Spaceguard Integrated System for Potentially Hazardous Object Survey

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Executive Summary

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Introduction
This report summarises the results of the contract Spaceguard Integrated System for Potentially Hazardous Objects Survey (SISyPHOS) between ESOC and The Spaceguard Foundation.

Asteroids and Comets are classical subjects of scientific investigation by the astronomers’ community worldwide. In the most recent years, a wider attention has been focused on these minor bodies of our solar system, not only by the specialised scientific community, but also by the wider public to which mass media are targeted.

Two major events can be identified as the causes of such enlarged attention: the first is the correlation between the impacts of minor bodies on our planet and global catastrophes; the second is the evidence given to such type of cosmic events by the impact of the periodic comet Shoemaker-Levy 9 with the planet Jupiter in July 1994.

The resulting public debate, also stimulated by mass media (newspapers, TV), has been and is oscillating between the two extreme positions of catastrophism and underestimation of the problem, while the astronomers’ community is making a significant effort to put it in the frame of a correct scientific approach. This study report is aimed at contributing to such effort to produce a correct analysis of the various facets of the problem posed by the threat of impact of minor bodies of the solar system with our planet.

The study has been performed under a contract of the European Space Agency (ESA), which is particularly motivated by the identification of the possible contributions of space-based facilities to the considered problem. This aspect is, therefore, given a special attention. A proper identification of the tasks to be assigned to space-based means can only be done if these means are considered as elements of an overall monitoring network, thus complementing and integrating, with their specifically assigned missions, the tasks accomplished by ground-based infrastructures (astronomical observatories, radar installations, etc.). This approach to the problem is therefore in perfect agreement with the line indicated both by the Council of Europe (Resolution 1080, 1996, "on the detection of asteroids and comets potentially dangerous to humankind") and by the Committee for the Peaceful Uses of Outer Space (COPUOS) of the United Nations (Report of the Third United Nations Conference on the Evaluation and Peaceful Uses of Outer Space, A/CONF.184/6, Vienna July 1999, approved by the UN General Assembly, December 1999).

The contract aims at studying and designing an observational system for detection, tracking and physical characterisation of Near-Earth Objects (NEO). Similar studies have already been performed in the past but have never taken into consideration the possible integration between a ground network of telescopes and a satellite system, integration to be achieved through an extended use of connecting centres mainly devoted to data acquisition, analysis and dissemination. In this report we will propose improvements of the existing observational network for detection and tracking. Moreover, we describe the serious problems affecting the current capability to efficiently carry out the observational work needed for physical characterisation; also, the existence of objects hardly observable by means of ground-based facilities is taken into account. The possible implementation of a space-based segment aimed at accomplishing the above tasks is carefully analysed in the present context.

It is important to define what are the objects considered in this study. Several analyses have shown that the major danger to the human society is represented by possible impacts of objects with diameters of 1 km and...
larger. However, it is clear that even a minor impact could have serious consequences, whose evaluation is not only a task for scientists.

The 1908 Tunguska event, which devastated more than 2,000 km$^2$ of Siberian taiga, was a 10 megaton explosion. Such an occurrence would have only regional, and not global consequences, but these would nonetheless affect deeply all human infrastructures (communications, power transport, sanitary systems), would a similar event take place in a densely populated region such as Europe. The important social issues related to even the minor impacts of the Tunguska type have never been studied in detail.

The impact issue, therefore, needs to be studied at different levels. This study aimed at securing a good understanding of the number, location, dynamics and physical nature of NEOs. It uses scientific methods and instrumentation. The study addresses an essential factor, but it does not solve the problem entirely.

The SISyPHOS Study

The SISyPHOS study has been organised in three major sections with the following purposes:

- To assess the current status of the research and detection capabilities of near-Earth objects and to identify the drawbacks and weak aspects of the current efforts, with particular attention to the benefits of the inclusion of a space segment,
- To design an integrated, international system including ground-based facilities, space-based observatories and ground centres for the collection, analysis and distribution of data,
- To identify possible options for the space segment and to perform a preliminary design of a suitable mission able to cope with the most urgent necessities.

The assessment of the current status of research has considered three types of assets: 1) stations essentially devoted to the discovery of unknown objects, 2) observatories carrying out follow-up astrometric observations needed to refine the knowledge of the objects’ orbital paths, 3) methods and instrumentation used for physical characterisation of NEOs (size, albedo, mass, composition). This part of the study has shown a great imbalance among these different tasks. While discovery is indeed proceeding at a rather high rate, especially for larger objects, the follow-up activity suffers from the lack of suitable instrumentation and lack of an efficient overall co-ordination. Although the recent set-up of the Spaceguard Central Node in 1999 has alleviated the last problem, the unavailability of suitable instruments still causes the loss of a very high percentage (around 30%) of newly discovered NEOs. These objects will certainly be rediscovered in the future, but it is clear that the overall efficiency of the system is far from being optimal.

More serious is the imbalance between visual and astrometric observations (necessary for discovery and follow-up) and physical studies. The latter are typically done using large telescopes (in the 2-4 m class) equipped with focal plane instruments working mainly in the infrared domain of the spectrum. However, the presence of the atmosphere limits strongly the efficiency of such observations. Moreover, the total observing time available for NEO observations at these telescopes is very limited, because of the competition with many other astronomical and astrophysical projects. On the other hand, the establishment of one or more dedicated facilities is very expensive, and the anticipated benefits for the global system not entirely satisfactory.

The second part of the study has focussed on the identification of requirements for an efficient global network, in terms of number, location and characteristics of the needed instrumentation and centres. Investigations have been defined, which would very much benefit from the presence of one or more space-based observatories. We have not entered the domain of in-situ measurements, which is obviously the most efficient method for understanding the physics of NEOs, and have limited our analysis to the advantages of transferring to space the usual ground-based observing techniques. We have shown clearly that there are at least two types of research that can better, or exclusively, be conducted from space:

- The characterisation of physical properties of NEOs using radiometric techniques (observations in the visible, near-IR and thermal IR), and
- The discovery and physical characterisation of objects with orbits mostly or completely interior to the Earth’s orbit (Atens and Inner Earth Objects, IEO).

Therefore, the third part of the present study has dealt with the design of a space system able to perform, at a reasonable cost, these two types of investigations. The study considers various options for such a system, including a satellite located in a circular, sun-synchronous orbit, in a Molniya type orbit and in the L2 Lagrangean point of the sun-earth system. Owing to the necessity to work in the thermal infrared (6-11 $\mu$m), the system needs a careful study of the thermal control, which is certainly the most demanding requirement.
Nonetheless, we have shown that a space mission of this type is possible and would greatly improve our understanding of the physical nature of NEOs. A good knowledge of this nature is very important in order to study counter-measures to be adopted, should an object be found on a collision course with our planet.

Discovery, follow-up, and physical characterisation

**Discovery.** The type of astronomical work needed to discover Near-Earth Objects is based on the normal techniques used to measure the position of celestial objects on the sky (astrometry). However, the discovery of NEOs - contrary to that of star clusters and galaxies - poses two major obstacles to observers, that require an ad hoc strategy of research and the implementation of appropriate hardware and software tools.

NEOs, like all objects in the solar system, move relatively fast with respect to the Earth and are often sufficiently close to our planet to make relevant the effect of parallax. Therefore, the frames taken to detect new objects must have short exposure times in order to avoid the formation of trails. However, the exposure time must be long enough to allow the observation of objects up to a given limiting magnitude. The most important requirement for a discovery program is to observe repeatedly as much of the sky as possible, so that the probability of missing an object over repeated scans is minimised. Several techniques have been developed in the last years for this purpose; their common characteristic is the availability of telescopes with a large field of view, equipped with fast read-out CCDs and the use of automatic (or semi-automatic) detection programs.

Besides the requirements imposed on the instrumentation and on the detection software, another important issue that any discovery program must address is the adopted search strategy. Again, there are various possible solutions able to maximise the results, one of the most important criteria being the trade-off between covered area and magnitude depth.

Once an image, or a sequence of images, has been taken and the objects' positions measured, it is necessary to identify the objects that have been observed. A typical search does in fact image a multitude of objects of all kinds, the majority of which are main belt asteroids. In many cases these objects have already been observed in the past; it is therefore necessary to check whether the detected objects are true new discoveries or represent re-discoveries of already known asteroids.

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Table 1 - NEO discovery summary until December 1999.

How many NEOs have been discovered up to now? Table 1 shows the statistics for all NEOs discovered by the major search programs until December 1999. The average rate of discovery of large (> 1 km) NEOs for 1998 was 54 per year, or almost 5 per month. The value for 1999 is of the order of 70 objects per year.

However, notwithstanding the rather good results achieved up to now, one should consider that about 30% of the newly discovered NEOs are lost because of insufficient follow-up observations. This makes the above evaluation of the situation rather optimistic.

**The problem of Aten objects.** Almost all the major discovery programs are sampling the sky close to the opposition point, with the noticeable exceptions of LINEAR and LONEOS. This strategy optimises the search for objects with semi-major axes larger than 1 AU, because these NEOs spend most of their time outside the
Earth's orbit, and may be observed in the best possible conditions near opposition. However, this strategy introduces a strong bias in favour of low-inclination objects of the types Apollo ($a > 1$, $q < 1.017$, $a$ being the semi-major axis and $q$ the perihelion distance, in AU) and Amor ($1.3 > q > 1.017$). Atens, on the contrary, have $a < 1$ and $Q > 0.987$ ($Q$ is the aphelion distance); if their orbits are slightly crossing the Earth's, it may happen that their positions in the sky are high on the ecliptic plane, for perspective reasons, and their times of residence outside the Earth's orbit can be very short. For these reasons it is probable that the Aten population is undersampled in our databases. In addition, it is very probable that another population of objects has never been observed. Theoretical investigations, coupled to numerical integration of NEO orbits over extended periods of time, indicate that Aten objects may evolve into orbits completely inside that of the Earth (i.e., with $Q < 0.987$). These objects, sometimes called **IEOs** (Interior to Earth's Orbit), have never been detected, for the simple fact that they are never located at opposition.

**Follow-up.** Once an object is discovered, a preliminary orbit is computed, provided that there are enough astrometric measurements. In principle three observations are sufficient but, due to the inevitable measurement errors, it is required that the object be observed at least on two consecutive nights, three times per night. This requirement poses a problem for the discovery programs: they actually produce a great number of single-night asteroid observations, mainly of main-belt objects. These observations are transmitted to the Minor Planet Center (the IAU clearing house for asteroid observations). They constitute a large set of measurements that are useless to compute new orbits, but can be used to link previously observed objects, or might be used in the future for the same purpose. These observations are called "single-nights".

The preliminary orbit is in general very uncertain and allows the computation of an ephemeris only for a very limited period of time. If no further observations are done within that time period, the object is generally lost, which is the case for a significant fraction of objects. It is therefore important that the community of observers be informed, in a very short time, about the objects that need further observations. This kind of low-level coordination is, at present, provided by the Minor Planet Center that, immediately after the computation of a preliminary orbit, includes all new NEO discoveries in a special web page called the "NEO Confirmation Page" ([http://cfa-www.harvard.edu/cfa/ps/NEO/ToConfirm.html](http://cfa-www.harvard.edu/cfa/ps/NEO/ToConfirm.html)). Since May 1999, a higher-level coordination is provided by the Spaceguard Central Node of The Spaceguard Foundation, in the form of "Priority lists" of objects in need of follow-up observations.

The follow-up activity differs substantially from the discovery activity. The sources of these differences may be summarised as follows:

- knowledge of the position in the sky
- visual magnitude of the object
- requirements for the instrument's FOV and performance.

Contrary to the discovery observations of new objects, the follow-up observations will rely on the knowledge, even if poor, of the position of the target in the sky. It is therefore possible in principle to image the object with a single exposure. However, depending upon the degree of uncertainty of the orbit, more than one frame may be needed in order to be confident to find the target. A strong constraint to this possibility is given by the visual magnitude of the object: if it is receding from Earth it becomes fainter, and may escape detection simply because a specific instrument is not powerful enough to image it. This occurrence represents the main limitation to follow-up observations, that are usually performed using small aperture telescopes.

The size of the instrument’s FOV may therefore constitute a problem. The area of sky in which an object is supposed to be located may be quite large, which might force observing teams to image a great number of fields in order to be sure to observe it. This, in turn, may be difficult, or impossible, depending on the available observing time, on the character of the team (professional, amateurial), on the weather conditions, on the visibility at the site.

The above considerations translate into a simple fact: the observing time needed to make follow-up of a single object is much larger than the observing time needed to discover it. This means that the number of observing stations must also be much larger, or the discovered objects will not receive the needed coverage. But there is another important aspect to take into consideration: not only the follow-up teams must be numerous, they must also be well co-ordinated. This is a crucial point because in many cases a poor coverage, resulting in the loss of the objects, depends basically upon the lack of interest that follows initial observations. It is a common fact that many teams monitor the NEO Confirmation Page and make follow-up for the most recent objects; after a few weeks, however, these objects are abandoned in favour of more recent discoveries.
Physics characterisation. The physical characterisation of NEOs requires reliable estimates of mass, density, size, mineralogical composition, spin rate, surface texture and internal structure.

The most relevant parameters, from the point of view of the consequences of a possible impact with the Earth, are the mass, the density and the overall mineralogical composition. Coupled with determinations of the encounter velocity, computed on the basis of a precise knowledge of the orbit, the above parameters allow to compute the kinetic energy of the body and the plausible resistance of the object to the friction experienced during the interaction with the Earth's atmosphere. The composition and internal structure of the projectile are important when the impact energy is relatively low (up to values of the order of 100-1000 MT; 1 MT is equal to 2.38 x 10^10 Joules, corresponding to the amount of energy released by the explosion of 10^6 tons of trinitrotoluene). The reason is that the ablation processes caused by the Earth's atmosphere can be very different depending on the composition and structure of the impactor. At very high impact energies, however, the whole impact process is essentially determined by the kinetic energy of the projectile.

Not all the above parameters are directly measurable. Asteroid masses, for example, could be derived through the measurement of mutual gravitational perturbations in case of close encounters but, in practice, the required astrometric accuracy is currently beyond the capability of available instruments. Moreover, mutual close encounters between asteroids do not occur with the frequency required to derive masses of any given object in a short time. For these reasons, the determination of mass must be accomplished in an indirect way, through measurements of size, shape and surface mineralogical composition, the latter being needed in order to get some reasonable estimate of the density.

Also in the case of size we face problems due to the smallness of most asteroids, precluding in practice the possibility to measure directly NEO sizes by means of pure optical imaging. In some cases the problem can be overcome by using radar techniques, which are able to provide a huge amount of information including sizes and shapes but are limited to objects making close approaches to the Earth (due to the faintness of radar echoes being inversely proportional to the fourth power of distance). Reliable indirect size determination techniques do exist, however, based essentially on simultaneous measurement of scattered light at visible wavelengths, and IR thermal emission.

Several observational techniques exist, and can be usefully applied, to get at least some reasonable estimates of the most crucial parameters characterising asteroid physical properties. Some of these techniques, however, can hardly be applied from ground-based observing stations, due to the absorption of incoming electromagnetic radiation by the Earth's atmosphere at critical wavelengths, mostly in the IR. Moreover, another major problem in this field is the limited availability of dedicated instruments (telescopes and focal plane instrumentation) and the currently insufficient allocation of human resources (teams devoted to observation and data reduction).

Data collection centres. Discovery data are communicated to the IAU Minor Planet Center, that computes preliminary orbits and manages the first phase of the data handling of a newly discovered NEO, by putting the object in the NEO Confirmation Page on the WWW, where observers can get preliminary ephemerides. When the object is confirmed by other observations, the MPC issues a Minor Planet Electronic Circular (MPEC), announcing the discovery. The MPC issues a daily MPEC containing all new observations and orbit computations done at the MPC for NEOs. On a monthly basis, the MPC issues a batch of Minor Planets Circulars, containing all observations and orbit computations of all asteroids.

Next come into play the centres doing observational planning and/or orbit computations: the Spaceguard Central Node of The Spaceguard Foundation, the Near-Earth Objects Dynamic Site at the University of Pisa, the Asteroid Observing Services at Lowell Observatory, the NEO Program Office centre of JPL and the European Asteroid Research Node at DLR-Berlin.

Among these centres the Spaceguard Central Node is of particular importance for several reasons: 1) it belongs to The Spaceguard Foundation, officially recognised by the IAU and by international organisations like the Council of Europe and the United Nations as the most appropriate entity able to provide a global, international co-ordination; 2) it has been set up, thanks to the contribution by ESA with a previous contract ("Study of a Global Network for Research on Near-Earth Objects", 1999), with the purpose to collect data on observing facilities and observational targets, and therefore to suggest the most appropriate observing strategies to the best suited observers. The Spaceguard Central Node is located in Rome, Italy, and can be reached at the address: http://spaceguard.ias.rm.cnr.it.

Importance of a space segment

The conclusion about the need for a dedicated space segment for NEO studies follows logically from the analysis of the current situation and the assessment of the problems that cannot find a satisfactory solution through ground-based observing facilities.
In particular, two major drawbacks affect the ongoing observational activities:

1) Physical characterisation is poorly and not efficiently carried out, due to the lack of dedicated instruments, related to the need of observing in the mid-IR in order to derive the sizes of the objects.

2) The existence of classes of objects, Atens and IEOs, that can hardly or not efficiently be monitored by ground-based observatories, due to the fact that these objects spend most of the time at small solar elongation.

The fact that a space observatory can efficiently carry out at the same time physical characterisation observations and survey of the sky in the region of small heliocentric elongations (40-50°) makes the development of a space segment very advisable in terms of both scientific potential and cost effectiveness.

The required payload is fairly simple, consisting, in its simplest configuration, of a modest-aperture telescope (60-80 cm in diameter) equipped with two sensors, one for visible wavelengths, and the other for thermal IR wavelengths up to 11 microns. Both sensors should allow the observations through a number of standard filters suitably covering the whole visible and near-IR wavelength spectral range. This instrument would be an invaluable complement of the current and future ground-based observational activity, since it would allow to obtain size and albedo determinations, using the radiometric technique, as well as multiband spectrophotometry, needed to derive the overall surface mineralogical composition of the targets. Moreover, the satellite would be able to carry out a systematic survey of the region of the sky between 40 and 50 degrees from the Sun, and should be able to discover nearly all the existing Atens larger than 1 km, and a large fraction of Atens and IEOs larger than 500 m, for a 5 years mission operational lifetime. Even a two-years mission would be able to discover 70-80% of the Atens and 40-50% of the IEOs larger than 500 m, a remarkable result when compared with the limited efficiency of ground-based instruments, even using state-of-the-art technology (see figure 1).

From the point of view of technical aspects, the most critical problem is the working temperature of the sensors, optics and baffle. These temperatures are dictated by the presence of a mid-IR sensor, and by the goal of having the instrument sensitivity limited only by the zodiacal background emission (something which is not possible with ground-based telescopes, due to the presence of the Earth's atmosphere). Moreover, the need of observing for a fraction up to one third of the operational time at solar elongation angles of the order of 40 degrees, introduces some complications that affect the overall thermal design of the instrument, and have strong implications for the choice of the most suitable orbit. Among the different possible options, the most promising one is a Lissajous orbit around the Lagrangean L2 point of the Sun-Earth system. A satellite near L2 is largely free from the thermal input of the Earth and the Moon, and should be able, when properly designed and effectively shielded by the thermal emission of the Sun, to achieve the required optics and baffle temperature by means of passive cooling by radiation. The sensor working temperature could be kept constant by means of an active cryocooler without any special problem, provided that the radiation from the

![Fig. 1 - Completeness of Aten discoveries as a function of limiting IR magnitude at 8.5 μm (from Tedesco and Muinonen, 2000, work in progress).](image)
most intense thermal sources, the Sun and the Earth-Moon, are properly shielded. All this requires also the choice of state-of-the-art IR arrays, based on Hg: Cd: Te.

Although a detailed thermal study of the whole spacecraft is needed to confirm these preliminary analyses, it seems that the overall mass will not exceed 600 kg.

The proposed payload would be an excellent instrument for NEO observations. Working in the mid-IR means that the efficiency is not strongly albedo-biased, as in the case of visible observations. Moreover, solar system bodies can be easily discriminated with respect to stellar objects on the basis of spectral emission (NEOs being typically 10 magnitudes brighter at 10 microns than at visible wavelengths). This means that observations could be efficiently performed also at small galactic latitudes and close to the galactic centre, where the field of view is dominated by huge numbers of stars at visible wavelengths.

On the basis of the above considerations, it is a firm and solid conclusion of the present study, that a space-based segment is strongly needed for complementing the ongoing ground-based observations. Any effort should be done in order to develop and put into operations a satellite specifically devoted to NEO physical characterisation and Aten/IEO search and orbital follow-up.

The Spaceguard Integrated System

It is possible to define an optimal configuration of the NEO discovery, tracking and analysis system (that is usually called the Spaceguard System). Such a system should be composed by three major elements:

1. A **Ground-based observational system**, including all observation stations for discovery, follow-up and physical studies
2. A **Space-based observational system**, devoted to physical characterisation and discovery and tracking of peculiar objects
3. A **Ground Network**, composed by the data collecting and analysis centres

The primary purpose of the ground subsystem will be to perform, as it partially does now, a continuous survey of the sky in search for NEOs and, simultaneously, to perform the needed follow-up. However, there are investigations that cannot be done from ground, or that would be much better done from space. It is therefore important to identify which observations might constitute the specific duty of a space subsystem. The current data collecting centres should, in this view, not only collect measurements, compute orbits, co-ordinate the activity and make predictions, but also integrate the data coming from the space segment with those obtained from ground. This is a major task that will require an ad hoc centre, possibly to be co-located with one of the existing ones.

**Ground System.** The experience accumulated in the past ten years allows a better definition of the requirements for the ground-based observations for discovery and follow-up in terms of size, location, and technical parameters of the instruments. A non-exhaustive list is provided here.

- Discovery instruments should have at least 1m aperture. There should be at least two such instruments in each hemisphere, well separated in longitude, plus possible back-up instruments.
- The FOV of these instruments should be of several square degrees and paved with fast read-out CCDs.
- The discovery sites should have large storage capabilities in order to retain all frames taken during the sky survey. These images should, after a first processing for detecting new objects, be transferred to an ad hoc data centre for further inspection and for documentation useful for non-NEO studies.
- The discovery centres should be sufficiently co-ordinated, in order not to duplicate efforts.
- Follow-up instruments may be of any class, but at least two telescopes in the 2m range are needed for follow-up of faint objects, one in each hemisphere. Moreover, sufficient observing time should be allocated at larger instruments (in the 4m class) for follow-up of very faint objects, when the necessity arises.
- More professional centres should be involved in follow-up observations.
- The follow-up centres must be efficiently co-ordinated at a high level, including planning of observations, recovery strategies, sharing of schedules, joint campaigns.
- All observing centres must be financially supported in order to be able to accomplish their task in a continuous fashion.
The key requirements and concepts for the instrumentation for ground-based NEO physical characterisation can be summarised as follows:

- Due to the limitations of radar techniques, which cannot guarantee even in the near future a sufficient observing rate, ground-based NEO characterisation should be based mostly on optical telescopes.

- Size determinations require radiometric techniques. This implies that observations must be performed at thermal IR wavelengths, around 6-10 \( \mu m \). At the same time, radiometry requires also a simultaneous measurement of the incoming flux at visible wavelengths.

- Telescopes working at thermal IR wavelengths must be specifically designed in order to limit to the minimum thermal contamination by the telescope itself.

- NEOs are bright at thermal IR wavelengths. They are typically 10 magnitudes brighter than at visible wavelengths. This means that radiometry is not particularly demanding in terms of telescope size, and in general the most important issue is to reduce the operating temperature, more than the aperture size of the telescope. However, the need of observing simultaneously the objects in the V band, where objects 1 km in size have magnitudes around 20, implies that telescopes of the 2m class are generally needed.

- Ground-based NEO physical characterisation would require the construction of dedicated telescopes able to operate both at visible and thermal IR wavelengths. This is technically and logistically challenging. Moreover, one such instrument would not be in general sufficient, due to the need of covering the whole celestial sphere.

- Surface mineralogical composition of NEOs can be obtained by means of visible spectrophotometry and/or spectroscopy. The wavelength coverage should ideally extend up to near-IR wavelengths, around 2-3 \( \mu m \). This is hardly achievable in practice using the available telescopes. Even working at a maximum wavelength of 1 \( \mu m \), there is currently not one telescope which could work full time for this purpose. For these reasons, the same instruments to be developed to do radiometric observations for size and albedo determination (see above), should conceivably perform also the spectrophotometric task.

- Any ground-based telescope will have difficulties to observe objects like Atens, which are not generally visible at large solar elongation angles.

**Space System.** The concept for a space-based system for NEO monitoring is based on the fact that some observational data are crucially important from the scientific viewpoint, but they cannot be obtained at a reasonable rate and/or at needed epoch using ground-based instruments.

From this point of view, a space-based system is fully conceivable for NEO monitoring purposes, and should be devoted to accomplish two main tasks:

- **Size and albedo determination using radiometric techniques**

- **Monitoring of the region at small solar elongations, where the objects having an orbital semi-major axis smaller than 1 AU are mostly or uniquely observable**

Therefore satellite–based sensors can make a significant contribution, providing data for:

**Physical characterisation of the detected objects:** from the two independent measurements of the visible and infrared emissions of the body, it is possible to derive the size and the albedo;

**Mineralogical composition of the detected objects:** visible and IR spectroscopy from space allow to identify the molecular compounds of the surface of the body, thus inferring the mass, and carrying on insight in physical characteristics which are difficult to study from ground;

**Discovery and follow-up of NEOs and especially of IEOs,** whose discovery is considered of the utmost importance as these objects are almost impossible to see from ground, but they are thought to be quite numerous and potentially dangerous;

**Higher duty cycles,** as the satellite would be fully dedicated to NEO search and characterisation and would not be affected by the night/day cycle.

From the specific point of view of the discovery of potential impactors, and consequently of the basic information needed for any development of defence strategies, a satellite would be extremely useful for:

- **Better determining the number of existing dangerous objects, especially the potentially very dangerous, but totally unknown IEOs,**

- **Evaluating the size of the potential impactors:** the size data is crucial to the evaluation of the mass, which in turn is a key parameter in determining the consequences of a possible impact with the Earth;
• Getting information about their structure and composition. This is essential to the computation of its density that is a key parameter in the evaluation of the impact outcomes: released energy depends on the mass of the impactor.

A well co-ordinated network including mission control, spacecraft management and data analysis centre will be a stable, viable, really global, integrated structure with both a space and a ground centre and will be able to meet the scientific, protection, and security requirements which are asked for from the scientific community.

The most important aspect in this respect is the coordination between spacecraft, ground control centre of the spacecraft, and Spaceguard ground network: depending on the observation carried out, data must be collected, processed and delivered to the proper node.

**Data centres.** The global picture that results from the above considerations is that of a distributed service including several centres, each one devoted to a particular aspect of the data processing work. Even if it is not possible at the moment to design a precise structure of this extended service (because of the unavoidable uncertainties in the structure of the whole system) the previous discussion allows drawing a list of major features that must be implemented anyway, the most important ones being:

1. Identification of the centres “validated” by the IAU for NEO data analysis
2. Interconnection of these centres, by sharing databases and analysis techniques
3. Continuous feedback to/from the observers in order to provide the best service
4. Coordination of ground-based and space-based observations
5. Management of data coming from the space subsystem

The set up of such a distributed network will require the concurrence of many different institutions. A prominent role will be that of the IAU, especially in revising the structure of the present MPC. The Spaceguard Foundation will contribute with the SCN and with institutional contacts with other organisations. Such contacts have already been established with the European Union and the European Southern Observatory and may lead, in the end, to the set up of a European Network including observatories, data centres and other scientific institutions. This Network will be eventually formally incorporated in the Spaceguard System.

**Outlook**

The work done so far has led to a refinement and update of the design of the so-called Spaceguard System. We now have a clear picture of the needs for conducting an efficient, medium-to-long-term monitoring of near-Earth objects. However, such a system cannot be put in place by a single country. The question therefore arises what would be a suitable international framework for the continuation of these studies and the implementation of a system like the one depicted in this Report.

There are several points, in this respect, that will need a more careful and extensive study. Some of these points have already been addressed by the UN-COPUOS document mentioned in the Introduction, and include:

• The creation of regional Spaceguard Centres to be co-ordinated by The Spaceguard Foundation,
• The distribution of observing centres on the Earth surface,
• The education and training of young scientists to be employed in the system operations,
• The consideration of "developing a common strategy that would include future activities related to near-Earth objects" (COPUOS Report, cit., p. 3).

The last of the above items is of particular importance, especially in view of the elaboration of international common projects involving several national and international agencies, as well as the International Astronomical Union. The present study may represent a valuable basis for the elaboration of such projects.

**Conclusions**

This study has produced the design of a global system for discovery, tracking and physical characterisation of near-Earth objects. This system includes ground and space observatories, connected through a number of centres for data collection, analysis and dissemination. Such a *Spaceguard Integrated System* ought to be established through an extended and well co-ordinated collaboration among different countries, with the
participation of scientific centres, space agencies and other professional agencies working in the domain of astronomy and protection of the environment.

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