

# Survey of Enabling Technologies for CAPS<sup>10</sup>

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## Introduction

The enabling technologies required for the development of a viable Comet/Asteroid Protection System (CAPS) can be divided into two principal areas: detection and deflection/orbit modification. 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.

In fact, many advanced detection technologies are currently in development for future in-space telescope systems such as the James Webb Space Telescope (JWST), formerly known as the Next Generation Space Telescope. It is anticipated that many of the JWST technologies would be available for application for CAPS detection concepts.

Deflection/orbit modification technologies are also currently being studied as part of advanced power and propulsion research. However, many of these technologies, such as extremely high-output power systems, advanced propulsion, heat rejection, and directed energy systems, would likely be farther term in availability than many of the detection technologies.

Discussed subsequently is a preliminary examination of the main technologies that have been identified as being essential to providing the element functionality defined during the CAPS conceptual study. The detailed requirements for many of the technology areas are still unknown, and many additional technologies will be identified as future in-depth studies are conducted in this area.

## Detection Technologies

Large-aperture, high-resolution advanced telescopes (ultraviolet, optical, and infrared) will be required for detection tasks. An overview of several key technologies needed for the Comet/Asteroid Protection System (CAPS) detection capability is provided. These technologies can be divided into three areas of focus: sensors, optics, and supporting subsystems.

### *Sensors*

The type of sensor utilized for near-Earth object (NEO) detection is critical. To maximize sensitivity, the sensor must exhibit high quantum efficiency (QE) over a bandwidth range consistent with the electromagnetic radiation reflected by comets and asteroids, and the sensor must exhibit low read noise characteristics. Charge-coupled devices (CCDs) have had an enormous impact on astronomy, and have fundamentally enabled the current Earth-based telescopic NEO detection efforts. CCD arrays have been

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<sup>10</sup>Chapter nomenclature available in chapter notes, p. 217.

rapidly increasing in size and capability, and several advancements in CCD technology could have benefits for CAPS detection concepts. One technology, known as “back-illuminated electron multiplying technology,” has demonstrated QEs of up to 95 percent, which is higher than any other detector. A second technology, known as “low light level CCD technology,” can effectively eliminate readout noise found in CCDs. Although there are many advances in CCD technology that could assist in NEO detection, susceptibility to radiation and pixel saturation may restrict the effectiveness of CCD arrays for long-duration detection efforts. The remainder of this section focuses on providing an overview of some advanced alternatives to CCD.

**Large area mosaic charge-injected device arrays.** Charge-injected device (CID) sensor arrays differ in many ways from and have several advantages over CCDs. For example, CIDs exhibit less light bloom from pixel to pixel when subjected to high intensity light, the individual pixels of CIDs are addressable, and CIDs are very radiation tolerant (ref. 1).

**Technology requirements.** CID sensor arrays can be used for angular measurement of target objects. For the visible band, a  $32\,000 \times 32\,000$  silicon detector array with an  $8\text{-}\mu\text{m}$  pitch is needed that is sensitive to wavelengths from  $0.4$  to  $1.0\ \mu\text{m}$  and having a QE of 80 percent. For the infrared (IR) band, the array shall be a  $4000 \times 4000$  extrinsic silicon-gallium array with a  $64\text{-}\mu\text{m}$  pitch, sensitive to wavelengths from  $8$  to  $18\ \mu\text{m}$ , and having a QE of 50 percent.

**Current status of technology.** Current CID technology is a  $1000 \times 1000$  silicon detector array with a  $27\text{-}\mu\text{m}$  pitch, sensitive to wavelengths from  $0.4$  to  $1.0\ \mu\text{m}$ , and having QEs of 65 to 70 percent in the visible band and  $\approx 50$  percent in the IR (ref. 1).

**Current technology research activities.** CID research is currently being conducted by the Rochester Institute of Technology, Missile Defense Agency (formerly the Ballistic Missile Defense Office), and CID Technologies, Inc., which was recently funded by the National Aeronautics and Space Administration (NASA) through Small Business Innovative Research (SBIR) grants.

**Other applications.** Other applications include imaging, X-ray imaging, and cameras.

**Superconducting camera.** The superconducting camera, or S-Cam, is a technology demonstrator developed by the Astrophysics Division of the European Space Agency’s Space Science Department (ref. 2). It is an optical camera, using single-photon counting detectors based on superconducting tunnel junctions (STJs), which provide a capability to measure the wavelength, time of arrival, and location of each photon impacting the detector.

**Technology requirements.** A detector system capable of determining the wavelength and arrival time of each photon would provide the ability to “tag” particular asteroids/comets and aid in identification and tracking efforts.

**Current status of technology.** System level tests of the first S-Cam were conducted from January to May 1998 followed by integrated systems tests from July through December 1998 at the European Space Research and Technology Centre, Holland. The completed S-Cam was delivered to the William Herschel Telescope (WHT) facility in La Palma in January 1999, with the first astronomical observations being conducted in February (ref. 3). Following successful technical validation, an upgraded system (S-Cam II) was used at WHT for science qualification runs conducted in December 1999 and April 2000. The S-Cam II has completed qualification testing and is the first astronomical cryogenic camera qualified for use (ref. 4). Currently, two fundamental limitations of STJs are small array size ( $18 \times 50$  element prototype) and the extreme cooling requirements for the detectors ( $<1\ \text{K}$ ).

**Current technology research activities.** The S-Cam and S-Cam II contain  $6 \times 6$  element STJ array detectors; however, a prototype  $18 \times 50$  element STJ array is currently under development with the goal of creating arrays with thousands and eventually millions of elements. NASA scientists at Goddard Space Flight Center and the Jet Propulsion Laboratory are also developing cryogenic detector technologies using STJ-based detector arrays.

**Other applications.** Other applications include biotechnology and medical/health.

### **Optics**

The optics used in the detection and tracking telescopes will employ lightweight mirror technologies, requiring active control technologies to form and maintain the mirror shape. Many of these technologies are currently being developed for the JWST program.

**Lightweight mirrors.** Because launch weight is a major cost driver, lightweight mirror technologies must be developed to reduce systems costs.

**Technology requirements.** A lightweight primary mirror with at least a 3.2-m diameter is needed for the CAPS survey and tracking telescopes. An areal density of less than  $15 \text{ kg/m}^2$  is likely to be required.

**Current status of technology.** Current technology is represented by the Hubble Space Telescope (HST) primary mirror, which has a 2.4-m glass mirror with an areal density of approximately  $180 \text{ kg/m}^2$  (ref. 5). There are no lightweight optical telescope mirrors that are currently mission capable; however, lightweight mirror demonstrators of 1 to 2 m are under development for the James Webb Space Telescope (JWST) program and Goddard Space Flight Center as technology pathfinders. The JWST will have a 6-m class deployable mirror and an areal density of approximately  $15 \text{ kg/m}^2$  (ref. 6).

**Current technology research activities.** The JWST program currently has two lightweight technology development projects for space optics, the Advanced Mirror System Demonstrator (AMSD) and the JWST Mirror System Demonstrator. Through these technology development projects, NASA and Department of Defense (DoD) partners have invested \$40 million to demonstrate mirrors with areal densities of less than  $15 \text{ kg/m}^2$  that are capable of operating in cryogenic temperatures (ref. 7):

#### AMSD

- Semirigid low-authority beryllium (Ball Aerospace & Technologies Corporation)
- Semirigid medium-authority ultra-low expansion glass (Eastman Kodak Company)
- Isogrid high-authority fused silica glass (Goodrich Corporation)

#### JWST Mirror System Demonstrator

- Meniscus very high-authority glass (University of Arizona)
- Rigid hybrid glass composite (Computer Optics Inc., REOSC Optique, France)
  - An isogrid-stiffened glass (Zerodur<sup>®</sup>) bonded to composite materials

Other projects are developing lightweight mirror technologies with areal densities approaching  $1 \text{ kg/m}^2$  (ref. 8):

Nickel metal mirror (Marshall Space Flight Center)

- Electroformed nickel mirror for X-ray detection

Silicon carbide mirror (Ultramet)

- Combination of a precision silicon carbide reflector surface and a high specific strength, low-mass silicon-carbide structural support

Dual Anamorphic Reflector Telescope (Jet Propulsion Laboratory)

- Ultralightweight reflective foil mirrors stretched over a rigid frame having a parabolic contour

Thin film mirrors (Sandia, National Laboratories)

- Smart material mirror that can change shape in response to electron impacts

Nanolamites (Jet Propulsion Laboratory and Lawrence Livermore National Laboratory)

- Thin shell mirrors

Inflatable membrane mirrors

- Polymer membranes—wrinkling properties of material creates difficulties for use in visible and infrared imaging

**Other applications.** Lightweight mirrors may be used in 4+ m space telescopes or large ground-based telescopes.

**Active mirror control.** Conventional mirrors use material stiffness to maintain surface quality and mirror shape, whereas ultralightweight mirrors will require active control of the deformable mirror (DM). High quality images will be produced through computer-controlled actuators that adjust the mirror shape to control on-orbit deformations. Mirrors of large diameters will also need to be segmented in order to be packaged into a launch vehicle shroud. These mirrors will require active control for deployment, proper alignment, and reshaping once on-orbit.

**Technology requirements.** Mirror control systems (including sensors and actuators) must be developed to provide Hubble-type mirror surface/shape accuracy with thin technology mirrors. The systems may have to operate at or near the cryogenic temperatures at which the mirrors and sensor/detector arrays will operate.

**Current status of technology.** There have been numerous lab demonstrations, but no known on-orbit deployment tests have been conducted at this time. The Wavefront Control Testbed project, also known as the Developmental Comparative Active Telescope Testbed, is located at Goddard Space Flight Center and is being used to validate technologies and demonstrate wavefront sensing and control for segmented optics (ref. 9).

**Current technology research activities.** The lightweight mirror projects of AMSD and the JWST Mirror System Demonstrator are also developing the associated active control systems consisting of reaction

structures and force actuators that are integrated with the mirrors. The Jet Propulsion Laboratory Dual Anamorphic Reflector Telescope project is investigating active control systems for membrane surface control as well as deployment and metrology. Sandia Labs is also exploring active mirror control of its thin film mirrors, which are constructed of a smart material (piezoelectric polyimide) whose shape is altered through the application of electrons from a computer-controlled electron gun.

Active control of a mirror surface at the low temperatures required by some mirrors necessitates the development of cryogenic actuators. Several cryogenic actuator concepts have been developed and evaluated in recent years by NASA, primarily through SBIR contracts. The JWST program is currently evaluating two cryogenic actuator concepts (ref. 10), one by Xinetics, Inc., and one by American Superconductor.

**Other applications.** Other applications include laser instruments and small satellite actuators.

### ***Supporting Systems***

Numerous supporting subsystem technologies will be required for successful operation of the detection and tracking telescopes, including disturbance isolation, active cooling, lightweight sunshade/baffles, precision pointing, accurate position and time knowledge, and advanced data management/communication systems. Development of many of these technologies is currently being funded by NASA for other advanced spacecraft programs.

**Disturbance isolation.** Spacecraft subsystem components such as reaction control wheels and cryogenic coolers create dynamic disturbances due to imbalances and vibrations. Both passive and active systems are available for isolating disturbances. Passive systems provide damping of disturbances through a fixed stiffness, while active systems use control algorithms and actuators to sense and respond to disturbances. Passive systems offer an advantage over active systems in that they require no power. However, passive systems do not provide adaptability to changing disturbances that active systems provide.

**Technology requirements.** Dynamic disturbances must be isolated from the telescope during collection of survey and tracking measurements in order to obtain precision pointing requirements. Specific requirements are to be determined.

**Current status of technology.** A passive isolation system, consisting of a viscous fluid-damped isolator, is currently employed on the HST to isolate disturbances created by the reaction control wheels (ref. 11).

Another passive isolation system designed for space application is the Honeywell D-Strut™, a viscous fluid-damped isolator. The Honeywell Hybrid D-Strut™ integrates an active system with the passive isolator to provide isolation at low frequencies (ref. 12).

**Current technology research activities.** Current research in disturbance isolation for advanced telescope concepts includes the application of fast steering mirrors for jitter control and low vibration cryocoolers for disturbance mitigation (for examples see the subsequent section on active cooling).

**Other applications.** Other applications include Earth observation satellites, launch vehicles.

**Active cooling.** 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.

**Technology requirements.** Visible light detector arrays must be cooled to 230 K with the temperature controlled to 0.1 K. IR detector arrays must be cooled to 10 K with the temperature controlled to 0.001 K.

**Current status of technology.** The cooling system for the HST Near Infrared Camera and Multi-Object Spectrometer, which was originally a solid nitrogen dewar, was recently upgraded (March 2002) to a Creare, Inc., Reverse-Brayton cooler that maintains detectors between 75 and 85 K with a 0.1 K control capability (ref. 13).

The Jet Propulsion Laboratory has developed a zero-vibration sorption cryocooler that will cool detectors to between 18 and 20 K. Flight units will be delivered in 2004 and 2005 as the NASA contribution to the European Space Agency (ESA) Planck mission, planned for launch in 2007 (ref. 14).

**Current technology research activities.** JPL's Advanced Cryocooler Technology Development Program is currently developing 6 and 18 K two-stage cooling technologies for the next generation space-based observatories: Terrestrial Planet Finder, JWST, and Constellation-X. Four teams are currently developing preliminary-level designs with an objective of creating engineering model coolers in the 2005 timeframe (ref. 15):

- Mechanical J-T Pre-cooled by Multistage Stirling (Ball Aerospace & Technologies Corporation)
- Two-Stage Turbo-Brayton with 75 K Radiative Pre-cooler (Creare, Inc.)
- Multistage pulse tube (Lockheed Martin)
- Mechanical J-T Pre-cooled by Multistage Pulse Tube (TRW)

Research into advanced cryogenic cooling technologies for low temperature focal planes is also supported by funding through NASA Research Announcements from the NASA enabling concepts and technologies (ECT) program—Advanced Measurement and Detection Element (ref. 16):

- Solid state optical refrigerators (Los Alamos National Laboratory)
- Continuous adiabatic demagnetization refrigerators: 10 K to 50 mK (Goddard Space Flight Center)
- 6 K Vibration-Free Turbo-Brayton Cryocooler (Creare, Inc.)
- Solid state microrefrigerator for 100 mK (Lawrence Livermore National Laboratory)
- Nanocomposite thermomagnetic cryocoolers (Howard University)

Other ECT supported tasks are directed by various NASA centers (ref. 16):

- 4 to 10 K Vibration-Free Coolers Turbo-Brayton
- Ultralow temperature continuous magnetic refrigeration
- Miniloop heat pipe

- Microelectromechanical system microthermal louvers
- Helium-carbon sorption cryocoolers

**Other applications.** Other applications include space-based IR sensor technology.

**Shading/baffle technology.** The CAPS telescope must be protected from looking at or near the Sun, or the detector focal plane may be destroyed. In addition, CAPS IR sensors must be maintained at cryogenic temperatures. Finally, making observations near the Sun's observed position is highly desirable to maximize the number of NEOs detected. Shading of the CAPS telescopes from the Sun could be performed using several techniques. For a lunar-based concept, a shelter such as a dome structure could be employed. For free-flying spacecraft, the shading could be in the form of an attached sunshade or a large deployable shade flying in formation with the telescope.

**Technology requirements.** It is highly desirable to have CAPS detection elements be capable of observing within 20 deg of the detector-sun line to increase the area of sky that can be sampled. In addition, the CAPS IR sensors must be cooled to 10 K.

**Current status of technology.** Hubble utilizes baffles and a cover door for shading as well as active cooling for IR sensors (see previous discussion on active cooling). A number of subscale deployable shades have been developed for ground testing applications, and a related concept for a flight experiment was developed; however, no in-space sun shield tests or operational deployments have been conducted to date.

**Current technology research activities.** The proposed JWST design includes a large, five-layer, inflated sunshield attached to the telescope by a thermal isolation astromast. The shade is designed primarily for thermal control as the telescope will not be able to look within 90 deg of the Sun. The back of the shield will maintain a temperature of  $\approx 90$  K, allowing the mirror, instruments, and associated structure to radiate directly to space and reach cryogenic temperatures. The development of sun shield concepts is being performed by industry partners, International Latex Corporation Dover and L'Garde (ref. 17).

The NASA ECT, Resilient Materials and Structures Element, is also sponsoring research into new space durable polymers, which have potential application to JWST sun shield development (ref. 18).

**Other applications.** Other applications include any space-based telescope that requires shielding from sunlight and collocation technology for formation flying satellites.

**Attitude knowledge and control/precision pointing.** Precision spacecraft and detector pointing will be needed to provide star field accuracy for guide stars. Distributed spacecraft technologies, such as formation flying and precise attitude control, will also be needed for an orbital-based interferometry capability.

**Technology requirements.** Star field accuracy for guide stars must be known to better than 0.001 arcsec, telescopes must be pointed to better than 0.001 arcsec, and attitude control rate management must be to 0.001 arcsec/s. These requirements are for noninterferometric measurements using the tracking telescopes. Significantly higher accuracy will be needed for astrometric interferometry.

**Current status of technology.** Star field is currently known to 0.002 arcsec. The ESA satellite Hipparcos, which operated from 1989 through 1993, updated the position and distance of more than 100000 stars (ref. 19).

The HST pointing capability is 0.01 arcsec with a drift of 0.007 arcsec over a 12-hr period (ref. 20).

**Current technology research activities.** The Full-sky Astrometric Mapping Explorer spacecraft was to continue work begun by the Hipparcos mission by sensing star fields to 50  $\mu$ as at 15th magnitude. However, the project is currently rescoping the mission due to withdrawal of NASA sponsorship (ref. 21).

The Space Interferometry Mission (SIM) will have a pointing capability of 1 to 4  $\mu$ as, or 1- $\mu$ as single measurement accuracy for Narrow Angle Astrometry and 4- $\mu$ as mission accuracy for Wide Angle Astrometry (ref. 22).

The NASA ECT program is currently funding research for distributed space systems technology within the Distributed and Micro-spacecraft Element, including (ref. 23):

- formation sensing and control
- intersatellite communications
- constellation management and mission operations

**Other applications.** Other applications include the provision of high accuracy star cataloging for attitude determination and improvement of general celestial knowledge.

**Extremely accurate position and time knowledge.** CAPS requires accurate knowledge of position and time so that it can precisely acquire targets.

**Technology requirements.** Linear distance between two interferometry telescopes must be known to within 1 nm.

**Current status of technology.** Current distances between unmanned spacecraft are measured in meters.

**Current technology research activities.** Starlight, a technology pathfinder for terrestrial planet finder (TPF), was originally planned for launch in 2006, but has been redirected to focus on ground demonstration of the technologies needed for the formation-flying interferometer concept of TPF (ref. 24):

- Formation interferometer testbed (fringe tracking)
- Metrology technologies
- Prototype autonomous formation flying sensor
- Formation flying algorithm development and simulation

The original goal of the flight program was to maintain position to 1 mm, angular bearing to 3 arcminutes.

SIM also has a number of ground-based test beds (ref. 25):

- Palomar Testbed Interferometer
- Nanometer Testbed - nanometer stability on a flexible structure
- Micro Arcsecond Metrology Testbed—subnanometer metrology

**Other applications.** Other applications include collocation of microsattellites for phased array radar and stereoscopic imagery.

**Advanced data management systems.** Advanced data management systems and rapid communications will be needed for processing observation data and cataloging NEOs.

**Technology requirements.** 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 down-linked, the resulting image data stored, and an object database created. Although recognized as a very important technology, this area was not investigated in significant depth during the CAPS conceptual study.

**Current status of technology.** Ultrahigh 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.

**Current technology research activities.** Research activities in this area are ongoing at many NASA centers, academic institutions, and private companies. Data processing and communications speeds are constantly being advanced by ever more demanding space missions, as well as terrestrial based drivers.

**Other applications.** Other applications include Earth observation missions, next-generation space-based observatories, and advanced solar system based communications systems.

## **Deflection/Orbit Modification Technologies**

To follow is an overview of the two technologies specifically applicable to the enabling of a controlled orbit modification capability for deflecting an impacting NEO or altering an NEO's orbit for resource utilization: high thrust, high specific impulse propulsion systems and high power electrical systems. Advanced thermal management systems to reject large amounts of waste heat are also required to be developed to support the in-space power systems. Specific laser technologies were not investigated in detail during the CAPS study; but reliable, high-power pulsed laser ablation systems would need to be developed. Adaptive laser optics, precision beamwidth focusing, and closed-loop control systems are some of the supporting technologies needed for a laser ablation system. The same, or similar, technologies could also permit the deployment of active laser ranging systems to assist in precision orbit determination. Finally, advanced autonomous or semiautonomous rendezvous and station-keeping capability would be needed to travel to the NEO and engage it at relatively close distances.

### ***High Thrust, High Specific Impulse Propulsion Systems***

High thrust, high specific impulse propulsion systems are needed for delivering orbit modification systems to target NEOs.

**Systems options.** Two options exist, nuclear electric propulsion (NEP), which uses high specific impulse/high voltage thrusters (powered by a nuclear reactor) to accelerate propellants, and nuclear thermal propulsion (NTP), which uses the heat generated by a reactor to directly accelerate the propellants.

**Technology requirements.** An advanced propulsion system is needed that can provide the capability of rapid rendezvous with an object.

**Current status of technology.** NASA nuclear technology programs are currently included in the new initiative, Project Prometheus, formerly the Nuclear Systems Initiative (NSI). There are two primary technology areas to be examined as part of Prometheus (ref. 26):

- Radioisotope-based systems
- Nuclear fission-based systems

The main goal of Project Prometheus is to develop technology for increasing spacecraft power capability, thus providing an increased capability for solar system exploration. The primary propulsion approach to be emphasized in this research is NEP.

While NEP is currently NASA's design focus, an extensive amount of research and development of NTP systems has been conducted over the years. The majority of NTP research was conducted between 1955 and 1968, with over \$1 billion invested in the Project Rover nuclear rocket program and the nuclear engine for rocket vehicle application (NERVA) research program (ref. 27). Project Rover was primarily a research program while NERVA focused on development and testing. These programs were canceled in 1973 after the development and ground testing of numerous NTP systems, which were never flight tested. NTP research has continued at a reduced scale over the years, with many additional NTP concepts developed (such as NERVA Derivative Nuclear Thermal Rockets and Bimodal NTP).

**Current technology research activities.** Several thruster technologies are currently being investigated for NEP applications (ref. 28):

- Ion engine
- Magnetoplasmadynamic
- Hall
- Variable specific impulse magnetoplasma rocket (VASIMR)
- Pulsed inductive thruster

The VASIMR was the primary concept considered for the CAPS analysis because it has the potential for yielding the fastest possible trip time. VASIMR is a high power magnetoplasma rocket that gives continuous and variable thrust at constant power (ref. 29). Hydrogen plasma is heated by radio frequency power to increase exhaust velocity up to 300 km/s. The power output of the engine is kept constant, thus thrust and specific impulse,  $I_{sp}$ , are inversely related. Thrust is increased proportional to the power level. The engine can optimize propellant usage and deliver a maximum payload in minimum time by varying thrust and  $I_{sp}$  (ref. 30). Therefore, VASIMR can yield the fastest possible trip time with a given amount of propellant by using constant power throttling. A 10-kW space demonstrator experiment has been

completed, and a VASIMR engine with 200-MW power could be available around the year 2050. The  $I_{sp}$  range of the engine would be 3000 to 30000 s, and the corresponding thrust range would be approximately 5000 N to 500 N (assuming 100 percent power efficiency).

As part of the ongoing research in NEP systems, an end-to-end NEP demonstrator has been developed by Marshall Space Flight Center to demonstrate an integrated NEP system using a simulated fission core (SAFE-30, discussed subsequently), a Stirling power conversion system, and an advanced ion thruster. NEP systems with a specific mass of 1 to 10 kg/kW could be available during the 2020 to 2040 timeframe, while 0.1- to 1-kg/kW class NEP systems are not envisioned until 2030 and beyond. An NEP system utilizing a VASIMR engine is currently estimated to have a maximum overall specific mass of 1.0 kg/kW (ref. 31).

**Other applications.** Other applications include exploration of the outer planets, human exploration missions to the planets, and human outposts on the Moon and other planets.

### ***High Power Systems (Space Fission Power)***

Systems capable of generating significantly high levels of power will be needed for powering the propulsion and laser systems of an intercept spacecraft to quickly reach a target body and then sufficiently modify its orbit to avoid an Earth impact. Nuclear fission power systems are currently the best known method of providing this capability. Extensive research on space fission power systems was conducted in the 1960s and new research into these technologies recently has been initiated under Project Prometheus.

**Systems needs.** Multimegawatt to gigawatt electrical power systems are needed for propulsion and laser applications.

**Technology requirements.** Power systems capable of generating 200 MW of electricity or greater are required to provide the energy necessary for the efficient high-thrust propulsion systems as described previously and the laser systems described subsequently.

**Current status of technology.** As mentioned in the previous section, all NASA nuclear technology programs were recently transitioned from the In-Space Propulsion Program to the NSI (now Project Prometheus), including the Nuclear Fission Power research.

The only flight of a United States fission reactor was the Space Nuclear Auxiliary Power (SNAP)-10A launched into a 1300-km Earth orbit in 1965. It was capable of generating greater than 500 W of power and operated for 43 days until a spacecraft malfunction ended the mission (ref. 32).

Other programs, through the 1990s, have developed nuclear power system technologies but have not flown in space: the Medium-Power Reactor Experiment, Space Power (SP)-100, SNAP-50/SPUR, SPAR/SP-100, Advanced Space Nuclear Power Program, and the Multi-Megawatt Program (ref. 32).

**Current technology research activities.** The safe affordable fission engine (SAFE)-30 test series is an on-going demonstration of a 30-kW system using nonnuclear testing. Resistance heaters are used to simulate the heat from fission while steel/sodium heat pipes remove the heat from the core, thus providing a close approximation to an actual fission system (ref. 32). The tests also involve a Stirling power conversion system coupled to the SAFE-30 and operated at full power. The primary goal of the tests is to obtain data for validating existing analytical models and for use in the design of future systems. Fifteen restarts were accomplished as of February 2001 and represented the first realistic test of a United States

space fission system since 1969. The SAFE-30 tests are being followed by the SAFE-300 test series, a demonstration of a 300-kW system that also uses nonnuclear testing methods. The tests are being conducted by Marshall Space Flight Center in cooperation with Los Alamos National Lab and Sandia National Lab (ref. 32).

Spacecraft and surface power plants with the capability of generating 10 to 100 kW are projected for the 2010 to 2020 timeframe. Multimegawatt (1 to 100 MW) spacecraft and surface power plants could be available during the 2020 to 2040 timeframe, while 100 to 1000 MW class systems are not envisioned until at least 2030 (ref. 32).

***Other applications.*** Other applications include exploration of the outer planets, human exploration missions to the planets, and human outposts on the Moon and planets.

### ***Pulsed Laser Ablation Systems***

Multimegawatt pulsed laser ablation systems capable of continuous operation over several months in interplanetary space are needed to impart sufficient momentum to deflect kilometer-class long-period objects that will impact the Earth on their first observed passages through the solar system.

**Systems options.** Space-based laser systems are necessary because the Earth's atmosphere makes terrestrial-based laser systems ineffective for the application of deflecting kilometer-class long-period objects. Stimulated raman scattering restricts the intensity of the laser beam that would propagate through the atmosphere, atmospheric scintillation requires highly advanced adaptive optics, and the tremendous distances involved require extremely large beam director apertures. A space-based laser could be located in cislunar space, but the power requirements would extend into the multigigawatt range to deflect an NEO approaching the Earth on a collision course. A laser payload carried to the target by a spacecraft with an extremely efficient propulsion system significantly reduces the power required and the complexity of the optics needed to focus a laser with sufficient intensity on the target. Many aspects of pulsed laser systems are classified and the performance of current systems and future technologies development programs is unknown. The goal of the CAPS study was to provide a preliminary estimate of the laser energy levels required to deflect various classes of impactors, not to determine the specific design parameters of a laser ablation system. Given the current state of space-based laser technology, many major breakthroughs would be required for the practical implementation of the high energy levels required for CAPS.

**Technology requirements.** Approximately  $4 \times 10^5$  gigajoules (GJs) of laser ablation energy would be required to deflect a 1-km long-period comet (LPC) on a center hit trajectory, with a density of  $200 \text{ kg/m}^3$ , by only 1 Earth radius if the laser ablation effort could be completed 6 months before a post-perihelial impact. This deflection scenario could be accomplished by a 100-MW laser system operating continuously for 45 days. More powerful (gigawatt class) laser systems would be required to deflect an object with greater density or provide additional margin for the final deflection distance. Approximately  $6 \times 10^6$  GJ of laser ablation energy would be required to deflect a 1-km LPC on a center hit trajectory, with a density of  $1000 \text{ kg/m}^3$ , by 3 Earth radii if the laser ablation effort could be completed 12 months before a preperihelial impact. This deflection effort would require approximately 70 days of continuous operation by a 1-GW laser system. A less powerful system would require significantly more time on target to provide the necessary incremental velocity change, or multiple laser systems could work cooperatively as a phased laser array to provide the necessary energy.

***Current status of technology.*** Many aspects of high energy laser technology development are classified. Much of the directed energy programs are focused on continuous wave lasers designed to heat and melt the skin of a vehicle or missile. The Mid-Infrared Advanced Chemical Laser is a megawatt-class, continuous wave, deuterium fluoride chemical laser that has accumulated approximately 3500 s of lasing time since 1980 (ref. 33). Laser ablation can be achieved with a continuous wave laser, but a series of high intensity laser pulses is more desirable for producing a vaporized jet of asteroid or comet material and maximizing the laser momentum coupling coefficient. Additionally, a continuous wave laser could heat the material near the target area sufficiently to cause undesirable fragmentation.

In the past 10 years, the peak pulsed laser power levels achieved with terrestrial laser test facilities have increased by a factor of approximately 1000. Most ultrahigh power lasers employ a technique called chirped pulse amplification. This revolutionary pulse-compression technique allows these power levels to be achieved with small table-top lasers (ref. 34). Building-sized lasers were required to produce these power levels just a decade ago. However, these ultrahigh power lasers are only capable of extremely short pulses, low energy, limited pulse repetition, and close range beam focusing.

A CAPS laser system would need much higher energy pulses (10 MJ) repeated many times per second (10 Hz) and applied over long time periods (several million seconds of lasing time applied over a period of a few months). A CAPS high energy laser system would need to interact with the target while separated by many kilometers. Additionally, there are many technology efforts that are necessary to make a high energy laser system applicable for planetary defense, such as beam control, uncooled optics, and precision pointing of the beam on the target.

***Current technology research activities.*** There are currently two major beamed energy weapon programs being conducted by the United States DoD that are widely cited in the unclassified literature. The United States Air Force's Airborne Laser (ABL) is a major weapon system program that has been under development since 1996 (ref. 35). The ABL utilizes a modified 747-400 airplane equipped with several laser systems designed to shoot down a ballistic missile during its boost phase. The ABL has a megawatt-class Chemical Oxygen Iodine Laser that heats and ruptures the missile skin, causing the booster to explode because it is fueled under pressure. The ABL program is expected to be operational by 2007. The Space-Based Laser (SBL) program is currently under development by the Ballistic Missile Defense Organization. It is envisioned that the SBL will consist of a constellation of several orbiting hydrogen fluoride laser platforms (ref. 36). A Space-Based Laser Integrated Flight Experiment is planned to orbit in 2012. This flight experiment could result in an operational SBL system shortly thereafter.

***Other applications.*** Other applications include ablative laser propulsion for spacecraft, Earth-to-orbit vehicles, and orbital debris removal; microwave or optical power beaming; and laser ranging for NEO precision orbit determination.

## **Concluding Remarks**

A preliminary survey of technologies essential to providing a viable Comet/Asteroid Protection System (CAPS) has been conducted. These enabling technologies are divided into two principal areas: detection and deflection/orbit modification. Many of the detection technologies are currently in development for future in-space telescope systems, such as the James Webb Space Telescope (JWST), and should be available in the appropriate timeframe for application to the CAPS. The deflection/orbit modification technologies are also being developed as part of advanced power and propulsion research; however, many of these technologies are farther term in availability than the detection technologies. Future in-depth studies will be necessary to define the detailed requirements for these technology areas and to examine any additional technologies that may exist.

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