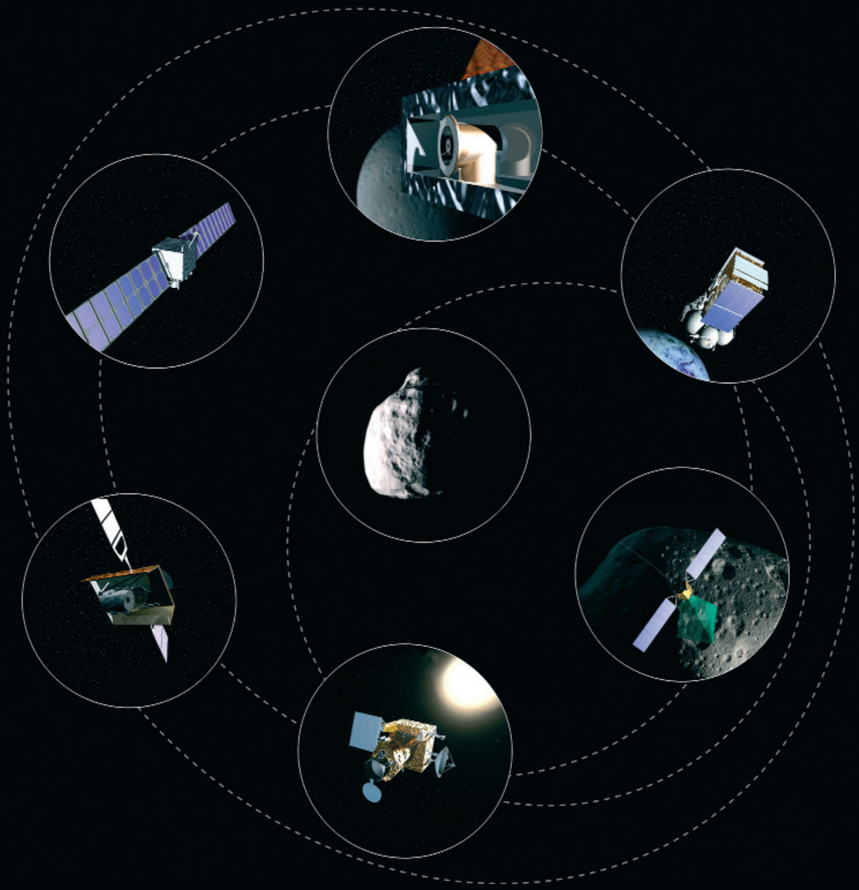
Space Mission Priorities for Near-Earth Object Risk Assessment and Reduction



Recommendations to ESA by the Near-Earth Object Mission Advisory Panel (NEOMAP)

July 2004

The Near-Earth Object Mission Advisory Panel (NEOMAP)

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Front page picture credits

Smart-1 spacecraft: ESA
Near-Earth asteroid (433) Eros: NEAR Shoemaker mission, Johns Hopkins University Applied Physics Laboratory
Barringer impact crater, Arizona: D. Roddy

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Glossary of Frequently Used Technical Terms and Acronyms

Albedo	Measure of the reflectivity of an object’s surface.
Aten	Near-Earth asteroid with semi-major axis smaller than Earth's.
AU	Astronomical Unit: mean Earth – Sun distance.
H	Absolute magnitude: the visual magnitude an observer would record if the asteroid were at a distance of 1 AU from the observer and the Sun, and at zero phase angle (note: H is measured on a logarithmic scale such that the numerical value of H decreases with increasing brightness. H can be used as a rough indicator of the size of an asteroid).
IEO	Inner-Earth Object: has an orbit entirely within the Earth’s.
LINEAR	Lincoln Near-Earth Asteroid Research: near-Earth object discovery facility using two1.0-metre aperture telescopes, operated by MIT's Lincoln Laboratory in cooperation with the US Air Force.
MOID	Minimum Orbit Intersection Distance (with respect to the Earth’s orbit in the context of near-Earth objects).
NEA	Near-Earth Asteroid: see NEO.
NEAT	Near-Earth Asteroid Tracking: near-Earth object discovery facility using two 1.2-metre aperture telescopes, operated by NASA/JPL in cooperation with the US Air Force.
NEO	Near-Earth Object: asteroid or comet in an orbit with perihelion distance less than 1.3 AU, i.e., that allows it to enter the Earth's neighbourhood.
Pan-STARRS	Panoramic Survey Telescope And Rapid Response System: wide-field imaging facility, currently under development at the University of Hawaii’s Institute for Astronomy, based on four 1.8-m aperture telescopes with the primary purpose of discovering and characterising NEOs.
Phase angle	The angle between the observer and the Sun, as measured from the object observed (e.g. 0º, 90º, 180º for the full, half, new Moon, respectively).
PHO	Potentially Hazardous Object: asteroids and comets with a MOID of 0.05 AU or less and an absolute magnitude of H = 22.0 or less (i.e. diameter ~ 150 m or more).
Regolith	Surface layer of fragmented rocky debris**.**

Executive Summary

Origin and magnitude of the impact hazard

Collisions between planetesimals, the precursors of present-day asteroids and comets, and growing planets were a natural phenomenon that forged the Solar System as we know it today. After the planets had formed, collisions with the remnant population of small bodies, i.e. asteroids and comets, continued, albeit at a declining rate. The problem we face today, and which is addressed in this report, arises because this natural process has not ceased.

For our heavily populated world and highly networked society the impact of an asteroid or comet on the Earth today could produce a natural catastrophe far more damaging to civilization than any in recorded history.

The threshold size above which an object can produce significant damage on the ground depends on its composition. It is thought that Meteor crater in Arizona (diameter = 1.2 km) was formed by a metallic impactor with a diameter of 50 m that struck the ground about 50,000 years ago with a velocity of some 20 km s^{-1}, releasing around 10^{17} J or 25 MT of energy. A similarly sized stony object that did not possess the material strength to withstand its transit through the atmosphere probably caused the explosion that occurred over the Tunguska river valley in Siberia in 1908. Although the Tunguska object did not reach the ground, the force of the explosion caused by the object's disintegration still flattened some 2000 km^2 of forest. Both types of event would be capable of destroying a city in a worst-case scenario. Objects with diameters below 50 m are likely to be disrupted at high altitude during transit through the atmosphere and cause little, if any, ground damage. Estimates of the frequency at which objects of 50-m diameter or more enter the atmosphere vary by an order of magnitude between one per 10,000 years and one per 1000 years.

The consequences of impacts of projectiles with diameters in the range 50 – 200 m would depend very much on the circumstances of the event (location, velocity, angle of entry into the atmosphere) and the composition and internal strength of the body. Such objects may explode in the atmosphere or survive to form a crater, but in any case the destructive energy released would be comparable, to within an order of magnitude, to that of the largest H-bomb ever detonated. An object of 200-m diameter would almost certainly reach the ground and produce a crater with a diameter of around 4 km (or a potentially destructive tsunami if it hit an ocean); damage would be at the regional or national level and in a worst-case scenario millions of deaths could result. The average time interval between impacts of objects of 200-m diameter or more is thought to be tens of thousands of years.

For objects with diameters of 1 km or more, i.e. above the threshold for possible destructive effects on a global scale, the estimates of different groups now seem to be converging on 1000 ± 200 for the total number in the near-Earth asteroid population. Of these, some 700 have been discovered to date. The latest estimate of the frequency of such impacts is one per 600,000 years.

While good progress is being made in the discovery of NEOs with diameters of 1 km or larger, *the population of NEOs in the hundreds of metres size category is still* *largely undiscovered; such objects impact far more frequently and can cause damage on a national scale or worse, leading to millions of deaths.*

NEOMAP objectives

In July 2002 the general studies programme of the European Space Agency (ESA) provided funding for preliminary studies of six space missions that could make significant contributions to our knowledge of near-Earth Objects. Three of these are observatory missions:

Earthguard-1 - a small space telescope for NEO discovery, especially the Aten and "inner-Earth objects" (IEOs) that are difficult or impossible to detect from the ground,

Euneos (European Near-Earth Object Survey) - a space telescope for NEO discovery,

NERO (NEO Remote Observations) - an optical/infrared space telescope for NEO physical characterisation and discovery,

and three are rendezvous missions:

SIMONE (Smallsat Intercept Missions to Objects Near Earth) - a fleet of low-cost microsatellites for multiple NEO rendezvous and in-situ remote sensing,

ISHTAR (Internal Structure High-resolution Tomography by Asteroid Rendezvous) - utilises radar tomography for in-situ study of internal structure,

Don Quijote - utilises explosive charges, an impactor, seismic detectors and accelerometers for in-situ study of internal structure and momentum transfer.

The missions are described in the main body of this report.

Following the completion and presentation of the six studies, the ESA Near-Earth Object Mission Advisory Panel (NEOMAP) was established in January 2004. NEOMAP, consisting of six European scientists active in studies of near-Earth asteroids, was charged with the task of advising ESA on cost-effective options for ESA participation in a space mission to contribute to our understanding of the terrestrial impact hazard and the physical nature of near-Earth asteroids. In particular, the NEOMAP was charged with:

- identifying the advantages of, and defining a solid rationale for, the utilisation of space missions for the assessment of the impact hazard,
- identifying which of those advantages can best complement ground-based observations and data,
- revising the scientific rationale for the six missions studied in the light of current knowledge and international initiatives,
- and producing a set of prioritised recommendations for observatory and rendezvous missions in an international context.

Criteria for Space Mission Priorities

The primary factors in the Panels' assessment of the **observatory missions** were:

1. Improved survey performance above what is possible from ground-based facilities (in terms of limiting magnitude and/or completeness).
2. Capability to recover discovered objects and determine precise orbits within the survey strategy itself.
3. Derivation of physical properties *only* if this does not compromise survey efficiency or completeness.

The primary factors in the Panels' assessment of the **rendezvous missions** were:

1. Accurate measurement of dimensions, shape and bulk density.
2. Capability to explore detailed internal structure and strength.
3. Measurement of surface structure and properties.
4. Unique value (i.e. measurements or operations unique to that mission concept).

Overall Prioritisation

Observatory missions

In the case of the observatory missions, the important question is: how complete would our knowledge of the NEO population be at the end of the mission? There is a growing consensus among the impact hazard community that the ultimate requirement is to achieve near completeness down to ~50 m, i.e., the threshold size for significant ground damage, which would give us a realistic possibility of discovering the next significant impactor well before it hits. The Panel noted that the proposed missions did not offer completeness down to such small sizes and would be unlikely to detect the next significant impactor, although they would offer up to 80% completeness for sizes corresponding to approximately H (absolute magnitude) < 20.5 (down to ~300 m).

A further aspect is competitiveness with on-going and planned ground-based NEO surveys. *Improvements in the performance of existing surveys and, in particular, plans for larger facilities, have led to a dramatic increase over the past few years in expectations for NEO discovery from the ground.* The current dominant NEO ground-based survey is Lincoln Laboratories' LINEAR program, followed closely by the NEAT project. Realistic simulations of LINEAR's performance have shown that by the year 2014 (roughly the end of the proposed EUNEOS mission), even if no improvements were made in the survey by that time, LINEAR would probably achieve 55% completion for potentially hazardous NEOs with H < 20.5. Considering that other surveys are operating in parallel, the completion level of all systems might potentially reach 70% to the same MOID (Minimum Orbit Intersection Distance) and H. Looking to the near future, Pan-STARRS is already under construction, with the first of the component telescopes due to become operational in 2006. Also currently under construction is the 4-m Discovery Channel Telescope, due to begin operation around 2008. Both of these facilities will focus on the discovery and orbit determination of sub-km bodies.

As these ground-based facilities should be operational before any of the considered space observatory missions, the panel concluded that obtaining 80-90% completeness for H < 20.5 bodies could be achieved within the next decade without the space observatory missions. Even if, for some unknown reason, Pan-STARRS or similar facilities are unsuccessful, it is clear that a similar survey is quite feasible from the ground. The case for a space-based NEO observatory should be reconsidered in 10 – 15 years time, after the residual hazard from NEOs not accessible to the ground-based surveys has become better defined.

Summary of the Panel's assessment of the observatory mission concepts.

Assessment Criteria	Earthguard-1	EUNEOS	NERO
1. Survey performance (limiting mag./completeness).	***	***	**
2. Object recovery/orbit determination within survey strategy itself.	**	**	*
3. Physical properties.	*	*	**

Note: The number of stars reflects relative performance potential in the respective assessment category.

Rendezvous missions

In the case of the rendezvous missions, the Panel recognised the continuing improvement in the fidelity and modelling of ground-based observations leading to improved shape and albedo models. However, it is clear that space missions have the potential to provide unique information on NEOs. Our current lack of precise knowledge of the physical characteristics of NEOs would be a critical limitation should a potential impactor be identified; given the accelerating pace of discovery from ground-based surveys, this becomes ever more likely. While astronomical observations can provide certain information, mainly on surface properties, there are many important parameters relevant to future mitigation experiments that will remain unknown without in-situ investigations.

Given the variety of objects already known, it is improbable that any rendezvous mission will investigate a NEO identical to the next impactor. However such missions allow us to define the techniques we would employ if such a body were discovered, in addition to providing ground-truth for comparison with our models based on theory and Earth-based observations.

Summary of the Panel's assessment of the rendezvous mission concepts.

Assessment Criteria	**Don Quijote**	**ISHTAR**	**SIMONE**
1. Dimensions, shape, bulk density.	***	***	***
2. Internal structure and strength.	**	***	*
3. Surface structure, properties.	***	**	**
4. Unique value.	**Mitigation preparation**	Internal structure of 2 NEOs	Multiple NEO types

Note: The number of stars reflects relative performance potential in the respective assessment category.

Taking all factors into account, the Panel unanimously agreed that the proposed rendezvous mission concepts were of significantly higher priority in terms of risk assessment and mitigation than the observatory mission concepts. In particular, the Panel noted that the ability to change the orbit of a NEO has not yet been demonstrated, so a vital link in the chain from threat identification to threat mitigation is missing.

NEOMAP Recommendations to ESA

Of the three **observatory missions** reviewed, the Panel considers the **EUNEOS** (and Earthguard-1) NEO survey concept to be most compatible with the criteria and priorities established in this report. EUNEOS appears 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 the present time a space-based NEO discovery mission, within the scope of those considered here, is not the highest priority given the combined efforts of the various ground-based surveys likely to be productive over the coming decade. A reasonable approach may be to re-consider a space-based NEO observatory mission at a later stage, once the residual hazard from NEOs not accessible to the ground-based surveys has become better defined.

Of the three **rendezvous missions** reviewed, the Panel considers the **Don Quijote** concept to be most compatible with the criteria and priorities established in this report. Don Quijote has the potential to teach us a great deal, not only about the internal structure of a NEO, but also about how to mechanically interact with it. Don Quijote is thus the only mission that could provide a vital missing link in the chain from threat identification to threat mitigation. Considering possible participation from countries outside Europe, the Panel felt that the Don Quijote concept is compatible with current interest and developments elsewhere and may readily attract the attention of potential partners.

Of all six missions reviewed, the Panel recommends that ESA gives highest priority to the Don Quijote concept as the basis for its participation in NEO impact-risk assessment and reduction.

1. Introduction

1.1. In the beginning…

According to modern astrophysical theory, our Solar System formed some 4.5 billion years ago from a collapsed interstellar cloud. In the dense protoplanetary disk of dust and gas that surrounded the young Sun, grains of dust collided and coalesced. Over a period of a few million years material in the disk accumulated via collisions into 1 – 10-km-sized bodies, called planetesimals. At this size gravity began to play an important role and the planetesimals attracted more and more material until planet-sized bodies formed. Collisions between planetesimals, the precursors of present-day asteroids and comets, and growing planets were a natural phenomenon that forged the Solar System as we know it today. After the planets had formed, collisions with the remnant population of small bodies, i.e. asteroids and comets, continued, albeit at a declining rate, and probably deposited significant quantities of minerals, water and organic materials on the surfaces of the Earth and other planets. In later epochs impacts on the Earth may have abruptly altered the course of evolution and paved the way for mankind. The problem we face today, and which is addressed in this report, arises because this natural process has not ceased.

Impacts of asteroids and comets are a natural phenomenon that continues to shape the surfaces of planets. However, for our heavily populated world and highly networked society the impact of an asteroid or comet on the Earth today could produce a natural catastrophe far more damaging to civilization than any in recorded history.

1.2. The magnitude of the impact hazard

The current frequency of impacts of near-Earth objects (NEOs) on the Earth has been thoroughly researched in recent years. Estimates are based on bias-corrected data from NEO search programmes, primarily LINEAR and, to a lesser extent, studies of impact cratering on the Moon. Perhaps the most comprehensive summary to date is that of Morrison et al. (2002), which includes a plot, reproduced here in Fig. 1.1, of the size-frequency distribution of the total population of near-Earth asteroids (NEAs) and the impact frequency on the Earth of asteroids of different sizes. For objects with diameters of 1 km or more, i.e. above the threshold for possible destructive effects on a global scale, the estimates of different groups now seem to be converging on 1000 ± 200 for the total number in the NEA population. Of these, some 700 have been discovered to date.

Comets can also collide with the Earth. Due to their porous and fragile structure, the short warning times of long-period comets, and the relatively large potential impact velocities, mitigating against them is generally beyond the capability of current technology. However, observations and dynamical computation (for a summary see Stokes et al. 2003) show that far fewer comets than asteroids make close approaches to the Earth. These findings are consistent with the results of Werner et al. (2002) and Stuart (2003), who show that the lunar cratering rate deduced from crater counts agrees very well with the expected rate of impacts of near-Earth asteroids alone. Stokes et al. (2003) conclude that "…the threat from all long-period or short-period comets whether active or dormant, is about 1% the threat from the NEA population".

Therefore, since near-Earth asteroids appear to be responsible for 99% of the impact hazard, and given that current technology, or modest developments thereof, should allow us to mitigate against an asteroid, this report concentrates on impact-risk assessment and hazardous-object mitigation for near-Earth asteroids.

Stuart (2003) has performed a detailed analysis of the discovery data from the very successful NEO search programme LINEAR, including de-biasing corrections for the telescope properties, survey strategy, orbital parameter and albedo distributions, i.e. factors that govern the ease with which different objects are detected and lead to differences between the discovered population and the real one. He concludes that the total number of NEAs with diameters larger than 1 km is 1090 ± 180 and that impacts of objects this size on the Earth occur on average every 600,000 ± 100,000 years.

However, while good progress is being made in the discovery of NEOs with diameters of 1 km or larger*, the population of NEOs in the hundreds of metres size category is still largely undiscovered; such objects impact far more frequently and can cause damage on a national scale or worse, leading to millions of deaths.*

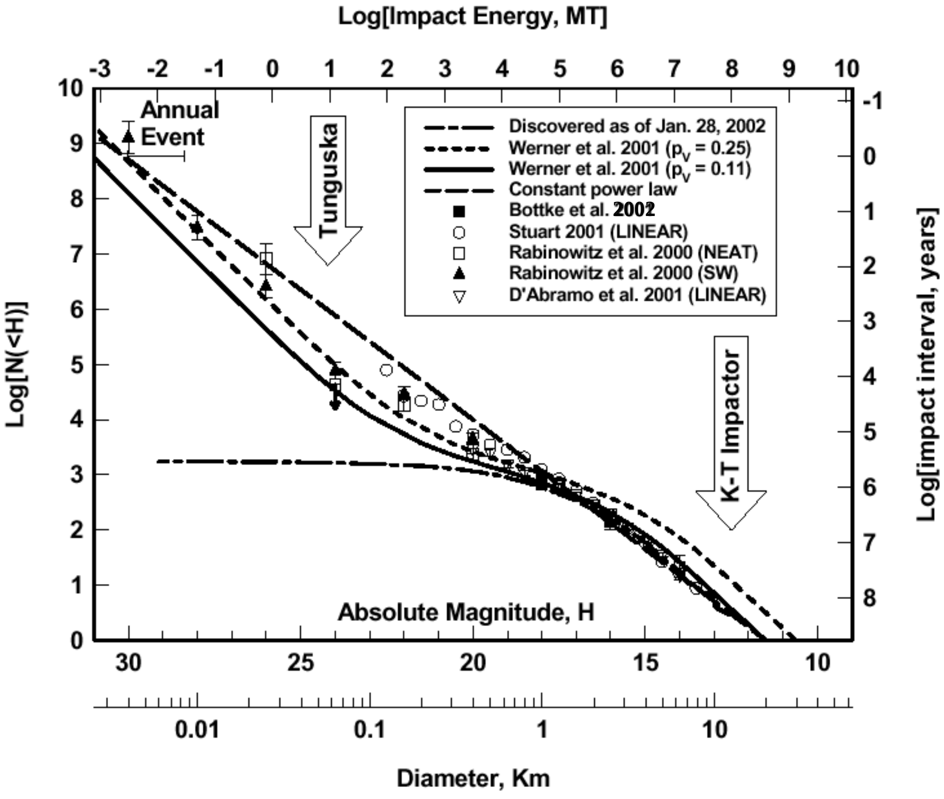


Fig. 1.1. Cumulative population of near-Earth asteroids versus absolute magnitude with equivalent scales for diameter, impact energy and expected impact interval. The straight line is a simple power law "worst case" approximation to the data (Morrison et al, 2002).

As Fig. 1.1 shows, the number of objects in the NEA population per size bin increases rapidly with decreasing size. Indeed, the Earth is continuously bombarded by dust and small fragments of interplanetary material, as is evident from the many meteors visible to a naked eye observer on any clear night. However, the Earth's atmosphere serves as a protective shield causing objects with diameters of less than about 30 – 100 m to be destroyed before they reach the ground.

The threshold size above which an object can produce significant damage on the ground depends on its composition. It is thought that Meteor crater in Arizona (diameter = 1.2 km) was formed by a metallic impactor with a diameter of 50 m that struck the ground about 50,000 years ago with a velocity of some 20 km s^{-1}, releasing around 10^{17} J or 25 MT of energy. A similarly sized stony object that did not possess the material strength to withstand its transit through the atmosphere probably caused the explosion that occurred over the Tunguska river valley in Siberia in 1908. Although the Tunguska object did not reach the ground, the force of the explosion caused by the object's disintegration still flattened some 2000 km^2 of forest. Since metallic objects constitute only around 3% of the impactor flux, a 50-m-sized object is much more likely to produce a Tunguska-like event than a crater. Nevertheless, both types of event would be capable of destroying a city in a worst-case scenario. Objects with diameters below 50 m are likely to be disrupted at high altitude during transit through the atmosphere and cause little, if any, ground damage. Estimates of the frequency at which objects of 50-m diameter or more enter the atmosphere vary by an order of magnitude between one per 10,000 years and one per 1000 years (see Fig. 1.1). The corresponding rate given by Stuart (2003) is one event per 2000 - 3000 years. A summary, based on the latest studies, of the estimated frequency and destructive energy of impactors of different sizes is given in Table 1.1.

Table 1.1. The estimated frequency and effects of impactors as a function of size.

Impactor size (m)	Mean impact interval (yr)	Energy released (megatons TNT)	Crater diameter (km)	Possible effects/comparable event
30	200	2	-	Fireball, shock-wave, minor damage.
50	2500	10	≤ 1	Tunguska explosion or small crater.
100	5000	80	2	Largest H-bomb detonation.
200	47,000	600	4	Destruction on national scale.
500	200,000	10,000	10	Destruction on European scale.
1000	600,000	80,000	20	Many millions dead, global effects.
5000	20 million	10 million	100	Billions dead, global climate change.
10,000	100 million	80 million	200	Extinction of human civilization.

Note: The energy release estimates assume a density of 3500 kg m^{-3} (stony body) and an impact velocity of 20 km s^{-1}.

The impact intervals given in Table 1.1 should be treated with caution. The values in the table are based on the frequency of impacts as a function of impactor *size*. However, it is more relevant to consider the frequency of impacts as a function of impactor *kinetic energy*, i.e. destructive effect, which requires knowledge of the mass and velocity at impact. For NEOs one can estimate the mass from the absolute magnitude, H, alone, using the conversion formula given by Chesley et al. (2002). It is remarkable that, despite the approximations involved, the result is accurate in most cases to within a factor of ~2. The velocity at impact can be estimated rather accurately from the orbital parameters. Figure 1.2 shows the absolute magnitude H of all the currently known Apollos and Atens (i.e., the orbital classes containing potentially hazardous NEAs) versus the square of velocity, V.

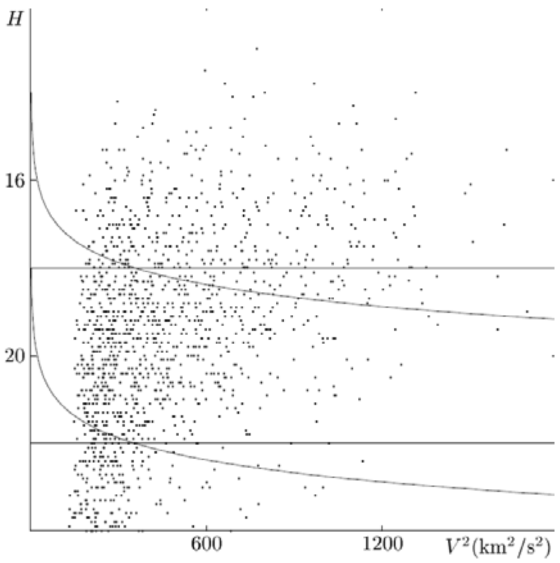


Fig. 1.2. A plot of all the currently known Apollos and Atens showing absolute magnitude H versus the square of the impact velocity at the surface of the Earth; the latter is computed from the orbital parameters, adding the contribution due to the Earth's gravity field.

The horizontal lines in the diagram correspond to objects with absolute magnitude H=18 (diameter ~ 1 km) and H=22 (diameter ~ 160 m). The upper curve gives H as a function of V^2 for a *fixed impactor energy*, corresponding to the energy of an H=18 impactor with V=18.8 km s^{-1}, the median value of V for the known Apollos and Atens. The lower curve gives H as a function of V^2 for the impactor energy corresponding to an H=22 impactor with V=18.8 km s^{-1}. Therefore, if we wish to know how many objects could produce an impact with the destructive energy equal to, or greater than, that of a typical 1-km (i.e., H=18, V=18.8 km s^{-1}) NEA, we have to consider all the objects *above the upper curve* in the diagram, and not only those above the upper horizontal line. Consequently, the impactor intervals given in Table 1.1 tend to underestimate the real NEO hazard.

The consequences of impacts of projectiles with diameters in the range 50-200 m would depend very much on the circumstances of the event (location, velocity, angle of entry into the atmosphere) and the composition and internal strength of the body. Such objects may explode in the atmosphere or survive to form a crater, but in any case the destructive energy released would be comparable, to within an order of magnitude, to that of the largest H-bomb ever detonated. An object of 200-m diameter would almost certainly reach the ground and produce a crater with a diameter of around 4 km (or a potentially destructive tsunami if it hit an ocean); damage would be at the regional or national level and in a worst-case scenario millions of deaths could result. According to Stuart (2003), impacts of objects with diameters of 200 m or more occur on average every 47,000 ± 6000 years. The locations of impact craters discovered to date are shown in Fig. 1.3.

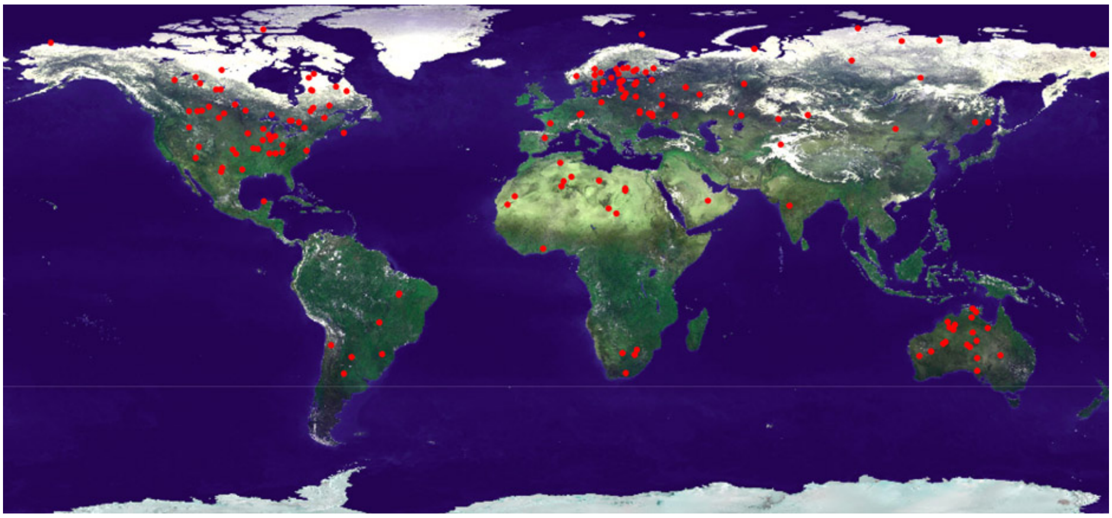


Fig. 1.3. The locations of terrestrial impact craters (Lunar and Planetary Laboratory, University of Arizona).

The current consensus amongst the impact-hazard community is that future NEO search telescopes should be made sensitive enough to achieve near completion for objects significantly smaller than 1 km (the "civilization-threatening" threshold in the original "Spaceguard Goal" set by the US Congress in 1994). According to Harris (2004), systems such as the US Pan-STARRS (Panoramic Survey Telescope And Rapid Response System), the DCT (Discovery Channel Telescope) and LSST (Large Aperture Synoptic Survey Telescope) would be capable of discovering 90% of the population of NEOs with diameters of around 200 m or more after 10 years of operation (see Fig. 1.4). However, some of these facilities will serve general astrophysical research and therefore reaching this level of completion will take longer. It is not clear how much of their time will be made available for NEO searching or what operational constraints search programmes will be subject to.

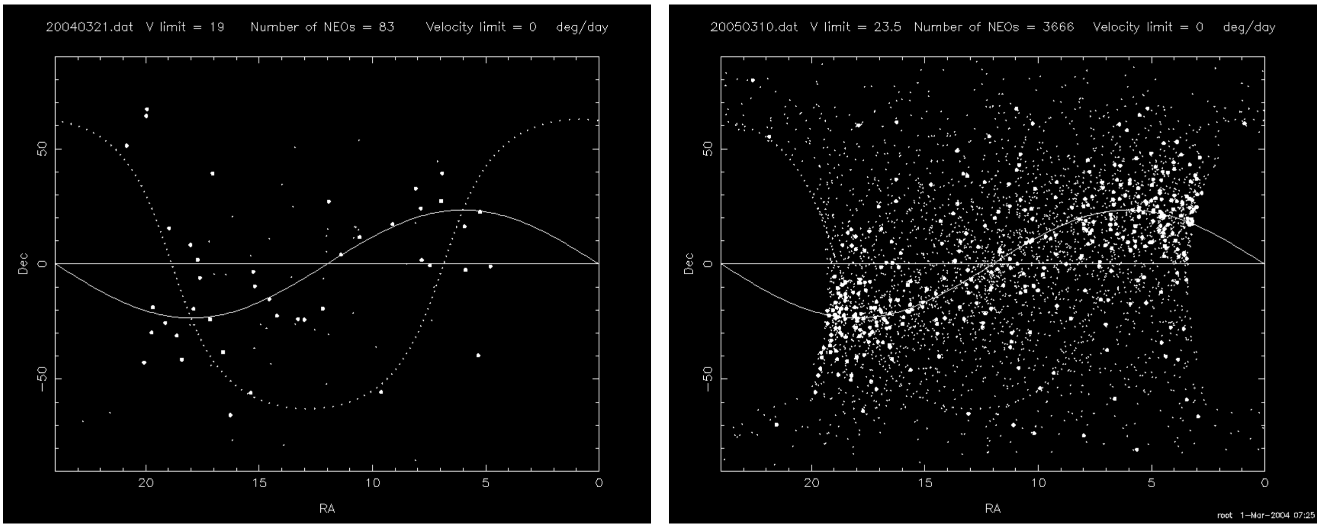


Fig. 1.4. Left-hand frame: the density of NEOs (~1 per 300 sq. degrees) above the detection limit V_{lim} = 19. Right-hand frame: the density of NEOs (~1 per 10 sq. degrees) above the detection limit V_{lim} = 23.5. A much larger number of objects will be detectable by Pan-STARRS; the difference is due to the vast population of sub-km NEOs that largely escapes detection by the less sensitive LINEAR. Based on the population model of Bottke et al. (2002).

1.3. Motivation for an ESA initiative

At present, the only country in the world with any significant national activity in the field of impact risk assessment is the USA: NASA currently spends some $4.0 million per year, mainly on NEO search programmes to fulfill the Spaceguard goal of cataloguing 90% of the NEOs with diameters of 1 km or more by 2008. The extension of dedicated NEO search programmes to cover objects as small as 200 m, as suggested at the NASA-supported 2002 Arlington Workshop on the Scientific Requirements for Mitigation of Hazardous Comets and Asteroids (Belton, 2004), would require a substantial increase in funding. Furthermore, the present funding provided by NASA does not address the physical characterisation of NEOs. While a number of groups in several countries are active in researching the physical properties of NEOs, the rate of discovery is far outstripping efforts to understand their physical nature, with the result that we are very ill equipped to begin considering feasible NEO mitigation techniques.

In comparison with efforts underway in the USA, the current level of activity in Europe in the area of NEO impact-risk assessment and hazardous-object mitigation is very limited. This is still the case, despite the recommendations of the Council of Europe Resolution 1080 of 26 March 1996 on the detection of asteroids and comets potentially dangerous to humankind. Since this Resolution is aimed specifically at European countries and ESA, we reproduce the main body of it here:

"…*Although, statistically speaking, the risk of major impacts in the near future is low, the possible consequences are so vast that every reasonable effort should be encouraged in order to minimise them.*

The Assembly therefore welcomes various initiatives - i.e. the Spaceguard Survey report published by NASA, the creation of the Working Group on Near-Earth Objects by the International Astronomical Union, and the recent decision of the NEO community to set up a Spaceguard Foundation to coordinate the efforts at an international level - as important steps paving the way towards the development of a world-wide surveillance programme aimed at discovering all potentially-hazardous NEOs and tracking their orbits forward by computer so that any impact could be foreseen some years in advance, allowing preventive actions to be taken as necessary.

The Assembly invites governments of member states and the European Space Agency (ESA) to urge the setting-up and development of the above-mentioned Spaceguard Foundation and to give the necessary support to an international programme which would:

- establish an inventory of NEOs as complete as possible with an emphasis on objects larger than 0.5 km in size;

- further our understanding of the physical nature of NEOs, as well as the assessment of the phenomena associated with a possible impact, at various levels of impactor kinetic energy and composition;

- regularly monitor detected objects over a period of time long enough to enable a sufficiently-accurate computation of their orbits, so that any collision could be predicted well in advance;

- assure the coordination of national initiatives, data collection and dissemination, and the equitable distribution of observatories between northern and southern hemispheres;

- participate in designing small, low-cost satellites for observing NEOs which cannot be detected from the ground, and for investigations which can most effectively be conducted from space;

- contribute to a long-term global strategy for remedies against possible impacts."

Strasbourg, March 20, 1996

A number of other prominent international organisations and workshops have appealed for increased efforts in the study of the impact hazard and possible mitigation techniques:

Relevant excerpt from the Report of the [UK] Task Force on Potentially Hazardous Near-Earth Objects, September 2000:

Recommendation 6

"We recommend that the [UK] government explore, with like-minded countries, the case for mounting a number of coordinated space rendezvous missions based on relatively inexpensive microsatellites, each to visit a different type of near-Earth object to establish its detailed characteristics."

Relevant excerpts from the Report of the 3rd United Nations Conference on the Exploration and Peaceful Uses of Outer Space (Declaration of Vienna):

"[...] actions should be taken [...] to improve the international coordination of activities related to near-Earth Objects, harmonizing the worldwide efforts directed at identification, follow-up observations and orbit prediction, while at the same time giving consideration to developing a common strategy that would include future activities related to near-Earth Objects [...]"

Approved by the UN General Assembly, December 1999.

Relevant excerpts from the findings and conclusions of the OECD Global Science Forum Workshop on NEOs: Risks, Policies and Actions, 20-22 January, 2003:

"Finding 4, Priority areas:

a. Strengthening ongoing efforts to discover NEOs, and to follow up the discoveries by further observations that allow precise orbit determinations and accurate impact predictions. […]

e. Studying the composition, surface and bulk properties, and other physical characteristics of NEOs, using both Earth- and space-based platforms."

Relevant excerpts from the conclusions of the NASA-supported Arlington Workshop on the Scientific Requirements for Mitigation of Hazardous Comets and Asteroids, 3-6 September, 2002:

"On space observations: […] interior properties throughout the body of potential impactors must be studied as well as the state of their surface materials. Seismic and radio reflection tomography investigations can get us deep into the interior and yield complementary information […] seismic techniques should provide excellent information on the structure of surface layers. […] Inevitably contact with the surface will be needed in order to understand its structural and compositional properties well enough for mitigation purposes. In addition, it may be necessary to perform in situ experiments and to study the effects of small-scale high-energy explosions on the surfaces of asteroids and comets.

On missions: […] a program of detailed interior and surface science exploration is needed. Development of enabling technologies is also a key element. For example, the development of asteroidal seismology, radio wave tomography, and emplacement of accurate radio Doppler transponders on all asteroids thought to be potentially hazardous are high priority. Several rendezvous missions with advanced high-energy propulsion systems will probably be required for mitigation *related projects, particularly where it is necessary to deliver payloads to the surface of target asteroids."*

Relevant excerpts from the recommendations of the White Paper Summarizing Findings and Recommendations from the 2004 Planetary Defense Conference: Protecting Earth from Asteroids (sponsored by the American Institute of Aeronautics and Astronautics and The Aerospace Corporation):

"Efficiently survey and catalog 100 meter-class NEOs. The central conclusion of the NASA Science Definition Team report on NEOs is that the global residual hazard (that which will remain after completion of the current Spaceguard Survey) is reducible by relatively inexpensive telescopic and/or spacecraft systems. Such systems can rapidly retire most of the residual hazard for a fraction of the hazard's fiscal costs.

Develop and fund […] missions to several asteroids to gather information that contributes to designing deflection missions. Critical information includes object sizes and dynamics, object type (e.g., binary), characteristics of surface and sub-surface materials, responses to explosive forces, and characteristics relating to attaching a spacecraft or other large structures to NEOs.

Conduct tests of deflection techniques leading to a demonstration of an ability to move an asteroid."

1.4. Space-based versus ground-based activities

The first task in NEO impact-risk assessment and hazardous-object mitigation is to discover potential impactors. Ground-based observations have revealed a large population of asteroids that are potentially hazardous to the Earth. However, on the basis of observations to date, the chances of any *known* object colliding with the Earth in the coming century are negligible. The only object with an accurately known orbit that might be considered a threat at present is the near-Earth asteroid 1950 DA, with a diameter of about 1 km, which has a 0.3% chance of colliding with the Earth in March 2880 (based on purely gravitational calculations).

It should be stressed, however, that while more than 60% of the estimated total population of near-Earth asteroids with diameters of 1 km or more have been discovered, the fraction of objects with diameters of 200 m or more that have been discovered is very much smaller (approximately 10%). *Therefore, it is still possible for a NEO with the energy to destroy an entire nation to impact with hardly any warning at all.*

In principle, if we could discover all the potentially hazardous NEOs and establish that none was going to approach the Earth for as long as the orbits could be accurately extrapolated, we would know that the actual risk of an impact during that time was zero. Since the orbits of NEOs evolve with time, we would have to continue monitoring them, but in this idealized case there would be little urgency to develop mitigation systems.

A very reasonable approach, then, is to increase the sensitivity of ground-based search programmes with the aim of discovering all potentially hazardous objects with diameters down to, say, 100 m. Impactors below this size would cause regional damage at most (Table 1.1). Several 4-m-class ground-based telescopes dedicated to NEO searching could probably discover 80% - 90% of the potentially hazardous

NEOs down to about 100 m within 20 years (Stokes et al. 2003). A space telescope with a mirror of 2-m diameter located in an inner-Earth orbit (at the orbit of Venus, for example) could accomplish the task in around half this time but at a greater cost.

A further advantage of a space telescope would be its ability to discover low-elongation (as seen from the Earth) objects in inner-Earth orbits that are very difficult or impossible to detect with ground-based telescopes. Objects in these orbits spend most of their time in the daytime sky and could, in principle, approach the Earth completely undetected. Although the ESA astrometry mission GAIA, scheduled for launch in 2011 - 2012, will not be optimised for NEO discovery, it is expected that it will detect a large number of asteroids, including NEOs, down to a V-band magnitude of about 20. GAIA could make important contributions to NEO impact-risk assessment by detecting objects in regions of the sky not easily accessible from the ground and in providing precise positional data for the accurate determination, or improvement, of NEO orbits.

NEO detection is one valuable contribution that could be made by a space mission. Another vital aspect of impact-risk assessment and hazardous-object mitigation is that of learning about the physical properties of NEOs. To design an effective mission to destroy or deflect a hazardous object it would be necessary to know, amongst other things, details of the inner structure and surface properties of the object. Information on the surface properties of asteroids can be gained from ground-based astronomical observations, especially spectroscopy. Many objects can be studied from the ground but the information obtained is relatively crude and limited in scope. On the other hand, we know virtually nothing about the internal structure of NEOs.

There is a great need for rendezvous missions to a number of different types of NEO to gather information we cannot access any other way and to provide “ground truth” for checking and calibrating ground-based results and physical models of asteroids.

1.5. Previous and current space missions to asteroids and comets

The USA has carried out a number of successful rendezvous and fly-by missions to asteroids and comets. Galileo imaged the main-belt asteroids (951) Gaspra in October 1991 and (243) Ida in August 1993 whilst en route to Jupiter. Other successful fly-bys were those of comets Borrelly by Deep Space 1 in September 2001 and Wild 2 by Stardust in January 2004. The most relevant US mission in the context of NEO impact-risk assessment and hazardous-object mitigation was the NEAR-Shoemaker mission to the near-Earth asteroid (433) Eros. Near Shoemaker, which obtained fascinating images of the main-belt asteroid (253) Mathilde during a fly-by on its way, spent one year in orbit around Eros and sent back a vast amount of image and spectral data on its surface structure and composition. The Near Shoemaker data show that Eros has a regolith tens of metres thick and is heavily cratered. Furthermore, the surface of Eros shows linear markings and grooves which indicate that it may be internally fractured, although it appears to be a consolidated body rather than a rubble pile.

Fig. 1.5. Image of the nucleus of Comet Halley as viewed by Giotto (ESA/MPIAe).

ESA has also gained much experience in developing space missions to rendezvous with minor bodies. ESA's first deep-space mission, Giotto, passed within 600 km of the nucleus of Comet Halley (Fig. 1.5) on 13 March 1986. Although Giotto was damaged during the flyby, most of its instruments remained operational. The mission was extended to allow an unprecedented encounter with a second comet, Grigg-Skjellerup.

ESA's Rosetta spacecraft, launched 2 March 2004 on an Ariane-5G rocket, is designed for the detailed exploration of a comet at close quarters. It consists of an orbiter and a small lander, each of which carries a large complement of scientific experiments. After flying past the main-belt asteroids (2867) Steins in September 2008 and (21) Lutetia in July 2010, Rosetta is due to enter orbit around Comet 67P/Churyumov-Gerasimenko in 2014. A small lander will be released onto the nucleus of the comet to carry out surface investigations (Fig. 1.6). The Rosetta orbiter will spend some 2 years carrying out observations of the nucleus as it heads towards the Sun.

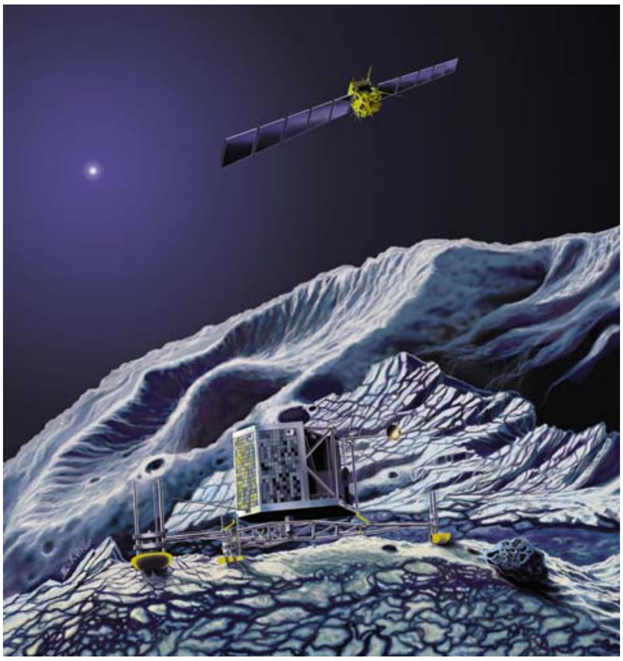


Fig. 1.6. Artist's impression of the Rosetta orbiter passing over the lander at comet 67P/Churyumov-Gerasimenko (ESA/Astrium - Erik Viktor).

Japan has launched a particularly ambitious space mission to a minor body. The near-Earth asteroid (25413) Itokawa is the target of the rendezvous mission Hayabusa (originally called MUSES-C), which was launched in May 2003. After arrival in October 2005, Hayabusa will spend some 5 months studying the asteroid and will actually set down briefly to gather a few grams of surface material. The spacecraft will then set off on its journey back to Earth where, 2 years later, it will release a re-entry capsule containing the surface samples.

1.6. NEOMAP objectives

In July 2002 the General Studies Programme of the European Space Agency (ESA) provided funding for preliminary studies of six space missions that could make significant contributions to our knowledge of near-Earth Objects. Three of these are observatory missions:

Earthguard-1 - a small space telescope for NEO discovery, especially the Atens and "inner-Earth objects" (IEOs) that are difficult or impossible to detect from the ground,

Euneos (European Near-Earth Object Survey) - a space telescope for NEO discovery,

NERO (NEO Remote Observations) - an optical/infrared space telescope for NEO physical characterisation and discovery,

and three are rendezvous missions:

SIMONE (Smallsat Intercept Missions to Objects Near Earth) - a fleet of low-cost microsatellites for NEO rendezvous and in-situ remote sensing,

ISHTAR (Internal Structure High-resolution Tomography by Asteroid Rendezvous) - utilises radar tomography for in-situ study of internal structure,

Don Quijote - utilises explosive charges, an impactor, seismic detectors and accelerometers for in-situ study of internal structure and momentum transfer.

The missions are described in the following sections of this report.

Following the completion and presentation of the six studies, the ESA Near-Earth Object Mission Advisory Panel (NEOMAP) was established in January 2004. NEOMAP, consisting of six European scientists active in studies of near-Earth asteroids, was charged with the task of advising ESA on cost-effective options for ESA participation in a space mission to contribute to our understanding of the terrestrial impact hazard and the physical nature of near-Earth asteroids. In particular, the NEOMAP was charged with:

- identifying the advantages of, and defining a solid rationale for, the utilisation of space missions for the assessment of the impact hazard,
- identifying which of those advantages can best complement ground-based observations and data,
- revising the scientific rationale for the six missions studied in the light of current knowledge and international initiatives,
- and producing a set of prioritised recommendations for observatory and rendezvous missions in an international context.

1.7. Structure of the report

In Section 2 the roles and complementary nature of ground-based and space-based investigations in the context of NEO impact-risk assessment and hazardous-object mitigation are discussed and the need for space missions is highlighted.

Section 3 explains the criteria on which the Panel's prioritisation of missions is based.

Section 4 summarises the capabilities and limitations of the three observatory missions, presents a comparative assessment of performance and information return, and reviews the missions in the light of the criteria presented in Section 3.

Section 5 summarises the capabilities and limitations of the three rendezvous missions, presents a comparative assessment of performance and information return, and reviews the missions in the light of the criteria presented in Section 3.

In Section 6 the Panel's prioritisation of the missions is discussed in the light of current knowledge of NEOs and the impact-risk, international initiatives and developments, and the criteria presented in Section 3.

In Section 7 the final NEOMAP recommendations are summarised.

2. The Role of Space Missions

2.1. Discovery and recovery

For the purpose of safeguarding the Earth, it would be sufficient to achieve discovery completeness for the NEO sub-population that effectively passes close to the Earth's orbit; as shown below (see Fig. 2.1) this can be done more rapidly from space. Most NEOs, in fact, despite having perihelion distance $q < 1$ AU and aphelion distance $Q > 1$ AU, do not cross the Earth's orbit in three-dimensional space and therefore they do not currently constitute any collision hazard for the Earth. For this reason, the notion of *Minimum Orbit Intersection Distance* (MOID) has been introduced, which is defined as the minimum distance between the orbits of two objects, e.g., the closest a NEO can approach the Earth in the absence of protective orbital resonances. NEOs with MOID < 0.05 AU and $H < 22.0$ (diameter ~ 150 m or more) are thus called Potentially Hazardous Objects (PHOs). The orbital evolution of such objects, which is influenced by their gravitational interactions with the planets, deserves careful monitoring. To date, over 600 PHOs have been discovered.

A desirable and realistic medium-term (~10 years) goal for PHO discovery is 90% of objects with diameters of 300 m or more, corresponding to $H < 20.5$. A diameter of 300 m corresponds to that at which the Tsunami risk peaks (Stokes et al. 2003) and an impact of an object of this size on land could result in destruction on a national scale or worse (Table 1.1). However, the prospects for achieving discovery completeness of the PHO population with $H < 20.5$ with current ground-based surveys within a reasonable time are unfortunately not good. Currently, the most effective NEO survey is LINEAR. Using the orbital element and absolute magnitude distributions of the total NEO population provided by the model of Bottke et al. (2002), simulations of the completeness of a LINEAR-like survey show that more than 90% completeness of the $H < 20.5$ PHO population could be achieved only if the limiting magnitude of the instrument was increased from $V = 19.35$ to $V = 24$. This would, however, require a dramatic increase in the size of the telescopes.

A major problem of ground-based surveys is their limited solar elongation coverage. Only a small fraction of the NEO population is visible at any time in the directions covered by ground-based surveys, so that a long observation timescale is required in order to detect all the objects. Moreover, the relative geometry between the Sun, the Earth and many PHOs is such that the bodies are at large solar elongations when they are at large heliocentric distance, and are at small solar elongation when they approach 1 AU. For this reason, the only way to detect all PHOs from the ground would be to push the limiting magnitudes to very faint values which, given the short exposures typical of NEO searches, would again require the use of very large telescopes.

A geocentric space-based telescope would improve the situation by extending the search to smaller elongations than possible from the ground (nevertheless not smaller than about 45 degrees) but would still suffer from the serious limitation, imposed by the relative geometry, of very large solar phase angles for objects close to the Earth. On the other hand, a survey performed with a telescope in a heliocentric orbit *fully interior to that of the Earth* would offer great advantages over ground-based surveys since: (1) the displacement of the viewing point towards the inner Solar System has the effect of moving most NEOs to larger solar elongation, (2) a telescope placed well inside the Earth's orbit is naturally capable of detecting objects residing closer to the Sun than the Earth, such as the IEOs and the Atens, which are very difficult or impossible to detect from the ground, and (3) all PHOs, which by definition must pass through or close to the ecliptic plane between 0.95 and 1.05 AU, can be easily detected from the inner Solar System by surveying a band of sky of moderate width around the ecliptic, extending over reasonable values of solar elongation.

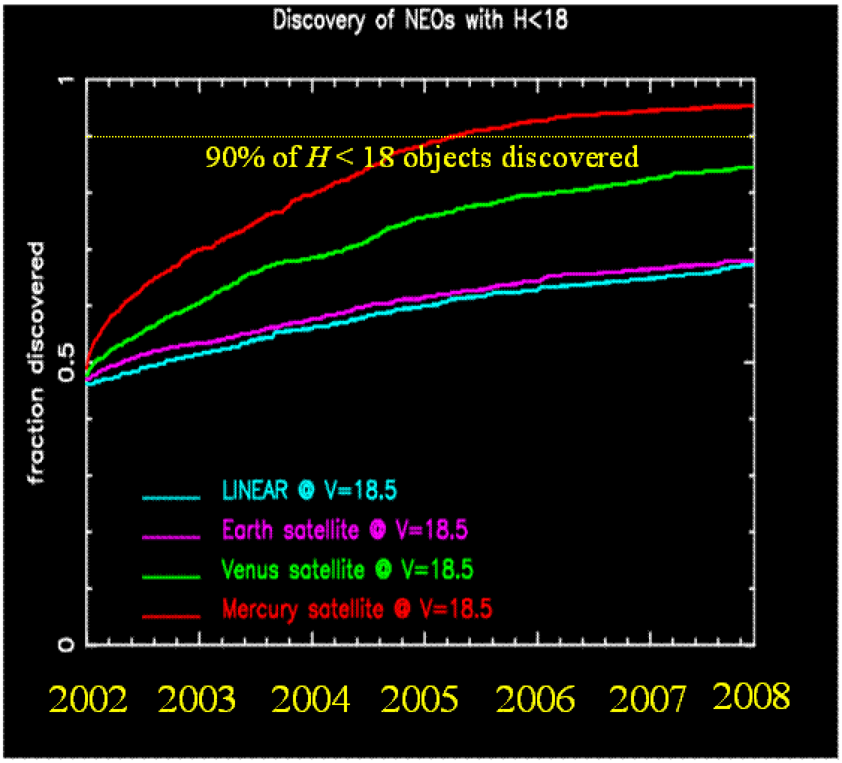


Fig. 2.1. Fraction of discovered NEOs with H < 18 as a function of time using different observation strategies (see text for details).

To approach discovery completeness of PHOs with H < 20.5 within 5 – 10 years, a space observatory would be the best strategy. The key parameter in determining the efficiency of a space-survey is the orbit of the observatory, with the survey becoming much more effective for locations nearer the Sun due to the favourable observing geometry. More precisely, starting from an observational completeness of ~ 50 % for the H < 18 NEO population, Fig. 2.1 shows how the completeness improves over a 6-year period with 1. a LINEAR-like survey (cyan), 2. a geocentric satellite (magenta), 3. an observatory placed in Venus' orbit (green) and 4. an observatory placed in Mercury's orbit (red). All surveys are assumed to have a limiting magnitude V=18.5 and the space surveys are assumed to observe the entire sky up to 45 degrees of solar elongation every day. This idealistic case illustrates the increase in survey efficiency as the observatory is moved to smaller and smaller heliocentric distances. Due to the background luminosity of solar light scattered by interplanetary dust (the zodiacal light), the increase in the sky brightness with decreasing heliocentric distance reduces the limiting magnitude of an instrument as it is moved towards the Sun. Nevertheless, even after accounting for this drop in the limiting magnitude with decreasing heliocentric distance, the detection efficiency for the H < 20.5 PHO population still increases significantly when the telescope is moved from an Earth-like to a Venus-like orbit (aphelion below 0.72 AU).

In order to predict whether detected NEOs may eventually collide with the Earth, it is crucial that the data provided by the survey allow the computation of highly accurate orbits for the discovered objects. The first step in this process is to recover the object. In order to achieve this, each object discovered must be followed for several days, until its trajectory on the sky covers an arc of several degrees. Indeed, a minimum of three successive observations is necessary to obtain a preliminary orbit and the duration of the observation arc should be at least 10 days. Recovery or "follow-up" observations are then required several months to a year after the first detection in order to provide data for the calculation of a precise orbit. Depending on the chosen observation strategy, it can be shown that the preliminary orbit derived from a space mission can be sufficiently accurate to allow the correlation of observation arcs of the same objects. Therefore, a space observatory can do its own recovery of the majority of the detected objects, including those that cannot be recovered from the ground. According to the NEO population model of Bottke et al. (2002) and simulations of discovery/recovery by space- and ground-based surveys, follow-up ground-based observations are possible for only a small fraction of the bodies (because most PHOs remain concentrated at small solar elongations).

It is important to stress, however, that while the number of objects for which follow-up observations from the ground are possible may be limited, it remains fundamental to observe them from the ground for orbital accuracy improvement. Indeed, a very precise measurement of the position and velocity of an object in space can be obtained by combining ground- and space-based observations through triangulation techniques.

Finally, in addition to the discovery of NEOs, a space observatory can also obtain information on physical properties by multi-wavelength detection. Optical spectrophotometry is helpful in constraining taxonomic type and combining optical observations with thermal-infrared measurements can provide diameters and albedos. Indeed, the thermal-infrared flux is almost independent of the object's albedo (since most objects have low or moderate albedo), and so the detection limits are more closely linked to asteroid size than they are in the scattered light regime. However, a major drawback of a thermal-infrared instrument is the need to cool the focal plane and the optics, which becomes technically difficult if the instrument is placed in an orbit close to the Sun. Thermal-infrared observations alone do not provide estimates of the apparent visual magnitude of an object, which is essential for co-ordination with ground-based observers equipped mainly with visual telescopes, therefore a visual channel is also required, adding extra complexity to the telescope design.

2.2. Physical properties

The physical properties of NEOs are fundamental to the assessment of impact risk in a number of ways. From Earth-based observations, we know that there are many different types of "animal" in the NEO "zoo"; stony, carbonaceous, cometary nuclei, rubble piles, binary systems, monolithic slabs (it is entirely possible that there are rare species awaiting discovery). The range of spectrally identified species is listed in Table 2.1.

Table 2.1. Albedos and probable mineralogies of asteroid spectral types identified in the NEO population.

Taxonomic Type	Typical Albedo	Probable Mineral Composition
D, P	0.03-0.06	Carbon, organics, silicates
C, B, F, G	0.03-0.10	Carbon, organics, hydrated silicates
M	0.1-0.2	Metals, enstatite
S	0.1-0.3	Silicates, metals
Q	0.2-0.5	Silicates, metals
V	0.2-0.5	Silicates (pyroxene, feldspar)
E	0.3-0.6	Enstatite + other iron-poor silicates
X	0.03-0.6	Unknown

There has been significant progress in recent years in all the areas in which the use of Earth-based telescopes is feasible. We have learned that NEOs with diameters > 200m are probably either highly fractured or rubble piles; new thermal models have been applied to NEOs to determine diameters and albedos more accurately; radar observations have demonstrated that binary objects are commonplace within the NEO population. However, a single mission to a NEO, the NEAR–Shoemaker spacecraft, substantially increased our knowledge of the bulk properties of silicate NEOs and revealed for the first time the metre-scale surface structure and properties. At the same time, the mission underlined the fact that measurements by in-situ spacecraft can be orders of magnitude more precise than those obtained from the ground.

There are many physical properties whose precise determination is either facilitated or only possible by in-situ measurements. First, measuring the masses and densities of NEOs allows precise calculation of the impact energy, which is the primary property of interest in risk assessment. At the same time, knowledge of the internal structure is necessary to determine how NEOs respond to both mitigation techniques and entry into the Earth’s atmosphere. Many NEOs have had their internal density constrained through indirect means. Rotation rate, combined with shape information, gives a lower limit to the mass of an object. If an object is binary, the orbital period combined with the shape and size of the components allows the overall bulk density of the bodies to be determined. The latter method can give an accurate estimate of the mass of the object but requires precise orbital and shape information, which is only achieved for a small fraction of the binary population. Needless to say, a slow spacecraft fly-by of an NEO can obtain a good mass estimate through the change in spacecraft trajectory caused by the gravitational perturbation. Even a basic rendezvous mission allows precise measurement of the mass together with at least a broad indication of the internal structure, all from spacecraft tracking measurements.

Second, knowledge of the structure and properties of the surface layers is also crucial for any planned mitigation exercise. All currently feasible methods of NEO deflection require some interaction with the surface, such as attachment of structures, localised vapourisation, or impacts; without detailed knowledge of how the surface will respond, the outcome of such an exercise is highly uncertain. While some indication of surface properties can be obtained from Earth-based measurements, especially radar experiments, the data can be difficult to interpret. This is an area where spacecraft missions are essential for even a basic level of knowledge.

Third, as alluded to above, it is necessary to understand how the physical characteristics vary throughout the NEO population. We cannot predict the properties of the next impactor, only statistical probabilities. A 100-m iron-nickel asteroid will almost certainly act differently to a 100-m carbonaceous body. Hence at some point we will need to obtain precise physical information for a range of sizes and compositional types. Space missions provide the “ground-truth” data which are required to fully understand how these parameters may be best constrained from the ground. If a high-probability impactor is discovered, Earth-based measurements will provide the initial information upon which a mitigation strategy can be based.

Finally, another (more subtle) goal is the knowledge of properties of the population such as albedo and surface composition. Our current understanding of the overall risk from NEOs is based on an extrapolation from the detected population. To perform this extrapolation successfully we must understand the surface reflectance properties of NEOs such as albedo and colour within the population as a whole, so that the observational biases can be properly accounted for.

In conclusion, in-situ rendezvous missions offer unique information, much of which is required for an accurate assessment of the risk posed by NEOs and as a basis for mitigation strategies.

3. Criteria for Space Mission Priorities

3.1. General considerations

The Panel's considerations focused on criteria relevant to the assessment of the risk to the Earth from NEO impacts. Scientific advances that are likely to result from the missions were not included explicitly in the Panel's assessment criteria. Neither was the actual task of mitigation addressed directly, since a confirmed impactor has not yet been found, although the rendezvous missions may be expected to produce results of relevance to the design of future mitigation missions. We can envisage a sequence of activities, which should not be regarded as running in series:

1. A *statistical* evaluation of the PHO population and the impact risk. This requires
   a) detection of a sufficiently large and representative fraction of the population of PHOs so that statistical timescales for the impact of objects of a given size, orbital class, and physical/compositional type can be determined, and
   b) derivation of the structure and physical properties of each class of NEO so that the consequences of an impact, and hence the relative contribution of each size and class to the risk, can be assessed.

2. Search for the next impactor. This requires detection of, and orbit determination and propagation for, PHOs that can potentially cause damage above a particular threshold. Put another way, this activity could be described as eliminating the uncertainty of a possible impact occurring within a certain timescale.

3. Preparation for mitigation, e.g., demonstration of the feasibility and outcome of possible future mitigation techniques by:
   a) determining the physical properties relevant to mitigation techniques (e.g. internal and surface-layer structure),
   b) testing the response of an asteroid to external stimuli.

   When/if a potential impactor is identified above a certain threshold impact probability, it will only be possible to commence mitigation activities if the critical properties of the impactor can be determined and appropriate mitigation strategies are already in place.

Each of the proposed missions addresses one or more of the above activities.

3.2. Observatory missions

An over-riding consideration in the assessment of proposed space missions is their performance in achieving a set of objectives and their cost effectiveness compared with competing ground-based techniques. Such missions should either perform tasks which are not possible from the Earth, or perform those tasks in a significantly improved way (with greater efficiency/accuracy/resolution, with greater speed or at lower cost).

In section 2 we discussed the role of space missions for discovery and recovery and for determination of physical properties. Observatory missions can, in theory, contribute to both these objectives and address items 1 and 2 described in Section 3.1.

The fundamental requirements of a survey are to identify all (or a defined subset of) objects to a certain limit and allow their recovery so that precise orbits can be determined. The determination of orbits to sufficient accuracy so that they can be followed up, either from the spacecraft or targeted ground-based telescopes, is essential. The space observatory itself must perform this task if there is an identified population of objects which are inaccessible from the Earth. This could either be through scheduled targeted follow-up by the spacecraft, or, preferably, by optimum design of the survey strategy. The benefits of the latter are increased efficiency and lower operational costs and complexity.

The benefits of performing physical observations coincident with the survey are that they potentially provide an unbiased and more complete sample. Historically, physical observations have not kept pace with new discoveries and are biased towards the brightest or most accessible objects. In addition, the physical observations resulting from a multi-wavelength approach may enhance the survey efficiency (e.g. an infrared survey does not contain the same albedo bias as an optical survey). However, it is important to distinguish between the characterisation of the *overall population* (activity 1b in section 3.1) and the need to determine the detailed properties of the *next impactor*. The first of these tasks can be achieved for a sufficiently large sample by means of ground-based follow-up or astronomical space observatories. If an object is discovered with a high impact probability then all available resources will be directed towards its observation. *Physical observations from a space-based survey mission should therefore only be considered if they do not compromise the ability of the survey to discover NEOs and determine accurate orbits.*

To summarise, the primary factors in the Panels' consideration of the observatory missions were:

1. Improved survey performance above what is possible from ground-based facilities (in terms of limiting magnitude and/or completeness).
2. Capability to recover discovered objects and determine precise orbits within the survey strategy itself.
3. Derivation of physical properties *only* if this does not compromise survey efficiency or completeness.

3.3. Rendezvous missions

As discussed previously, the most important factor in our considerations was how a rendezvous mission would improve our understanding of the impact risk and reduce the uncertainties in any future mitigation exercise. It must be recognised that none of the proposed missions would (in all likelihood) be targeted at an object on an impact trajectory. However, given our lack of knowledge concerning the detailed characteristics of NEOs, all the proposed rendezvous missions would be highly effective. The Panel did not consider purely scientific benefits. That said, there is obviously a significant overlap here, as it is scientific investigation that forms the basis of the risk assessment and development of mitigation strategies.

The Panel concentrated on four primary criteria relating to rendezvous missions necessary for moving our knowledge of the impact risk forward. The first was the precise measurement of dimensions and shape, leading to the internal density distribution. Part of this consideration was the accuracy to which this would be measured, i.e. imaging alone gives a much poorer result than the use of a laser altimeter. Leading on from this, the Panel regarded the determination of internal structure and strength as a high priority. While the homogeneity of the internal mass distribution can be inferred from a close orbit, technology now exists to probe the internal structure at higher fidelity.

Third, the Panel focused on knowledge of the physical properties of the surface, regolithic or otherwise. A baseline achieved by all missions would be high-resolution imaging, as achieved by NEAR-Shoemaker on the large NEO (433) Eros. The Panel regarded highly any mission that achieved results beyond this, in terms of either structure or distinct physical properties.

Additionally, no two rendezvous missions are the same; each has a unique aspect that distinguishes it. In terms of the missions considered here, the unique aspects that the Panel concentrated on were the detailed interior probing of two NEOs (Ishtar), the physical characterisation of several NEOs (SIMONE), and the internal and external response of an asteroid to a direct impact (Don Quijote). Given the overriding goals of risk assessment and reduction, all experiments were looked at in regard to their application to future mitigation experiments. This aspect was difficult, as it is sometimes not known *a priori* how a particular experiment would contribute in this area. As an example, the NEAR-Shoemaker mission revealed smooth "ponds" composed of fine-grained material on the surface of Eros. It is currently thought that these have formed through electrostatic processes, giving insight into a scientifically interesting phenomenon. However this may also be important for surface-based mitigation technologies, which may either land or operate in a dusty environment.

In summary, the primary factors in the Panels' consideration of the rendezvous missions were:

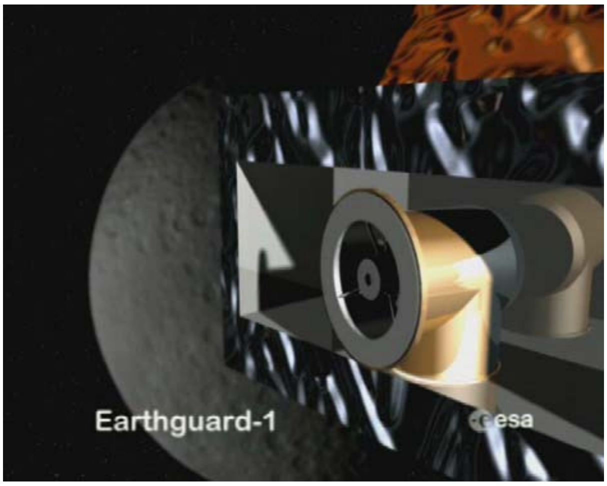
1. Accurate measurement of dimensions, shape and bulk density.
2. Capability to explore detailed internal structure and strength.
3. Measurement of surface structure and properties.
4. Unique value (i.e. measurements or operations unique to that mission concept).

4. Observatory Missions

In the following three sections the characteristics and estimated performances of the three observatory missions are briefly described. The material in these sections draws heavily on that in the corresponding study reports.

4.1. Earthguard-1

4.1.1. Proposed mission objectives



The idea behind Earthguard-1 is to search from a space platform in the visible band for NEOs, *especially those that are difficult or even impossible to detect with Earth-based telescopes.* A prime motivation of the Earthguard-1 study was to investigate the potential advantages of a survey telescope located at Mercury, in the light of a possible piggy-back launch opportunity on the ESA BepiColombo mission.

The requirements defined in the Earthguard-1 study are:

- Detect asteroids with diameters larger than about 100 m that are impossible or difficult to observe with ground-based NEO search telescopes. Requires space-based telescope with a limiting V-band magnitude of 18.5, situated ideally in the orbit of Mercury, and automatic detection of moving objects.
- Determine orbital types (IEOs, Atens, Apollos, etc). Requires derivation of preliminary orbital parameters from repeated observations of object positions.
- Facilitate follow-up observations of interesting objects by other telescopes or Earthguard-1 itself. Requires scanning and linking strategies aimed at providing orbital parameters of sufficient accuracy to allow objects to be located again up to a few months later.
- Make crude size estimates. Requires estimation of absolute magnitude (H-value) from measured brightness and knowledge of the orbit.

4.1.2. Spacecraft and payload

The Earthguard-I study resulted in a preliminary design of a telescope, including a turntable with one degree of freedom, sensor electronics and a data processing unit, which could be accommodated on a planned spacecraft such as BepiColombo, or a dedicated spacecraft which would be inserted into a heliocentric orbit of around 0.5 AU utilizing low-thrust propulsion. While the main thrust of the Earthguard-1 study was to take advantage of the relatively cheap piggy-back option on BepiColombo, two other options were investigated using low-thrust propulsion with a high specific impulse:

- Solar Sail Propulsion, and
- Solar Electric (Ion) Propulsion (SEP).

For both options a preliminary mass budget and mission scenario for insertion into a heliocentric orbit of around 0.5 AU were derived. It was concluded that the mass for the SEP option would exceed the capability of an Ariane 5 piggy-back launch. The solar sail option may present a cheaper alternative. Solar sail technology is currently being developed by Kayser-Threde with funding from ESA and DLR.

The baseline telescope optical design consists of an adapted 20 - 25-cm diameter Ritchey-Chretien telescope with a refractive three-element field corrector. The focal plane incorporates the science detector, a 2k x 2k CCD with a pixel field of view of 3.5 arcsec and a detector field of view of 2° x 2°, and 3 star tracking sensors. The signal from the star trackers is used to control the autonomous image stabilization system. The data processing unit is responsible for the near-real time detection of light sources in the fields, for the discrimination of spurious detections and for the identification of moving-object candidates.

Attitude control jitter causes image smearing which leads to degradation of astrometric accuracy, a decrease in the limiting detectable brightness, and source confusion with field stars. There is therefore a requirement to keep the image stable within a fraction of a pixel for the duration of an exposure. An autonomous image stabilization system at the instrument level relaxes the requirements on the spacecraft. Two types of image stabilization system are possible: 1) tip-tilt stabilization via mirror actuation and 2) on-chip charge shifting on an orthogonal transfer CCD. The orthogonal transfer CCD, developed recently, permits parallel clocking horizontally as well as vertically. This type of device achieves image motion compensation by moving the electrons within the CCD to follow the optical image falling on the device. The latter system has important advantages in that it is built in to the detector, is much faster than a mechanical system, and requires no moving optical components.

4.1.3. Observation strategy and simulations

Simulations of the Earthguard-1 performance were carried out for mission durations of 1 year and 3 years. Most of the time the instrument would be operated in survey mode, although in practice there would be an option to operate in observatory mode to carry out follow-up observations of some fraction of the discoveries. The survey strategy is designed to maximize the number of detections of NEOs and to ensure a reliable determination of their orbits. In the survey mode, the turntable-mounted telescope repeatedly scans strips in the sky (typically 2° wide and about 50° long) located along great circles in the vicinity of the ecliptic. By stepping the spacecraft around the Sun-pointing axis, coverage in ecliptic latitude is achieved. Furthermore, due to the orbital motion of Mercury, the spacecraft Sun-pointing axis drifts by about 4°/day in longitude. With this strategy NEOs would be detected in general many times on subsequent scans before they left the scanned region (or before the scanned region drifted away), thereby allowing a preliminary orbit determination. The drift of the spacecraft axis would ensure that the full range of longitudes is observed several times during the mission lifetime.

Moving-object candidates are identified by the on-board software by correlating the positions of all light sources in consecutive frames of the same field. Cosmic-ray hits and other artifacts are identified by acquiring two exposures in rapid succession. By transmitting only the coordinates of candidate objects (instead of the image data), the telemetry requirements of the experiment are moderate, amounting to about 1 kB s^{-1}.

Several observation strategies were numerically simulated in order to estimate the efficiency of the discovery process. The model calculation of the expected number of discovered objects was based on the prediction of the distribution of the orbital elements of a model population of about 58000 near-Earth Asteroids (Bottke et al., 2002). The programme determines the positions of all of these objects for a specific sequence of images. If an object is in the field of the camera according to the schedule of the exposures, the brightness of the object is calculated. The brightness calculation takes account of geocentric and heliocentric distance, the phase effect, and the motion of the objects on the image (“smearing”). The S/N is calculated from the charge due to background objects, the dark current and the readout noise per pixel.

It was found that observations from both orbits (Mercury and R=0.5 AU) result in a large number of discoveries for all NEO groups, and allow the determination of reliable orbits for a good fraction of them, therefore achieving the scientific goal of the experiment. Table 4.1 summarizes the numbers of objects found (and percentages of the estimated total populations) for selected mission parameters.

Table 4.1. Numbers of objects found ($H < 18.0$) for selected mission parameters in simulations of Earthguard-1 performance.

Type	Merc/90°/20cm/1yr.	Merc/90°/20cm/3yr.	0.5AU/90°/20cm/1yr.	0.5AU/90°/25cm/3yr.
Amor	20 (7.2%)	48 (17.3%)	28 (10.1%)	71 (25.5%)
Apollo	132 (22.3%)	277 (48%)	114 (19.6%)	282 (48.5%)
Aten	33 (52.4%)	44 (70%)	24 (38.1%)	41 (65.1%)
IEO	18 (62.1%)	20 (69%)	14 (48.3%)	19 (65.5%)

Notes: The numbers in brackets are percentages of the total numbers of the different object types with $H < 18.0$ in the Bottke et al. population. The column headings refer to orbit location/elongation of scan centre/telescope primary mirror diameter/mission duration.

The following general conclusions were reached:

1. Increasing the telescope size (from 20 cm to 25 cm) increases the detection rate by 25%-30%.
2. Increasing the mission duration from 1 year to 3 years increases the detection count and the orbital determinations roughly by a factor 2.
3. Scans centred around 90° elongation generally appear to produce somewhat better results compared to opposition scans. It must be stressed, however, that this conclusion might be reversed if new observation constraints specific to a particular mission are introduced.
4. Using a small amount (e.g. 5%) of Earthguard-1 observation time in observatory mode for follow-up of selected objects could significantly improve the number of objects for which reliable orbits are obtained.

4.2. EUNEOS

4.2.1 Proposed mission objectives.

The aim of the EUNEOS (EUropean Near-Earth Object Survey) mission is to achieve within 5 years ~ 80 % discovery completeness of potentially hazardous NEOs (PHOs) with absolute magnitude H < 20.5 (diameter > 300 m). For this purpose, a 30-cm diameter optical telescope in an orbit totally interior to that of Venus is proposed, performing a systematic survey of a selected band of the sky. To reach the proposed orbit with virtually no additional manoeuvre after leaving Earth orbit, a gravity-assist fly-by of Venus is envisaged.

4.2.2 Spacecraft and payload

The proposed EUNEOS operational orbit imposes some specific, yet manageable constraints on the EUNEOS satellite design, mainly on the thermal, power generation and telecommunication aspects, since the satellite could be as close at 0.5 AU from the Sun and as far as 1.7 AU from the Earth. Taking account of these constraints in the design leads to a satellite dry mass, including a 20% system margin, of 514 kg. The addition of the propellant mass of 27 kg, results in a total launch mass of 541 kg.

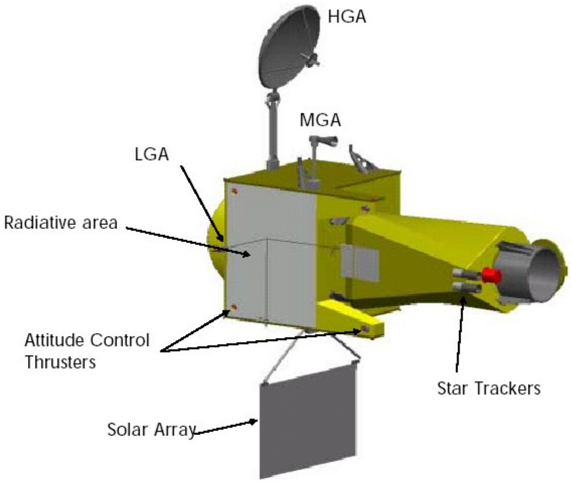


Fig. 4.1. EUNEOS spacecraft.

The payload specifications are: a spectral range of 370 nm – 950 nm, a pixel field of view of 1.3 arcsec^2 and a total detector field of view of 3° x 3°. The proposed EUNEOS layout is essentially derived from the Corotel instrument design proposed for CNES's COROT mission. The entrance pupil required to achieve the required sensitivity is estimated to be 30 cm. The main structural components are two mirrors (primary and secondary) based on light-weight Zerodur glass, a dioptric assembly and a focal plane array (FPA) of 8k by 8k pixels made up of 2 x 4 CCD 42-80 detectors. The temperature of the FPA is controlled at 220 K.

To reach the EUNEOS operational orbit without intense thrusting after Earth departure, it is proposed to use Venus gravity assist via a Hohmann transfer between the Earth and Venus. With a Soyuz-type launcher, the mass that can be injected is well above the envisaged EUNEOS satellite mass, which would allow the launch (and the cost) to be shared with another satellite.

4.2.3 Observational strategy and simulations

The space observatory should be placed in an orbit that does not penetrate beyond Venus' heliocentric distance (inner-Venus orbit), and should have a telescope with a limiting magnitude at 1 AU of 21. The aphelion and perihelion of the proposed orbit are at 0.72 AU and 0.5 AU, respectively.

Since it is crucial that the data provided by the survey allow the computation of very accurate orbits for the discovered objects, it is necessary for the survey to re-visit sequentially a large area of the sky. This allows the re-detection of the discovered bodies at each scan of the survey area during a long time-interval. Since all potentially hazardous NEOs must cross the ecliptic plane at a heliocentric distance larger than that of EUNEOS, it is suggested that the instrument scans a band of sky around the ecliptic, with height (maximal ecliptic latitude) and width (maximal distance from opposition) as large as possible. Simulations show that there is no significant gain obtained when scanning a band of the sky larger than 21 degrees in declination and 270 degrees in elongation. These values are therefore taken as requirements for the EUNEOS system. Fig. 4.2 shows the location of EUNEOS' orbit and its observational strategy. The same 3° x 3° field of sky would be observed five times, to lower the probability of false detections due to cosmic rays, at 3-minute intervals, with an observation time of 30 s.

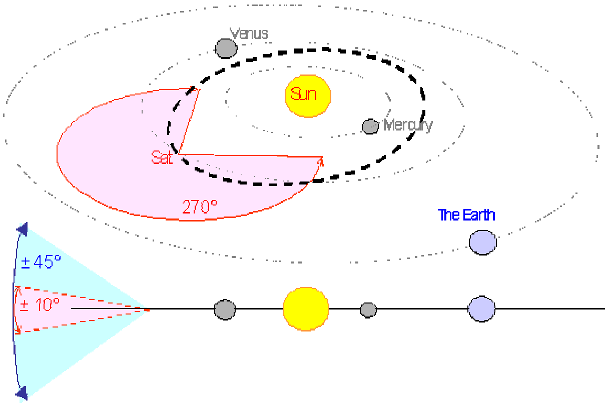


Fig. 4.2. EUNEOS orbit and observational strategy.

Simulations of the EUNEOS survey were performed under the following assumptions: The model of the NEO distribution is the one of Bottke et al. (2002) which predicts the existence of about 1,000 PHOs larger than 300 m in diameter in an overall population of about 1,000 NEOs larger than 1 km and 7,000 larger than 300 m. The specified limiting magnitude of 21 at 1 AU is scaled to the heliocentric distance of the satellite, in order to take account of the heliocentric distance dependency of the zodiacal light.

The discovery efficiency is summarized below for different classes of NEOs. Note that "discovered" means that an object is detected during at least three consecutive visits of the survey area. This allows accurate determination of the orbits, without any need for immediate follow-up from the ground. For example, the resulting accuracy of the orbital semimajor axis would be better than 10^{-3} AU for 96% of the discovered objects, and better than 10^{-4} AU for 85% of the discovered objects. Thus the success of EUNEOS would not depend on immediate ground-based follow-up during the mission. This is an important point because at the moment of discovery by EUNEOS most of the objects would be invisible from the Earth, being too faint or too close to the Sun.

To summarize, with a primary mirror of 30-cm diameter and a 5-year mission EUNEOS should discover the following approximate fractions of objects brighter than H = 20.5 (diameter larger than about 300 m) - see also Fig. 4.3:

- 80% of the population of potentially hazardous NEOs,

- 68% of all NEOs,

- 95% of the population of Inner-Earth Objects (IEOs), bringing the observational knowledge of this population from the current level (none) to almost completion.

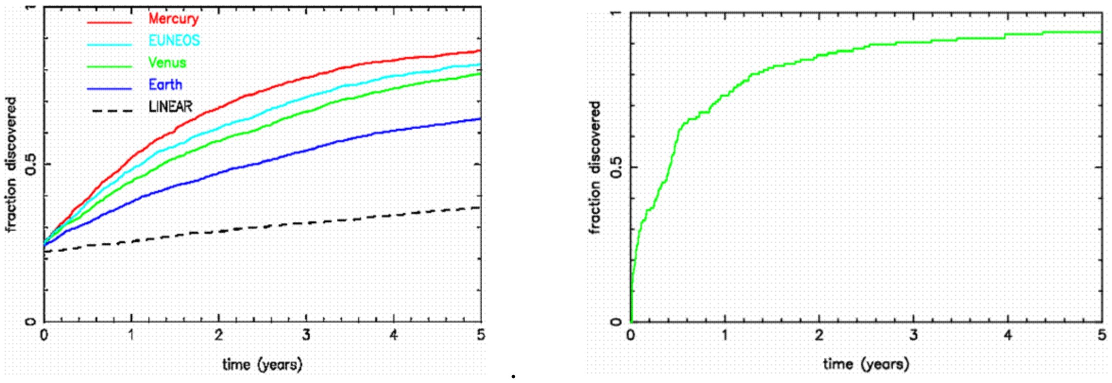
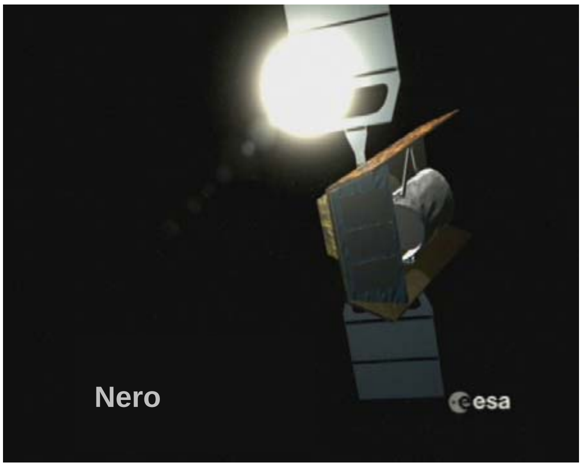


Fig. 4.3. Left: fraction of PHOs with H < 20.5 discovered by observatories in various locations; right: fraction of IEOs with H < 20.5 discovered by EUNEOS. EUNEOS specifications were assumed with a limiting magnitude of V = 21 at 1 AU in all cases except LINEAR (V_{lim} = 18.5).

4.3. NERO (Remote Observation of NEOs from Space)

4.3.1 Proposed mission objectives



NERO consists of a dedicated space observatory aimed at complementing ground-based systems for the discovery and physical study of NEOs. Its main objectives are:
a) the determination of the sizes and albedos of NEOs, and b) the discovery of Atens and IEOs.

The observations would be done both at visible and at infrared wavelengths, both in survey and pointed observation modes; this latter mode will be used for physical observations and, when necessary, for astrometric follow-up.

In contrast to other survey missions, whose main aim is to complete the discovery of NEOs down to a certain absolute magnitude, NERO aims in addition to obtain the most important unknown parameter for NEOs of a given magnitude, i.e. their size. Observations at infrared wavelengths are crucial to achieving this goal.

4.3.2 Spacecraft and payload

The requirements imposed by the scientific objectives on the spacecraft are as follows:

- accommodate instrumentation with focal plane arrays working at visible (0.35-1.0 µm) and thermal-infrared (6-11 µm) wavelengths,
- operate with a Sun-oriented, constrained attitude,
- mission duration of at least 2 years, with the possibility of extending it to 5 years,
- provide on-board processing capabilities.

The spacecraft is three-axis stabilised and consists of a main body and two deployable solar arrays. The design is driven by the requirements to minimise thermal heat and stress inputs into the telescope, to allow pointing down to 40º of solar elongation, and to assure the required lifetime.

A sunshield protects the instrumentation from the thermal radiation emanating from the Sun, the Earth and the Moon. Lines of sight from the focal plane to other major celestial off-axis sources (planets, stars, zodiacal light) are blocked by baffles.

The NERO design includes a Ritchey-Chretien telescope with an 80-cm aperture and both optical and IR sensors. The optical sensor is a 1024 x 1024 pixel CCD with a pixel field of view of 1.8 arcsec and a readout frequency of 200 kpix s^{-1}; the infrared sensor is a 256 x 256 HgCdTe array with a pixel field of view of 7 arcsec, covering the wavelength range 6-11 µm. The field of view is 30 x 30 arcmin.

The proposed orbit is a Lissajous halo orbit at the L2 Sun-Earth Lagrangian point that allows the constraints imposed by the cooling system and system design to be satisfied. An alternative scenario consisting of a Lissajous halo orbit at the L2 Sun-

Venus Lagrangian Point offers some advantages with respect to the efficiency of radiometric observations, but at the cost of a worse radiation environment, a more complicated orbital and operational scenario and a more complex system design.

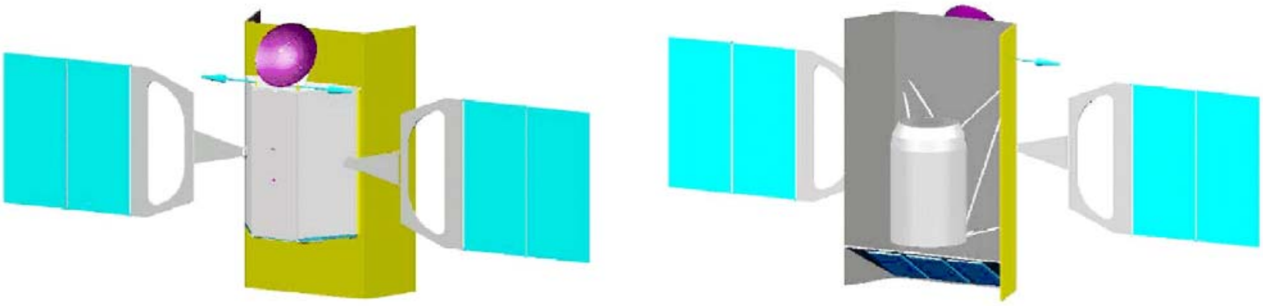


Fig. 4.4. Two views of the NERO spacecraft; left: service module side; right: telescope side.

A number of launchers are suitable for NERO; an analysis of the various possibilities, based on launcher mass performance, available payload volume, launcher maturity and cost, and the requirements on structural frequency and strength, has led to the choice of either a Soyuz-Fregat or a Delta II 7925. Both launcher types can give the desired performances at a cost of 30-45 M$ (Soyuz-Fregat) and 45-50 M$ (Delta II).

4.3.3 Observational strategy and simulations

The observational strategy consists of scanning a wide area of the sky a large number of times during much of the mission lifetime. Two observations of the same field will be separated by a few hours.

To meet the requested scientific objectives a sky area as wide as 300 square degrees has to be observed twice every 5 days. This requires a minimum number of 2400 frames, each 30 x 30 arcmin wide. A fraction of 20% of the observing time will be available for pointed observations of selected objects, e.g. for good radiometric characterisation of known asteroids observed near opposition. This will leave 4 days (96 hours) devoted to the survey. With the above parameters, the time available for each frame is 0.04 hours (144 seconds). The total integration time is dictated by the V channel, for which the integration time is much longer than that required by the IR channel, even including the HgCdTe array readout time. In V an integration time of 15 s plus a readout time of 5 s gives 20 s for an observation; adding 124 s for pointing and stabilisation results in a total time requirement per field of 144 s.

Table 4.2 summarises the performance of NERO in terms of NEA discoveries (the completeness levels are for the NEA population of Tedesco et al. (2000), for objects larger than 1 km) with the two alternative scenarios for the placement of the spacecraft.

Table 4.2. NERO performance.

Issue	Earth[1]	Venus[1]	Remarks
Phase angle at discovery	Larger	Smaller	Visual benefits from smaller phase angle; IR models more reliable
Parallax	Less	More	Pro: aids orbit determination; Con: complicates identification
IEO discovery completeness	48%	39%	Based upon five-year simulation at ecliptic latitudes < |85| (2)
IEO discovery completeness	48%	25%	Based upon five-year simulation at ecliptic latitudes < |45| (2)
IEO discovery completeness	46%	-	Based upon five-year simulation at ecliptic latitudes < |15| (2)
Aten discovery completeness	89%	94%	Based upon five-year simulation at ecliptic latitudes < |85| (2)
Aten discovery completeness	88%	77%	Based upon five-year simulation at ecliptic latitudes < |45| (2)
Aten discovery completeness	82%	-	Based upon five-year simulation at ecliptic latitudes < |15| (2)
Aten V mag range at discovery	16 - 22	12 - 20	(2)
IEO V mag range at discovery	16 - 21	10 - 18	(2)
Rate of motion at discovery	Low	High	

Notes: (1) Search area is around solar elongation 60º ± 15º from Earth L2 and around solar elongation 180º ± 15º from Venus L2.

(2) Considering only NEAs with IR mag < 9.0 at 8 μm and scan area which can be covered by the IR sensor in five days.

4.4. Comparative assessment of performance

In comparing the detection/discovery efficiencies of the observatory missions it is important to note that the simulations performed in the cases of Earthguard and EUNEOS are based on the same NEO population, namely the one of Bottke et al. (2002), while the simulations performed in the NERO study are based on a different population, namely that described by Tedesco et al. (2000). The latter is based essentially on the known population, while the population of Bottke et al. is a model generated by means of numerical integrations, starting from the source regions of NEOs and matching the contributions of the different sources to survey results, with the help of appropriate bias models for the surveys. Thus it is not possible to compare the results given for NERO to those of the other two observatory missions in a straightforward way.

NERO is the only observatory mission proposed that obtains physical information as an intrinsic part of the detection process, by combining the data from the optical and infrared detectors. The value of this is significant: rather than produce an absolute magnitude distribution, it would directly reveal the true size distribution of the detected NEOs, i.e., the survey would be size limited, rather than H-limited. Such a system could be highly complementary to ground-based surveys using larger apertures, as it would give an excellent measure of the albedo distribution of the larger NEOs. The derived albedo distribution would lead to more accurate size estimates from the H-values provided by the ground-based surveys.

However, the inclusion of the infrared capability requires mission and design compromises that result in the survey itself being less efficient than that of either Earthguard-1 or EUNEOS (this takes into account the differences in the NEO population models described above). *The Panel's main criterion for the assessment of observatory missions was level of completeness*. Should a single NEO be identified with an impact probability of > 1%, there is no doubt that many Earth-based observatories would be used for physical characterisation. While the derivation of the size and albedo for *every* NEO detected is an excellent goal for *scientific* purposes, the Panel felt that this should not be allowed to compromise the highest priority task in the context of impact hazard assessment, namely that of detection and accurate orbit determination.

The Earthguard-1 and EUNEOS concepts are essentially the same. The Earthguard-1 concept originated from the idea of placing a NEO telescope on a planned Mercury mission. The Panel noted that this specific opportunity offered by BepiColombo probably no longer exists, and there was some concern about the use of novel unproven technologies such as solar sailing as an alternative means of reaching the required orbit.

Besides these considerations, both missions are efficient in terms of detection rates as a function of H. Both envisage an optical survey from a spacecraft at < 1AU which, due to the corresponding increase in NEO brightness and lower sky background, allows much more efficient detection of sub-km NEOs than from the surface of the Earth. Earthguard-1 could discover some 60% or more of H < 18 (D > 1 km) NEOs in a 3-year mission; EUNEOS could detect 80% of PHOs with H < 20.5 (D > 300 m), and 95% of IEOs with H < 20.5 in a 5-year mission. The difference between these performances is almost entirely due to the size of the optical telescope and length of mission assumed. While some possibility of physical studies might be envisaged (i.e. polarimetry), the Panel unanimously agreed that such studies should not take place if they affected the survey completeness.

The Panel's assessment of the observatory mission concepts based on the criteria established by the Panel, discussed in Section 3.2, are summarized in Table 4.3.

Table 4.3. Overview of the Panel's assessment of the observatory mission concepts.

Assessment Criteria (cf. Sect. 3)	Earthguard-1	EUNEOS	NERO
1. Survey performance (limiting mag./completeness).	***	***	**
2. Object recovery/orbit determination within survey strategy itself.	**	**	*
3. Physical properties.	*	*	**

Note: The number of stars reflects relative performance potential in the respective assessment category.

4.5. Priorities

Making the inventory of all PHOs that are capable of causing at least regional damage is essential, since it may lead to identification of the next impactor(s) and should allow impacts to be predicted with a long warning time. Even considering the existence of current ground-based surveys, and the potential development of future NEO detection systems, such as Pan-STARRS, a space mission remains competitive if it can achieve the goal on a significantly shorter time scale. This would probably require the mission to be fully devoted to the goal of discovery and orbit determination, as any time devoted to physical characterisation would necessarily compromise the discovery/recovery efficiency.

Simulations of discovery by different kinds of surveys (see Fig. 4.3) show that a spacecraft placed in an orbit entirely interior to that of Venus with an appropriate scanning strategy remains the best choice for discovery and orbit determination of most PHOs with $H < 20.5$.

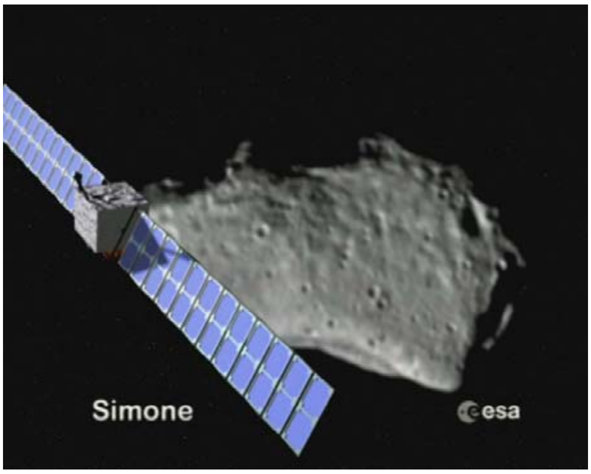
Therefore, on the basis of the criteria discussed above, and in the absence of a piggy-back opportunity on a Mercury mission for Earthguard-1, the Panel concluded that of the proposed observatory missions, EUNEOS is to be preferred.

5. Rendezvous Missions

In the following three sections the characteristics and estimated performances of the three rendezvous missions are briefly described. The material in these sections draws heavily on that in the corresponding study reports.

5.1. SIMONE

5.1.1 Proposed mission objectives



SIMONE is a fleet of low-cost, microsatellites that individually rendezvous with different types of NEO and perform remote sensing observations to characterise physical properties relevant to the development of effective mitigation strategies against different types of objects that could threaten Earth in the future. The mission design is optimised for low mass and low cost to ensure that multiple spacecraft can be constructed within the constraints of the study. The scientific objectives reflect the reconnaissance role of the mission, emphasising the key properties relevant to impact mitigation and the need to study a group of objects that collectively demonstrate most of the possible characteristics that threatening NEOs may possess, providing a range of “ground-truth” measurements for properties that are difficult, or impossible, to determine from Earth. SIMONE is therefore proposed as a precursor to an in-depth mission to an individual target.

The measurement objectives in priority order are:

- Bulk density: Requiring both the mass and the volume (size, shape) to be measured. For the particular spectral/physical class it then allows predictions of the mass (and thus impact energy) to be made for other objects that are determined to be of the same class from ground-based observations. Bulk density can also provide an indication of porosity. The accuracy goals are mass and dimensions to better than 1%, for bulk density to better than 5%.
- Gravity field: Spherical/elliptical harmonics of the gravity field, together with a shape model, allow the derivation of large-scale internal density variations using a mass distribution model. These variations may have a bearing on the dynamical behaviour of a similar object on Earth approach, entry and impact, as well as providing extra evidence as to the internal structure for aiding mitigation strategy development.
- Surface topography/morphology: The high-resolution surface information, in conjunction with compositional information, can be interpreted to give indications of the object’s internal structure. Surface features to examine include craters, grooves, fracture lines, regolith and boulders. From surface measurements a detailed shape model can be constructed to improve mass and hence bulk density determination accuracy.
- Composition: Provides spatial information to allow macroporosity to be estimated. Precise elemental/mineralogical composition can only be determined by a spacecraft

encounter. Variations in composition across the surface can be correlated with topographic/morphological features, adding to the information available for assessment of the object's subsurface properties/structure.

The SIMONE study included details of all aspects of the mission (spacecraft and systems design, mission plan, payload and operations) to demonstrate feasibility within the severe mass and cost constraints.

5.1.2 Payload

A model instrument payload was identified to satisfy the measurement requirements with "core", "high priority" and "optional" components. Instruments from past, current and near-future missions were assessed with respect to the SIMONE measurement requirements and payload capability, the need to minimise the cost of modifications or new development, and the availability of instruments within ESA. Trade-offs resulted in the selection of a baseline payload of core and high priority instruments (Table 5.1). The remaining optional instrument types, thermal-infrared spectrometer and magnetometer, fell outside the envisaged payload capacity of SIMONE and thus were not adopted for the baseline payload. The total mass of the 5 instruments amounts to 12.4 kg, including 0.7 kg margin. Several options for mass reduction, if required (albeit at the expense of some development and the resulting cost/risk) were identified.

Table 5.1. SIMONE payload

Experiment	*Measurement Objectives*	*Status & Source*	*Performance*	*Options for Mass Reduction and Estimated Benefit*
MIS Multispectral Imager Core	Size, shape, surface topography / morphology Contributes to measurement of bulk density, mineralogical composition, rotation state and binarity Mission operations	AMIE FM delivered by CSEM (Switzerland); filter wheel upgrade required but straightforward	5.3° x 5.3° fov 4 position filter wheel from visible to near IR Resolution 1m at 11 km	Share electronics box with that of NIS (0.3 kg) (b). Delete filters (NIS provides mineralogical composition but global heterogeneity search lost) (0.2 kg). Share optics with ALT and/or NIS (see below).
RSI Radio Science Instrument Core	Mass and possibly gravity field (J2) contributing to bulk density Mission operations	Conventional hardware, some requirements on mission operations	Range rate 0.03 mm s^{-1} over 100s Range 1-10 m	None identified. An onboard ultrastable oscillator is not required for the proposed measurement regime.
ALT Altimeter High Priority	Size, shape, surface topography / morphology Contribution to mass, gravity field (J2) and bulk density Mission operations	Clementine LIDAR FM delivered by LLNL, ~1994	<0.5 mrad beam divergence 0.057° fov	Delete HiRes detector (0.2-0.5 kg?) Share optics with MIS (0.3 kg).
XRS X-Ray Spectrometer High priority	Elemental composition	D-CIXS FM delivered by RAL (UK) and XSM FM delivered by Observatory, U. of Helsinki (Fin)	2 - 10° fov 0.5 to 10 keV energy <150 eV resolution	None identified
NIS Near IR spectrometer High Priority	Mineralogical composition	SIR FM delivered by MPIAe (Germany)	1.11 mrad fov 0.94 to 2.4 mm range 6 nm resolution	Share electronics box with that of MIS (see above). Share optics with MIS (0.3 kg?).

5.1.3 Spacecraft and mission design

Up to 5 SIMONE microsatellites were proposed within the budget envelope of an ESA Flexi-mission (as directed by the Invitation to Tender), allowing the corresponding number of different types of NEO to be studied. In order to achieve this target, a low-cost approach was required with the SIMONE microsatellites based around a single spacecraft system design, configuration and payload, significantly lowering recurring costs (Fig. 5.1). Piggyback launch opportunities on the Ariane Structure for Auxiliary Payloads (ASAP) on Ariane-5 would be exploited in order to minimise launch costs. The small size of the spacecraft dictated the use of electric propulsion. The study assumed an ion engine providing up to18 mN of thrust. The design is realisable through the use of emerging key technologies (low-mass, high-power solar arrays; gridded ion engine; high-density, high-efficiency electronics; compact sensors and actuators; lightweight spacecraft structures). The calculated power requirement is well within the 1020 W provided by the solar arrays.

The SIMONE study included a substantial design and subsystem accommodation study to demonstrate mission feasibility and readiness for a prompt project start with launches as early as 2007/8.

The total spacecraft mass is 120 kg, including 13.1 kg of available payload mass, 29.8 kg of propellant and 11 kg of margin.

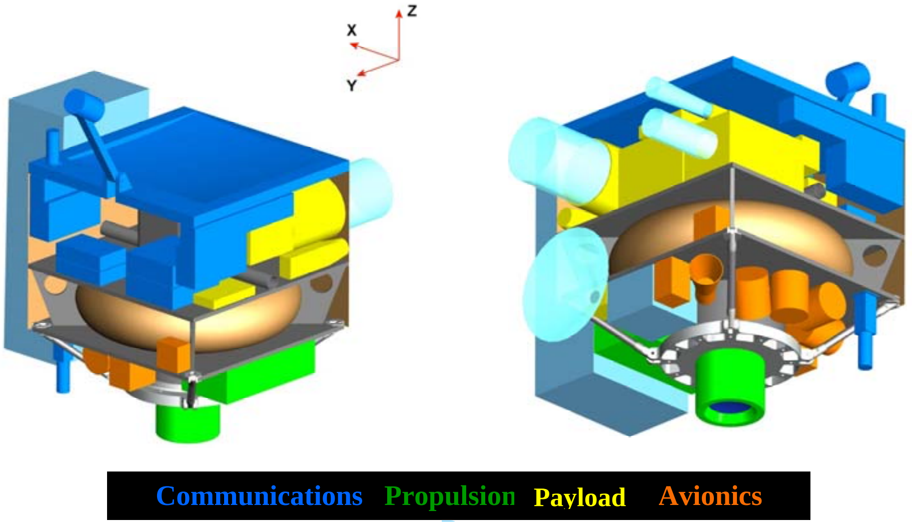


Fig. 5.1. SIMONE spacecraft (one solar-array wing and exterior panels removed for clarity).

The target selection process was applied to the known NEO population, based on ΔV, absolute magnitude and quality of orbit. Six targets were selected from the short list of 15 to satisfy the primary mission objective of characterising the physical/chemical properties of different types of NEO and detailed low-thrust trajectory optimisation was performed for each target. Fuel mass requirements and mission times (3 to 4.5 years) were well within the fuel mass and engine operation lifetimes. Only two launches would be required for all 5 missions to the selected targets, leading to potential reductions in launch costs for the SIMONE programme. Costs would be minimized by employing a mission control centre manned by a small team for 5 years to support all 5 flights, using a single ground segment, employing spacecraft autonomy to reduce the number of ground contacts, and re-use of existing software. The data storage and transmission requirements are quantified for the defined payload and operations strategy and are consistent with 1 Gb on-board memory and 1 pass per day. The calculated data rate at 2 AU is 1.4 kb s^{-1}.

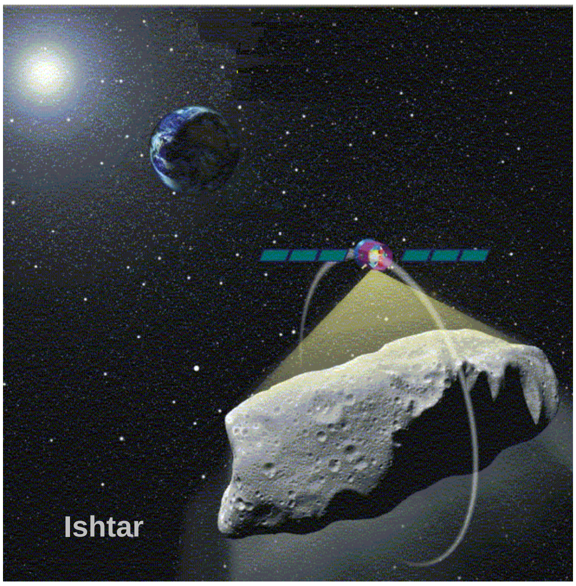
The mission phases are described in Table 5.2.

Table 5.2. SIMONE mission phases

#	*Mission Phase*	*Duration*	*Description*
1	Launch and Early Orbit Phase (LEOP)	~3-4 days	Deployment from an Ariane-5 launch vehicle into GTO, and attainment of a stable 3-axis attitude control mode following ejection from the Ariane upper stage
2	Check Out Phase	~2 weeks	Complete system functional tests during visibility periods with the ground station.
3	Parking Orbit Phase	~1 month to achieve Parking Orbit, then TBD months wait (depending upon time to optimum Escape Phase start)	Raising of the orbit above the radiation belts into a safe (i.e. low radiation dose) “parking orbit”. Wait for the Earth-Escape Phase to start.
4	Earth Escape Phase	~1 month	Expand the orbit using the on-board ion propulsion system. Lunar swing-by gravity-assist manoeuvre to change inclination and lower propellant consumption. Exceed Earth gravitational sphere of influence into a heliocentric orbit for the Rendezvous Phase.
5	Rendezvous Phase	~24-42 months (depending upon the NEO target orbit)	Combination of phased long-duration low thrust arcs and coast (no thrust) arcs in heliocentric orbit. Potential Earth swing-by gravity assist manoeuvre to lower propellant consumption. Follow an optimised transfer trajectory that ultimately matches the spacecraft’s orbit with that of the target NEO orbit. Trajectory correction manoeuvres are determined based upon radio navigation techniques. Acquisition of the target NEO using the multispectral imager payload for optical navigation relative to the target. Long-range approach to the target until reaching a stand-off distance of 300 to 1500 km ready for the Measurement Phase.
6	Measurement Phase	~4 months (depending upon science data acquisition plan)	Co-fly with the target NEO at ~100 km and take in-situ measurements with the payload instruments to determine size and shape, search for binary companion. Close ballistic swing-bys at ~1 m s^{-1} at a minimum distance of a few NEO radii to determine gravity field and mass, using the radio science instrument. “Imaging” swing-bys at ~10-km altitude to obtain high-resolution (1m) images of NEO surface features/composition, topography using stereo mapping and altimeter. Orbital phase only if stable orbit can be identified.

5.2. ISHTAR

5.2.1. Proposed mission objectives



The principal objective of the ISHTAR mission (Internal Structure High-resolution Tomography by Asteroid Rendezvous) is to characterise all the physical parameters of an asteroid that are key to assessing its impact hazard and to the development of effective mitigation strategies. The proposed small spacecraft, utilizing solar electric propulsion will rendezvous with (at least) two near Earth asteroids representing the most abundant taxonomic classes, which are expected to exhibit significantly different internal structures and compositions. The key instrument is a radar tomographer for probing the interior structure.

To determine how dangerous an asteroid is in case of impact, two parameters are crucial: the bulk mass, which determines the total energy of impact and the internal cohesion, which determines the likelihood of fragmentation in the atmosphere. To develop ways of deflecting or destroying an asteroid, again internal cohesion is a key parameter, because it determines the energy necessary to break it up into small fragments or the likelihood of fragmentation when trying to deflect it. Other important parameters for developing mitigation strategies are the asteroid surface and subsurface properties, such as depth of regolith, surface geology, etc. The main goal of ISHTAR is to determine those parameters that affect the internal cohesion of the asteroid. In particular, the radar tomographer will probe the internal structure, while the remaining payload will determine the mass, mass distribution, density and surface properties.

Due to the high diversity of physical characteristics within the near-Earth asteroid population, it is also considered a high priority for the mission to visit more than one asteroid within the same mission, so that our conclusions are not based simply on a sample of one. In particular, a large fraction of NEOs can be classified either as stony or carbonaceous, with significantly different density, composition and (presumably) internal structure. Therefore, the baseline ISHTAR mission is designed to visit two asteroids, one carbonaceous and one stony.

5.2.2. Payload

The key measurement objectives can be achieved with four instruments, centred around a radar tomographer, essential for probing the interior of the asteroid:

The *Radar Tomographer* uses low-frequency radio waves that can penetrate deep inside solid rock, down to depths of hundreds or even thousands of metres. The depth of penetration is determined by the radar frequency and by the composition of the asteroid. On ISHTAR, the radar tomographer is used in a synthetic-aperture reflection mode, where the signal reflected off the asteroid is measured from a “virtual” grid of locations around the object, allowing reconstruction of a 3D image of the asteroid interior (Fig. 5.2). The spatial resolution of this “SAR” radar is determined by the number of points in the grid and the frequency used. The ISHTAR radar tomographer, operating at two frequencies of 10 and 30 MHz, will be able to penetrate to depths of over 300m below the surface with spatial resolution of up to 10 m (in length, width and depth).

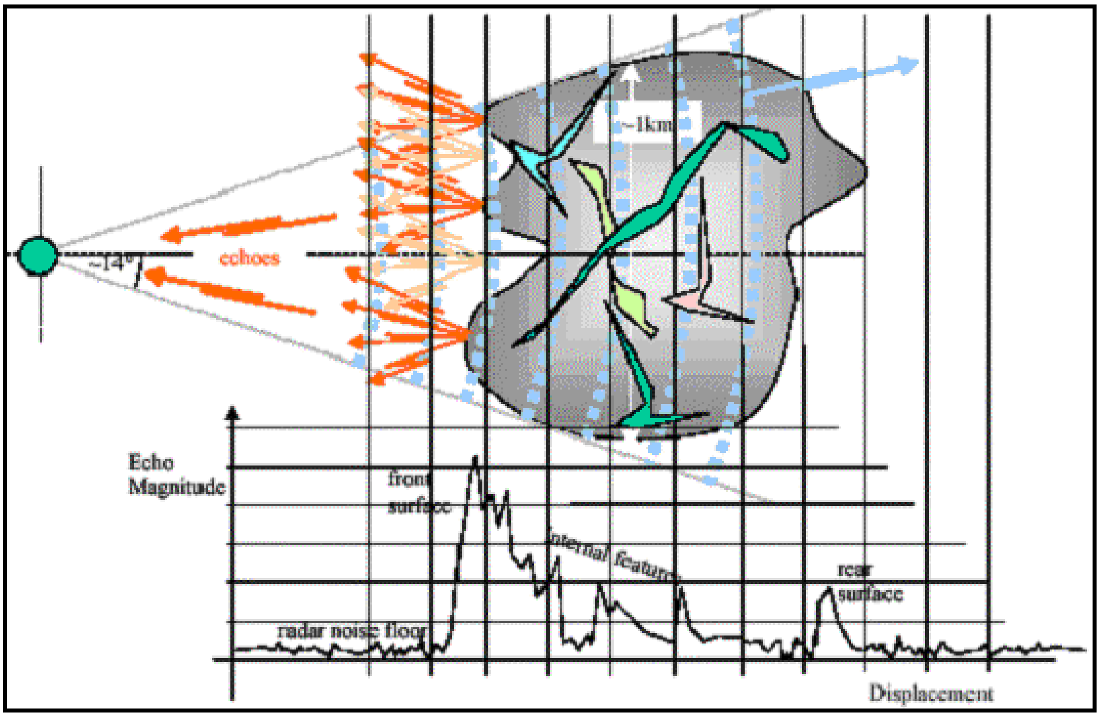


Fig. 5.2. Possible internal and external reflective features identified by the radar tomographer.

A *Radio Science Experiment* measures the asteroid gravity field (total mass and mass distribution), using the spacecraft communication systems to transmit and receive radio signals to/from Earth. The RSE will allow the location of the spacecraft with respect to the Earth to be determined within a few metres and enable the asteroid gravity field to be reconstructed from the deflections in the spacecraft trajectory. The measurement is based on a Doppler ranging technique that provides both the distance and the radial velocity of the spacecraft relative to the ground station. It is estimated that ISHTAR will be able to measure the mass of the asteroid to within 0.5% and also to detect an asymmetric mass distribution in the asteroid interior.

A *Multispectral Imager* measures the surface properties by means of a miniature CCD camera operating at visible wavelengths and provided with 3 broadband spectral filters to obtain colour information. The MI will map the surface of the asteroid to study its topology, geology and to measure the asteroid volume thus enabling the density to be determined to within 2% accuracy. The camera will also be able to measure the asteroid rotation and to search for surface regolith, resolving details of the order of 1.0 m.

An *IR Spectrometer* provides an infrared spectrum of the asteroid surface in the wavelength region between 1.0 µm and 2.5 µm, which can be used to determine the mineralogical composition of the asteroid surface.

5.2.3. Spacecraft and mission design

The ISHTAR spacecraft was designed to achieve its mission goals as a low-cost mission by keeping the spacecraft small, while minimizing the spacecraft complexity. Whenever possible the design uses existing state-of-the-art systems for the payload as well as the other spacecraft subsystems. In fact, all ISHTAR components are based on existing technology, with the exception of the radar tomographer, which is however still made of space-qualified components and it is an evolution of ground-based instrumentation.

Consistent with this low-cost approach, ISHTAR is baselined for an inexpensive Dnepr launcher and a launch mass of 408 kg, (about half the Dnepr launch capability) including 20% system margin. The total spacecraft dry mass is only 300 kg, with 25 kg of payload. A further mass saving of 20-30 kg is possible via the use of an Earth gravity assist manoeuvre in the mission design, which leads to significant propellant savings.

The spacecraft structure is based on an octagonal, wound monocoque structure in CFRP developed by Astrium Ltd, and capable of delivering high levels of robustness and stability at very low cost. The propulsion system utilizes 3 ion engines (1 redundant) providing up to 18 mN of thrust each. These engines require relatively large solar arrays providing 1600 W of power. This, however, has the indirect advantage that plenty of power is available for telecommunications and the science instruments once ISHTAR reaches its target asteroids.

The dual X and Ka band transmitter working through a 1.0-m diameter parabolic high gain antenna allows downloading of science data at rates of over 1 kb s^{-1} from distances of around 2.0 AU from Earth.

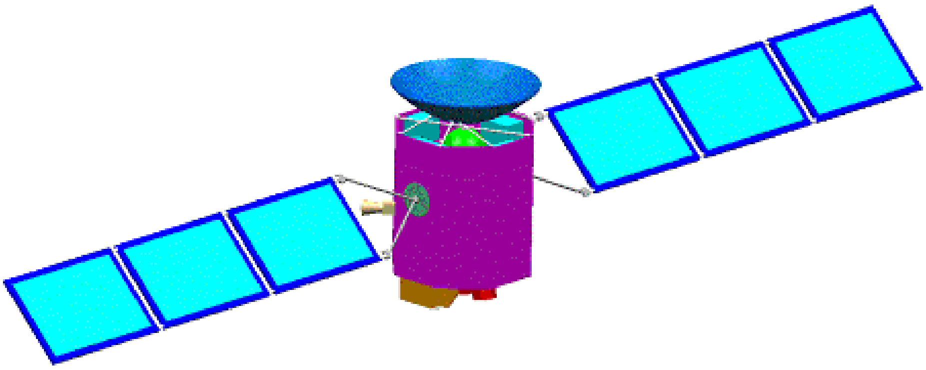


Fig. 5.3. Schematic view of the ISHTAR spacecraft.

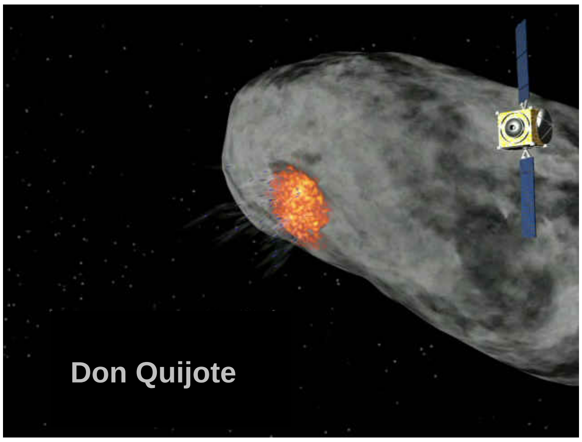
The ISHTAR mission was designed to be sufficiently flexible to be able to access a wide range of targets. A pair of asteroids was specially selected for their scientific interest and used to size the mission, but in its current design ISHTAR is actually capable of reaching over 30 different asteroid pairs, leaving great flexibility for both target selection and choice of launch date. A solar electric propulsion system was selected as the one providing the best performance for this type of mission.

In the baseline mission ISHTAR would launch in September 2011 with a Dnepr rocket to reach asteroid (4660) Nereus after 3 years of interplanetary cruise. After a stay at Nereus of nearly 15 months, during which extensive science measurements could be performed, ISHTAR would then transfer to asteroid (5797) Bivoj, which it would reach after another 2 years. After reaching Bivoj ISHTAR would repeat the same type of science measurement during a period of at least 3 months. The total mission duration is approximately 7 years.

While the radio science and imaging can be performed at relatively high altitudes from the asteroid surface (10 - 20 km or more), the radar tomographer requires smaller distances (the lower the altitude the better). To avoid excessive perturbation of the spacecraft orbit by the (potentially highly irregular) asteroid gravity field, orbital altitude will be limited to about 2 - 3 km, where stable orbits exist. The study shows that even for a highly elongated asteroid with a 2:1 aspect ratio, it is possible to find stable orbits at 3-km altitude that are also synchronous with the Sun, avoiding the spacecraft going into eclipse. The good ground coverage also required by the radar can be achieved by placing ISHTAR into a near-polar orbit.

5.3. Don Quijote

5.3.1. Proposed mission objectives



The objectives of the Don Quijote mission are two-fold: 1) to obtain knowledge of the physical nature of asteroids which has a very high scientific priority but is inaccessible to the current generation of asteroid missions and 2) to obtain knowledge which would be critical in case an asteroid on a collision course with the Earth had to be deflected. Don Quijote would allow the first detailed determination of the interior structure of 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.

To achieve these objectives the study foresees two spacecraft, to be launched on separate interplanetary trajectories. The science spacecraft, called Sancho, would arrive at the asteroid first and, after a rendezvous manoeuver, would observe and measure the target asteroid over a period of several months. The measurement techniques include active 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 retreats to a safe distance for the impact, returns to a close orbit to determine the changes in the asteroid's orbit and rotation state, as well as in its shape, and (optionally) to collect samples of the dust ejected during the crater formation.

The key measurements to be made by the science spacecraft Sancho are the following:

1. Determine the *asteroid internal structure*, especially the sizes of the main solid pieces, the average particle size and thickness of regolith and of the debris layers in the space left between the main pieces.
2. Constrain the *mechanical properties of the asteroid material*.
3. Determine the *orbital deflection of the asteroid* as a result of the impact, with an accuracy of about 10%.
4. Measure the *mass of the asteroid, the ratio of the moments of inertia* and the *low order harmonics of its gravity field*
5. Model the *asteroid shape* before and after the impact, to detect changes.
6. Measure the *asteroid rotation state* before and immediately after the impact with an accuracy of about 10%. Also detect, if possible, the *dissipation of the non-principal axis rotation after the impact* to determine the internal dissipation factor Q.
7. Determine the asteroid *large-scale mineralogical composition*. This is important in order to eventually establish correlations between observed spectral properties and internal structure.
8. Provide a *model for non-gravitational forces*, such as theYarkovsky effect, acting on the asteroid orbit and rotation. This requires a thermal model.

Calculations performed in the Don Quijote study for a reference asteroid of diameter 500 m and density 2.6 gm cm^{-3} give an impact-induced displacement of the asteroid of 1400 m over a period of 4 months. The rotation rate of the asteroid may be changed by some 0.5º per day. Such changes should be readily measurable via Sancho.

5.3.2. Payload

The following instrumentation has been deemed necessary to carry out the mission's objectives:

1. *Camera for high resolution imaging of the asteroid.* To obtain a full 3D model of the asteroid before and after the Hidalgo impact.
2. *Infrared mapping spectrometer, with low spatial resolution and high spectral resolution*. To measure the surface mineralogy. For the thermal model, it is necessary to make measurements in the thermal-infrared region too.
3. *Radio science payload.* This includes X- and K-band transponders and an accelerometer.
4. *Seismic science:*

   Penetrators. A network of at least four penetrators on the surface of the asteroid is planned. Beside the instruments the penetrators comprise the required subsystems for surface operation. Each penetrator carries a seismometer, an accelerometer, and a temperature sensor:
   - *Seismometers*. 3-axis short period seismometers are required. During the impact of Hidalgo the seismometers will reach saturation due to the high accelerations. Therefore, a set of *accelerometers* is foreseen, which are only operated during the impact of Hidalgo.
   - *Thermometer*. In order to support the measurements in the thermal infrared and the construction of the thermal model of the asteroid.

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

5.3.3. Spacecraft and mission design

The Don Quijote mission is divided into four dedicated mission elements. These are the orbiter Sancho that carries the camera, the infrared spectrometer, the penetrators/surface elements (P/SE), and the seismic sources (SS). The P/SE and the SS are considered as separate elements, since they perform the "landing" and surface operation on the asteroid, which is in itself a complex "sub-mission" of Don Quijote. The fourth element is Hidalgo, which serves solely as an impactor; its main task is to hit the asteroid with a given positional accuracy and relative velocity.

The Sancho spacecraft is a box shaped structure, which houses the different units necessary for the operation of the spacecraft and instruments. The dimensions of the structure for both spacecraft are 1.4 x 1.5 x 1.5 m. The launch tubes for the penetrators have a length of about 1.7 m and inner diameters of 10 cm for the seismic sources and 15 cm for the penetrators. The imager and the infrared spectrometer are mounted at the nadir side, outside the structure, and are placed on the radiator such that the infrared detectors are adequately cooled without a dedicated cooler.

For the deployment of the P/SE, launch mechanisms are mounted on one side of the spacecraft. Launch is by means of 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 SS are launched in the same way as the penetrators. At least four are planned 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 the most critical aspect of the Don Quijote mission.

Hidalgo will in principle be a rebuild of Sancho without the instruments and launch mechanisms for the penetrators and seismic sources. The Hidalgo spacecraft will therefore be simpler than Sancho and thus smaller in mass. A noticeable exception is the final targeting system which must be accurate and highly autonomous even in non-nominal situations.

One difficulty in the mission design is 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 ΔV (i.e. cost). The mission timeline example in Table 5.3 characterises the reference mission to the nominal target (10302) 1989 ML (estimated size = 500 m):

Table 5.3. Don Quijote reference mission.

Time (From launch)	Sancho Departure mass: 582.3 kg Injection mass: 394.0 kg	Hidalgo Departure mass: 388.2 kg Injection mass: 379.1 kg
launch	Both S/C are launched together on nearly identical trajectories that will encounter the Earth 6 months later (or multiple thereof).	
~ 180 d	Earth swing-by: sent to target asteroid.	Earth swing-by: sent to Venus.
~ 909 d (2.49 y)		Venus swing-by: sent to target asteroid.
~ 1478 d (4.05 y)	Arrival at target asteroid with $\Delta V = 1.089$ km s^{-1}. Global mapping from about 10 asteroid radii followed by close observations of specific areas from a distance of 1 asteroid radius. Perform seismic experiments.	
~ 1706 d (4.67 y)	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.	

5.4. Comparative assessment of performance

Compared to the observatory missions, the three rendezvous missions span a larger variety of goals and means to obtain them. SIMONE is a multi-spacecraft mission aimed at the characterisation of certain physical properties of NEAs of different types, ISHTAR is a single spacecraft mission aimed at more detailed characterisation of the physical parameters of a couple of asteroids, and Don Quijote is a double-spacecraft mission aimed at the detailed characterisation of a single asteroid, with the emphasis on mechanical contact for the purpose of deflection. In all cases valuable information would be returned for the development of mitigation strategies.

SIMONE is essentially a reconnaissance mission, and its objectives are the determination of bulk density, gravity field, surface topography/morphology, and composition of a number of target asteroids. SIMONE's information return would be less detailed than the other two missions, but it would cover a wider range of asteroid types. SIMONE could be considered an exploratory precursor mission to a detailed single-target study by a later rendezvous mission. It is clear that the scientific return from SIMONE would be very significant, especially for our understanding of the NEA population as a whole. On the other hand, the information gathered by SIMONE would be less directly applicable to the mitigation issue than that obtainable by the other two missions.

In terms of the variety of targets, ISHTAR would be limited to the two most abundant taxonomic classes represented among NEAs. However, ISHTAR should provide very detailed results, in particular information on the interior structure of the NEAs visited from radar tomography. The remaining payload would determine the mass distribution, density and surface properties. The smaller number of targets visited is compensated for by ISHTAR's potential to provide details of the interior structure of the targets, which makes ISHTAR more attractive from the mitigation point of view.

The third mission, Don Quijote, would target only one asteroid with two spacecraft having very different tasks. One spacecraft would make a large number of measurements of the dynamical and physical properties of the target and would release penetrators, each carrying a seismometer, accelerometer, and temperature sensor. Small explosive charges would create the seismic signals used to probe the internal structure of the target. The purpose of the second spacecraft would be to hit the asteroid with a given positional accuracy and high relative velocity. The first spacecraft, together with ground-based observatories, would then measure the resulting changes in the body's dynamical state (rotational and orbital motion). Such measurements would be directly relevant to the planning of any effective future deflection mission. An important goal of the Don Quijote concept is to demonstrate that the information necessary for the design of an effective mitigation mission can actually be gathered in this way. Such a mission could then be flown as a precursor mission to the actual mitigation mission. In the Panel's view, the Don Quijote concept is the most mitigation-relevant of the three rendezvous mission concepts examined.

The Panel's assessment of the rendezvous mission concepts based on the criteria established by the Panel, discussed in Section 3.3, are summarized in Table 5.4.

Table 5.4. Overview of the Panel's assessment of the rendezvous mission concepts.

Assessment Criteria (cf. Sect. 3)	**Don Quijote**	**ISHTAR**	**SIMONE**
1. Dimensions, shape, bulk density.	***	***	***
2. Internal structure and strength.	**	***	*
3. Surface structure, properties.	***	**	**
4. Unique value.	**Mitigation preparation**	Internal structure of 2 NEOs	Multiple NEO types

Note: The number of stars reflects relative performance potential in the respective assessment category.

5.5. Priorities

The aim of the rendezvous missions is to address the main limitation in our mitigation capabilities, i.e., lack of knowledge of the physical characteristics of the threatening object. In fact, this is possibly the most pressing item still to be addressed in the chain of actions from discovery to mitigation. The first links of the chain, discovery and orbit determination, are being addressed by ground-based surveys and follow-up; the task of monitoring known NEOs to enable potentially dangerous close approaches to be predicted is also satisfactorily taken care of. Beyond these steps little has been done in preparation for the mitigation of a dangerous object. To be more specific, we are not yet in a position to predict with any confidence the effects of a powerful transfer of energy to an asteroid.

Asteroid deflection methods that aim at an almost instantaneous change of the asteroid velocity, such as the use of an impactor or standoff nuclear explosion, depend critically on our ability to predict the mechanical response of the asteroid under extreme stress. Firstly, the critical energy threshold beyond which the asteroid would break into many pieces, severely complicating the mitigation problem, is heavily dependent on the internal mechanical properties of the object. Secondly, the amount of linear momentum transfer is currently not accurately predictable. The momentum transfer is determined primarily by the amount of ejected material and its velocity distribution, both of which are highly dependent on the mechanical properties of the asteroid's interior to a depth of around a few crater radii.

All three rendezvous missions would reveal the shape, mass, bulk density and the homogeneity of the internal structure, at least to some degree. However, only Don Quijote would physically interact with the surface and measure the quantities that are directly related to our ability to deflect a dangerous object. Therefore, the panel concludes that in the context of NEO impact risk assessment and mitigation preparation, the Don Quijote mission concept should be given priority.

6. Discussion of Overall Prioritisation

Having considered all of the mission concepts under their respective criteria and established priorities (Sections 4.5 and 5.5), the Panel needed to address the relative effectiveness of the observatory versus rendezvous concepts.

In the case of the observatory missions, the important question was how complete would our knowledge of the NEO population be at the end of the mission? There is a growing consensus among the impact hazard community that the ultimate requirement is to achieve near completeness down to ~50 m, i.e., the threshold size for significant ground damage, which would give us a realistic possibility of discovering the next significant impactor well before it hits. The Panel noted that the proposed missions did not offer completeness down to such small sizes and would be unlikely to detect the next significant impactor, although they would offer up to 80% completeness for sizes corresponding to approximately H (absolute magnitude) < 20.5 (down to ~300 m).

While a diameter of 300 m corresponds to a desirable and realistic medium-term goal for PHO discovery, as discussed in Section 2.1, the primary reason for the limit of H = 20.5 is the scale of the mission concepts, governed by the original cost guidelines imposed on the studies. As noted in Section 1.4, a space telescope with a mirror of 2-m diameter located in an inner-Earth orbit (at the orbit of Venus, for example) could probably discover 80% - 90% of the potentially hazardous NEOs down to about 100 m within 10 years. But such missions would cost far more than the concepts considered by the Panel. However, the studies considered by the Panel show that, provided the near-continuous slewing of large space telescopes is technically feasible, such a survey is possible.

A further aspect is competitiveness with on-going and planned ground-based NEO surveys. *Improvements in the performance of existing surveys and, in particular, plans for larger facilities, have led to a dramatic increase over the past few years in expectations for NEO discovery from the ground.* The current dominant NEO ground-based survey is Lincoln Laboratories' LINEAR programme, followed closely by the NEAT project. Realistic simulations of LINEAR's performance have shown that by the year 2014 (roughly the end of the proposed EUNEOS mission), even if no improvements were made in the survey by that time, LINEAR would probably achieve 55% completion for potentially hazardous NEOs with H < 20.5. Considering that other surveys are operating in parallel, the completion level of all systems might potentially reach 70% to the same MOID (Minimum Orbit Intersection Distance) and H.

Looking to the near future, Pan-STARRS is already under construction, with the first of the component telescopes due to become operational in 2006. Also currently under construction is the 4-m Discovery Channel Telescope due to begin operation around 2008. Both of these facilities will focus on the discovery and orbit determination of sub-km bodies. As these ground-based facilities should be operational before any of the space observatory missions considered here, the Panel concluded that obtaining 80-90% completeness for

H < 20.5 bodies could be achieved within the next decade without the space observatory missions. Even if, for some unknown reason, Pan-STARRS or similar facilities are unsuccessful, it is clear that a similar survey is quite feasible from the ground.

Turning to the rendezvous missions, the Panel recognised the continuing improvement in the fidelity and modelling of ground-based observations leading to improved shape and albedo models. However, it is clear that space missions have the potential to provide unique information on NEOs. Our current lack of precise knowledge of the physical characteristics of NEOs would be a critical limitation should a potential impactor be identified; given the accelerating pace of discovery from ground-based surveys, this becomes ever more likely. While astronomical observations can provide certain information, mainly on surface properties, there are many important parameters relevant to future mitigation experiments that will remain unknown without in-situ investigations.

Given the variety of objects already known, it is improbable that any rendezvous mission will investigate a NEO identical to the next impactor. However such missions allow us to define the techniques we would employ if such a body were discovered, in addition to providing ground-truth for comparison with our models based on theory and Earth-based observations.

Taking all these factors into account, the Panel unanimously agreed that the proposed rendezvous mission concepts were of significantly higher priority in terms of risk assessment and mitigation preparation than the observatory mission concepts.

In particular, the measurement of the coupling constant between kinetic impactors and NEO surfaces is feasible with current technology and the Panel believed that this would be the most important task that could be performed within the cost envelope. So far we have demonstrated the ability to discover NEOs, accurately predict their future orbits, and measure their physical properties via ground-based telescopes, space-based observatories and rendezvous missions. *At this time, the ability to change the orbit of a NEO has not yet been demonstrated, so a vital link in the chain from threat identification to threat mitigation is missing.* While the Deep Impact mission will impact a comet nucleus in 2005, the lack of a precise measurement of the change of orbit means that the momentum change will be poorly constrained. A rendezvous mission within the cost envelope of the missions considered in this report can provide this “missing link”.

It must be emphasised that the NEOMAP conclusions were governed by the need to address the impact hazard issue specifically, and the circumstances prevailing at the time this report was produced. For example, at some stage in the next decade or two, we expect that ~80-90% of H < 20.5 potentially hazardous NEOs will have been discovered and have orbits accurate enough for good impact risk calculations over the next 100 years. At that stage, a re-assessment of priorities might conclude that the remaining unknown risk from these objects dominates the calculated threat. As the undiscovered objects will naturally be located in orbits that hinder their detection from Earth, it might then be prudent to pursue an observatory mission such as those considered here. Alternatively, if the Panel had considered *purely scientific* criteria for NEO missions, the outcome may again have been different. For example, there is no doubt that the goals of studying the population of IEOs, and the detailed surface geology of different NEOs, are of high scientific priority.

7. NEOMAP Recommendations to ESA

It should be recalled that in the Panel's opinion the current most urgent tasks for NEO impact-risk assessment and hazardous-object mitigation are, in order of priority:

1. The discovery of potentially hazardous NEOs and determination of their orbits.
2. The exploration of the physical structure of NEOs for the benefit of defining potential mitigation strategies.

Increase in our knowledge of the nature of NEOs for purely scientific reasons was not amongst the criteria used by the Panel in its review of the six mission studies.

Of the three observatory missions reviewed, the Panel considers the EUNEOS (and Earthguard-1) NEO survey concept to be most compatible with the criteria and priorities established in this report. EUNEOS appears to be a feasible, efficient and largely self-reliant mission with the single aim of discovering potentially hazardous NEOs and establishing their orbits.

Of the three rendezvous missions reviewed, the Panel considers the Don Quijote concept to be most compatible with the criteria and priorities established in this report. Don Quijote has the potential to teach us a great deal, not only about the internal structure of a NEA, but also about how to mechanically interact with it. Don Quijote is thus the only mission that could provide a vital link in the chain from threat identification to threat mitigation. Considering possible participation from countries outside Europe, the Panel felt that the Don Quijote concept is compatible with current interest and developments elsewhere (cf. Sections 1.3, 1.5) and may readily attract the attention of potential partners.

The Panel has given very careful consideration to the latest information available on the currently operational and planned ground-based NEO survey systems. It was concluded that at the present time a space-based NEO discovery mission, within the scope of those considered here, is not the highest priority given the combined efforts of the various ground-based surveys likely to be productive over the coming decade. A reasonable approach may be to re-consider a space-based NEO observatory mission at a later stage, once the residual hazard from NEOs not accessible to the ground-based surveys has become better defined.

Therefore, of all six missions reviewed, the Panel recommends that ESA gives highest priority to the Don Quijote concept as the basis for its participation in NEO impact-risk assessment and reduction.

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