The European Union funded NEOShield project: a global approach to near-Earth object impact threat mitigation

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The European Union funded NEOShield project: A global approach to near-Earth object impact threat mitigation

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ABSTRACT

Although discussions are underway within the Action Team 14 of the United Nations COPUOS, there is currently no concerted international plan addressing the impact threat from near-Earth objects (NEOs) and how to organize, prepare and implement mitigation measures. We report on a new international project to address impact hazard mitigation issues, being the subject of a proposal submitted to the European Commission in response to the 2011 FP7 Call "Prevention of impacts from near-Earth objects on our planet". Our consortium consists of 13 research institutes, universities, and industrial partners from 6 countries and includes leading US and Russian space organizations. The primary aim of the project, NEOShield, is to investigate in detail the three most promising mitigation techniques: the kinetic impactor, blast deflection, and the gravity tractor, and devise feasible demonstration missions. Furthermore, we will investigate options for an international strategy for implementation when an actual impact threat arises.

The NEOShield project was formally accepted by the European Commission on 17th November 2011 and funded with a total of 5.8 million Euros for a period of 3.5 years. The kick-off meeting took place at the DLR Institute of Planetary Research, Berlin, in January 2012. In this paper we present a brief overview of the planned scope of the project.

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1. Introduction

Collisions of asteroids and comets with the Earth have taken place frequently over geological history and have altered the evolutionary course of life; there is no reason why they should not continue to hit the Earth at irregular and unpredictable intervals in the future. Thousands of NEOs, mainly asteroids, have been discovered over the past 20 years and the reality of the impact hazard has been laid bare. Can we protect our civilization from the next major impact?

The NEOShield project plan includes a detailed analysis of the open questions relating to realistic options for preventing the collision of a NEO with the Earth. Solutions will be provided to critical scientific and technical issues that currently stand in the way of demonstrating the feasibility of promising mitigation options via test missions. While a mitigation test mission is beyond the financial scope of the present project funding, we aim to provide detailed test-mission designs for the most feasible mitigation concepts, facilitating the rapid development of actual test missions at a later stage. The work plan includes laboratory experiments and associated modelling to improve our understanding of the nature of NEOs and allow the feasibility of mitigation techniques and mission designs to be accurately assessed.

Our project includes appropriate partners from established space-faring nations outside the European Union. We will formulate a global response campaign roadmap that may be implemented when a serious impact threat arises. Our efforts will take account of, and complement, other international initiatives, such as those of the UN COPUOS Action Team 14 on NEOs. The roadmap will consider the necessary international decision-making milestones, required reconnaissance observations, both from the ground and from rendezvous spacecraft, practical prerequisites, such as precise orbit tracking, and a campaign of perhaps several mitigation missions, depending on circumstances.

The NEOShield work effort is split roughly equally between scientific work and technical design and development work. The scientific effort includes studies of the physical properties of NEOs using available Earth-based observational data and in-situ spacecraft data, instrumentation and a strategy for reconnaissance observations of a threatening object, laboratory gas-gun impact experiments and computer simulations of impacts into asteroids, and the identification of suitable demonstration-mission targets. The technical effort includes the development of crucial technologies, such as the autonomous guidance of a kinetic impactor to a precise point on the surface of the target, and the detailed design of realistic missions for the purpose of demonstrating the applicability and feasibility of one or more of the techniques investigated. Theoretical work on the blast deflection method of mitigation, and considerations of a global response campaign roadmap, are included in the technical work packages.

2. Near-Earth object physical properties

A successful mitigation strategy requires some knowledge of the physical properties of the threatening object [1]. Over the past 20 years much information on the physical properties of asteroids, including the NEOs (433) Eros and (25143) Itokawa, has been provided by rendezvous or fly-by spacecraft. Space missions to asteroids provide us with "ground-truth" data which enable ground-based observational results and data-analysis techniques to be verified. To date such investigations have been motivated by pure scientific considerations. However, the information requirements from a *mitigation* point of view are different to those of scientific investigations. Our project will address purely mitigation-relevant questions, such as: what prior knowledge of NEO properties (e.g. surface and bulk structure, mineralogy, mass, shape, rotation state) are required for mitigation mission design and planning? How can the relevant knowledge be acquired most efficiently, with what type of observations, reconnaissance mission(s), instrumentation, etc? Ground-based and space-borne assets will be considered, including radar facilities; ground- and space-based telescopes can be used for imaging, photometry, spectroscopy, and thermal-infrared observations, as well as for stellar occultation observations. The requirements will be identified in terms of the required precision of the physical parameters and the time available. In particular the balance between observations from the ground and space, and 'in-situ' observations by means of reconnaissance missions, including the instrumentation requirements for reconnaissance missions, will be addressed.

Numerical simulations of catastrophic disruptions of asteroids have shown that the impact energy required to adequately deflect an asteroid depends heavily on its structure. However, no study based on full numerical simulations of impact deflection has been made so far to assess the dependence of momentum transfer on the internal structure of a NEO. The NEO population consists of bodies with a variety of spectral features indicative of different mineralogies, and there is evidence that the porosity of small asteroids varies greatly with mineralogical composition. It is important to model the fragmentation of both porous and non-porous bodies in order to understand the impact or blast response of different types of NEOs. However, accurate modelling requires experimental results and none are available as yet relating momentum transfer on impact to internal structure and porosity. Our project includes laboratory experimental work and associated modelling to provide the necessary data pertaining to the behaviour of a NEO when hit by an impactor or subject to a stand-off blast. The laboratory data will be used to validate numerical models of the impact process at small scales; those models will then be scaled up to realistic NEO sizes and used to investigate the momentum transfer efficiency as a function of relevant target parameters, such as porosity and surface characteristics. Inherent in this process is the assumption that the same basic physics applies at small and large scales. Numerical and theoretical procedures with different scaling approaches will be used and the results compared. In this way the limitations of different approaches can be explored and refinements developed. Ultimate verification of our methods will require a kinetic- impactor demonstration mission.

Together with data on NEO physical properties already available, the experimental results and modelling will help us to improve our understanding of the nature of NEOs and allow the feasibility of mission designs to be accurately assessed, thus significantly increasing our ability to provide mission designs with maximized probabilities of success.

3. Monitoring the effects of a mitigation attempt or demo mission

Any mitigation attempt or demonstration mission has to be closely monitored to ensure the desired effect is actually achieved. It is vital to ensure that a change in the NEO's orbit does not place it on a trajectory that would result in an increased risk of impact at a later time, e.g. a few decades in the future. Thus the issue of "keyholes" has to be considered: a keyhole is a small region of space near the Earth, which pre-determines an impact on the Earth several years later if a potentially hazardous asteroid happens to pass through it. The planning of a mitigation attempt or demonstration mission has to include a detailed analysis of the orbital evolution of the target NEO. How should the orbital change be monitored? What kind of observations and precision of orbital characterization are required? The required type and accuracy of observational support will be an integral part of the mitigation- and demo-mission concepts and designs developed in our project.

3.1. Ground Damage Limitation

In the final phase of its trajectory an impacting NEO penetrates the Earth's atmosphere. The atmosphere influences the fragmentation and resulting damage on the Earth's surface. There is no clear understanding of this final phase of the impact event, and its dependence on the angle and speed of entry, size, orientation, structure, composition, etc. of the NEO, which is required to inform the decision to mitigate and the choice of mitigation option, and for consideration of the minimum level of resources required to prevent serious damage on the ground. An understanding of potential damage is clearly vital in circumstances in which available mitigation resources are stretched to the limit (e.g. in the case of a short warning time or a large NEO). We will assess the potential ground damage resulting from an impact, and from NEO fragments arising as a result of a destruction or deflection attempt, which may influence the choice of mitigation technique applied.

4. Demo-mission target choice

At the time of writing some 8000 NEOs have been discovered, a number that increases by about 70 each month. Which of the known NEOs should be used as targets for mitigation demonstration missions? Suitability depends on factors such as accessibility, diameter and shape, mass, minimum orbit intersection distance to the Earth, or Earth MOID, mineralogy, albedo, rotation state, and possible binary nature. Ideally, target characteristics should be similar to those expected of the next significant NEO to threaten the Earth and warrant a mitigation attempt. The operation of new facilities such as Pan-STARRS1 will ensure that over 10,000 NEOs will be known by the end of this project. Given the very large and increasing number of known NEOs a significant effort is required to maintain a catalogue of optimum targets for demonstration missions. Potential targets for a gravity tractor demo mission may not be suitable for tests of other mitigation techniques. A major product of our work will be a consolidated list of the most important NEO dynamical and physical characteristics required of a demo-mission target, the best potential targets within the known NEO population, and the remaining measurements (if any) required to confirm the suitability of particular NEOs as demo-mission targets.

5. Mitigation demo-mission technical considerations

In order to maximize the chances of success of a mitigation attempt it is vital to test the mitigation technique and related technologies beforehand. The feasibility of appropriate mitigation demonstration missions will be examined and appropriate detailed mission designs provided. Various options will be investigated with a view to providing concrete suggestions for technically and financially realistic international space missions that could demonstrate the applicability and effectiveness of one or more of the techniques investigated in the project.

When a serious impact threat occurs it is unclear in which circumstances a particular technique should be preferred over another or what type of strategy involving a combination of reconnaissance missions and mitigation techniques might have the greatest chance of success. Since NEOs in the size range 100 - 500 m are at least an order of magnitude more frequent than km-sized objects, it seems prudent to focus mitigation planning on the smaller size range, in which case, given a probable decade or two of warning time from modern NEO monitoring programmes, the kinetic impactor may provide the best approach [2, 3]. For NEOs with diameters larger than 1 km, or warning times shorter than a few years, we would have no choice at present but to consider the blast-deflection option. For warning times exceeding 20 years, or as a corrective measure in the case of a kinetic impactor attempt that falls short of expectations, the gravity tractor provides a finely-controllable slow-push alternative.

5.1. Kinetic impactor

The kinetic impactor concept has been studied in Europe in the framework of ESA's Don Quijote mission study programme [4], but many open questions remain to be addressed. The efficiency of momentum transfer from the impactor to the hazardous NEO depends not only on the physical properties of the target as discussed above, but also on the impact accuracy. What are the crucial design parameters of the impactor spacecraft guidance control system for robust targeting? How does the necessary camera resolution and autonomous control-loop response time depend on approach velocity, target size, thruster sizing, the required accuracy of the impact location, etc? What is the trade-off between impactor approach trajectory, impact accuracy, and potentially unfavourable illumination conditions (e.g. approach from a high solar phase angle). How does impact accuracy depend on phase angle? How does impact accuracy depend on fuel sloshing during the critical final autonomous manoeuvres of the impactor spacecraft? How can the effects of fuel sloshing be minimized? While fuel sloshing technology is addressed in ESA's technology plan for the Cosmic Vision programme, our project will address the issue in a systems engineering approach, i.e. how to minimize fuel sloshing by appropriate spacecraft and mission operation design. The emphasis of the technology development will be on spacecraft guidance, navigation, and control (GNC) aspects, in terms of both absolute and relative navigation.

5.2. Gravity tractor

The kinetic impactor concept has already been developed in Europe in mission studies, and the auto-navigation process required to impact an object with a spacecraft was demonstrated by NASA's Deep Impact mission in 2005. In contrast, the gravity tractor concept exists only at a theoretical level [5]. We propose to develop the gravity tractor concept to the mission design level, thereby examining the feasibility and reliability of this method and exploring practical solutions to associated technical challenges, such as: Which control laws and trajectories provide hovering manoeuvres that minimize fuel consumption and maximize the asteroid's deflection? What are the trade-offs between the mass of the tractor, the distance between the tractor and the NEO, the control laws, and the time required to produce the required deflection? Reliability is a crucial issue given the long periods (several years to a decade) that may be required for gravity traction to produce the required deflection (although use of a gravity tractor for keyhole avoidance, or for a finely-controllable corrective measure after a deflection attempt by means of a kinetic impactor, would generally require much less time). What are the requirements for autonomous spacecraft control procedures to manage hovering station keeping and maintain stability of the traction system in the (very nearby) presence of an irregular rotating mass?

5.3. Alternative approaches

Deflecting a NEO by means of an explosion (referred to here as "blast deflection"), is a potentially effective mitigation method in certain circumstances. Obviously, the most powerful explosive technology at mankind's disposal is nuclear. Given the political and ethical problems associated with nuclear explosive technology, this method is generally considered appropriate only in extreme circumstances in which no other current mitigation option is viable (e.g. short warning time or NEO diameter larger than 1 km). Currently there is no international agreement in place to cover this eventuality. While the circumstances requiring use of the nuclear mitigation option are very unlikely to arise, a serious

NEO mitigation strategy has to consider this method [6]. Neither the research work carried out within this project nor the space-mission designs developed will involve nuclear weapons technology. However, we aim to address certain questions relating to the blast deflection technique in detail, such as: Under what circumstances would stand-off, surface, or buried blasts be more effective? If burial of the explosive charge is required, is current penetrator technology adequate? Would surface ejecta significantly enhance the impulse? If so, how can the production of ejecta be maximized. How does the danger of complete disruption of the NEO depend on its mass, structure, mineralogy and other physical properties? Under what circumstances might disruption be a desirable option? How does the tensile strength and porosity of a body influence its response to an explosion? Given the strong dependence of the response on NEO physical properties, the amount and kinematics of the debris, and spacecraft payload mass, the post-deflection analysis, including atmosphere entry issues, will play a significant role in the assessment of the blast deflection option.

Blast deflection missions, including demo missions, would be unique enterprises from the international policy and law standpoint. The approval of an internationally recognized decision-making authority would be an essential prerequisite to the deployment of powerful explosive devices on space missions. What is the risk trade-off between construction, preparation and launch of explosive devices and completely dismissing blast-deflection as a mitigation option?

While the primary aim of the project is to investigate the three mitigation techniques that appear currently to be the most promising, i.e. the kinetic impactor, the gravity tractor, and blast deflection, any alternative technique identified as having similar potential may be studied in the course of the project.

6. Global response campaign roadmap

In the light of results arising from our research into the feasibility of the various mitigation approaches and the mission design work, we aim to formulate for the first time a global response campaign roadmap that may be implemented when an actual significant impact threat arises. For a number of realistic scenarios (e.g. using the case of Apophis) the roadmap will consider the necessary international decision-making milestones, required reconnaissance observations, both from the ground and from rendezvous spacecraft, practical prerequisites, such as precise orbit tracking and availability of appropriate launchers, and a campaign of perhaps several mitigation missions depending on circumstances, such as time available before impact. The roles and responsibilities of international organizations such as the UN and the EU, in addition to space agencies and other authorities, will be considered. Account will be taken of complementary efforts currently in progress (e.g. UN Action Team 14 on NEOs, ESA's Space-Situational-Awareness programme) and colleagues outside our consortium involved in such activities will be invited to contribute to the establishment of a broad international strategy.

7. Outlook

Protecting the Earth from NEO impacts is a global problem and, as such, any mitigation strategy should involve at least the most scientifically and technologically capable nations. Our project includes major experts in this field from the USA and Russia, countries whose competences in space technology are beyond question and that already have active and significant research programmes in the area of NEO mitigation. While an actual mitigation demonstration mission is financially beyond the scope of the present project, we aim to provide the first designs of appropriate demo missions for the kinetic impactor and other mitigation concepts sufficiently detailed to facilitate the rapid development of actual demo missions in subsequent rounds of project funding in a European/international frame. Liaison with space agencies will be mutually beneficial during the course of the project, but in particular in the final stages when options for future implementation of proposed demo missions designed in the course of the project will be discussed. To this end we propose to hold meetings with interested space-agency representatives, especially in the initial and final phases of the project. While ESA's current Space-Situational-Awareness activities and those proposed by this consortium do not overlap, it is clear that both sides should remain aware of each other's progress. Within the framework of the project we aim to investigate the best approach to facilitating an international, multi-agency-financed, mitigation demonstration mission.

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