Comet/Asteroid Protection System: Concept Study Executive Summary[1]

DANIEL D. MAZANEK
NASA Langley Research Center

RASC Charter and CAPS Vision

The charter of the Revolutionary Aerospace Systems Concepts (RASC) activity is to develop and assess revolutionary aerospace system concepts and architectures and to identify the requirements for critical technologies to enable the realization of these concepts 25 or more years from now. These concepts and architectures serve to identify technology investment areas that the National Aeronautics and Space Administration (NASA) needs to support presently in order to elevate the progress of these technologies to be of benefit in the future.

When the RASC program was soliciting study proposals, it was suggested to take the initial steps in conceptualizing a future protection system that could provide a revolutionary advancement in the detection and precision orbit determination of impacting comets and asteroids coupled with a pre-established, robust method for altering their orbits in a controlled and rapid manner. This document provides a summary of the preliminary concept for the space-based Comet/Asteroid Protection System (CAPS), which was one of the studies performed under RASC in 2001 and 2002. It should be emphasized that at this time CAPS is only a conceptual study, and no direct plans are currently being made to implement CAPS. The vision for this future system architecture is primarily to provide planetary defense. However, the system should also provide productive science, resource utilization, and technology development when it is not needed for the extremely infrequent diversion of impacting comets and asteroids. A future for mankind is envisioned wherein asteroids and comets are routinely moved to processing facilities with a permanent infrastructure that is capable of and prepared to divert those objects posing a hazard.

Background

An enormous number of asteroids and comets orbit the Sun, ranging in size from pebbles to mountains. Earth approaching asteroids and comets are collectively termed near-Earth objects (NEOs). Fortunately, only a tiny number of these objects cross the Earth's orbit, and our atmosphere protects us from small and structurally weak objects; however, smaller NEOs vastly outnumber the larger, thus resulting in a higher impact frequency. The goal of current search efforts is to catalog and characterize by 2008 the orbits of 90 percent of near-Earth asteroids (NEAs) larger than 1 km in diameter, currently estimated to number between 900 and 1300. Devastating impacts can also occur from smaller NEAs, short-period comets (SPCs) in asteroid-like orbits, and long-period comets (LPCs) that do not regularly enter near-Earth space because their orbital periods range from 200 years to millions of years.

Impacts are extremely infrequent events relative to a human lifetime, but have the potential for massive loss of life and property. Impacts have occurred in the past and will occur in the future. The energy released from the impact of even a small NEO, like the one that exploded in the sky over the Tunguska region of Siberia in 1908, is equivalent to the explosive energy of a thermonuclear device (without the radioactivity). The energy released from an impactor capable of causing surface damage ranges from ≈10 megatons (Mt) of TNT to billions of megatons (1 Mt = 4.184×10^{15} joules). A 10-Mt impact can result from an object approximately 50 m in diameter and is roughly equal to 700 Hiroshima-size explosions. This class of impact is estimated to occur every several hundred years (or possibly less) and

[1]Chapter nomenclature available in chapter notes, p. 217.

can cause regional destruction. An impact with a 1-km diameter object, capable of releasing more than 100 000 Mt and resulting in a global catastrophe, can be expected to occur every several hundred thousand years to a million years. An impact from a 10-km object, like the one believed to have caused the great dinosaur extinction 65 million years ago, can be expected on an interval of 10 million years or greater. Because the last significant NEO impact with the Earth occurred nearly a century ago, the ability for mankind to internalize the reality of this threat is understandably difficult.

Despite enormous destructive potential, there are many positive aspects of asteroids and comets. They represent a significant resource for commercial exploitation, space exploration, and scientific research. They may even provide clues regarding the origin of life on Earth. It is worthwhile to identify and understand these planetary neighbors both for what they can provide us and for what they are capable of taking away.

Motivation for CAPS

While terrestrial-based telescopes can address many aspects of NEO detection, the ability to discover and track faint and/or small comets and asteroids is tremendously enhanced, if not enabled, from space. It is recognized, and appreciated, that the currently funded terrestrial-based detection efforts are a vital and logical first step. Focusing on the detection of large asteroids capable of global destruction is the best expenditure of limited resources; however, various aspects of the impact threat are largely unaddressed by these efforts. Currently there is no specific search for LPCs, small NEAs, or small SPCs. Additionally, coordinated follow-up observations are critical to limit the likelihood of losing a newly discovered NEO and to precisely determine the object's orbit. One shortcoming of current ground-based efforts is the difficulty in providing these follow-up measurements, which are provided in part by amateur astronomers. Looking for much smaller and fainter targets is likely to exceed the current capabilities of many asteroid and comet "hunters."

Just as the Hubble Space Telescope has expanded our ability to see the universe without the limitations imposed by Earth's atmosphere, a space-based NEO detection system would allow us to expand the range of observable comets and asteroids and to provide coordinated follow-up observations. A space-based detection system is capable of making observations on a continuous basis without the various constraints (daylight, weather, etc.) imposed on Earth-based systems, and NEO searches need not be focused on the solar opposition point. If detection systems can be designed to observe faint NEOs that appear to be near the Sun, which is impossible from the ground because the atmosphere scatters sunlight during the daytime, it would be possible to see objects close to the Sun and on the solar far side where solar illumination conditions are favorable. Additionally, it is critical to ascertain, to the greatest extent possible, the composition and physical characteristics of these objects. A space-based approach can solve this aspect of the problem through both remote observations and rendezvous missions with the NEO.

It is likely that the next object to impact Earth will be a small near-Earth asteroid or comet. The most significant danger from smaller NEOs (several hundred meters in diameter) could come from ocean impacts, which may generate tsunamis capable of massive destruction on distant shorelines. Even if this type of impact is not preventable, a limited amount of warning time could permit the evacuation of coastal populations, which could save millions of lives, prevent untold suffering, and mitigate loss of property. Finally, it is likely that a globally devastating impact with a 1-km class LPC will not be known decades or even years in advance with our current detection efforts. Searching for and protecting ourselves against these types of impactors is a worthwhile endeavor. A space-based detection system, despite being more costly and complex than Earth-based initiatives, is the most promising way of expanding the range of detectable objects and surveying the entire celestial sky on a regular basis. Current ground-based efforts should certainly be expanded in the near term, and a coordinated space-based system should be defined and implemented in the future. CAPS is an attempt to begin the definition of that future space-based system and identify the technology development areas that are needed to enable its implementation.

Finally, any attempt to deflect an impacting NEO with reasonable lead time is likely to be accomplished only by using a space-based deflection system. Many deflection approaches are possible given sufficient warning time, particularly decades of advance notice. Immediate threats are extremely difficult to defend against, and likely require highly capable spacecraft that can quickly engage the target and provide large, rapid changes in the object's orbital velocity to avert a collision. These requirements, plus the desire to modify the orbit in a controlled manner, considerably restrict the potential methods that could be used to alter an impactor's trajectory. It is essential to understand that the issues associated with detection and deflection of an impactor are intimately connected, particularly if we are not afforded decades of warning time that would be necessary for large NEAs. The requirements for the detection system could be significantly reduced given an extremely robust deflection capability. However, due to the enormous amounts of energy required to move these massive bodies, any additional warning time is an extremely valuable asset.

Concept Overview

CAPS is a future (25 or more years from now) space-based system concept designed to detect and protect against the entire range of threatening comets and asteroids. The initial focus is to determine the feasibility of protecting against 1-km class long-period comets, including inactive nuclei. The system is designed also to protect against smaller LPCs, as well as NEAs and SPCs capable of regional destruction. Although the primary motivation for CAPS is to provide protection against impacting comets and asteroids, it is anticipated that the system and technologies developed would have many additional benefits extending to governments (U.S. and international), the commercial sector, the scientific community, and academia. The CAPS detection system would provide an astronomical asset that could observe extremely faint or small targets (both planetary bodies and extrasolar objects), allowing an unprecedented level of scientific observations while surveying the entire celestial sky on a regular basis. The CAPS orbit modification system could enable exploitation of the vast economic resources available from NEOs and promote synergistic technologies for other future space missions. Technologies that will permit the future exploration and colonization of the solar system (e.g., high power and thermal management systems, high thrust and specific impulse propulsion, and power beaming) are also applicable to the deflection of Earth impacting comets and asteroids. Additionally, there is tremendous benefit in "practicing" how to move these objects from a threat mitigation standpoint; developing the capability to alter the orbits of comets and asteroids routinely for nondefensive purposes could greatly increase the probability that we can successfully divert a future impactor.

Combining the words "comet" and "asteroid" in the CAPS acronym intends to convey the idea of utilizing a combined approach for protection against both types of cosmic projectiles. Conventional ground-based telescopes may provide little or no advanced warning of collisions with small NEAs or LPCs, and developing and maintaining separate space-based systems may be impractical. Precision orbit determination of most NEAs and SPCs can be expected to be obtained several orbital periods prior to a collision, provided that we actually have the ability to observe them. This would not be the case for impacting LPCs, whose orbits need to be characterized very accurately over a small observation arc on their first observed perihelial passages through the solar system. If the situation occurs wherein a small NEA is first detected on its final approach, preventing an impact may prove problematic. In this case, CAPS would at least provide an accurate assessment of where the object would impact and enough warning time to allow some appropriate civil defense effort to be carried out successfully.

The timely detection of LPCs, even those of significant size, presents many intractable problems. LPCs can be extremely faint (albedos of $\approx$0.02) until the sublimation of their volatile frozen gases begins.

Moreover, comets can remain in a dormant state during perihelial passage, or they can exhaust their volatiles and become extinct nuclei. Observing LPCs at significant distances from the Sun is a formidable task. The ability to predict their orbits accurately, and hence determine whether or not they represent a threat, is dependent upon the number, resolution, and spacing of observations of these objects. Finally, the comet's trajectory can be significantly altered by nongravitational forces if it becomes active, affecting our ability to predict its path and properly alter it. The ability to observe faint LPCs and rapidly determine their orbits is consistent with protection against small, previously undiscovered NEAs. A system capable of protecting against LPCs, placed properly in heliocentric space, should also be capable of protecting against small NEAs and small SPCs.

The baseline detection concept advocates the use of high-resolution telescopes with advanced detector arrays, coordinated telescope control for NEO surveying and tracking, rapid spectral imaging for NEO identification and characterization, and interferometric techniques to obtain precision orbit determination when required. Detection telescopes would be orbiting and/or lunar surface-based, providing surveys of nearly the entire celestial sky approximately every 30 days. Orbiting telescopes could be placed in heliocentric orbits, including Earth-Sun libration points, or around a planetary body or moon. The CAPS detection system would provide a high probability that impacting NEOs are detected, and their orbits accurately characterized with significant warning time, even upon a first observed near-Earth approach.

The primary orbit modification approach uses a spacecraft that combines a multimegawatt or gigawatt-class electrical power system, a high thrust and specific impulse propulsion system for rapid rendezvous, and a pulsed laser ablation payload for changing the target's orbit. This combination of technologies may offer a future orbit modification system that could deflect impactors of various compositions and provide an effective method for altering the orbits of NEOs for resource utilization. If laser power levels required for a single spacecraft are prohibitive, multiple spacecraft with more modest laser payloads could be deployed to the target.

Detection

It is worthwhile to describe what is meant by "detection" in relation to the CAPS detection system. Detection includes initial NEO discovery, follow-up observations, precision orbit determination, and some level of physical characterization. Although all aspects of the detection problem are critical, for objects with a very limited observational period the accurate assessment of their trajectories is vital.

The initial benchmark for the CAPS detection system is to be able to identify an impactor with a diameter of 1 km or greater at a distance of at least 5 astronomical units (au) from Earth, and to identify objects as small as 50 m in diameter at a distance of 0.2 au from Earth. In general, these distance limits would provide warning times of approximately 1 year for a 1-km LPC and a few weeks to approximately a month for a small NEA that has not been previously cataloged. A system possessing the sensitivity to observe 1-km objects at 5 au would be capable of detecting many 50-m class asteroids significantly farther away than 0.2 au, so the warning times for uncataloged NEAs could be significantly longer. Ultimately, the ability to identify an LPC on an impact course at a distance of 5 au from Earth may not provide sufficient warning time, and observing further out may be valuable. Conversely, due to the unpredictable nature of comets, both with respect to their orbits and structural integrities, it may not be prudent to take any defensive action until the object is much closer. The threat of impact may change significantly if the comet becomes active, or if it fragments into a number of sizable objects. The extremely short warning times for LPCs, the large changes in orbital velocity required for averting an impact, and the orbital and compositional uncertainties make this aspect of the impact hazard particularly difficult to solve.

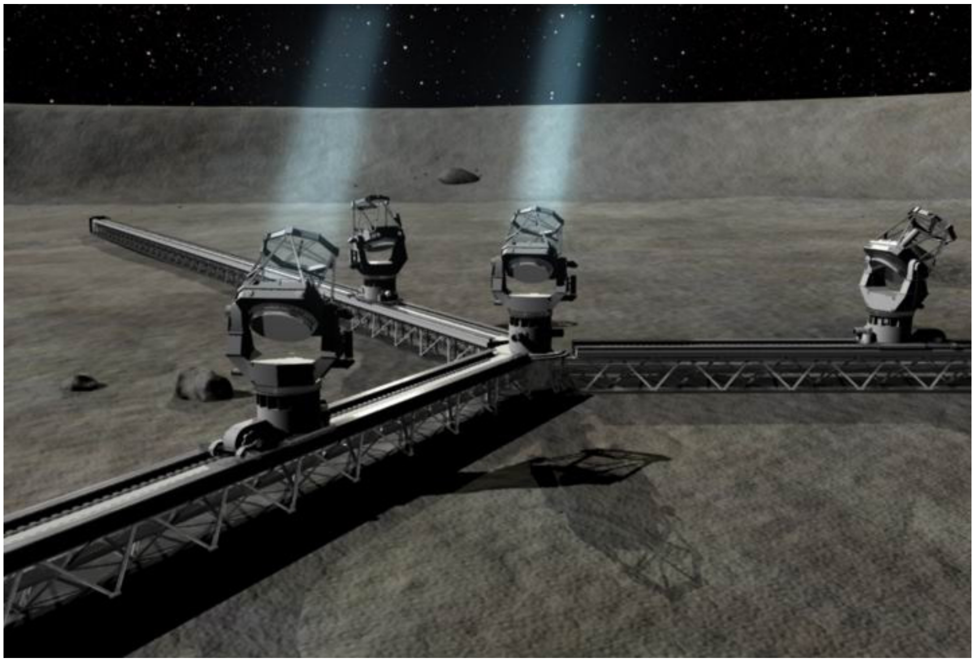

Figure 1. Depiction of detection system using a lunar-based approach.

The envisioned CAPS detection system would feature large aperture (3- to 6-m diameter), high-resolution telescopes capable of imaging in the ultraviolet, optical, and infrared wavelengths. Coordinated telescope control for NEO surveying and tracking would be incorporated to maximize follow-up observations, and baffling and/or shading would be employed to permit observations close to the Sun. Figure 1 depicts a lunar-based option with a detection node consisting of a wide field-of-view (FOV) survey telescope located in the center and three narrow FOV tracking telescopes (telescope enclosures and/or baffling are not shown). Two detection nodes, located in the northern and southern lunar hemispheres, could provide nearly complete sky coverage every month. Each telescope would have large area mosaic detector arrays (approximately 36000 × 36000 pixels), with the survey telescopes having a 1.0 × 1.0-degree FOV and the tracking telescopes having a 0.1 × 0.1-degree FOV. Spectral imaging would be implemented as early as possible in the detection process. Advanced detectors capable of rapid identification of NEOs and their spectral signals could greatly simplify operations and minimize requirements on the tracking telescopes. If NEOs could be uniquely identified in multiple survey images, a preliminary orbit could be determined with minimal risk of "losing" the object. The tracking telescopes would be used in an interferometric mode when higher precision astrometric observations are needed to confirm an object is on an impacting trajectory. Finally, active laser ranging could be used to provide range and range-rate data to augment precision orbit determination. Active laser ranging is preferable to radar systems due to the potentially large distances between the target and the detection system. The tracking telescopes could be used as receivers for the laser ranging system, or the return signal of faint NEOs could be enhanced through active illumination to aid in interferometry measurements.

Deflection/Orbit Modification

Altering the trajectory of a confirmed impactor as early as possible minimizes the required change in velocity (ΔV). This is particularly true for comets and asteroids that are an immediate threat because the required ΔV can increase by several orders of magnitude during the final months before impact. Besides rapid, controlled trajectory modification, one goal of CAPS orbit modification is to be effective against

NEOs of various compositions. Asteroids range from primarily stony to mostly metallic, with various proportions of each type of material, and may contain deep, powdery regolith that can affect deflection efforts, particularly landing and attaching to the object. Comets contain a mixture of nonvolatile materials and large amounts of frozen volatiles. When a comet becomes active, these volatiles create a diffuse cloud surrounding the nucleus called the coma. This variety of compositions and environments makes the issue of deflection difficult and suggests orbit modification methods that can move the NEO without landing on it may be highly advantageous. Because time may be critical, this approach could also diminish the need for detailed physical characteristic observations to be made before dispatching a deflection effort.

Many methods for altering the trajectory of a comet or asteroid have been proposed (ref. 1), but the most feasible approaches require a spacecraft to intercept or rendezvous with the target. Given a spacecraft with an advanced propulsion system (such as plasma or nuclear) capable of rapid rendezvous with the target, one deflection approach would be to physically attach to the object and thrust in the proper direction to change the object's orbit. There are many technical issues associated with this approach, but the one that is fundamentally limiting is the propellant required. Providing large quantities of propellant to permit a rapid rendezvous or intercept is difficult, but delivering enough propellant to alter the orbit of a massive asteroid or comet nucleus is impractical for an immediate threat. This situation is also possible for large NEAs found many years before impact; although the required ΔV is small, they can be extremely massive. One approach that can circumvent this problem and alter the trajectory of the object in a highly controlled manner is to use pulsed laser ablative propulsion. A sufficiently intense laser pulse ablates the surface of the NEO by causing plasma blow off. The spacecraft would station-keep with the object at a "small" standoff distance while the laser ablation is performed. The momentum change from a single laser pulse is very small; however, the cumulative result is very effective because the laser can interact with the object over significant periods of time. The laser ablation technique can overcome the mass penalties associated with other nondisruptive approaches because no propellant is required to generate the ΔV (the material of the celestial object is the propellant source). Additionally, laser ablation is effective against a wide range of surface materials and does not require any landing or physical attachment to the object.

For diverting asteroids and comets at significant heliocentric distances, the power and optical requirements of a laser ablation system located on or near Earth may be too extreme to contemplate in the next few decades. The CAPS hybrid solution, depicted in figure 2, can minimize these requirements by utilizing the spacecraft to deliver the laser as a payload to a particular celestial body and by making dual use of the power system. The laser ablation system would require an extremely powerful electrical generator, which is likely needed for the propulsion system to provide the rapid rendezvous phase of the mission. Even this approach requires the development of highly capable space-based power, propulsion, and laser systems. An alternative approach would be to send multiple spacecraft with laser payloads to the target, where they would work cooperatively to provide the required change in orbital velocity. This approach would be highly desirable from redundancy and mission risk standpoints.

Ultimately, a spacecraft capable of rapid interception of an incoming impactor is extremely beneficial, and several approaches for modifying the NEO's orbit could be incorporated into the deflection system. One of the most commonly cited methods for deflecting or pulverizing a threatening NEO on its final approach is the use of a nuclear detonation (ref. 1); however, there are many issues associated with this technique (such as fragmentation or radiation), and it is unlikely that the CAPS goal of controlled orbit modification can be achieved in such a fashion. Moreover, there is a great deal of uncertainty as to how effective a nuclear explosion would be against a porous or nonmonolithic object that is effectively a

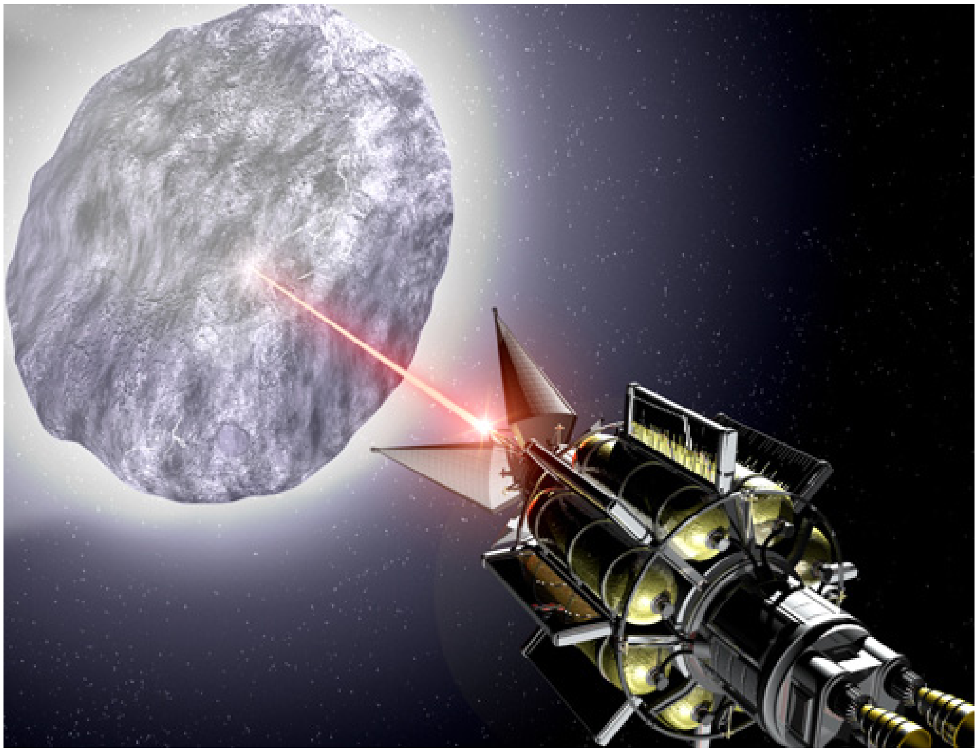

Figure 2. Depiction of rendezvous spacecraft with laser ablation payload.

gravitationally bound "rubble pile" (ref. 2). Compatible secondary payloads could be carried as an additional level of redundancy for a deflection mission, or a phased approach using rendezvous and intercept trajectories with various payloads could provide a robust defense. Regardless of the deflection method used, rapid engagement of an object is critical for preventing an impact from a newly discovered LPC or asteroid.

Study Focus Areas

The focus of the CAPS study has been on understanding the various aspects of this extremely complex problem and identifying a spaced-based detection system concept that maximizes the range of detectable objects and provides a high probability that the objects will be detected with significant warning time, *even upon a first observed near-Earth approach.*

The CAPS study efforts were focused on several key areas: precision orbit determination, preliminary detection element design to allow astrometric interferometry, simulation environment development, and orbit modification mission functionality using a rapid rendezvous spacecraft with a laser ablation payload. Resource limitations prevented many aspects of the system from being addressed during this conceptual study. Although extremely important for implementation, the following are example areas that were not addressed in-depth during the CAPS study: launch, cost, assembly and deployment, and system reliability, maintainability, and availability (RMA).

Technologies Identified

Finally, the CAPS study was tasked with identifying revolutionary technologies and techniques that permit the detection and orbit modification of potentially hazardous near-Earth objects, as well as nonimpacting asteroids and comets that could be used as a resource. The definition of "revolutionary" can vary significantly from individual to individual; it may be seen by one as radical new technologies or by another as a novel combination of existing technologies. It is hoped that the study will identify technologies that result in a fundamental change in approaching the impact hazard. A more realistic outcome, however, is that a combination of options and techniques requiring varying levels of advancement will be combined into a viable system solution.

There are many possible technologies that can be applied to both the detection and deflection of NEOs. By understanding the requirements for CAPS, the applicability of new technologies can be identified and their performances can be evaluated. It is also important to point out that one strongly desired outcome for the RASC program is to identify synergistic technologies that can be applied across a wide range of future space missions. For example, future technologies that permit human missions to traverse the solar system rapidly could be highly compatible with the rapid interception of an impactor. Likewise, laser power beaming (such as visible, ultraviolet, or microwave) may be applicable for space-based energy transfer for remote power applications, as well as NEO orbit modification. The following paragraph provides some of the key technologies that have been identified as having possible application for CAPS.

The enabling technologies required for the development of a viable protection system can be divided into the two areas of detection and deflection/orbit modification. Many of the detection technologies are currently in development for advanced in-space telescope systems such as the James Webb Telescope (formerly known as the Next Generation Space Telescope). Orbit modification technologies are also currently being studied as part of advanced power and propulsion research. With the proper funding levels, many of the technologies needed to support a CAPS architecture could be achievable within the next 15 to 20 years. The high power, propulsion, heat rejection, and directed energy systems would likely be farther term than some of the detection technologies.

The following are key technologies for CAPS detection capability:

- Large aperture, high-resolution advanced telescopes (ultraviolet, optical, and infrared) will be required for detection as well as tracking tasks.

- Advanced lightweight mirrors could be used to reduce the launch weight of CAPS detection assets and thus reduce the overall system cost. Examples of these technologies include low-mass membrane mirror optics and liquid surface mirrors. It is likely that active control will also be required to maintain precise mirror shape.

- Large area mosaic charge-injected device (CID) sensor arrays (approximately $36\,000 \times 36\,000$ pixels) are needed for rapid surveying and tracking (precise determination of a target object's angular position). CIDs exhibit less light bloom from pixel to pixel when subjected to high intensity light as compared with charge-coupled device (CCD) arrays, and they are also less sensitive to radiation.

- Advanced detectors capable of rapid NEO identification would be extremely valuable. The S-Cam, currently under development by the European Space Agency (ESA), uses superconducting tunneling junctions (STJs), which can count individual photons and provide associated spectral information. These data could be used to detect and "tag" asteroids and comets for simplified follow-up observations, cataloging, and future identification.

- Active cooling is required to achieve optimal performance from the sensors, whether they are CCDs, CIDs, or STJs, with temperature requirements being only a fraction of a degree Kelvin in the case of STJs.

- Baffling and/or shading technologies would permit observations close to the Sun (possibly within 15° of the Sun line), increasing the area of sky that can be sampled. The shading could be in the form of an attached sunshade, a large deployable shade flying in formation with the telescope, or an internal occulting disk such as that used in particular coronagraphs.

- Optical interferometric techniques and/or laser ranging systems would allow for precision orbit determination.

- Precision spacecraft and detector pointing will be needed to provide star field accuracy for guide stars to better than 0.001 arcsec. Accurate position and time knowledge is also needed so that the CAPS detection system can precisely acquire targets. If interferometric techniques are employed, the linear distance between two telescopes must be known to within approximately 1 nmi, and precise position determination and control with nano-/picometer knowledge must be available.

- Advanced data management systems and rapid communications will be needed for processing observation data and cataloging NEOs. Significant image data will be generated by multiple large CCD/CID arrays from multiple telescopes potentially at remote locations. These data will have to be processed and downlinked, the resulting image data stored, and an object database created. Ultra-high data rates for downlink may be achievable using optical communications technology. Potential high bandwidth intersatellite communications may also be needed for interferometry or database synchronization.

The following are key technologies for CAPS deflection/orbit modification capability:

- High thrust, high specific impulse propulsion systems (such as plasma or nuclear) would allow delivery of orbit modification systems to target NEOs.

- Multimegawatt to gigawatt-class electrical power systems are required for propulsion and laser applications.

- Advanced thermal management systems are critical to reject large amounts of waste heat.

- Reliable, high-power pulsed laser ablation systems with adaptive laser optics, precision beam-width focusing, and closed-loop control system would provide continuous orbit modification capability. Systems could also potentially be used as an active ranging system for precision orbit determination.

- Advanced autonomous or semi-autonomous rendezvous and station-keeping capability provide for engaging the NEO at close distances. Formation flying capability and precise attitude control may also be needed for interferometry using orbiting detectors.

Summary

Many of the major issues have been identified for a futuristic capability to protect against impacting comets and asteroids, and a preliminary space-based concept has been envisioned. Some of the basic concept elements, approaches, methodologies, and features have been identified. When contemplating the ability to monitor comets and asteroids continuously, there are many trade-offs between orbiting observatories and detection systems on planetary bodies without an atmosphere. Future orbit modification techniques have the potential for rapid and controlled alteration of NEO orbits, provided that high-power, compatible thermal management systems are developed. Much additional work and analysis are required to identify a final system concept, and many trade studies need to be performed to select the best mix of system capability, reliability, maintainability, and cost. Finally, it is fully appreciated that at the present time space systems are much more costly than terrestrial-based systems. Hopefully, this will change in the future. Regardless, understanding what it would take to defend against a much wider range of the impact threat will foster ideas, innovations, and technologies that could one day enable the development of such a system. This understanding is vital to provide ways of reducing the costs and quantifying the benefits that are achievable with a system like CAPS.

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