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Near-Earth objects

Information on research in the field of near-Earth objects carried out by international organizations and other entities

Note by the Secretariat

Contents

* A/AC.105/C.1/L.277.

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I. Introduction

In accordance with the agreement reached at the forty-first session of the Scientific and Technical Subcommittee (A/AC.105/823, annex II, para. 18) and endorsed by the Committee on the Peaceful Uses of Outer Space at its forty-seventh session (A/59/20, para. 140), the Secretariat invited international organizations, regional bodies and other entities active in the field of near-Earth object (NEO) research to submit reports on their activities relating to near-Earth object research for consideration by the Subcommittee. The present document contains reports received by 17 December 2004.

II. Replies received from international organizations and other entities

European Space Agency

Overview of activities of the European Space Agency in the field of near-Earth object research: hazard mitigation

Summary

1. Near-Earth objects (NEOs) pose a global threat. There exists overwhelming evidence showing that impacts of large objects with dimensions in the order of kilometres (km) have had catastrophic consequences in the past. Although such impacts happen very infrequently, even objects smaller than several kilometres in diameter cause significant damage when they hit the Earth at random intervals of hundreds or thousands of years.

2. In the past, the European Space Agency (ESA) has supported industrial and academic research in the field of NEOs in the context of its General Studies Programme in close cooperation with its Space Science Programme. Such activities enable ESA to define the best way in which Europe can make a significant, yet realistic, contribution to international efforts towards assessment of the NEO hazard.

3. Several parallel mission feasibility studies were carried out within the NEO Space Mission Preparation activity of the General Studies Programme.[1] The outcome of these studies was assessed by the NEO Mission Advisory Panel (NEOMAP) of ESA, an independent board of recognized experts on various aspects of the NEO problem. Following presentation of the NEOMAP recommendations in July 2004, work is now focused on the “Don Quijote” mission concept. That concept has been prioritized, mainly from a technological perspective, as it offers the greatest potential for a significant mission return; it has also been prioritized from a scientific perspective. The concept has a modular architecture that could facilitate its implementation in the context of a cooperative project and that has raised considerable interest among the media and the general public. The concept has served as a reference scenario for recent discussions with the technical and scientific experts of the Japan Aerospace Exploration Agency (JAXA), who are currently involved in the ongoing Hayabusa asteroid mission, on their possible

participation in ESA internal assessments. The discussions were planned to continue in December 2004 and January 2005 at the ESA European Space Research and Technology Centre (ESTEC) Concurrent Design Facility. During the discussions, the interest of the JAXA technical and scientific experts in participating was confirmed and the potential benefits for both parties became apparent. Those include the pooling of know-how and the assessment of possible future opportunities for cooperation in planetary surface science and space technology development.

4. The importance of international initiatives to further the understanding of NEOs is well understood. The global dimension of the NEO hazard and the level of awareness of large numbers of the general public make the study of this risk especially suitable for international cooperation. Any resulting project or space mission could be relatively modest in financial terms.

Introduction

5. Near-Earth objects are not simply a scientific curiosity. In practical terms, if NEOs were to collide with the Earth, they could cause the worst possible natural disasters.

6. In Europe, a large number of activities in the field of NEO impact risk assessment has been initiated by academics, but few by institutions. The activities at the institutional level do not meet the recommendations of Council of Europe resolution 1080 of 20 March 1996 on the detection of asteroids and comets potentially dangerous to humankind.

7. In resolution 1080, the Council invited Governments of member States, those States enjoying observer status and ESA to give the necessary support to an international programme that would establish an inventory of NEOs as complete as possible, with an emphasis on objects larger than 0.5 km in size; further the understanding of the physical nature of NEOs, as well as the assessment of the phenomena associated with a possible impact, taking into consideration their various levels of kinetic energy and composition; participate in designing small, low-cost satellites for observing NEOs that cannot be detected from the ground and for investigations that could most effectively be conducted from space; and contribute to a long-term global strategy for remedies against possible impacts.

8. The importance of international initiatives to further the understanding of NEOs has been highlighted on many occasions: in the Vienna Declaration on Space and Human Development, adopted by the Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE III)[2] and endorsed by the General Assembly in its resolution 54/68 of 6 December 1999; in Council of Europe resolution 1080 of 20 March 1996 on the detection of asteroids and comets potentially dangerous to humankind; in the findings and conclusions of the Organization for Economic Cooperation and Development (OECD) Global Science Forum Workshop on Near Earth Objects: Risks, Policies and Actions, held in Frascati, Italy, from 20 to 22 January 2003; and in the position paper entitled "Protecting Earth from Asteroids and Comets" published by the American Institute of Aeronautics and Astronautics (AIAA) in October 2004. The long-term space policy of ESA also identified NEO research as a task that should be actively pursued.[3]

9. The global dimension of the NEO hazard and the level of awareness of large numbers of the general public make it a subject that is especially suitable for international cooperation and any resulting project could be on modest financial terms. However, relations among space-faring nations are complex in nature and there is a wide diversity of interests and possible approaches to the NEO issue. ESA has decided to follow a step-by-step approach, assessing European interests and capabilities first, then defining a strategy at the European level as a preparatory step for a framework of future international cooperation. This approach is based on several studies and ongoing internal assessments that enable the development of a coherent European strategy for the utilization of spacecraft missions to assess both the NEO hazard and the current technological capability to tackle it.

The role of space missions in the assessment of the near-Earth object hazard

10. To date, most NEO-related efforts made by European countries have concentrated on the theoretical modelling of the NEO population, the coordination and improvement of ground-based survey programmes, the distribution and analysis of astrometric data, the determination of NEO orbits, the remote physical characterization of NEOs and the modelling of their physical properties. Some of these activities are supported directly by ESA. The Spaceguard Central Node (SCN) is hosted by ESA at the European Space Research Institute (ESRIN) and advises ESA on issues related to NEOs.

11. Studies commissioned by ESA have indicated that a large potential exists to utilize dedicated space-based assets to further understanding of the NEO hazard (see annex II) and have elucidated the European options for dealing with it.

12. Those studies were organized in the belief that a phased approach would be necessary to assess the threat and develop effective mitigation techniques. Two broad types of space mission were identified: survey-type and "rendezvous" missions. Both types of mission would be highly complementary to the current ground-based efforts and, in some cases, superior to them.

13. Survey-type NEO missions are dedicated to the detection, tracking (that is, orbit determination) and remote characterization (for example, determination of taxonomic type and surface albedo of NEOs). The main objective of such missions is to compile, improve and expand a catalogue of dangerous objects. Although space-borne telescopes cannot be made as large and powerful as can terrestrial telescopes, improved viewing geometry and observation conditions enable improved access to certain types of object, such as Atens and Inner Earth Objects that, due to their proximity to the Sun in the sky, are often difficult to observe. These favourable conditions lead to efficient surveys in which objects as small as a few hundred metres (m) in size may be detected and catalogued. From space, it is possible to access a broader range of wavelengths (for example, infrared) and a better duty cycle than from the ground. All this could make a significant contribution to extending current observation efforts.

14. In situ characterization missions seek to determine precisely mass, volume and internal structure, among other physical properties of the objects. Space-borne instruments are the best and often the only means of obtaining such data, which are essential for the assessment of the consequences of an impact and the countermeasures that could be taken to prevent it.

15. Test missions leading to demonstration of the ability to move an asteroid have been identified as the type of in situ NEO missions that have the highest interest, both from the NEO characterization and the technological points of view.

Near-Earth object space mission preparation phase I: mission studies

16. Previous ESA studies had revealed the usefulness of NEO space missions and, in order to assess in detail the usefulness of all possible mission types, a call for mission and/or instrument ideas was issued by the ESA Advanced Concepts and Studies Office under the "Near Earth Objects Space Mission Preparation Study" (see annex II). Six mission concepts were selected on the advice of a panel of recognized NEO experts. In February 2003, the six parallel "pre-phase A" studies were successfully completed. The studies represented an assessment of six different space mission concepts, all of which were dedicated to gathering information on several aspects of the NEO hazard in order to identify the most effective countermeasures.

17. The studies demonstrated that space assets could complement ground-based observations and therefore represented a credible and interesting means of assessing NEO risk, including from the point of view of risk and cost. All study proposals assumed a budget of €150 million.

18. The six mission concepts are described below:

(a) The European Near-Earth Object Survey (EUNEOS) was proposed and studied by Alcatel Space, Observatoire de la Côte d'Azur and the Spaceguard Foundation. The concept proposed was a space survey from a heliocentric orbit interior to that of Venus that would discover the most dangerous NEOs, the so-called Potentially Hazardous Objects, which are often the most difficult to detect from ground-based observatories due to the need to observe close to the horizon at small solar elongations;

(b) "Earthguard-I" was proposed by the Kayser-Threde company, the German Aerospace Centre (DLR), the Spaceguard Foundation and the International Space University. A hitchhiker telescope on a future mission in the inner solar system, such as the BepiColombo Mercury orbiter, or on a dedicated spacecraft platform, would discover and follow up on NEOs in a similar way to EUNEOS;

(c) The Spaceguard Integrated System for Potentially Hazardous Objects Survey (SISYPHOS) was proposed by the Alenia Spazio company, Surrey Satellite Technology Ltd. and Osservatorio Astronomico di Torino. A space-based observatory would detect and carry out remote sensing and the physical characterization of NEOs: their size, composition, surface roughness, and so forth;

(d) The Small Satellite Intercept Mission to Objects Near Earth (SIMONE) was proposed by the QinetiQ company, the Planetary and Space Sciences Research Institute of the Open University of the United Kingdom of Great Britain and Northern Ireland (PSSRI), Science Systems Ltd., the Telespazio company and Politecnico di Milano. A fleet of low-cost, small satellites would fly by and/or rendezvous with a number of NEOs to characterize the population or to obtain first-hand information on potentially dangerous asteroids;

(e) The Internal High-Resolution Tomography by Asteroid Rendevous (ISHTAR) mission was proposed by the European Aeronautic Defence and Space

Company (EADS) Astrium Ltd., the Observatoire de Paris-Meudon, the Osservatorio Astronomico di Roma, the Laboratoire de Planétologie at Grenoble, France, PSSRI and the University of Cologne. An orbiter would use radar tomography (that is, the imaging of the interior of a solid body using ground-penetrating radar) to probe the target object interior, to study its structure (for example, homogeneous, porous, fractured or simply a loose aggregate of separate boulders) and to assess the seriousness of the threat;

(f) The "Don Quijote" mission was proposed by the Deimos Space Company, EADS-Astrium Ltd., the University of Pisa and the Spaceguard Foundation. A pair of spacecraft, to be called Hidalgo and Sancho, would study asteroids. One would hit a target asteroid at a very high relative speed, while the other would observe from an orbit around the asteroid before, during and after the impact in order to extract information on the asteroid's internal structure and its other physical properties. Of the six concepts, this is the only one that would lead to a simple demonstration of asteroid orbit modification.

Near-Earth object space mission preparation phase II: Near-Earth object Mission Advisory Panel

19. The six missions mentioned in the previous section represent interesting options and it is useful to review all of them. Nevertheless, in practical terms, priorities have to be established.

20. The next stage in the development of a European road map of NEO space systems involved the establishment of NEOMAP, a panel of six scientists from ESA member States who had expertise in various aspects of NEOs (such as detection, orbit determination and physical characterization) and the impact threat they pose to the planet. They were asked to discuss the results of the NEO mission studies and make recommendations on the next actions that should be taken.

21. NEOMAP comprises the following experts:

A. W. Harris (DLR, Germany) (Chairperson)

W. Benz (Institute of Physics of the University of Berne, Switzerland)

A. Fitzsimmons (Astrophysics and Planetary Science Division, Queen's University of Belfast, United Kingdom)

S. F. Green (PSSRI, United Kingdom)

P. Michel (Observatoire de la Côte d'Azur, France)

G. Valsecchi (Cosmic Physics and Space Astrophysics Institute, Italy).

22. The initial tasks of NEOMAP were as follows:

(a) To identify advantages and define a solid rationale for the utilization of space missions to assess the NEO impact hazard. The object of the exercise was not to repeat previous work, but to provide a brief summary of the main conclusions;

(b) To identify which of those advantages associated with the use of space systems could complement ground-based observation and data. A summary was made of previous relevant studies and additional information added to bring the studies up to date;

(c) To revise and update the scientific priorities for NEO hazard assessment mission concepts entirely in terms of their value in reducing the risk of impact by NEOs and not by the value of the results to pure science;

(d) To judge the value of each mission concept and the potential benefits resulting from the implementation of the missions, considering them in the context of current or future international initiatives, either ground surveys or other planned space missions;

(e) To produce a set of prioritized recommendations for each mission category (surveys and rendezvous) and a proposal for a space mission cooperative project or projects at the international level.

23. NEOMAP was convened on 14 January 2004 at ESTEC in the Netherlands and proceeded to work, over the following five months, on a set of recommendations, which were announced at an event held at ESRIN, Frascati, Italy, on 9 July 2004.

24. They were subsequently published in a report entitled "Space mission priorities for near-Earth object risk assessment and reduction",[4] and are summarized below:

(a) Of the three observatory missions reviewed, NEOMAP considered the EUNEOS and Earthguard-I NEO survey concepts to be most compatible with the criteria and priorities established above. EUNEOS appeared to be a feasible, efficient and largely self-reliant mission with the single aim of discovering potentially hazardous NEOs and establishing their orbits. However, it was concluded that, at that time, a space-based NEO-discovery mission, within the scope of the missions considered, was not of the highest priority given that the combined efforts of the various ground-based surveys were likely to be productive over the following decade. It was decided that a space-based NEO observatory mission could be discussed again, at a later stage, once the residual hazard from NEOs not accessible to the ground-based surveys had been better defined;

(b) Of the three rendezvous missions reviewed, NEOMAP considered the Don Quijote concept to be the most compatible with the criteria and priorities established above as it had the potential to show not only the internal structure of a NEO, but also how to interact with it mechanically. Don Quijote was thus the only mission of the three that could provide a vital missing link in the chain from threat identification to threat mitigation. Considering possible participation from countries outside Europe, it was felt that the Don Quijote concept was compatible with current interests and developments elsewhere and might readily attract the attention of potential partners;

(c) Of the six missions reviewed, NEOMAP recommended that ESA give the highest priority to the Don Quijote concept as the basis for its participation in NEO impact risk assessment and reduction.

Prospects for international cooperation

25. NEOMAP continues to work in support of ESA internal review of the Don Quijote concept. Currently, the activities related to NEOMAP are pursued by the ESA Advanced Concepts and Studies Office, with the support of the ESTEC Concurrent Design Facility.

26. In December 2004 and January 2005, Don Quijote served as a reference scenario for discussions with JAXA technical and scientific experts on their possible participation in the ongoing ESA internal assessments. The JAXA technical and scientific experts are currently involved in the ongoing Hayabusa asteroid mission and the Lunar A Moon orbiter. Their interest in participating has been confirmed and the potential benefits for both parties (that is, the pooling of know-how and assessment of possible future opportunities for cooperation in planetary surface science and space technology development) became apparent during the discussions.

27. The Don Quijote mission was presented to the international community at the Planetary Defence Conference: Protecting Earth from Asteroids, held in Orange County, California, United States of America, in February 2004, as an example of a NEO precursor mission, paving the way to an effective NEO deflection mission.

28. At that conference and on all the other occasions on which the mission was presented, such as at the general assembly of the Committee on Space Research, held in July 2004, and at the International Astronautical Congress, held in October 2004, it became apparent that:

(a) The concept of a NEO precursor mission, as opposed to a costly fully-fledged deflection mission test that could face a large number of uncertainties, had attracted considerable interest among the NEO community. That was reflected not only in the NEOMAP recommendations, but also in other reports, such as the position paper of AIAA entitled “Protecting Earth from Asteroids and Comets”;

(b) Given the wide and complementary experience available in this field and the potential benefits for the cooperating partners, a NEO mission would be an ideal international cooperative project, especially if a modular mission architecture with well-defined interfaces that facilitated independent contributions from the cooperating partners was considered;

(c) Therefore, a multi-element spacecraft, carrying out investigations in the close proximity or surface of a NEO, would be suitable for implementation, especially if it addressed aspects related to risk reduction technology;

(d) Because of the quality and level of detail of the studies carried out so far, ESA has gained a very good understanding of the existing mission options and is therefore in a good position to coordinate work in this area. The Don Quijote mission represents an excellent reference scenario to consider possible cooperation options.

Conclusion

29. The development of space systems dedicated to the assessment of the NEO hazard would provide an excellent opportunity for international cooperation, from which all partners would benefit in terms of mission return, technology development and public relations, at a comparatively modest cost. Therefore, it is necessary to establish contacts and explore an appropriate cooperation framework model with international partners interested in the initiative.

Annex I

The proposed Don Quijote mission

1. A brief summary of the outcome of the initial industrial study commissioned by the European Space Agency (ESA) is provided below. The results are currently being reviewed by ESA internally at its Concurrent Design Facility, with the support of the ESA Advanced Concepts Team. Figure I shows the Don Quijote mission with its two components, Sancho and Hidalgo, on top of the Soyuz-Fregat launcher upper stage.

Figure I
Proposed Don Quijote mission: the Sancho and Hidalgo spacecraft as they would appear on top of the Soyuz-Fregat launcher upper stage

I. Proposed mission objectives

2. The objectives of the Don Quijote mission would be twofold:

(a) To obtain knowledge of the physical nature of asteroids. The objective has a very high scientific priority but is unattainable with the current generation of asteroid missions;

(b) To obtain knowledge that would be critical in the event that an asteroid was found on a collision course with the Earth and had to be deflected. Don Quijote would allow the first detailed determination of the interior structure of such an asteroid, its mechanical properties, as well as a direct measurement of its response to an impact, thereby providing crucial information for all further development of mitigation strategies, including numerical modelling.

3. In order to achieve these objectives, the study envisages the use of two spacecraft, which would be launched on separate interplanetary trajectories. The science spacecraft, called Sancho, would arrive at the asteroid first and, after a rendezvous manoeuvre, would observe and measure the target asteroid over a period of several months. The measurement techniques would include seismology. The second spacecraft, the impactor, called Hidalgo, would then impact the asteroid at a relative speed of at least 10 km s^{-1}. Sancho, which would retreat to a safe distance before the impact, would then return to a close orbit to determine the changes in the asteroid's orbit and state of rotation, as well as in its shape, and (optionally) to collect samples of the fresh subsurface material exposed by the crater formation.

4. The following are the key measurements that would be made by the science spacecraft, Sancho:

(a) Determine the orbital deflection of the asteroid as a result of the impact, to an accuracy of approximately 10 per cent;

(b) Determine the mechanical properties of the asteroid material;

(c) Measure the mass of the asteroid, the ratio of the moments of inertia and the low-order harmonics of the gravity field of the asteroid;

(d) Model the asteroid shape before and after the impact, to detect changes;

(e) Determine the internal structure of the asteroid, in particular the sizes of the main solid pieces, the average particle size and thickness of the regolith and of the debris layers in the space left between the main pieces;

(f) Measure the state of rotation of the asteroid before and immediately after the impact to an accuracy of approximately 10 per cent. Also detect, if possible, the dissipation of the non-principal axis rotation after the impact to determine the internal dissipation factor (Q);

(g) Determine the asteroid large-scale mineralogical composition. This would be important in order to eventually establish correlations between observed spectral properties and internal structure;

(h) Provide a model for non-gravitational forces, such as the Yarkovsky effect, acting on the asteroid orbit and rotation. This requires a thermal model.

5. Calculations performed in the Don Quijote industrial study for a reference asteroid of a diameter of 500 meters (m) and a density of 2.6 gm cm^{-3} indicated that there would be an impact-induced displacement of the asteroid of 1,400 m over a period of four months. The rotation rate of the asteroid might be changed by some 0.5 degrees per day. Such changes should be readily measurable using Sancho.

II. Payload

6. It has been determined that the following instrumentation would be necessary to carry out the mission objectives:

(a) A camera for high-resolution imaging of the asteroid to obtain a full three-dimensional model of the asteroid before and after the Hidalgo impact;

(b) An infrared mapping spectrometer with low spatial resolution and high spectral resolution to measure the surface mineralogy. For the thermal model, it would also be necessary to make measurements in the thermal-infrared region;

(c) A radio science payload; this includes X- and K-band transponders and an accelerometer;

(d) Seismic science:

(i) Penetrators. It is planned to have a network of at least four penetrators on the surface of an asteroid. Beside the instruments, the penetrators comprise the required subsystems for surface operation. Each penetrator carries a seismometer, an accelerometer and a temperature sensor;

(ii) Seismometers. 3-axis short-period seismometers are required. During the impact of Hidalgo, the seismometers will reach saturation due to the high accelerations. Therefore, it is envisaged to use a set of accelerometers that would only be operated during the impact of Hidalgo. Figure II shows the impact of Hidalgo on asteroid 1989 ML and Sancho's observation of the events;

(iii) Thermometer. In order to support the measurements in the thermal infrared and the construction of the thermal model of the asteroid;

(iv) Seismic sources. Small explosive charges (equivalent to a few 100 grams of TNT with a timed detonator), which would create the seismic signals used to determine the internal structure of the asteroid.

Figure II
Projected impact of the Hidalgo spacecraft on asteroid 1989 ML as witnessed by Sancho spacecraft

III. Spacecraft and mission design

7. In accordance with the initial industrial study, which is now being reviewed and updated at the ESA Concurrent Design Facility, the Don Quijote mission would be divided into several dedicated mission elements: the camera, the infrared spectrometer, the penetrators/surface elements and the seismic sources carried on the orbiter, Sancho. The penetrators/surface elements and the seismic sources are considered separate elements, since they would perform the "landing" and surface operation on the asteroid, which would be in itself a complex "sub-mission" of Don Quijote. An additional element would be Hidalgo, which would serve solely as an impactor. Its main task would be to hit the asteroid with a given positional accuracy and relative velocity.

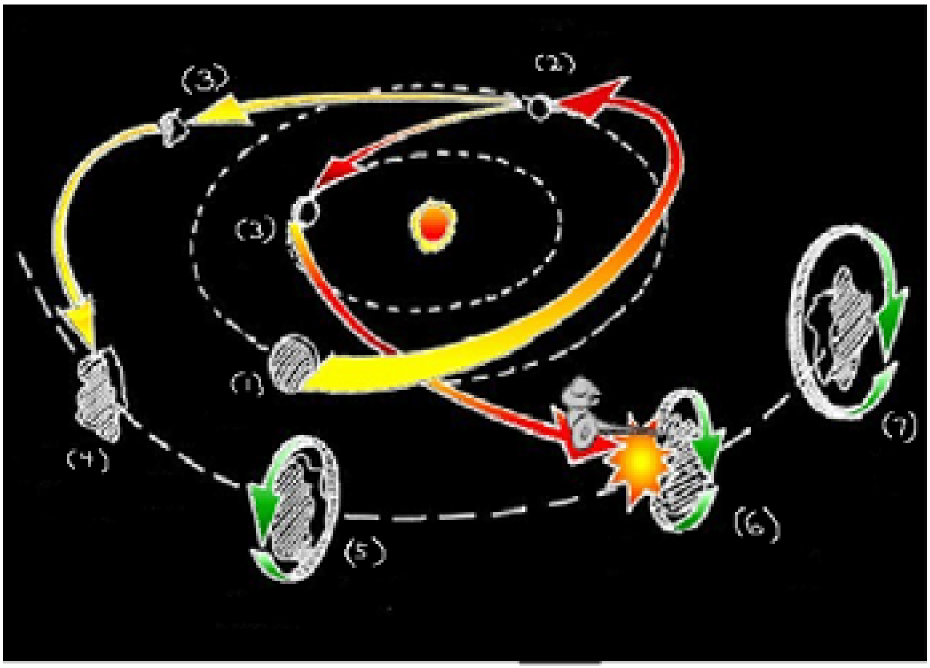
8. The Sancho spacecraft would be a box-shaped structure, which would house the different units necessary for the operation of the spacecraft and instruments. The imager and the infrared spectrometer would be mounted at the nadir side, outside the structure, and would be placed on the radiator to ensure adequate thermal control of the infrared detectors.

9. For the deployment of penetrators, launch mechanisms would be mounted on one side of the spacecraft. The launch would be carried out by a small solid rocket engine. The impact velocity should be in the range of 50-100 m s^{-1} in order to ensure a proper penetration depth and appropriate coupling to the asteroid. The seismic sources would be launched in the same way as the penetrators. It is envisaged to deploy a minimum of four prior to Hidalgo's impact and four afterwards, preferably at the same locations in order to measure impact-induced changes. The deployment and use of this seismic network is considered one of the most challenging aspects of the Don Quijote mission. Figure III provides an overview of the proposed design of the Don Quijote mission.

10. Hidalgo could, in principle, use the same spacecraft platform as Sancho, but, with no payload other than a navigation camera and, possibly, some simple technology experiments, it should be lighter than Sancho and simpler in general terms. The exception would be the final targeting system, which should be accurate and highly autonomous even in non-nominal situations (that is, situations in which the target is non-specific).

11. One of the possibilities considered in the study of the mission design was to find trajectories to the same object, departing at the same time but arriving at different times with completely different arrival velocities and geometry, while minimizing the total velocity variation (ΔV) (that is, cost). The mission timeline example in table 1 characterizes the reference mission to the nominal target (10302) 1989 ML (estimated size = 500 m).

Figure III
Proposed design of the Don Quijote mission



(1) Earth departure
(2) Earth fly-by
(3) Hidalgo Venus fly-by/Sancho Asteroid fly-by
(4) Arrival of Sancho at target
(5) Asteroid analysis
(6) Impact of Hidalgo on the target
(7) Post-impact analysis

Table 1
The Don Quijote reference mission

Time from launch	Sancho spacecraft Departure mass: 582.3 kg Injection mass: 394.0 kg	Hidalgo spacecraft Departure mass: 388.2 kg Injection mass: 379.1 kg
	Spacecraft launched together on nearly identical trajectories to encounter the Earth six months later (or multiple thereof).	
~ 180 days	Earth swing-by: sent to target asteroid.	Earth swing-by: sent to Venus.
~ 909 days (2.49 years)		Venus swing-by: sent to target asteroid.
~ 1,478 days (4.05 years)	Arrival at target asteroid with $\Delta V = 1.089$ km s^{-1}. Global mapping from a distance of about 10 asteroid radii, followed by close observations of specific areas from a distance of 1 asteroid radius. Perform seismic experiments.	
~ 1,706 days (4.67 years)	Prior to impact, move to safe distance. Observe impact. Resume measuring of asteroid to determine impact-induced changes (orbit, rotation, etc.). Resume seismic experiments.	Impact on target asteroid with $\Delta V = 13.44$ km s^{-1}. End of mission.
5 years	End of mission.	

Note: ΔV = velocity variation.

Annex II

European Space Agency studies and contracts on near-Earth objects

Contract No.	*Name of study*	*Contractor*	*URL*
AO/12314/97/D/IM	Study of a Global Network for Research on Near-Earth Objects	Prime: Spaceguard Foundation (Italy)	None
AO/13265/98/D/IM	Spaceguard Integrated System for Potentially Hazardous Objects Survey (SISYPHOS)	Prime: Spaceguard Foundation (Italy) Subcontractor: Alenia Spazio (Italy)	www.esa.int/gsp/completed/card_98_A15.html
AO/14018/00/F/TB	Understanding the distribution of NEOs	Prime: Observatoire de la Côte d'Azur (France)	www.esa.int/gsp/completed/card_00_S92.html
RFQ/14472/00/D-HK	NEO Hazard Mitigation Publication Survey	Prime: Technische Universität, Dresden (Germany)	www.esa.int/gsp/completed/card_00_N94.html
AO/16257/02/F/IZ	NEO Space Mission Preparation Study: European Near-Earth Object Survey (EUNEOS)	Prime: Alcatel Space (France) Subcontractors: Observatoire de la Côte d'Azur (France), Spaceguard Foundation (Italy)	www.esa.int/gsp/completed/neo/euneos.html
AO/16256/02/F/IZ	NEO Space Mission Preparation Study: Earthguard-I	Prime: Kayser-Threde (Germany) Subcontractors: German Aerospace Center (Germany), Spaceguard Foundation (Italy), International Space University	www.esa.int/gsp/completed/neo/earthguard.htm
AO/16253/02/F/IZ	NEO Space Mission Preparation Study: Remote Observation of NEOs from Space	Prime: Alenia Spazio (Italy) Subcontractors: Surrey Satellite Technology Ltd. (United Kingdom of Great Britain and Northern Ireland), Osservatorio Astronomico di Torino (Italy)	www.esa.int/gsp/completed/neo/remote.html
AO/16254/02/F/IZ	NEO Space Mission Preparation Study: Small Satellite Intercept Mission to Objects Near Earth (SIMONE)	Prime: QinetiQ (United Kingdom) Subcontractors: Planetary and Space Sciences Research Institute (United Kingdom), Science Systems Ltd. (United Kingdom), Telespazio (Italy), Politecnico di Milano (Italy)	www.esa.int/gsp/completed/neo/simone.html

Contract No.	*Name of study*	*Contractor*	*URL*
AO/16255/02/F/IZ	NEO Space Mission Preparation Study: Internal High-Resolution Tomography by Asteroid Rendevous (ISHTAR) mission	Prime: Astrium Ltd. (United Kingdom) Subcontractors: Observatoire de Paris-Meudon (France), Osservatorio Astronomico Roma (Italy), Laboratoire de Planétologie, Grenoble (France), Planetary and Space Sciences Research Institute (United Kingdom), University of Cologne (Germany)	www.esa.int/gsp/completed/neo/ishtar.htm
AO/16252/02/F/IZ	NEO Space Mission Preparation Study: Don Quijote	Prime: Deimos Space (Spain) Subcontractors: Astrium GmbH (Germany), University of Pisa (Italy), Spaceguard Foundation (Italy)	www.esa.int/gsp/completed/neo/donquijote.html

The Spaceguard Foundation

Report on activities carried out during the period 1996-2004

Introduction

1. Astronomical and geo-palaeontological research has shown that impacts of near-Earth objects (asteroids and comets) on the Earth have influenced the past evolution of life and still represent a significant threat to the human population, comparable to that posed by other major natural disasters.

2. The probability of impacts depends on the size of the objects, the distribution of which follows a reasonably well-known law of power. Catastrophic events capable of jeopardizing the survival of living species have a rate of recurrence of tens to hundreds of millions of years. More modest events, but events nevertheless capable of threatening civilization and causing considerable damage to people and property, occur at a much more frequent rate, of the order of hundreds or thousands of years. Of particular concern is the possibility of impact-generated tsunamis, which is receiving increasing attention from all countries with extended coastal areas.

3. In the past 10 years, several NEO-observing programmes have been started in the United States. The goal of these first attempts to investigate this newly identified hazard is to discover, before 2008, most of the potentially impacting objects larger than approximately 1 km, since those are the objects that could cause a catastrophe on a global scale. It is estimated that about 60 per cent of them have now been found. It is probable, however, that the above-stated goal will not be met, as the current rate of discovery is somewhat slower than expected, mainly because there are objects in dynamical conditions that can only be discovered if sufficiently powerful instruments are used. Furthermore, the possibility of major tsunami events that could be triggered by the impact of medium-sized bodies (100-300 m) has now been extensively studied and all studies show that this kind of hazard is large enough to require an appropriate response.

4. Various international organizations, including the Council of Europe, OECD and the United Nations have invited all countries to take steps to increase the current efforts and to lower the size-limit of this search to objects in the 200-300 m diameter range. It is clear that the ongoing surveys, which are aimed at the detection of 1 km objects, are unable to discover a substantial fraction of smaller objects and it is also clear that a suitable search programme must be located in the southern hemisphere, where there are currently none, to complement the searches already active in the northern hemisphere.

5. It is within this framework that the Spaceguard Foundation, a non-profit organization with the main purpose of supporting and coordinating international research on NEOs, was established in 1996.

The Spaceguard Foundation: history and purpose

6. The idea of establishing an international organization to ensure the coordination of NEO observational activities was put forward many times at the end of the 1980s. Since the formation by the National Aeronautics and Space

Administration of the United States, in 1991, of two working groups to analyse the threat posed by NEOs (the Working Group "Discovery", chaired by Dave Morrison, and the Working Group "Interception", chaired by Jürgen Rahe and John Rather), there has been general consensus that this field of study would require broad participation by many countries.

7. It was mainly to that end that Commission 20 of the International Astronomical Union (IAU) on positions and motions of asteroids, comets and satellites, took the initiative to present a resolution on the matter to the twenty-first General Assembly of IAU, in 1991. A further five commissions of IAU endorsed the resolution. The resolution called for the formation of an ad hoc inter-commission group for the purpose of studying the NEO issue and in order to facilitate wide international participation in that study.

8. The Working Group on Near-Earth Objects prepared a report for the twenty-second General Assembly of IAU, held in 1994, in which it recommended that studies and initiatives relating to NEOs be placed under the aegis of an international authority.

9. In September 1995, the Working Group organized a workshop entitled "Beginning the Spaceguard Survey". The purpose of the workshop was to underline the need for a coordinated effort and to establish a basis for international collaboration on the issue. During a long and stimulating discussion, the participants in the workshop decided to establish an organization that would contribute to the support and coordination of research on NEOs all over the world. On the last day of the workshop, the Working Group formed a small committee charged with exploring possible ways of forming such an organization. After several months of deliberations, it was decided that the first step would be to set up an Italian association called "The Spaceguard Foundation", with the participation of the Working Group members. The Spaceguard Foundation was officially inaugurated in Rome on 26 March 1996.

10. The Spaceguard Foundation is a non-governmental, international organization with a membership of space professionals. It has three principal goals:

(a) To promote and coordinate at an international level activities related to the discovery, tracking and orbital computations of NEOs;

(b) To promote studies, at the theoretical, observational and experimental levels, of the physical and mineralogical properties of minor bodies in the solar system, with particular attention to NEOs;

(c) To promote and coordinate the establishment of a ground network (to be called "the spaceguard system"), possibly backed up by a satellite network, for making continuous observations for the discovery and astrometric and physical tracking of NEOs.

11. Almost at the same time as the new organization was established, the problem of the threat posed by NEOs was brought to the attention of the Committee on Science and Technology of the Council of Europe. The Spaceguard Foundation assisted members of the Committee in preparing for the discussions and the Committee unanimously approved a resolution that was presented to the Parliamentary Assembly and approved as Council of Europe resolution 1080 on 20 March 1996.

12. The issue of NEO observations has also been examined by the Committee on the Peaceful Uses of Outer Space. The Report on the Sixth United Nations/European Space Agency Workshop on Basic Space Science: Ground-Based and Space-Borne Astronomy, hosted by the German Space Agency, on behalf of the Government of Germany at the Max-Planck-Institute for Radioastronomy (A/AC.105/657) mentioned NEO observations in its recommendations. The NEO issue was also placed on the agenda of UNISPACE III. The Vienna Declaration on Space and Human Development referred to the need for better coordination of NEO research.

13. The Spaceguard Foundation has assisted the United Kingdom Task Force on Potentially Hazardous Near-Earth Objects in the preparation of a report submitted to the Government of the United Kingdom. After the release of that report, the United Kingdom representative at the Global Science Forum of OECD proposed the formation of a working group on NEOs to examine the social aspects of the problem. That working group organized a workshop, held at ESRIN in 2003, and invited scientists and officials in the fields of civil defence and politics to attend. The report of the workshop was distributed to all Governments of OECD member States.

The Spaceguard Central Node

14. In order to establish whether a particular NEO poses a threat to the Earth, it is necessary to know its orbit well on the basis of astrometric positions that cover a long time interval. For the calculation of a reliable orbit, it is necessary to track NEOs immediately after discovery, and again at other convenient apparitions years later.

15. Since, in the past, discovery activities had not been accompanied by a corresponding level of follow-up efforts, the Spaceguard Foundation, with the financial support of ESA, set up the Spaceguard Central Node (SCN) in 1999.[5] The main purpose of SCN is to coordinate follow-up NEO observations throughout the world.

1. Activities of the Spaceguard Central Node during the period 1999-2004

16. The main interaction between SCN and the community of NEO observers takes place through the SCN website. On that website, observers can find a number of lists, some of which are updated on a daily basis. Observers can be contacted directly if a situation requires prompt action.

17. The most important of the SCN lists is the Priority List, in which targets are classified into four categories on the basis of the urgency of their re-observation. The Priority List is compiled daily by a programme that analyses the geometry and the sky uncertainty of each newly discovered NEO during the discovery (that is, current) apparition and the next apparition. The goal is to make the sky uncertainty at the next apparition so small that the recovery of the NEO is virtually certain. The required computations are not feasible for the vast majority (if not the totality) of observers and the fact that the relevant results are freely consultable on a website is of great help to the observers as it maximizes the usefulness of their astrometric observations.

18. Most of the other SCN lists are static and updated manually. They cover issues such as announcements, the results of observing campaigns and the observing schedules of large telescopes performing observations of very faint objects.

19. A particularly important activity of SCN is the observational campaigns to remove virtual impactors. It can happen for some NEOs that a future collision of the asteroid with the Earth cannot be excluded only on the basis of the available astrometric observations: the orbit solutions corresponding to such cases are called virtual impactors. The orbital analysis necessary to find virtual impactors is carried out in two centres: the Near-Earth Objects Dynamic Site of the University of Pisa, Italy, established in 1999, and Sentry at the Jet Propulsion Laboratory, in the United States, established in 2002. SCN routinely organizes dedicated campaigns to improve the calculated orbit of NEOs with virtual impactors through the acquisition of further good-quality astrometric observations. It can happen that the NEO becomes unobservable before all its virtual impactors are eliminated. In that case, the observing campaign should at least achieve an orbital accuracy allowing a future recovery.

20. In order to overcome or reduce to a minimum the risk of losing a NEO while it still has virtual impactors, SCN has encouraged directly or indirectly the use of larger telescopes; instruments of up to 3.5 m in diameter have been used occasionally since 2000, especially at Mauna Kea and Kitt Peak observatories in the United States. However, it was only at the beginning of 2002 that the first "Target-of-Opportunity" programme started, using the 2.5 m Isaac Newton Telescope and the 1.0 m Jacobus Kapteyn Telescope facilities at La Palma, Spain. The Target-of-Opportunity programme has the advantage of making a large telescope available when needed. In the spring of 2003, such follow-up coverage was extended to extremely faint NEOs (of magnitude 25-26) using the European Southern Observatory 8.2 m Very Large Telescope at Paranal, Chile. These initiatives complement the efforts made routinely with small and medium-sized telescopes.

21. Finally, another significant activity of SCN is the popularization of matters relating to NEOs through an extensive section of its website, as well as through an online magazine entitled "Tumbling Stone".

2. Results

22. In four years of activity, more than 2,000 NEOs have been presented in SCN lists. The main scientific results achieved in that period are described below.

23. The effectiveness of the main SCN list, the Priority List, is illustrated by a comparison of statistics of orbits of newly discovered NEOs in the triennium 1996-1998 with those of the period from the beginning of 2000 to 2003, during which SCN has operated. The fraction of newly discovered NEOs for which the follow-up either ensured the recoverability at the first post-discovery apparition or allowed a precovery grew from 55 to 69 per cent. Thus, before the operations of SCN started, almost one half of the newly discovered NEOs did not have good calculated orbits at the end of the discovery apparition, and SCN coordination reduced that fraction to less than one third.

24. Figure I below shows in more detail the fraction as a function of absolute magnitude (H) of recoverable NEOs, while figure II shows those that were precovered in astronomical archives (photographic or charged-coupled-device) or

for which pre-existing astrometric observations were identified. The two other figures show NEOs that were essentially lost (figure III) and badly lost (figure IV). Lost NEOs mean that a direct recovery might be possible but it usually requires a large effort because of a very large sky uncertainty. Badly lost NEOs mean that a direct recovery attempt is not cost-effective in terms of telescope resources. In general, it is possible to notice a shift of lost and badly lost NEOs to fainter magnitudes.

Figure I
Fraction of recoverable near-Earth objects as a function of absolute magnitude (H)

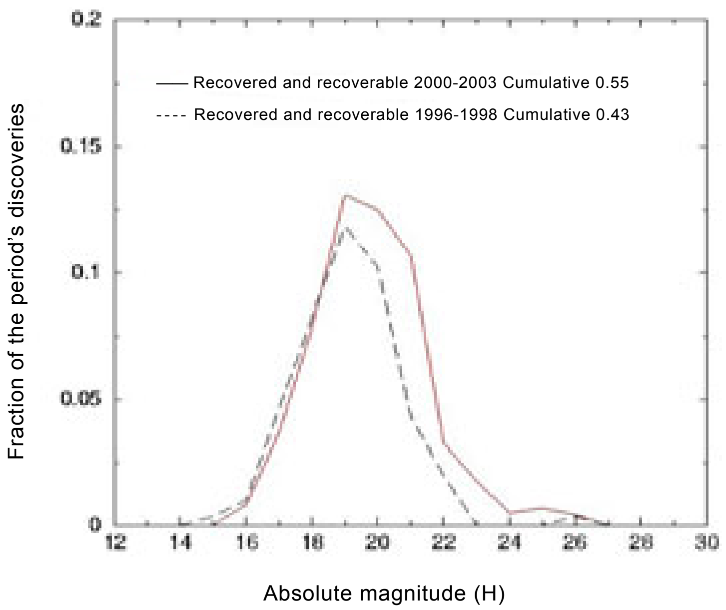


Figure II
Fraction of near-Earth objects identified with pre-existing observations or found in astronomical archives, as a function of absolute magnitude (H)

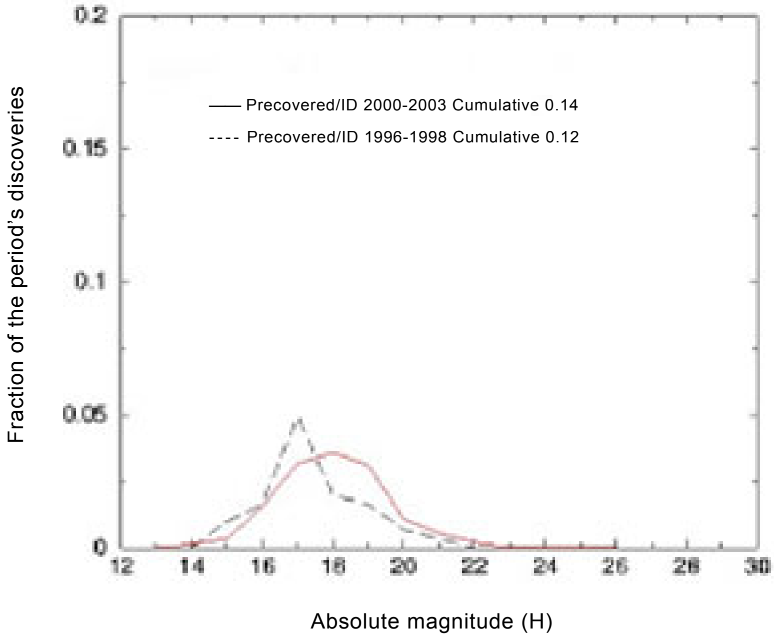


Figure III
Fraction of lost near-Earth objects whose recovery would require considerable effort

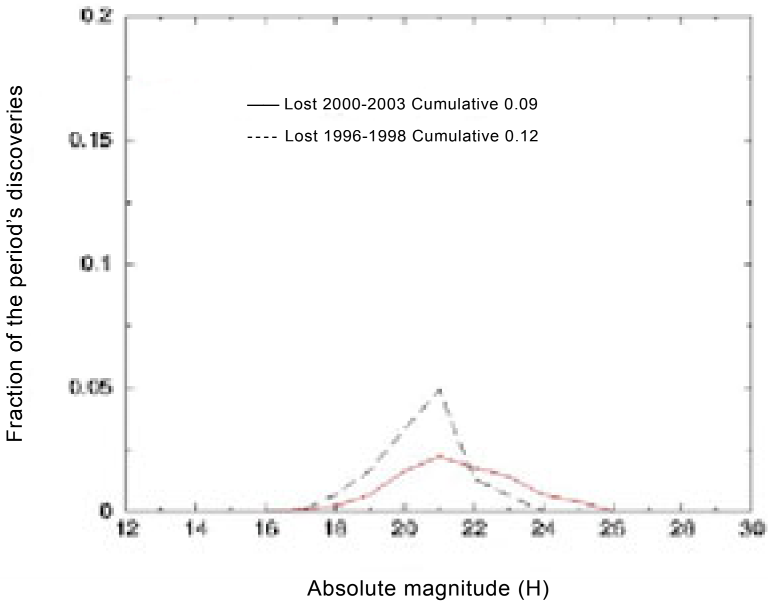
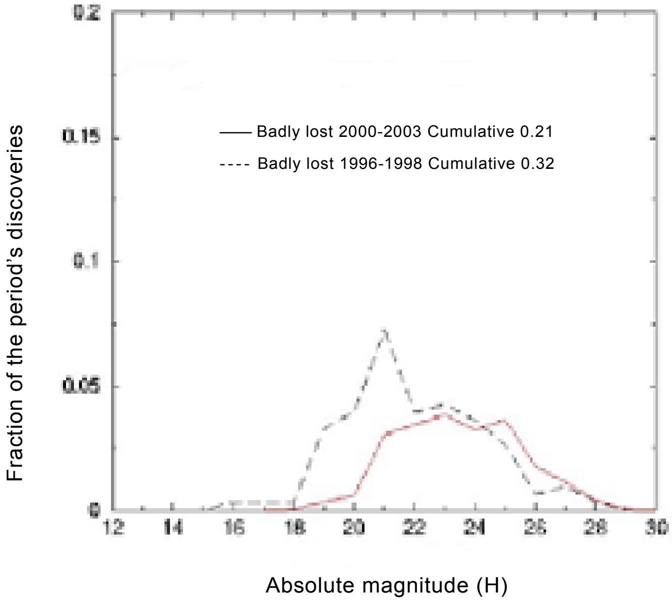


Figure IV
Fraction of badly lost near-Earth objects whose recovery would not be cost-effective



25. In terms of the elimination of virtual impactors, most of the observing campaigns were successful. When they were not successful, this was not due to a lack of follow-up coordination. For example, in the case of 2002 MN, some virtual impactors could not be removed. The discovery apparition of this object presented a very peculiar geometry, such that, although the NEO was followed as long as possible, the astrometry acquired in this manner did not significantly contribute to the improvement of the calculated orbit. In fact, 2002 MN, for most of the time, was moving away from the Earth with a motion almost exactly radial; when this phase was over and some transversal contribution could be obtained, the object was already too faint.

3. Conclusion

26. SCN coordination activity has been able to maximize the usefulness of the work on NEO astrometry of many professional and amateur observers around the world. SCN daily, behind-the-scenes, prioritization calculations free observers from the need to establish criteria on what to observe; they need only organize an observing programme based on the suggestions provided by SCN lists. In this way, SCN operations have contributed to improving the dynamical database of known NEOs, quantitatively and qualitatively.

Other activities of the Spaceguard Foundation

27. SCN is the principal technical activity of the Spaceguard Foundation. However, over this period, the Spaceguard Foundation pursued many other projects, mainly in the field of science policy. This section briefly reviews those projects.

1. Relations with the European Space Agency

28. ESA was the first and remains the most important supporter of the Spaceguard Foundation. This is partly due to the explicit invitation made by the Council of Europe in its resolution 1080, which urged the setting up and development of the Spaceguard Foundation. ESA support is also a consequence of its interest in space missions to minor bodies.

29. ESA has issued two contracts to the Spaceguard Foundation. The first, the Study of a Global Network for Research on Near-Earth Objects (1999), led to the setting up of the Spaceguard Central Node. The second, the Spaceguard Integrated System for Potentially Hazardous Object Survey (2000), involved the study of a system composed of a ground segment, a space segment (an observatory in the Lagrangian point L_2) and a global network controlled by SCN.

30. In 2003, ESA decided to promote six mission studies to NEOs. Three consisted of observatories located in regions suitable for the discovery of objects difficult to observe from the ground; the other three were fly-by or rendezvous missions able to perform a wide range of in situ analyses. The Spaceguard Foundation was asked to review all these studies from a scientific point of view. One of the three, the Don Quijote mission, one purpose of which was to attempt, for the first time, a deflection manoeuvre, was selected in 2004 for further study and possible implementation.

31. ESA, the Spaceguard Foundation and the Cosmic Physics and Space Astrophysics Institute of Italy signed an agreement on the location and operation of the Spaceguard Central Node at ESRIN, Frascati, Italy.

2. Relations with the European Science Foundation

32. The European Science Foundation (ESF) became interested in the NEO issue in 1993, at the time of the implementation of the "Response of the Earth System to Impact Processes" programme of ESF. This programme was aimed at understanding the effects of NEO impact on the development and evolution of the Earth. Such impacts are a key and common process in the solar system. The follow-up to this programme was the formation, in 2001, of an ad hoc working group to place the NEO issue in the context of a possible European initiative. The Spaceguard Foundation was requested to participate in this group, which produced a final report in November 2001.[6]

3. Relations with the European Southern Observatory

33. The first contacts between the Spaceguard Foundation and the European Southern Observatory took place in February 2000, when the Spaceguard Foundation made a presentation on the NEO hazard at the European Southern Observatory headquarters in Garching, Germany. The purpose of the presentation was to discuss the possible interest and role of the Observatory in a European search programme in order to make use of the excellent facilities of the European Southern Observatory in Chile.

34. Following this first contact, a project was studied and presented to the European Commission in 2003. The project, called "European Deep-Sky Near-Earth Objects Survey", was a joint initiative of the Spaceguard Foundation, the European Southern Observatory, ESA, the Nordic Optical Telescope Scientific Association

and seven European countries. Although not approved within the framework of the New and Emerging Science and Technology programme, the project was well received.

4. Relations with the International Council for Science

35. The last initiative in which the Spaceguard Foundation participated was a programme endorsed by the International Council for Science. The original proposal, made by IAU in 2002, was to form a working group to examine the NEO problem, not only from an astronomical perspective, but also from the point of view of different disciplines in the scientific and social fields. The Spaceguard Foundation assisted IAU in preparing the proposal, which was approved for implementation in 2003.

36. The first activity organized under the programme was a workshop, held on Tenerife, in the Canary Islands of Spain, in November and December 2004, attended by 40 scientists from different disciplines. They met to discuss the implications of a comet/asteroid impact and its effect on human society. A final document from the workshop is in preparation.

Conclusions

37. The main goal of the Spaceguard Foundation, the coordination of the existing observational efforts for the discovery and follow-up of NEOs, was achieved with the establishment of SCN. That achievement was made possible by the support of ESA and the voluntary participation of Spaceguard Foundation members. The Spaceguard Foundation provides a forum through which the international scientific and technical community can contribute to the assessment of and finding a solution to a problem that has very serious implications for the future of human society.

38. The success of future initiatives of the Spaceguard Foundation depends upon greater interest being shown by and support being provided by national Governments. The Foundation would welcome support in that area from the Committee on the Peaceful Uses of Outer Space.

Notes

[1] Information on the NEO Space Mission Preparation initiative is available at www.esa.int/gsp/NEO.

[2] *Report of the Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space, Vienna, 19-30 July 1999* (United Nations publication, Sales No. E.00.I.3), chap. I, resolution 1.

[3] European Space Agency, Long-Term Space Policy Committee, *Investing in Space: the Challenge for Europe* (ESA SP-2000, May 1999).

[4] The recommendations of the Near-Earth Object Mission Advisory Panel are available at the following website: www.esa.int/gsp/NEO/other/NEOMAP_report_June23_wCover.pdf.

[5] The website of the Spaceguard Central Node is at http://spaceguard.esa.int.

[6] *Future of Europe in Space Research: ESF Recommendations to Ministers of ESA Member States* (European Science Foundation, October 2001), p. 7 (available at www.esf.org/publication/122/Space.pdf).