Space Mission Planning Advisory Group (SMPAG)

Roadmap of Relevant Research for Planetary Defense

Work plan activity: 5

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Living document

SMPAG-RP-001

v. 2.0

October 2017

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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.

Despite significant progress over the past decade or so much more needs to be accomplished before the international community can feel adequately protected from a potentially catastrophic asteroid impact. At the present time it is felt that more effort should be devoted in particular to the development and execution of test missions to enable deflection concepts to be tried out on real asteroids, remotely-sensed physical characterization of small NEOs (radar, infrared, etc.), in-situ characterization via space missions, 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 more than 16000 NEOs to date, some of which make uncomfortably close approaches to the Earth. Furthermore, most remaining doubt regarding the cause and violence of the Tunguska event of 1908 was swept away after the blast waves from the relatively small (~20 meter sized) object that caused the Chelyabinsk superbolide of 2013 February 15 injured some 1500 people and damaged thousands of buildings (Fig. 1), 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 enable us to understand more accurately the scientific and technical issues relating to the impact hazard and NEO mitigation. However, further effort is required to determine the most effective and appropriate methods for NEO deflection in different circumstances, to understand the practical and legal implications of a deflection attempt that only partially succeeds or fails completely, and to facilitate more reliable predictions of the consequences of an impact on the Earth. The primary aims of this work are 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. These aims cover efforts to:

i. identify and update the most effective means of deflecting a NEO in the light of improving scientific understanding and technological capabilities,

ii. reduce the risk of a NEO deflection attempt failing,

iii. facilitate more accurate predictions of the consequences of an impact on the Earth, and the possible outcomes of a deflection attempt (which may succeed, only partially succeed, or fail completely).

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, in-situ exploration, or sample-return missions, 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.

Fig. 1: The Chelyabinsk superbolide of 2013 February 15 injured some 1500 people and damaged thousands of buildings.

2. Significant currently or recently funded activities related to mitigation

A prerequisite to future planning is an overview of current activities. Below we present examples of prominent mitigation-related activities worldwide that are currently funded or have received funding in recent years (see Appendix A for a tabular summary). Further tabular information on the coordination and funding of major activities, and projects currently under development, is given in Sections 4 and 5.

USA

Planetary Defense Coordination Office, NASA HQ:

The Planetary Defense Coordination Office (PDCO) was formally established in January 2016. The NEO Observation Program, which was started by NASA in 1998, is carried on as an integral element of the PDCO. The PDCO is responsible for:

- Ensuring the early detection of potentially hazardous objects (PHOs) – asteroids and comets whose orbits are predicted to bring them within 0.05 Astronomical Units of Earth; and of a size large enough to reach Earth's surface – that is, greater than perhaps 30 to 50 meters;
- Tracking and characterizing PHOs and issuing warnings about potential impacts;
- Providing timely and accurate communications about PHOs; and
- Performing as a lead coordination node in U.S. Government planning for response to an actual impact threat.

http://www.nasa.gov/planetarydefense/overview

Center for NEO Studies (CNEOS), Jet Propulsion Laboratory:

The NASA PDCO-sponsored CNEOS 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 at least 100 years (Sentry). In collaboration with NASA's Goddard Space Flight Center, the CNEOS maintains the NEO Human spaceflight Accessible Targets Study (NHATS) table of optimal opportunities for either human or robotic spacecraft to reach known near-Earth asteroids. The CNEOS and Aerospace Corporation have together created an online interactive tool "NASA/JPL NEO Deflection App" (http://neo.jpl.nasa.gov/nda/), which can be used to plan deflection missions to hypothetical hazardous asteroids.

http://neo.jpl.nasa.gov

Asteroid Threat Assessment Project (ATAP):

The ATAP is sponsored by the NASA PDCO at the NASA Ames Research Center to undertake four tasks to help meet the objectives of the planetary defense community. The four tasks are (1) Characterization of Near-Earth Asteroids, (2) Physics-Based Modeling of Meteor Entry and Breakup, (3) Surface (both land and ocean) Impact Modeling, and (4) Physics-Based Impact Risk Assessment. Task 1 is focused on building validated models of the physical properties of potentially hazardous asteroids (PHAs) based on observations, and what can be learned from meteorite collections. This information is web-accessible. Task 2 extends existing NASA physics-based entry technology codes so they can reliably predict environments for severe Earth atmospheric entries (up to ~ 20 km s^{-1} entry speeds). Task 2 also seeks improved understanding of fundamental processes that occur during airbursts. Task 3 is focused on predicting the near field effects caused by airbursts (including land and water). Task 4 has the requirement to specify the minimum size of PHAs that require mitigation action that must be taken and the associated lead-time required for their detection. Alternatively, the requirement for Task 4 is to determine the maximum size of a PHA whose effects could be mitigated by civil defense measures.

OSIRIS-Rex:

The OSIRIS-REx (Lauretta et al., 2012) sample-return mission was launched successfully on September 8, 2016. The sample mechanism is designed to collect between 60 grams and a few kilograms (Fig. 2), depending on the surface properties of the target, namely the primitive B-type NEA (101955) Bennu, having a diameter of some 450 m. At the time of writing the spacecraft has just completed its Earth flyby gravity assist to reach the asteroid and mission operations are proceeding nominally. Arrival at the asteroid is scheduled for August 2018. OSIRIS-REx will provide useful characterization data on a potentially hazardous asteroid and abundant information and experience on close proximity operations around a relatively small asteroid in space.

http://www.asteroidmission.org/

Fig. 2: Artist's concept of the OSIRIS-REx spacecraft collecting a sample. Credit: NASA Goddard Space Flight Center

Interplanetary 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). The main US-owned interplanetary radars are the 300-m stationary Arecibo radar in Puerto Rico and the 70-m steerable Goldstone Observatory.

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 size, albedo, and other parameters to be derived for many of the asteroids observed. Starting in 2013 NEOWISE continues to detect and characterize asteroids in the two short-wavelength bands in the post-cryogenic phase allowing diameters and albedos to be obtained, but with reduced accuracy compared to the results of the cryogenic phase.

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

Spitzer:

The US-European "ExploreNEOs" program continues to use the Spitzer Space Telescope (Fig. 3), now in its post-cryogenic "warm" mission phase, to observe previously detected NEOs. The aim of the program is to explore the size and albedo distributions of the NEO population, in particular objects that are below the sensitivity level of other currently available facilities. Spitzer's Infrared Array Camera, the only instrument available in the warm phase, has imaging capability at 3.6 μm and 4.5 μm. Flux data derived from observations in these two channels can be used to provide estimates of sizes and albedos of NEOs down to some 100 m in diameter.

http://nearearthobjects.nau.edu

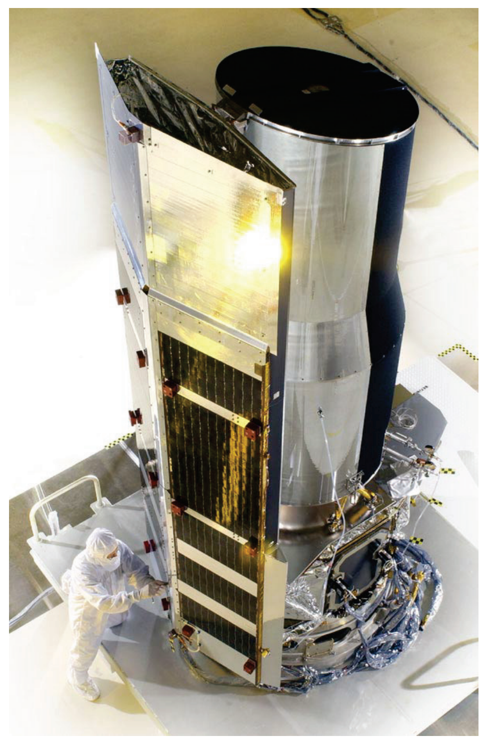

Fig. 3: Spitzer telescope assembly. Credit: NASA

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 within a five-year mission, and determine sizes accurate to within 20%. The NEOCam proposal was previously funded by NASA for technology development of an IR focal plane and was 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. In 2017 NEOCam was not one of the missions selected, however it was granted funding by NASA to continue a Phase-A concept study for an additional year to focus the mission design on planetary defense objectives.

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

Asteroid Impact Deflection Assessment (AIDA) – Double Asteroid Redirect Test (DART):

The aim of AIDA is to deflect the small secondary of the binary asteroid (65803) Didymos, chosen so that the perturbation to the orbit of the secondary can be observed from groundbased facilities in 2022. The mission has two independent components: the projectile spacecraft, “Double Asteroid Redirection Test”, DART, which is under development by NASA in the US, and the European rendezvous spacecraft “Asteroid Impact Monitor”, AIM (see Section 3). DART is funded by NASA into 2018 through at least completion of its Phase-B design. The funding situation of AIM is unclear at present.

http://www.nasa.gov/planetarydefense/aida

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 or destroying an asteroid with a very short warning (HAIV, Hypervelocity Asteroid Intercept Vehicle, Barbee et al., 2015). 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 pieces.

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

Research into resources extraction from asteroids and corresponding technology development can be relevant for asteroid deflection. Potential synergies between the fields of asteroid deflection and space mining should be explored:

Planetary Resources (previously Arkyd Astronautics):

The private company, Planetary Resources, aims to “mine” asteroids, initially for water which can be broken down into hydrogen and oxygen for use as propellant. The company was founded in 2010; funding is from private sources in addition to a $25 million euros investment from the Luxembourg government. In 2016 the company had more than 60 employees and is located in Redmond, Washington (USA) and Luxembourg. Planetary Resources launched the cubesat Arkyd 3 Reflight as a test of their technology in 2015. Future plans include the launches of Arkyd 6A and 6B with mid-infrared imagers in 2017-2018 and an asteroid reconnaissance mission in 2020-21.

http://www.planetaryresources.com

Deep Space Industries:

Deep Space Industries has similar aims to Planetary Resources. It was founded in 2013 and is also privately funded. The Californian company set up an office in Luxembourg in 2016 as part of a deal with the government of Luxembourg which has invested in the company.

http://deepspaceindustries.com/

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, Fig. 4) 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.)

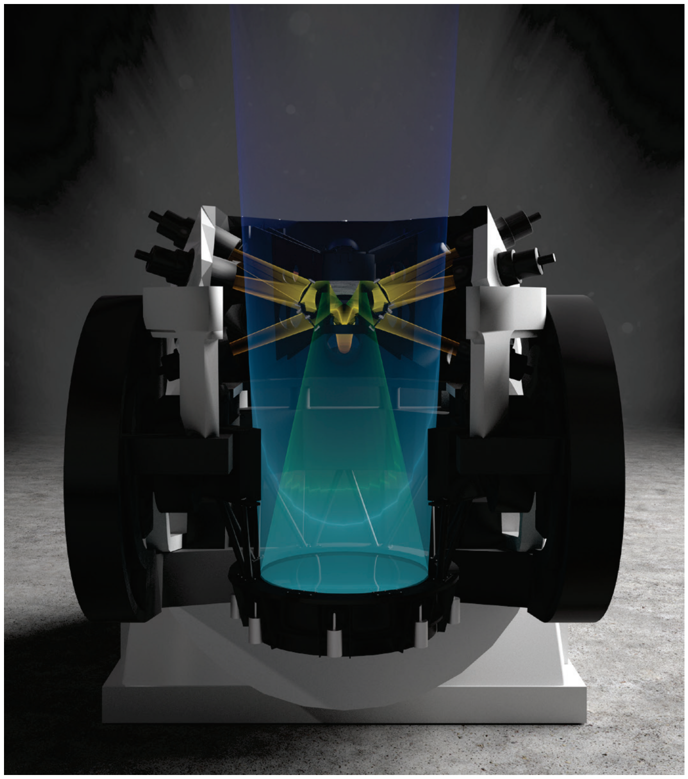

Fig. 4: Fly-eye concept. Credit: ESA/A. Baker

In November 2014 ESA hosted its first information meeting and 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

NEODyS:

NEODyS provides information and services for all near-Earth asteroids, with each object having its own home page. NEODys is currently supported by ESA, the University of Pisa, and IASF-INAF, Rome. A gradual transfer of responsibility for NEODyS to ESA is planned, to incorporate it into the programmatic envelope of the NEO segment of the Space Situational Awareness (SSA) Program. The NEODyS service is expected to become part of a new comprehensive

SSA-NEO information service, together with other components such as the Spaceguard Central Node and the EARN Asteroid Database. Non-ESA groups will continue to share the workload and responsibility for the time being, and in the longer term will continue to contribute with research and development functions.

http://newton.dm.unipi.it/neodys/index.php?pc=0

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 contributions to our understanding of the physical properties of hazardous NEOs include 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 continued 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 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 aims to 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. An example of a mission to test the kinetic impactor concept, which has been studied within the NEOShield-2 project, is NEOTωIST (see Section 4).

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/

http://www.neoshield.eu/science-technology-asteroid-impact/publications/

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/

Laser ablation:

Laboratory experiments on the laser ablation method of asteroid deflection are being carried out at the University of Strathclyde, UK. Irradiation of the surface of an asteroid with laser light causes the surface of the asteroid to sublimate, forming a gaseous plume of ejecta, which provides a continuous and controllable low thrust.

https://www.strath.ac.uk/ascl/research/missionsystems/asteroiddeflectiontechnologies/laserablationexperiments/

AIM:

The European component of the AIDA mission (see under USA and Section 4) would act as a companion rendezvous spacecraft to the DART impactor and allow the target object, namely the moon of the binary asteroid (65803) Didymos, to be characterized in detail by observing the target before, during, and after the impact event. The funding situation of AIM is unclear at present.

http://www.esa.int/Our_Activities/Space_Engineering_Technology/Asteroid_Impact_Mission

Asteroid mining:

Luxembourg decided in June 2016 to establish a 200 mio € fund to support research in asteroid mining over the next 10 years. We note that there is a significant overlap in research and technology goals between the asteroid mining and impact prevention initiatives (e.g. understanding asteroid physical properties, and rendezvous missions to, and mechanical interaction with, asteroids.)

Luleå University of Technology:

Luleå University of Technology in Sweden set up a research group in Asteroid Redirection/Utilization in 2014. The group’s work will include methods and strategies for asteroid redirection, primarily for resources exploitation.

https://www.ltu.se/research/subjects/Rymdtekniska-system/Asteroid-Redirection-Utilization-1.125186?l=en

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) Ryugu, 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.

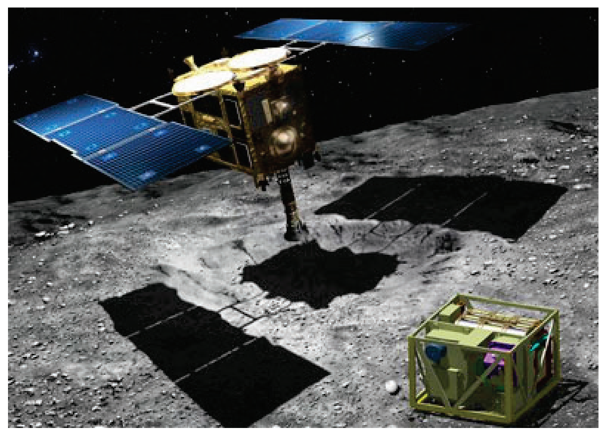

Fig. 5: Artist's concept of Hayabusa 2 and MASCOT at Ryugu. Credit: CNES

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

Russia

The Russian Academy of Sciences is active in orbit calculations as well as the development of an end-to-end software package for emergency deflection campaign planning.

http://www.ras.ru/en/index.aspx

Saint Petersburg State University

The Institute of Applied Astronomy of the Russian Academy of Sciences carries out orbit calculations.

http://eng.spbu.ru

TSNIIMASH:

Research in atmospheric trajectory analysis and ground damage modeling, as well as the blast deflection method is being performed at TSNIMASH (NEOShield-1 partner).

http://www.tsniimash.ru

Tomsk State University

The Department of Celestial Mechanics and Astrometry simulates nuclear explosions on asteroids as a means of deflection (Aleksandrova et al. 2016).

http://tsu.ru

China

Tsinghua University:

Tsinghua University's School of Aerospace is researching solar sails and how they can be used to assist kinetic impactor and gravity tractor deflection missions (Gong et al., 2009).

http://www.tsinghua.edu.cn/publish/hyen/index.html

Harbin Institute of Technology:

The School of Law at Harbin Institute of Technology has published articles on the legal issues of NEO deflection missions. (Tronchetti, 2015).

http://law.hit.edu.cn/#

Chinese Academy of Sciences:

FAST (Five-hundred-meter Aperture Spherical Telescope) is a 500m-diameter radio telescope, which could theoretically be used as part of a radar system to explore the shapes, surface roughness, and other physical characteristics of asteroids. Operation of the telescope began in 2016.

http://fast.bao.ac.cn/en/

Canada

University of Western Ontario:

The Centre for Planetary Science and Exploration carries out research on meteorites, asteroid atmospheric explosions based on infrasound data from the CTBTO network, and orbital dynamics of asteroids (Brown et al. 2013; Wiegert, 2015).

http://cpsx.uwo.ca/research/research_themes.html

South Korea

KASI (Korea Astronomy and Space Science Institute) operates the KMTNet (Korea Microlensing Telescope Network), which consists of 3 identical 1.6 m optical telescopes in South Africa, Chile and Australia with an 18k x 18k mosaic CCD. The primary science of these telescopes is searching for exoplanets and variable objects, as well as data mining the observations for asteroids and comets. About a third of the observing time until 2019 will be made available for project proposals from the general Korean science community. One of the 7 projects selected was the DEEP South project (Deep Ecliptic Patrol of the Southern Sky), with the purpose of searching for, and physically characterizing, asteroids and comets.

http://kmtnet.kasi.re.kr/kmtnet-eng/programs/

International

Radar astronomy with VLBI networks:

A number of organizations cooperate on VLBI observations for various projects in astronomy and astrophysics. Some of the VLBI telescopes have been, or could in principle be, used for bistatic radar characterization of NEOs. Existing VLBI networks include:

- The African VLBI Network (AVN): an initiative in radio astronomy research in a number of African countries with the support of African ministers and universities, and the European Union. In July 2017 Ghana had "first light" in its refurbished 32-meter steerable (former telecommunication) antenna, and progress is being made in Botswana, Kenya, Namibia, Zambia, Mauritius and Madagascar to convert telecommunication antennas into radio astronomy telescopes, build new ones, or prepare for “big data” processing.

  http://www.ska.ac.za/science-engineering/avn/

- The European VLBI Network (EVN): an interferometric array of more than a dozen radio telescopes (Fig. 6).

  http://www.evlbi.org

- The Korean VLBI Network: consists of mainly three 21 m radio telescopes and one 14 m dish, which can function together as an interferometer. The Korean VLBI network is part of the East Asian VLBI Network and collaborates with the European VLBI Network.

  https://www.kasi.re.kr/eng/pageView/89

- Institute of Applied Astronomy, Russian Academy of Science Quasar VLBI network http://iaaras.ru/en/quasar/; http://lfvn.astronomer.ru/optic/evpatoria/rt70/index.htm

Fig. 6: The European VLBI Network of telescopes in 2016 and its collaboration partners. Credit: Paul Boven

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 (Fig. 7a), are particularly relevant. A rapid-response network of suitable telescopes would allow many small objects to be characterized during the discovery apparition. A dedicated space based thermal-infrared telescope, as a successor to the Wide-Field Infrared Survey Explorer (WISE, Fig. 7b), 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.

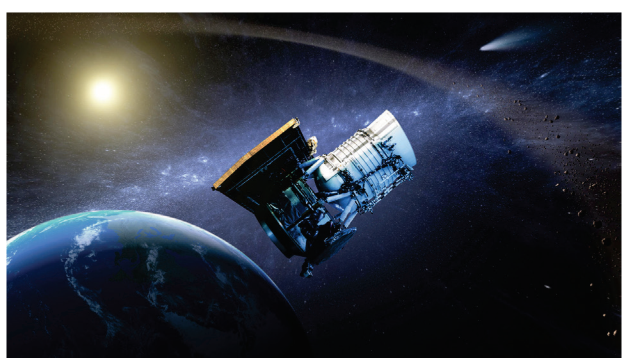

Fig. 7a (left): 305 m diameter Arecibo radar facility. Fig. 7b (right): Artist's impression of the WISE spacecraft in orbit around Earth. Credit: NASA

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 (Fig. 8), 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.

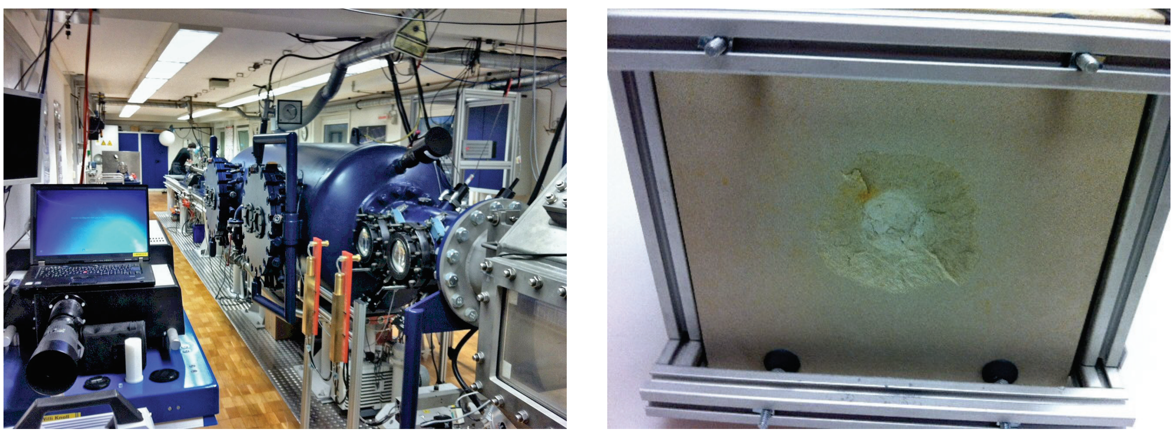

Fig. 8: Hypervelocity gas gun and target block of asteroid analog material, Fraunhofer Ernst Mach Institute, Freiburg, Germany. Credit: Alan Harris, NEOShield

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 (see Appendix B) 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. 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") (Cheng et al., 2016), which would be developed in the US, and the European rendezvous spacecraft AIM (Asteroid Impact Monitor) (Michel et al., 2016). 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.

NEOTωIST is an alternative, relatively inexpensive, test of the kinetic impactor concept, which has been studied in NEOShield-2 (Drube et al., 2016; Engel et al., 2016). The idea is 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 both impactor and reconnaissance 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.

Improve knowledge of impact probability:

After identification of an object with a significant probability of impacting the Earth it would be essential to improve our knowledge of the object’s orbit as quickly as possible. Groundbased assets should be employed in the first instance. However, if the probability of impact continued to rise, given sufficient time, a fly-by mission could play a vital role in providing dynamical and physical information to inform decisions concerning an emergency deflection campaign and emergency response planning on the ground. Studies of such missions in realistic scenarios should be encouraged and supported, including timing, requisite instrumentation, and improvements in knowledge of the impact probability and physical characteristics of the object that could be expected.

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. Examples of preliminary work in this area are Rumpf et al. (2016, 2017).

Emergency response organizations should be made aware of the possibility of an asteroid impact and its possible effects, and assisted in the preparation of appropriate plans of action. ESA and NASA have already held several tabletop exercise workshops for emergency response organizations but such exercises should also be organized for other countries/regions. International emergency response organizations, such as the European Commission's Humanitarian Aid and Civil Protection department (ECHO), could play an important role in this regard.

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. A suite of three software tools, which serve as an aid in the selection of the most suitable deflection mission given the circumstances of the potential impact scenario, has been developed within the NEOShield project (Cano et al., 2015).

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.

Preliminary software tools to calculate possible post-deflection trajectories, their probabilities, and long-term evolution, taking account of all possible failure modes of a deflection attempt are being developed (e.g. see Eggl. et al., 2016).

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 (Fig. 9), 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 (see Appendix B for a list of mitigation methods).

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.

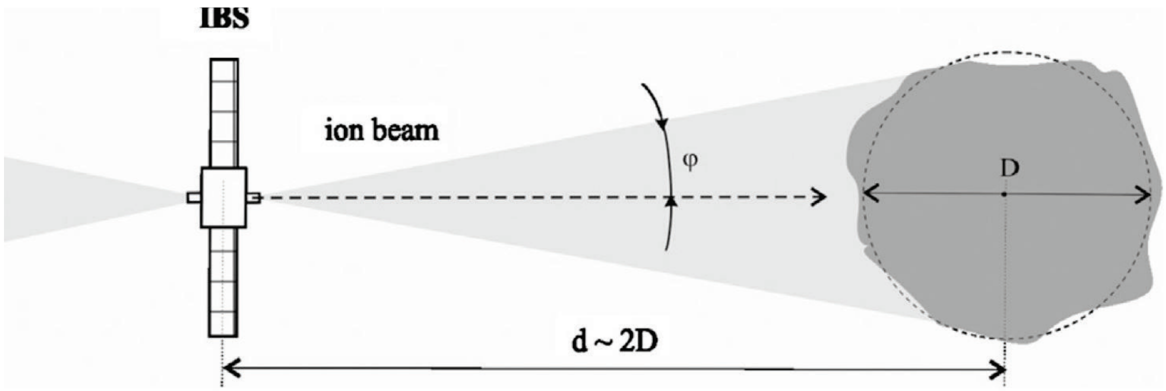

Fig. 9: Schematic diagram of the principle of the "ion-beam shepherd" deflection concept. A collimated beam of quasi-neutral plasma is directed at the asteroid surface. The spacecraft, placed at a distance of a few asteroid diameters, would need a second propulsion system to compensate for the ion engine reaction and keep a constant distance between the asteroid and the shepherd spacecraft. From Bombardelli et al., (2013).

Legal issues:

Scientific and technical advances in the field of planetary defense have now reached a stage at which associated legal issues must be considered. Effort is required to formulate and prioritize relevant legal questions, which have to be considered in the context of the scientific, technical, and socio-economic circumstances, and existing treaties.

At the February 2016 session of SMPAG it was agreed to establish a working group to discuss and make proposals on the legal issues relevant to the execution of NEO deflection missions, both for test purposes and in an emergency situation, and associated aspects of planetary defense. The group, consisting of space law experts and scientists/engineers, started work in November 2016.

NOTE: Please notify the primary authors of any relevant activities related to mitigation that are not included in the current issue of this document. In addition to omissions, the authors would welcome notification of errors or any suggestions for improvements.*

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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	10-12 M€ 2013-2016 (4 years).
ESA/NASA	AIDA	2013-2017	Asteroid Impact Deflection Assessment. mission phase A/B1 study at ESA/NASA	Europe, USA	Concept development funded
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
USA NASA Science Mission Directorate	NASA Planetary Defense Coordination Office	2016 -	Oversight and coordination of all NASA-funded projects related to planetary defense and coordination of US government efforts	USA	50.0 M $US per year
Luxembourg Government	Asteroid mining	2017-2027	Support research and development for asteroid mining (which could prove relevant for planetary defense).	Luxembourg	200 M€ total
Other?					

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

Funding source	Program/ project	Time period	Main objectives	Country
NASA/ESA	AIDA (two spacecraft, DART+AIM)	Launch 2020	Impact moon of asteroid Didymos to change its orbit (DART); characterization of the target and monitoring of the impact (AIM).	USA/Europe
Iowa State Univ., crowdfunding, sponsorships	Hyper-velocity Asteroid Intercept Vehicle (HAIV)		Study of a kinetic-impactor + explosive NEO deflection system	USA
NASA	NEOCam	Funding through 2017	Discovery; physical characterization (IR)	USA
Various countries	Asia-Pacific Asteroid Observation Network	2014-	Surrey and physical characterization of asteroids and comets	China, Japan, South Korea, Malaysia, Mongolia, Taiwan, Thailand, Usbekistan
Various countries, The Leverhulme-Royal Society Trust, Newton Fund in UK	African VLBI Network		Radio astronomy with potential for bistatic radar characterization of NEOs	African countries
Other?				

6. Summary and Conclusions

Despite significant progress over the past decade or so much more needs to be accomplished before the international community can feel adequately protected from a potentially catastrophic asteroid impact. We have identified the following areas as requiring continued or increased effort at the present time:

- The development and execution of technically and financially realistic test missions to enable deflection concepts to be tried out on real asteroids.

- Remotely-sensed physical characterization of small NEOs (radar, infrared, visible, etc. observations; analysis of archival data). Asteroid observing strategies and campaigns need to be coordinated internationally to make the most efficient use of available telescope time. A dedicated space based thermal-infrared telescope would be a very valuable asset for simultaneous NEO discovery and characterization.

- The development of a rapid-response network for physical characterization of asteroids during the discovery apparition.

- The development and execution of space missions for surface material sample return and/or in-situ characterization of asteroids.

- Laboratory tests for a range of asteroid analog materials to better understand impact effects on asteroids.

- Computer modeling with more complex and realistic conditions to understand impact effects on asteroids.

- The development of plans for a rapid-reconnaissance space mission to be launched promptly in case of a real impact threat, to gather information on the physical properties of the asteroid and its orbit.

- The development of new deflection techniques for small NEOs.

- The development of reliable codes for Earth impact consequences assessment taking account of the full range of expected effects.

- The development of software tools for emergency deflection campaign planning to inform decision making.

- Exploration of synergies between the fields of NEO deflection and asteroid mining.

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 it 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.*

Acknowledgements

The work leading to the first release of this document was partially supported by the European Union's Horizon 2020 research and innovation programme under grant agreement no. 640351 (project NEOShield-2).

Appendix A: Matrix of current mitigation-related activities as an aid to future planning

	Asia	Europe	Russia	America
Kinetic impactor method	Solar sail assisted kinetic impactor concept - Tsinghua University, China	AIM - CNRS/Obs. Côte d'Azur (lead), France Mission design - Airbus-DS, Germany; Deimos Space, Spain; CNRS/Obs. Côte d'Azur, France NEOTωIST concept - Airbus-DS; DLR, Germany; Airbus-DS, France Post-deflection rapid determination of impact effects and beta-factor - Airbus-DS, Germany		AIDA DART mission in Phase B1 NASA - John Hopkins Univ. (lead); Lawrence Livermore National Laboratory, USA
Blast deflection method			TSNIIMASH Tomsk State Univ.	Lawrence Livermore National Laboratory; Los Alamos National Laboratory; HAIV mission - Asteroid Deflection Research Center, Iowa State Univ., USA
Slow pull/push methods	Solar sail assisted gravity tractor concept - Tsinghua University, China	Laser ablation - Univ. of Strathclyde, UK Gravity tractor - Univ. Surrey, UK		Gravity tractor - SETI, USA Laser ablation - Univ. Alabama, UC Santa Barbara, USA
Relevant asteroid space missions	Hayabusa-2 sample return asteroid mission, Japan	Hayabusa-2 - LESIA, CNRS/Côte d'Azur Observatory, France Hayabusa-2, MASCOT lander - DLR, Germany OSIRIS-REx (NASA) - LESIA; CNRS/Obs. Côte d'Azur, France		Osiris-Rex sample return asteroid mission, USA
GNC development for deflection mission		Airbus-FR, France; Deimos Space, Spain; GMV Space Systems, Spain		
Mission designs and non GNC technologies		Mission Designs - Airbus-DS, Germany; Airbus-DS, UK; Surrey Satellite Technology Ltd, UK Nuclear power sources - UK National Nuclear Laboratories		Asteroid Deflection Research Center, Iowa State Univ., USA
Instruments for deflection missions		Instrument suites for deflection methods - Obs. Paris, France Instrument suites for NEA internal struture characterization - IPAG/Grenoble; LATMOS/Paris, France		Gravimetry - Gedex, Canada
Computer modeling of deflection attempts		Modeling of kinetic impacts on asteroids and the ejecta -CNRS/Obs. Côte d'Azur, France; Univ. Bern, Switzerland Modeling laser ablation - DEIMOS, Spain		Lawrence Livermore National Laboratory; Applied Physics Lab., John Hopkins Univ.; Univ. of Washington, USA
Modeling impact effects in the atmosphere and on the ground		NEO Impact Assesment tools - ESA SSA Hypervelocity re-entry - ONERA, France Risk assessment in the atmosphere - IMCCE, France	Atmospheric trajectory analysis and ground damage -TSNIIMASH	Asteroid Threat Assessment Project, NASA Ames Ground damage + meteor entry and breakup - NASA; Los Alamos National laboratory; Sandia National Labs., USA Atmospheric impact effects, infrasound data - Univ. of Western Ontario, Canada Rapid Response to the next TC3 Consortium, SETI, USA Ocean impacts - Lawrence Livermore National Laboratory, USA
Hyper velocity impact laboratory experiments	Horizontal & vertical light-gas guns - ISAS/JAXA, Japan Horizontal light-gas gun - Kobe University, Japan Horizontal light-gas gun - Chiba Inst. of Technology, Japan	Horizontal light-gas gun - Fraunhofer EMI, Germany All-axis light gas gun - Open Univ., UK Double-stage light gas gun - Univ. Kent, UK		Light-gas guns - NASA Ames; Boeing Industry, USA
Tools for emergency deflection campaign planning		Software package for deflection mission planning in development: DEIMOS, Spain; IMCCE, France	End-to-end software package in development - Russian Academy of Sciences	NASA/JPL NEO Deflection App, USA
Orbit calculations	National Astronomical Observatory of Japan, JAXA	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	Russian Academy of Sciences; Saint Petersburg State Univ., Russia	JPL Center for NEO Studies, USA The Minor Planet Center, USA Dynamical evolution - Univ. of Western Ontario, Canada
Observatories used for physical characterization of NEOs	e.g. Bisei Spaceguard Center, National Astronomical Obs. of Japan. Deep South (Deep Ecliptic Patrol Of the Southern Sky) Project using the KMTNet (Korea Microlensing Telescope Network), KASI, South Korea. Five-hundred-meter Aperture Spherical Telescope, Chinese Academy of Sciences. East Asian VLBI Network	e.g.: Optical Ground Station, 1-m telescope, Tenerife, ESA Ondrejov Observatory, Czech Republic Klet Observatory (1-m telescope), Czech Republic Calo Alto Obs., DLR, Germany Pic du Midi station, France European VLBI Network	e.g.: Quasar VLBI network	e.g.: InfraRed Telescope Facility; Goldstone Solar System Radar; Arecibo Radar; WISE IR space telescope; Mt. Lemmon Obs., Lowell Observatory, USA
Deflection mission legal issues	School of Law, Harbin Institute of Technology, China	DLR, Germany; Univ. Rom, Italy; Univ. Vienna; Karl Franzens Univ. Graz, Austria; BELSP, Belgium; ESA		NASA HQ; Univ. of Nebraska, USA; Mexican Space Agency

Appendix B: Summary of mitigation methods for asteroids and comets

Purpose: To provide a comprehensive list of mitigation methods for PHOs (potentially hazardous objects, i.e. asteroids and comets), including their main challenges, and a rough estimate of their technical maturity at the present time.

Includes input from: Gerhard Drolshagen (formerly of ESA, SMPAG Chair), Detlef Koschny (ESA), William Ailor (International Academy of Astronautics), and Lindley Johnson (NASA).

For a measure of the technical maturity level, the NASA Technical Readiness Level (TRL) is used (Mankins, J.C., et al., 1995):

TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and “flight qualified” through test and demonstration (ground or space)
TRL 9	Actual system “flight proven” through successful mission operations

The choice of mitigation method will depend on the size and orbit of the object, the amount of time before impact, and the technical maturity of the methods at the time of decision.

The list of methods has been split into 3 categories:

Impulsive methods

The impulsive methods are preferred at present, as they are powerful and fast acting, with the kinetic impactor being the technically simplest solution and the nuclear option possibly being the only option in the worst-case scenarios.

Slow push/pull methods

The slow push/pull methods give much more control over the precise change in the object’s orbit, and might become the preferred methods for small objects or small orbit changes in the coming years, when the technical maturity has increased.

Exotic methods

The exotic methods are ideas that could be exploited in the future though very little research has been done as of yet.

The following list was compiled based on inspiration from the following articles and reports: Eckersley and Brown (2013), NASAs Report to Congress (2007), Sanchez, et al. (2009).

Impulsive methods (TRL 5-7)

Kinetic impact method

Method: A high velocity impact of a spacecraft into a PHO transfers momentum to it, thereby changing the orbit of the PHO. Ejected material from the impact can enhance the orbit change.

Main challenge: To impact a small target at high speed requires a very precise guidance, navigation and control system (GNC); effective against relatively small objects (<200 meters).

Nuclear option

Method: A nuclear explosion close to a PHO or on/below its surface. The radiation vaporizes the surface material and ejects it at high speed. The pressure wave from an explosion on/below the surface can also cause large pieces of the PHO to fly off. With sufficient energy the PHO can be split completely into small pieces (some of which might however recombine).

Main challenge: Political opposition.

Chemical Blast Deflection

Method: The pressure wave from a sub-surface chemical explosion causes PHO material to be ejected from the surface causing thrust.

Main challenge: Placing the explosive below the surface; achieving sufficiently powerful blast.

Slow push/pull methods (duration of the order of years, TRL 3-6)

Gravity tractor

Method: A spacecraft hovers close to a PHO using the gravitational attraction between it and the PHO to slowly modify the PHO's orbit.

Main challenge: Requires a massive spacecraft and long-term reliable operation close to a PHO.

Enhanced gravity tractor

Method: A spacecraft collects mass from the PHO to enhance its own gravitational field thereby speeding up the orbit change.

Main challenge: Successful collection of mass in addition to long-term reliable operation close to a PHO with the extra mass.

Ion beam shepherd

Method: A spacecraft beams ions onto the surface of a PHO (and also in the opposite direction to prevent it drifting off station). The ions hitting the surface at high speed create a small momentum change in the PHO.

Main challenge: Long-term reliable operation of an ion engine and GNC system.

Laser ablation

Method: A laser beam is aimed at the PHO. The energy creates flash vaporization of the surface. The ejected material provides a thrust on a PHO in the opposite direction.

Main challenge: The laser technology

More exotic concepts (TRL 1-2)

Spin-up and shatter

Method: Attach rockets at an angle to the surface of the asteroid to spin it up (i.e the Catherine-Wheel principle) beyond the rubble-pile rotation limit, causing the PHO to disintegrate.

Main challenges: Surface attachment, provision of rocket fuel, collision danger from ejected debris.

Thrust on the surface

Method: Place a spacecraft on the surface of the PHO and use the propulsion system to thrust outwards, thus pushing on the object. Due to its rotation the PHO needs to be spun-down first, or the thrust needs to be timed such that it is only active for a brief period once per rotation.

Main challenge: Surface attachment, rotation of the PHO.

Mass driver

Method: Land a spacecraft on the surface of the PHO, collect material from the surface and eject it at high speeds to create a thrust.

Main challenge: Collecting mass and ejecting it efficiently from a rotating PHO with little gravity.

Reflectivity change of the PHO

Method: Modify the reflectivity of the PHO’s surface by changing its color. A light surface causes a greater momentum reaction from reflected photons. A dark color would change the thermal emission of the asteroid, causing more emission on the afternoon side, which speeds up or slows down the PHO in its orbit, depending on its direction of spin (the Yarkovsky effect). The Yarkovsky effect is expected to be the dominant effect (Vokrouhlický and Milani, 2000; Hyland et al., 2010).

Main challenge: Technical complications of coloring the surface; deflection effect is very weak.

Conductive coating

Method: Apply a conductive coating to the surface to alter the orbit via interaction with the interplanetary magnetic field or by using an ‘electrostatic tractor’ spacecraft.

Main challenge: Technical complications of covering the surface.

Solar Shadow

Method: Deploy a sunshade large enough to partially or fully shadow the PHO, in order to change the solar radiation pressure or the Yarkovsky effect.

Main challenge: Deployment of a sunshade large enough.

Focused solar light

Method: Focus solar light via mirrors onto a point on the PHO surface creating flash vaporization of the surface. The ejected material imparts an impulse on the PHO in the opposite direction.

Main challenge: The large mirror structure; contamination from the surface material.

Microwave energy

Method: Direct microwave energy into the surface of the PHO to evaporate the water within the surface material causing small explosions, which act as thrusters. The method would be applicable only to those asteroid types with significant water content.

Main challenges: Sufficiently powerful microwave emitter, directing the microwave energy.

Increase comet activity

Method: Provoke enhanced cometary activity at a specific location to create an ejection of surface mass in a single event or multiple events.

Main challenge: Control of the direction of ejecta.

Mechanical resonator

Method: Land a mechanical resonator on the PHO to create vibrational pulses at the PHO’s natural frequency causing it to break apart.

Main challenge: Adequate surface attachment to efficiently transfer the vibration to the PHO.

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