Network (IAWN).

The tasks of this SMPAG work plan activity are:

1. Monitor relevant activities of space agencies and other organizations.

2. Identify technological and scientific activities relevant to space missions for planetary defense (e.g. for in-situ reconnaissance, deflection demonstration and emergency deflection missions) requiring emphasis in future work; such activities may include mission-related observational projects, e.g. for NEO physical characterization, and laboratory experiments and modeling/analysis work.

3. Develop/update an international strategy for future missions and mission-related research and development work in support of planetary defense.

4. Analyze and report on the effectiveness of international collaboration and funding of mitigation activities.

At the present time it is felt that more effort should be devoted in particular to remotely-sensed physical characterization of small NEOs (radar, infrared, etc.), in-situ characterization via space missions, tests of NEO deflection techniques, and the development of new deflection techniques for small NEOs. A major problem, especially in Europe at present, is the short-term nature of research funding in the field of planetary defense, and the consequent lack of continuity in efforts to minimize the permanent threat to our civilization from impacts of asteroids and comets.

1. Introduction

Impacts of near-Earth objects (NEOs) have contributed to mass extinctions and the evolution of life on Earth, and it is a proven fact that NEOs will continue to hit the Earth at irregular intervals in the future, with the potential for catastrophic damage to life and property. Awareness of the threat presented by NEOs has grown rapidly during the past few decades as a result of, for example, the impact of Comet Shoemaker-Levy 9 on Jupiter in 1994, observations of fresh craters appearing on the Moon and Mars, and the discovery of over 11000 NEOs to date, some of which make uncomfortably close approaches to the Earth. Furthermore, all remaining doubt regarding the cause and violence of the Tunguska event of 1908 was swept away after the blast waves from the Chelyabinsk superbolide of 2013 February 15 injured some 1500 people and damaged thousands of buildings, providing a vivid demonstration that impacts of NEOs on the Earth present an on-going significant danger to life and property.

The results of increased international activity in the fields of NEO discovery, monitoring, and physical characterization over the past few decades now more accurately enable us to understand the scientific and practical issues relating to the impact hazard and NEO mitigation, and better define the problems that need to be tackled in the future.

The aim of this work is to monitor worldwide activity in the field of the impact hazard and highlight areas in which further scientific research and technical development work is necessary. This initiative covers efforts to identify and update the most effective means of deflecting a NEO in the light of improving scientific understanding and technological capabilities, reduce the risk of a NEO deflection attempt failing, and facilitate more accurate predictions of the possible consequences of a deflection attempt (which may succeed, only partially succeed, or fail completely) and/or an impact on the Earth. Efforts relating to NEO discovery and follow-up observations are not covered here as they fall under the remit of the International Asteroid Warning Network (IAWN). On the other hand, mitigation-relevant physical characterization, whether by means of astronomical observations or in-situ exploration, is essential for predicting how a NEO would respond to a deflection attempt and/or the consequences of an airburst or crater-forming impact.

The work of the SMPAG is motivated by the need to provide a focus for, and improved coordination of, the diverse research efforts in different countries and fields.

This document is intended to be a regularly updated “roadmap”, or strategy, for international mitigation-related scientific and technical activities, to serve as a guide to future efforts.

2. Significant Currently or Recently Funded Activities

USA

NEO Program, JPL:

The NASA NEO Program computes high precision orbits for all known NEOs and provides a high precision ephemeris computation service (Horizons). It also maintains a small-body database for all asteroids and comets, and makes predictions of close approaches to Earth (and other planets). The potential risk of collision with Earth is assessed by computing impact probabilities over 100 years (Sentry). The NASA NEO Program maintains the NEO Human spaceflight Accessible Targets Study (NHATS) table.

http://neo.jpl.nasa.gov

OSIRIS-Rex:

OSIRIS-REx (Lauretta et al., 2012) is a sample-return mission called OSIRIS-REx (Lauretta et al., 2012) with launch currently scheduled for September 2016. The sample mechanism is designed to collect between 60 grams and a few kilograms, depending on the surface properties of the target, namely the primitive B-type NEA (101955) Bennu, having a diameter of some 450 m.

http://www.asteroidmission.org/

Asteroid radar (e.g. Goldstone, Arecibo):

Radar is a powerful method for the characterization of NEOs, especially their sizes, shapes, and surface structure. A radar echo contains information not only on the position and velocity of a NEO, but also on a number of mitigation-relevant physical parameters. Radiation transmitted at a single frequency is returned from a rotating asteroid with a spread of (Doppler-shifted) frequencies, each component frequency being associated with a particular time delay depending on the distance to the reflecting surface element. The “delay-Doppler” distribution of echo power is determined by the size, spin rate, orientation, and shape, of the target asteroid, and radar reflectivity of the surface material. The strength of the echo, normalized to the size and distance of the target (“radar albedo”), can provide information on the mineralogy of the asteroid surface, in particular its metal content. For an overview of radar observations of asteroids see Benner et al. (2015).

http://echo.jpl.nasa.gov/

WISE:

A survey of the sizes and albedos of over 100,000 asteroids has been carried out by the NASA WISE (Wide-field Infrared Survey Explorer) space telescope. WISE was launched to Earth-orbit in December 2009 carrying a 40-cm diameter telescope and infrared detectors. WISE surveyed the sky for 12 months and the objects observed included a total of at least 584 NEOs, of which more than 130 were new discoveries (Mainzer et al., 2011). The specially funded NEOWISE program analyzed images collected by the WISE spacecraft to derive information on the NEOs detected. The fact that the cryogenic phase of the WISE mission measured asteroid thermal emission in up to 4 infrared bands, centered on 3.4, 4.6, 12, and 22 μm, allowed reliable values of diameter, albedo, and other parameters to be derived for many of the asteroids observed.

http://neowise.ipac.caltech.edu/

NEOCAM:

The JPL-managed Near-Earth Object Camera (NEOCam) is a mission proposal designed to discover and characterize most PHOs. NEOCam consists of a spaceborne infrared telescope and a wide-field camera operating at thermal infrared wavelengths which, it is claimed, would discover 67% of NEOs larger than 140m. The NEOCam proposal was previously funded by NASA for technology development and is currently one of five Discovery mission proposals selected by NASA for refinement during 2015-2016 as a first step to choosing one or two missions for flight opportunities as early as 2020.

http://neocam.ipac.caltech.edu/

Sentinel:

Sentinel is a space-based infrared survey mission concept, proposed by the B612 Foundation, to discover and catalog 90% of NEOs with diameters larger than 140 m. It is planned to launch the Sentinel Space Telescope into a Venus-like orbit around the sun, which significantly improves the efficiency of asteroid discovery during its 6.5 year mission. Public donations are a critical part of the Sentinel funding plan.

http://sentinelmission.org/

Iowa State Univ. Asteroid Deflection Research Center:

Iowa State's Asteroid Deflection Research Center (ADRC) was established in April 2008 with the aim of developing NEO impact-prevention technologies. That goal has been expanded to include the idea of sending manned missions to asteroids. The ADRC received its first research grant in December 2008, when the NASA-supported Iowa Space Grant Consortium (ISGC) awarded a three-year, $340,000 grant to the research team. The grant's objectives included support for initial research in the ADRC, as well as providing seed money for efforts to obtain additional grants. The ADRC is pursuing the idea of a two-body spacecraft capable of deflecting an asteroid with a very short warning (HAIV, Hypervelocity Asteroid Intercept Vehicle). The fore body first hits the asteroid with a kinetic impact, producing a crater on the object's surface. The aft body then delivers an explosive device into the crater to break up the asteroid into small harmless pieces, eliminating the threat. The HAIV can also be used simply as a kinetic impactor in less serious situations. Public donations are a critical part of the HAIV funding plan.

http://www.adrc.iastate.edu/

Europe

ESA's Space Situational Awareness Program:

ESA's Space Situational Awareness (SSA) program was established in 2009 after authorization by the Ministerial Council in November 2008. The goal of the program is to provide information and data on the space environment, particularly regarding hazards to infrastructure in orbit and on the ground. The program covers hazards due to near-Earth objects, space debris, and space weather. In 2013 the SSA program established the European NEO Coordination Center at ESRIN close to Rome, to serve as the central access point for a network of European providers of information on NEOs. The NEO segment of ESA's SSA activities also includes the development of a wide-field, rapid-scan search program called Fly-Eye (Farnocchia et al., 2012) with the goal of discovering very small NEOs to provide advance warning of impacts. The goal is to provide at least a week's warning of impactors in the size range 30-50 meters (longer for larger objects), such that evacuation of the impact area, or the provision to the public of appropriate advice, will be possible. (NASA is developing a program with a similar purpose called the Asteroid Terrestrial-Impact Last Alert System, with plans for up to 8 small telescopes; Tonry, 2011.)

In November 2014 ESA hosted an information meeting and a table-top exercise for representatives of the European emergency response community, similar to earlier exercises organized by NASA, in collaboration with the US Federal Emergency Management Agency (FEMA), and by the Planetary Defense Conference in Flagstaff, Arizona, in 2013. The objectives of such exercises are to inform the emergency response communities of the special circumstances of a developing impact emergency and to learn from them what type of information they would need from the NEO science community in the time leading up to an impact event.

http://www.esa.int/Our_Activities/Operations/Space_Situational_Awareness/Near-Earth_Objects_-_NEO_Segment

NEOShield:

The NEOShield project is an international near-Earth object (NEO) research initiative with a total budget of 5.8 mio. €, funded by the European Commission's FP7 research program. The NEOShield Consortium consists of 13 research institutes, universities, and industrial partners from 6 countries, including Russia and the USA. The project was funded for 3.5 years, from January 2012 until May 2015, and was coordinated by the German Aerospace Center (DLR). The aims of NEOShield were to investigate the NEO impact hazard and prepare the way for a space mission to test our ability to prevent an impact on the Earth of a threatening NEO (Harris et al., 2013, 2015). NEOShield has contributed significantly to our understanding of the physical properties of hazardous NEOs through the analysis of astronomical data, laboratory experiments on asteroid analog materials, and associated computer modeling and simulations. On the technical side, a trade-off study of different NEO deflection methods provided insight into which methods are most appropriate in different circumstances (e.g. taking account of NEO size, type, and warning time). Detailed designs of realistic deflection test missions and a report on an international roadmap for dealing with a hazardous NEO are the final products from the NEOShield project.

NEOShield research, however, continues within the European Commission's Horizon 2020 program, which awarded funding of around 6 mio. € to the NEOShield-2 project for 2.5 years, commencing on 1 March 2015. NEOShield-2, which has 11 partner organizations, is coordinated by Airbus Defense and Space, Germany. Project tasks include further improvement of our knowledge of the physical characteristics of potentially hazardous NEOs by carrying out astronomical observations of selected NEOs and analyzing the rapidly growing archive of data on NEOs, including observations made with satellite observatories. On the technical side, NEOShield-2 will advance the TRL of crucial spacecraft systems required for maneuvering close to small, low-gravity asteroids and for certain NEO deflection methods. Beyond NEOShield-2, an important future task will be to test deflection concepts with demonstration missions using real NEOs as targets.

We note here, however, that the 2015 call for proposals of the European Commission does not include further research dedicated to planetary defense.

A number of reports on completed NEOShield tasks, which are relevant to the work of SMPAG, are available via the NEOShield and NEOShield-2 website: http://www.neoshield.net/

Stardust:

Stardust is a European-Commission-funded training and research network focusing on developing techniques for asteroid and space debris monitoring, removal/deflection, and exploitation; its aim is to train the next generation of engineers, scientists and decision makers involved in protecting the planet and space assets. Stardust aims to integrate multiple disciplines, from robotics, to applied mathematics, from computational intelligence to astrodynamics, to find practical and effective solutions to the asteroid and space debris issues.

The Stardust consortium is composed of 10 full network partners and 4 associated partners in 7 EU member states. Stardust began in February 2013 and is funded for 4 years with a total budget of 4 mio. €.

http://www.stardust2013.eu/

Japan

Hayabusa 2:

The Japanese space agency, JAXA, launched the Hayabusa 2 mission (Tsuda et al., 2013), on December 3, 2014, with the aim of returning a sample from the primitive (i.e. relatively unprocessed) C-class NEA (162173) 1999 JU3, which has a diameter of about 750 m. The payload includes a small copper projectile designed to impact the surface of the NEA at about 2 km s^{-1}, and a small camera to observe the event. Observations in real time of the production of a crater would provide data of direct relevance to deflection studies. In addition, a small European lander called MASCOT will perform in-situ compositional measurements.

http://global.jaxa.jp/projects/sat/hayabusa2/

Russia

Other

3. Priorities for Future Work

Physical characterization

Mitigation-relevant physical characterization is an important pre-requisite to reliable estimates of the effects of an impact on the ground, and the design of effective deflection missions. It is important to understand the requirements for rapid acquisition of mitigation-relevant parameters of the threatening object when an emergency arises, and to have a good overview of the ranges of parameter values (shapes, rotation rates, albedo, taxonomy/composition, etc., and any size-dependence of these) present in the NEO population. Given that the NEO discovery rate is still increasing, with more and more smaller objects being found by search programs of increasing sensitivity, we need to increase efforts to investigate the physical properties of NEOs, especially potentially hazardous objects, that are relevant to predicting ground damage and the design of deflection campaigns. A further motivation for increasing efforts in physical characterization is the identification of suitable, representative, NEOs for deflection test missions (see below).

Astronomical observations in the visible and infrared spectral ranges (photometry and low-resolution spectroscopy), and with radar, are particularly relevant. A rapid-response network of suitable telescopes would allow many small objects to be characterized during the discovery apparition. A space based thermal-infrared telescope, combined with groundbased optical assets for follow up, would be able to combine accelerated NEO discovery with some immediate characterization (sizes, albedos, and in some cases indications of thermal inertia and taxonomy). Observing strategies and campaigns need to be coordinated internationally to make the most efficient use of available telescopes. Studies making use of archival observational data and data on physical properties (e.g. the EARN NEO database) should also be encouraged and supported.

In-situ characterization via rendezvous and fly-by missions contributes important ground truth to complement the growing archives of astronomical data on NEOs. Examples of such missions currently funded or underway are Hayabusa 2 (Japan, with French and German participation) and OSIRIS-Rex (US with Canadian and French participation). More such missions would significantly increase our understanding of the diversity of mitigation-relevant NEO physical characteristics.

Laboratory work

For deflection methods that rely on an impacting spacecraft it is very important to be able to predict the magnitude of the additional momentum that can be imparted to an object by the ejecta produced in the impact. The ejecta-related momentum enhancement is described by a modeling parameter called the β factor. The amount of ejecta produced depends very strongly on the porosity and strength of the target material. Modeling and numerical simulations of the impact process require detailed characterization of asteroid analog materials (e.g. porosity, density, chemical composition) over a wide range of strain rates using different kinds of testing facilities. Impact experiments on asteroid analog materials with hypervelocity gas guns, such as those at NASA Ames, the Fraunhofer Ernst Mach Institute in Freiburg, Germany, and the Open University in the UK, can provide greater understanding of the impact process and the physics of ejecta production.

Laboratory work coupled with computer modeling can significantly increase our ability to predict the outcome of an attempt to deflect a NEO with an impacting spacecraft.

Computer modeling

A priority for the future is to develop and extend current modeling and computer simulation efforts to include more complex and realistic NEO target conditions, for example shattered and rubble-pile structures, the effects of rotation, and realistic mineralogies, porosities, densities, etc.

The aims of computer modeling work include deepening our understanding of how the internal structure of small (50 m – 1 km diameter) NEOs influences how they would respond to impulsive deflection methods, and the relative effectiveness of different deflection techniques, such as the kinetic impactor and use of an explosive device, in a variety of realistic circumstances, e.g. size of NEO, mineralogy, density, time available, etc.

Deflection test missions

It is important not only to improve our understanding of the mitigation-relevant physical properties of small NEAs, but also to develop technically and financially realistic test missions to enable deflection concepts to be tried out on real NEA targets. Given the diverse observed shapes, mineralogies, and strong evidence for relatively low bulk densities, high porosities, and loose rubble-pile structures among NEAs, demonstrating that we can actually measurably change the orbit of a NEA is a vital step in building confidence that we can defend our civilization from a serious impact. The NEOShield project has performed industrial studies of test missions for the kinetic impactor, gravity tractor, and blast deflection concepts, as well as studies of the future evolution of NEA orbits after deflection attempts.

Examples of deflection test mission concepts are Don Quijote, consisting of a reconnaissance orbiter and a small impactor spacecraft, detailed studies of which were funded and coordinated by ESA in 2006, and the Asteroid Impact Deflection Assessment (AIDA) concept, in which ESA, Johns Hopkins University's Applied Physical Laboratory, NASA, the Côte d'Azur Observatory, and the German Aerospace Center are collaborating at the time of writing (October 2015). While the Don Quijote concept as such has not been funded to date, it has served as the inspiration for aspects of the NEOShield program and European participation in the Asteroid Impact Deflection Assessment (AIDA) concept. The aim of AIDA (Cheng et al., 2015) is to deflect the small secondary of a binary asteroid, chosen so that the perturbation to the orbit of the secondary can be observed from groundbased facilities in 2022. The target is the binary asteroid (65803) Didymos. The mission has two independent components: the projectile spacecraft, DART ("Double Asteroid Redirection Test"), which would be developed in the US, and the European rendezvous spacecraft AIM (Asteroid Impact Monitor). DART would serve as a test of our ability to impact a small (150 meter-diameter) object, while AIM would allow it to be characterized in detail by observing the target before, during, and after the impact event. The advantage of the AIDA concept, compared to a mission to deflect a normal NEA, lies in the relative ease with which the orbit of a small binary moon around the primary can be changed to a measurable extent, and the fact that in the case of Didymos, due to the favorable observation geometry, the change can be measured by groundbased telescopes monitoring the variability of reflected sunlight caused by eclipses and occultations in the binary system.

An alternative, relatively inexpensive, test of the kinetic impactor concept, under consideration in on-going NEOShield work (Drube et al., 2015), would be to impact a NEA far from its rotation axis, thus causing a change in its rotation rate, which, depending on the choice of the target, could be measurable with groundbased telescopes. The change in rotation rate would provide insight into the same near-surface structural characteristics on which the efficiency of the kinetic impactor deflection concept depends.

Priorities in terms of deflection-related space mission technology development include improved autonomous spacecraft control systems for application on an impactor spacecraft, and to facilitate navigation close to a low-gravity, irregularly shaped asteroid, and the development of techniques for precise NEO orbit determination using a reconnaissance spacecraft.

Results from the type of studies outlined above, whether or not they lead to a funded test mission, 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.

Impact assessment tools

To help decision makers plan a reasonable measured response in an emergency impact hazard scenario, the ability to reliably predict the consequences of allowing the object to impact would be a vital prerequisite. The effects in question include:

- Airbursts and atmospheric phenomena with potential to cause serious damage on the ground, including shock waves, thermal radiation, etc.
- Tsunamis and their propagation.
- Crater formation, earthquakes, ejecta effects on the ground, winds, fires, etc.
- Possible long-term adverse climate effects.
- The effects of an impact on infrastructure, the local economy, etc., taking into account the spatial distribution of key facilities.

Reliable codes need to be developed based on quantitative and phenomenological models, taking account of the full range of expected effects, including an analysis of uncertainties, to serve the purposes of education and training, and for operational use in the case of an impact-hazard emergency.

Software tools for emergency deflection campaign planning

The development, testing, and optimization of tools to aid decision-making and facilitate development of the most effective response to the particular circumstances of an identified significant impact threat should be supported. The tools should address the choice of deflection technique, timeline for mission development, launch, and execution, trajectory options, etc., in the light of the known dynamical and physical properties of the hazardous object and available time before the predicted impact.

NEO orbit evolution following a deflection attempt

A deflection attempt, whether it be a test mission or a real emergency response, will have an uncertain outcome. It is necessary to model the uncertainties involved and the range of possible outcomes, from complete failure to larger than expected deflection (due to, for example, underestimation of the momentum-enhancing β factor – see above), in order to understand the possible set of subsequent trajectories of the object and their probabilities. In the case of an emergency deflection, we would want to know how the deflection attempt might influence the overall long-term future impact risk, including possible subsequent passage of the NEO through keyholes. In the case of a deflection test mission, the public would like to be re-assured that the test deflection, no matter what the outcome, could not significantly increase the risk of a future impact of the test target on the Earth.

Software tools need to be developed to calculate possible post-deflection trajectories, their probabilities, and long-term evolution, taking account of all possible failure modes of a deflection attempt.

Studies of new NEO deflection methods

Research to date in this field has tended to concentrate on NEO deflection methods, such as the kinetic impactor and gravity tractor, which are feasible with current technology, or likely to become feasible in a few years' time. However, alternative methods, such as those based on ion-beam propulsion, laser ablation, and others that may become practical in the course of future technological development, may in time prove to be more practical and effective per kilogram of launch mass in many cases, depending on the details of the hazard scenario.

Serious research into new methods of NEO deflection, including what appear today to be speculative concepts, should be encouraged and supported. Emphasis should be placed on concepts to deal with objects at the smaller end of the NEO size distribution (e.g. 50 m – 200 m diameter), which is the size range in which most new discoveries fall and for which impact probabilities are relatively high.

4. Table of International Coordination and Funding

Funding source	Program/ project	Time period	Main objectives	Countries	Funding
ESA Space Situational Awareness Program	NEO segment	2009 -	NEO database; NEO discovery; follow-up; early warning; impact damage; deflection methods	Participating ESA member states	Currently (2015) 1 M€ per year?
European Commission	NEOShield	2012 - 2015	Physical characterization; deflection techniques; deflection test-mission design	France, Germany, Russia, Spain, UK, USA	5.8 M€ total
European Commission	NEOShield-2	2015 - 2017	Physical characterization; deflection test-mission design; technology for in-situ NEO characterization	France, Germany, Italy, Spain, UK	4.2 M€ total + overheads
European Commission	Stardust	2013 - 2017	Training of scientists and engineers in NEO and space debris monitoring, removal/deflection, and exploitation	Germany, Italy, Serbia, Spain, UK	4.0 M€ total
NASA? Other?					

5. Table of Developing National Projects with Potential for International Participation

Funding source	Program/ project	Time period	Main objectives	Country	Funding
B612 Foundation	Sentinel		Discovery; physical characterization (IR)	USA	
Iowa State Univ., crowdfunding, sponsorships	Hyper-velocity Asteroid Intercept Vehicle (HAIV)		Development of a kinetic-impactor + explosive NEO deflection system	USA	
Japan?					
NASA	NEOCam	Launch 2020?	Discovery; physical characterization (IR)	USA	
Russia?					
Other?					

6. Summary and Conclusions

At the present time the following important areas are significantly under-represented in efforts to tackle the impact hazard issue:

- Remotely-sensed physical characterization of small NEOs (radar, infrared, etc.)
- In-situ characterization via space missions
- Tests of NEO deflection techniques
- Development of new deflection techniques for small NEOs

Funding for the tasks described in this document has increased significantly in recent years but is concentrated in the US and Europe, and in the case of Europe is largely dependent on short-term funding with no guarantee of continuity. The lack of continuity is a major problem in a field in which many projects are necessarily long-term (e.g. the development and execution of a space mission can take a decade or more), and specialized personnel with vital expertise are lost as soon as funding runs out. The impact-hazard problem is a permanent problem that requires permanent research and development work.

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Acknowledgements

Appendix

Tabular roadmap (matrix) of current activities per country/space agency with deficiencies in required effort highlighted for emphasis in future planning

[**DRAFT]**

	Canada	China	Europe	Japan	Russia	USA
Kinetic impactor method		Solar sail assisted kinetic impactor concept - Tsinghua University	AIM mission Phase A study - ESA + CNRS/Côte d'Azur Observatory Mission design - Airbus-DE + Deimos Space + CNRS/Côte d'Azur Observatory			AIDA mission Phase A/B1 study at ESA and NASA Lawrence Livermore National Laboratory Applied Physics Laboratory (John Hopkins University)
Blast deflection method					TSNIMASH	Lawrence Livermore National Laboratory Asteroid Deflection Research Center, Iowa State University
Slow pull/push methods		Ion beam shepherd concept - Beijing Institute of Technology; Solar sail assisted gravity tractor concept - Tsinghua University	Laser ablation - University of Strathclyde Gravity tractor - Surrey University			Gravity tractor - SETI Enhanced gravity tractor - NASA laser ablation - The University of Alabama
Deflection test mission studies			AIM mission in Phase A: ESA + CNRS/Côte d'Azur Observatory (leads) NEOTωIST mission + other NEOShield mission studies Don Quijote feasibility study			DART mission in Phase B1 NASA - John Hopkins University (lead) HAIV mission - Asteroid Deflection Research Center, Iowa State University
Relevant asteroid space mission			Hayabusa-2 - LESIA + CNRS/Côte d'Azur Observatory Hayabusa-2, MASCOT lander - DLR OSIRIS-REx (NASA) - LESIA + CNRS/Côte d'Azur Observatory	Hayabusa-1 and Hayabusa-2 sample return asteroid missions		Deep Impact mission -NASA Osiris-Rex sample return asteroid mission
GNC development for deflection mission			Airbus-FR Deimos Space GMV Space Systems			Asteroid Deflection Research Center, Iowa State University, USA
Mission designs and non GNC technologies			Mission Designs - Airbus DE + Airbus UK + Surrey Satellite Technology Ltd Nuclear power sources - UK National Nuclear Laboratories			
Instruments for deflection missions	Gravimetry - Gedex		Instruments suites for different deflection methods - Observatory of Paris Instrument suites for NEA internal struture characterisation - IPAG/Grenoble + LATMOS/Paris			
Computer modelling of deflection attempts			Modeling of kinetic impacts on asteroids and the ejecta - CNRS/Côte d'Azur Observatory + University of Bern Modelling laser ablation - DEIMOS			Lawrence Livermore National Laboratory Applied Physics Laboratory, John Hopkins University University of Washington
Modeling impact effects in the atmosphere and on the ground			NEO Impact Assesment tools - ESA SSA Hypervelocity re-entry - ONERA Risk assessment in the atmosphere -IMCCE		Atmospheric trajectory analysis and ground damage - TSNIMASH	Ground damage + meteor entry and breakup - NASA + Sandia National Laboratories Impact in the ocean - Lawrence Livermore National Laboratory
Hyper velocity impact laboratory experiments			Horizontal light-gas gun - Fraunhofer EMI, Germany All-Axis light gas gun - Open University, UK Double-stage light gas gun - University of Kent, UK	Horizontal & Vertical light-gas guns - ISAS/JAXA, Japan Horizontal light-gas gun - Kobe University, Japan Horizontal light-gas gun - Chiba Institute of Technology, Japan		Light-gas guns - NASA Ames Boeing Industry
Tools for emergency deflection campaign planning			Software package for deflection mission planning in development: DEIMOS + IMCCE		End-to-end software package in development - Russian Academy of Sciences	
Trajectory calculations	Dynamical evolution - Western University		Non-gravitational perturbations and orbit computations - NEODys, Italy PoDET (hub for orbit and ephemrides computations) - IMCCE, France Modeling and assessment of orbits (impulsive and time integrated deflection) - IMCCE, France Trajectory optimisation - Airbus UK	JAXA, National Astronomical Observatory of Japan	Orbit calculations - Russian Academy of Sciences + Saint Petersburg State University	JPL NEO Program The Minor Planet Center
Observatories used for physical characterization of NEOs			e.g.: Optical Ground Station, 1-m telescope, Tenerife - ESA Ondrejov Observatory - Czech Republic Klet Observatory (1-m telescope), Czech Republic Calar+A1 Alto Observatory - DLR, Berlin Pic du Midi station, France	Bisei Spaceguard Center, National Astronomical Observatory of Japan		e.g.: Goldstone Radar Arecibo Radar WISE IR space telescope Mt. Lemmon Observatory Lowell Observatory
Deflection mission legal issues		Fabio Tronchetti, School of Law, Harbin Institute of Technology	Hannes Mayer, Karl Franzens Universität Graz, Austria			