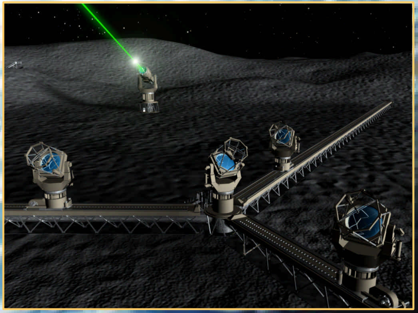
Comet/Asteroid Protection System (CAPS)

Concept Summary & Proposed FY02 Focus Area Descriptions



Daniel D. Mazanek
NASA LaRC - ASCAC/SSB
d.d.mazanek@larc.nasa.gov / 757-864-1739
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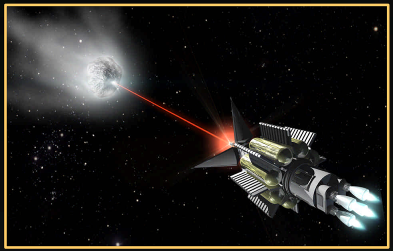


Background – Problem & Current Efforts

- An infrequent, but significant hazard to life and property exists due to Earth impacting asteroids and comets. Earth approaching asteroids and comets are collectively termed near-Earth objects (NEOs).
- NEOs also represent a significant resource for commercial exploitation, space exploration, and scientific research.
- Objects larger than 1 km are generally considered the greatest risk, since they are capable of producing global climate and mass extinctions.
- The goal of current efforts, funded by NASA (Code-S) and other sources, is to catalog and characterize the orbits of 90% of all near-Earth asteroids (NEAs) larger than 1 km in diameter by 2008.

Background – Range of Threat

- Smaller (< 100 m) near-Earth asteroids (NEAs) are much more numerous (possibly millions). Probability of Earth collision is much higher, but damage would be more localized. Impact near an urban area or coastline could result in considerable loss of life, extensive damage, and economic disruption (potentially trillions of dollars).

- The Tunguska event of 1908, believed to be an aerial explosion of a 60 m comet fragment, released ~20 megatons of energy (1600 Hiroshima-size bombs) and devastated ~2,000 km^2 of Siberian forest.

- Long Period Comets (LPCs) do not regularly enter near-Earth space (200 - 14 million year orbital periods). Potential threat with potentially little or no warning time using conventional ground-based telescopes. Previous sightings are not typically available to assist with orbit determination (OD). LPCs could >25% of the impact threat.

- No specific search for long period comets and smaller near-Earth asteroids is being conducted. These objects represent a threat with potentially little or no warning time using conventional ground-based telescopes.

Background - Earth vs. Space-Based Detection

- Current NEO detection efforts use dedicated ground-based telescopes equipped with CCD (Charge Coupled Device) detectors and automated identification routines.
- Detection of small and/or dim NEOs (Visual Magnitude > 24) by ground-based telescopes is significantly limited due to:
  - Atmospheric extinction and turbulence.
  - Geographic limitations of telescope location.
  - Earth's day/night cycle, poor weather and lunar intrusions.
  - Warning times for LPCs may only be on the order of weeks or months. Only 10% of known LPCs have been discovered more than 100 days before perihelion. Potentially no warning time for smaller NEAs that have not been cataloged.
- Space-based systems can overcome ground-based detection limitations:
  - Improved sensitivity, increased observation time and reduced revisit times.
  - Optimal placement of detection systems and coordinated observations (can observe closer to Sun).
  - Significantly increased warning times are possible.

CAPS Mission Overview

- Primary FY01 RASC focus - develop system concept that provides a “revolutionary” advancement in the detection of NEOs. Initial implementation possible in the next 20 to 40 years.

- RASC goal - develop a system concept that maximizes the range of detectable objects (size and/or distance), and provides a high probability that the objects will be detected with significant warning time, even upon their first observed near-Earth approach.
  - 1+ km NEOs 5-7 AU from Earth (1 AU = 150 million km)
  - 50+ m NEOs < 1 AU from Earth

- Focus is on solving the problem of LPC detection & orbit determination, with the constraint that the solution should also be able to greatly expand the range of detectable NEAs.

- Investigate “revolutionary” technologies and techniques that permit the detection and orbit modification/deflection of potentially hazardous NEOs and non-impacting NEOs that can be used as a resource. Various options may be combined to create an integrated system solution.

System Concept Philosophy – Multi-Functional Value

- Although CAPS is being designed to provide a protection system against impacting NEOs, the system *and* technologies developed should have multi-functional value that extend to various NASA enterprises and other government entities (U.S. and international), the commercial sector, the scientific community, and academia.

- Detection System
  - **Provide *"single"* system concept that can detect and provide precision orbit determination for both LPCs and NEAs (in particular small, previously undetected NEAs).**
  - **Provide an astronomical asset that can provide unprecedented scientific observations of the entire celestial sky on a regular basis - both planetary bodies and extra-solar objects.**
  - **Catalog of smaller NEAs (50-100 m class) would provide a valuable resource:**
    - Exploitation - mining, utilization, terra-forming, etc. Estimated "terrestrial" value of a 50 m asteroid is on the order of several billion dollars (function of composition).
    - Exploration - scientific missions, resource utilization, safe in-space transportation, etc.
    - Kinetic energy impact mitigation resource - "cosmic billiards."

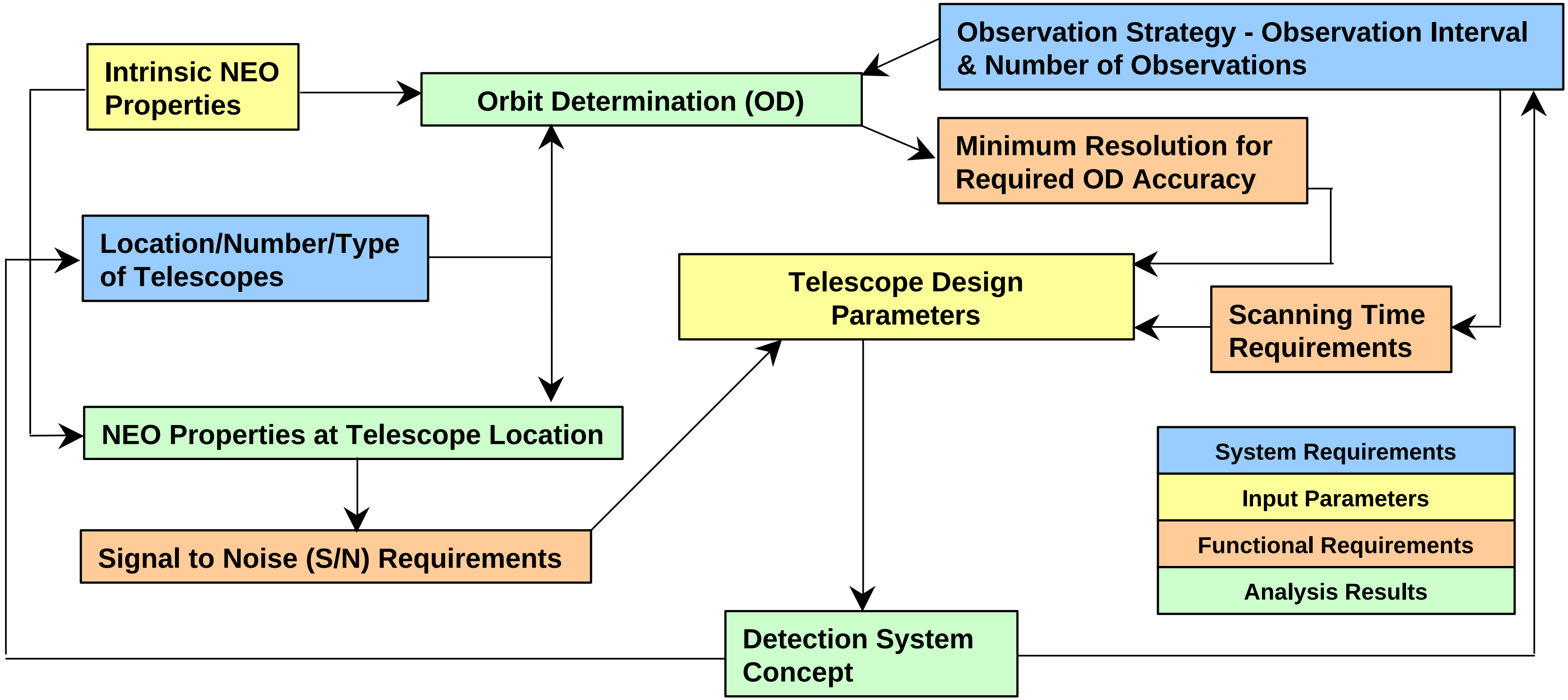
- Deflection/Orbit Modification System
  - **Provide controlled orbit modification in such a manner that it could be used for impact deflection and/or to exploit small NEAs for commercial, exploration, and other future uses of these resources.**
  - **System components and technologies could have in-space transportation applications for crewed and robotic missions (plasma propulsion, high power energy, power beaming).**
  - **Controlled orbit modification of small NEAs could also be utilized for kinetic impact deflection of much larger impactors (10km class).**

Mission Functionality

The CAPS mission can be divided into several basic functions:

- Detection
  - **Survey** - initial goal is to survey the entire celestial sky every 30 days.
  - **Tracking** – follow-up observations to provide initial trajectory estimates and refine orbits over time.
  - **Precision orbit determination** – much more accurate orbit determination for objects that cannot be ruled out as Earth impactors after sufficient tracking.
  - **Object physical characteristics determination –** NEO mineralogy, surface geology, shape, rotation rate, etc. using remote sensing (e.g., spectral imaging) and possible object rendezvous with nano-satellite probes.
- Deflection/Orbit Modification
  - **Provide *rapid*, *controlled* modification of orbital trajectory for selected NEOs.**
  - **Defense + utilization -** goal of approach is to provide a common orbit modification technique that can be used to deflect an impactor in a timely manner, and also modify the orbits of selected NEOs so that they can be utilized as a resource.
- Command & Data Handling
  - **Data processing, storage and NEO cataloging**
  - **Communications (between CAPS elements & Earth relay)**
  - **Command and control of CAPS elements.**

CAPS Detection Design Relationships



Fundamental conflict between desire to scan the celestial sky rapidly but have adequate resolution for orbit determination.

Detection Architecture Concepts

- The CAPS study team is focusing on three different detection architectures to accomplish the mission functions:
  - Lunar surface based
  - Heliocentric orbit (nominally at 1AU – potentially Lagrange points)
  - Earth orbiting

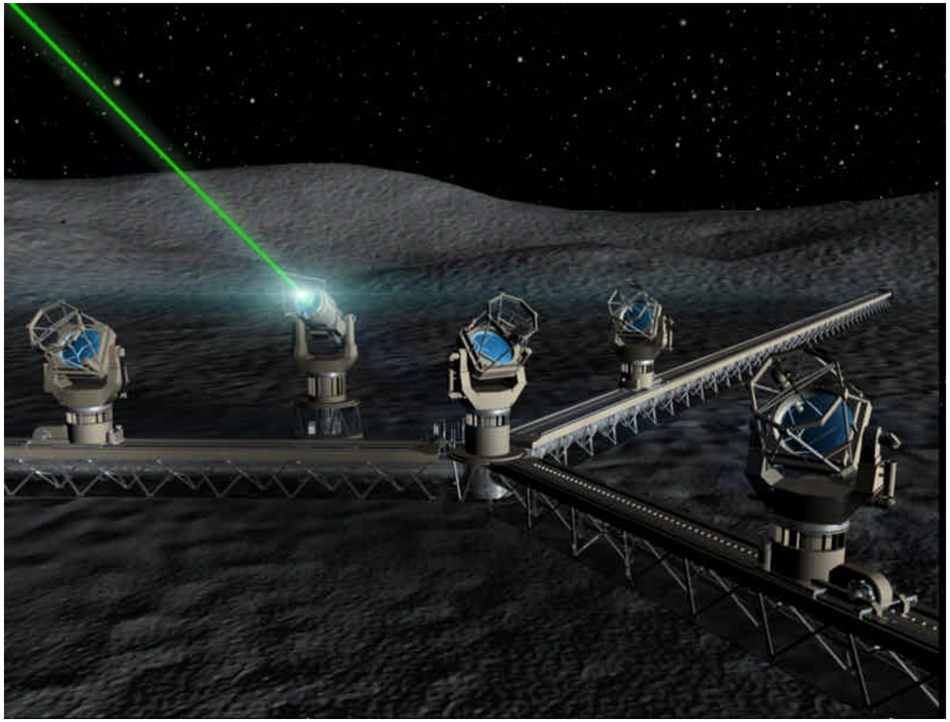
- CAPS could utilize existing/future Earth ground-based assets. Future dedicated facilities, such as the Large-Aperture Synoptic Survey Telescope, could be linked.

- The placement of CAPS assets is greatly influenced by assumptions regarding the availability of synergistic space infrastructure (e.g., Lunar base). The final system may be configured with elements at various locations.

- Architecture should provide a robust system concept capable of indefinite operational lifetime (highly autonomous, minimal servicing/maintenance, subsystem upgrades, etc.).

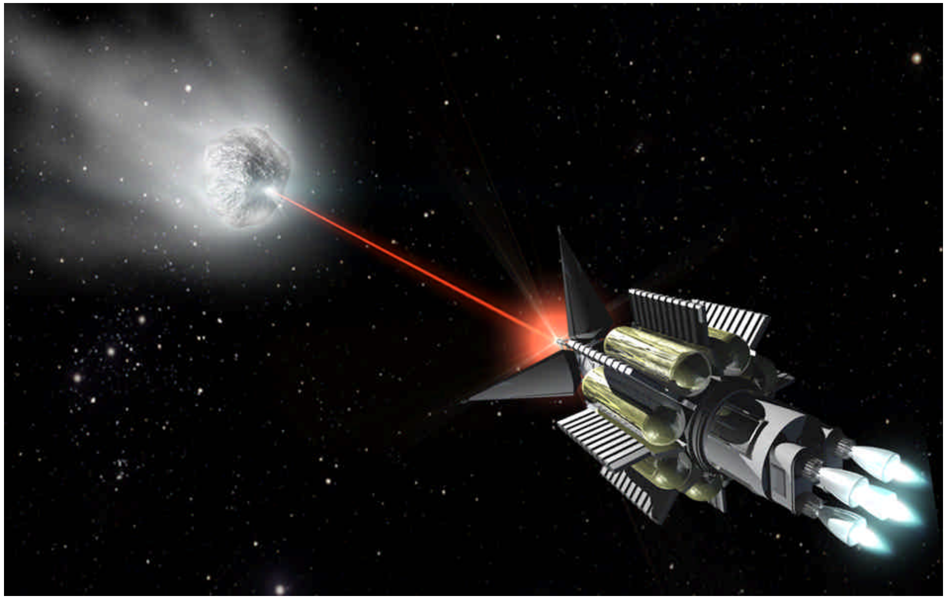
CAPS Concept Overview

- Space-based system concept (orbiting and/or Lunar surface based) that combines the following elements and techniques into an integrated detection and protection system providing *permanent*, *continuous* NEO monitoring, and *rapid*, *controlled* modification of orbital trajectory for selected NEOs. CAPS implementation could be performed in a stepwise manner as required technologies mature.
- Detection:
  - Advanced, multi-resolution optical/infrared (IR) telescopes with large mosaic arrays. Coordinated NEO telescope control for NEO surveying and tracking.
  - Optical interferometry techniques using the survey/tracking telescopes to obtain precision orbit determination (OD) when needed. Increase the effective diameter of the telescope by using multiple telescopes (100+ m baseline).
  - Active laser ranging to augment and/or enable precision OD.



CAPS Concept Overview

- Orbit Modification/Deflection:
  - Ablative, non-cooperative propulsion using high power pulsed laser to provide continuous orbit modification capability (NEO rendezvous vs. permanent fixed location).
  - Direct modification of NEO's orbit for defense and/or utilization; modification of smaller NEO's orbit to deflect larger impactor.
  - Major advantages over other maneuvering techniques:
    - **Landing on NEO not required**
    - **Propellant for NEO ΔV not required**
    - **Ablation technique effective on a wide range of surface materials**
    - **Non-disruptive orbit modification**
    - **Can engage multiple objects if target is not a single NEO**



CAPS Technologies

- **Optical/IR telescope**
  - Large area mosaic CCD/CID arrays (CID = Charge Injection Detector)
  - Light weight mirrors with roughness < 2 Å
  - Active mirror control
  - Active cooling
  - Shading/baffle technology

- **Optical interferometry**
  - Precise position determination and control (nano/pico meter knowledge)
  - Adaptive optics and light combination technologies
  - Formation flying capability and precise attitude control for orbiting telescopes
  - High bandwidth crosslink communication

- **Space-based laser systems (single/phased arrays) for orbit determination and modification**
  - Significant power required (shared with other users/systems)
    - Active ranging system for precision OD (100 MW peak pulse power)
    - Ablative, non-cooperative propulsion for orbit modification/deflection (GW class peak pulse power for permanent fixed laser, significantly lower for NEO rendezvous system)
  - Adaptive laser optics and precision focusing of beamwidth
  - Precision pointing and tracking
  - Closed-loop laser control systems

CAPS Technologies

- **Construction and maintenance of space structures**
  - Detection system concept may require a large structure to support telescope resources.
  - Human and/or robotic.
- **Attitude knowledge & control / precision pointing**
- **Extremely accurate position and time knowledge**
- **Isolation of disturbances from the telescope measurements**
  - Vibrations and disturbance forces/torques must be minimized so that accuracy of NEO measurements or laser pointing is not impacted.
- **Advanced data management systems**
  - Communications
    - Image data for multiple telescopes potentially at remote locations.
    - Potential high bandwidth inter-satellite communications for interferometry or database synchronization.
  - Data Storage
    - Storage of both image data and object database.
  - Data Processing & Compression
    - Multiple large CCD/CID arrays with significant image data to process and downlink (especially for satellites performing multiple functions).
- **Systems integration of telescopes and lasers - control & coordination of remotely located elements**

CAPS - Issues & Concerns

- **Large number of NEOs that would be discovered (millions)**
  - Likely that follow-up observations using tracking scopes would initially be inadequate.
  - "Object tagging"- having the ability to uniquely/semi-uniquely identify a detected object as rapidly as possible (e.g., during the survey) would greatly decrease the likelihood of "losing" the object.
- **Background Star Field**
  - Accurate Star Field Knowledge **(**guide stars for attitude knowledge)
  - Celestial density at galactic plane (Milky Way) (more resolution required?)
  - Current estimates indicate >3 billion stars of visual magnitude 27 or greater
- **Software complexity and validation**
  - Telescope computational algorithms
  - Command and control software among multiple elements
  - Database updates/synchronization and onboard image analysis
- **Telescope Construction**
  - Mirror design (space assembly) & focal plane design (multiple arrays)
  - Sun avoidance and glint rejection (shutter, baffles)
- **Inter-element communications for multiple telescopes performing interferometry and/or onboard image analysis.**
- **Spacecraft availability and maintenance – long term system viability**.
- **Laser system power, optics and beamwidth requirements.**

Proposed FY02 CAPS Focus Area #1

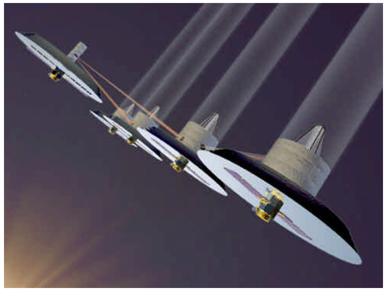
- Continue orbit determination analyses and refine analysis software to allow incorporation of potential observations for a CAPS detection architecture.
  - **Solicit peer review of orbit determination (OD) methodology that we have implemented during this past year. Main areas that need to be addressed:**
    - Is the "off-the-shelf" Method of Least Squares we are using the proper method for NEO (Near-Earth Objects) orbit determination (heliocentric orbits)? Are there advanced algorithms that can be applied? Can Long Period Comets (LPCs) and Near Earth Asteroids (NEAs) be handled with the same approach?
    - Is the erroneous predicted miss distance (our defined measure of merit) a meaningful way of measuring orbit determination accuracy? Others use error ellipsoids: are those more meaningful?
    - Are there known rules describing the heliocentric orbit geometries of objects/observatories, and temporal spacing of observations that are favorable (and unfavorable) to orbit determination of NEOs?
  - **Capability to incorporate variable, time/distance based resolution errors and determine impact on orbit determination - survey, track, high resolution.**
  - **Compare accuracy of LPC OD (first close Earth approach) vs. "standard" NEA problem where the orbit is known from several close approaches and impact will occur many years in the future.**
  - **Incorporate performance of optical interferometry and laser ranging techniques to improve the orbit determination accuracy.**
  - **Understand the significant perturbations to two-body motion (assumed in CAPS analysis) of comets and asteroids.**
  - **Understand the accuracy that is required in orbit determination before deciding that a mitigation effort is warranted. What accuracy is required to make mitigation effective?**

Proposed FY02 CAPS Focus Area #2

- Begin the development of integrated system analysis tool to assess the effectiveness of a CAPS architecture and/or elements. This time-based simulator would facilitate the evaluation of detection and orbit modification concepts identified for CAPS, and their interdependent functionality.
  - **Initial objectives:**
    - **Research existing tools and develop underlying implementation framework for simulator - developed/compiled code (leverage on-going SEE work at LaRC?) vs. modified COTS, etc.**
      - Accurate simulation of the solar system (Sun, planets, moons) and ability to input a user defined number of NEOs into the simulator for analysis and assign basic properties to objects (diameter, albedo, etc.).
      - Ability to model multiple spacecraft and sensors orbiting any body in the solar system or based on the surface of any planet or moon (including Earth based).
      - Ability to specify nominal orientation of spacecraft and define scanning parameters of sensors.
      - Allow the user to specify an impact trajectory and define time of collision for a NEO and be able to start simulation at any desired time prior to collision.
      - Develop basic framework for incorporating the rules that govern how a CAPS detection elements interact with the NEOs and other elements (initially, basic time based rules) and provide all necessary relational information between CAPS elements and NEOs.
    - **Develop tool to function in two basic detection analysis modes:**
      - Survey mode - many NEOs in simulation and determine the ability of surveying strategy to detect them.
      - Tracking mode - one or a few NEOs and determine how far in advance the orbit of a LPC or un-cataloged NEA would be known well enough to confirm an Earth impact.
  - **Examples of Future applications:**
    - Scanning/search algorithms, telescope sensitivity (interferometry/laser ranging techniques and many other aspects of the detection problem could be evaluated as the tool matures.
    - Analysis tool could be expanded to evaluate the effectiveness of orbit modification/deflection techniques.

Proposed FY02 CAPS Focus Area #3

- An assessment of the applicability of optical interferometry to provide high precision orbit determination for NEOs.
  - **Determine what range of NEOs (if any) that this technique could be used for (characterized by distance, angular motion, brightness limitations, size, etc. – LPCs vs. NEAs).**
  - **Identify the requirements and performance of the system (interface with orbit determination analysis support):**
    - Number and basic performance characteristics of individual optical elements
    - Accuracy of position and stabilization of optical element positions
    - Accuracy of knowledge of optical element relative positions
    - Attitude control accuracy for pointing system
    - Integration times required
    - Observable objects limiting magnitude, size, distance, etc.
    - Fringe signal-to-noise ratio
    - Range of system baselines that can be achieved
    - Measurement resolution of system



  - **Identify enabling technologies, determine current level of development, and estimate required technology development in the future.**
  - **Compare orbiting vs. surface based systems to determine trades and drivers and determine whether system could be Earth based.**
  - **Assess the overall instrument complexity and the implications for interferometer integration and test and autonomous on-orbit operation.**
  - **Determine if this technique could provide direct imaging of large/close NEOs that could be useful for orbit modification/deflection efforts.**

Proposed FY02 CAPS Focus Area #4

- Investigate the applicability of active laser ranging for precision orbit determination and other information for NEOs.
  - **Applicability of laser ranging system to provide range/range-rate data for LPCs (1km diameter comet ~7 AU from Earth) and NEAs.**
  - **Identify the requirements and performance of system (interface with orbit determination analysis support):**
    - Power
    - Adaptive laser optics and precision focusing of beamwidth
    - Precision pointing and tracking
    - Closed-loop laser control systems
    - Receiver system
  - **Identify additional NEO characteristics that can be determined - size, shape, spin rate, etc.**
  - **Comparison of laser ranging to comparable radar systems.**
  - **Compare orbiting vs. surface based systems to determine trades and drivers and determine whether system could be Earth based.**
  - **Identify enabling technologies, determine current level of development, and estimate required technology development in the future.**
  - **Identify synergistic aspects of laser system (power beaming) and or power generation system (e.g., lunar base shared power).**

Proposed FY02 CAPS Focus Area #5

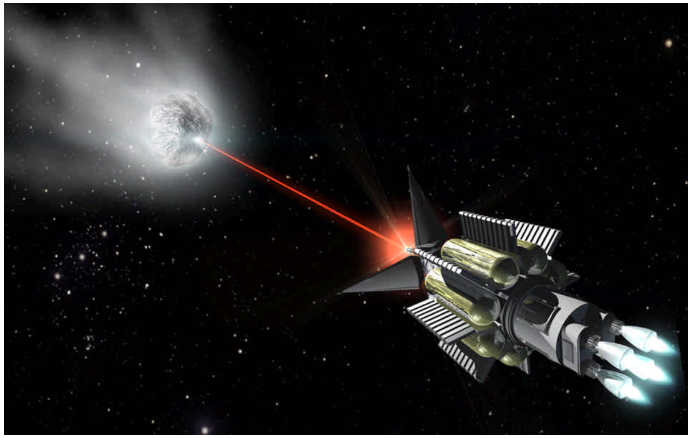
- Investigate the applicability of spectral imaging for NEO identification and determine how measurements could be incorporated into a CAPS detection system.
  - **Determine requirements for spectral imaging to determine object composition and how this technique could be integrated with optical/IR telescope design.**
  - **Determine the feasibility of using spectral imaging to facilitate the NEO survey process by identifying newly discovered NEOs and simplifying initial orbit determination complexity.**
    - Spectral emission differences between detected objects during survey – "object tagging."
    - Differences in the spectral emissions of a object reflecting light (NEO) and an object that is emitting light (stars, nebula, etc.) to assist in distringuishing NEOs from background objects.
  - **Identify the requirements and performance of system (interface with orbit determination analysis support).**
  - **Identify enabling technologies, determine current level of development, and estimate required technology development in the future.**

Proposed FY02 CAPS Focus Area #6

- Investigate the applicability of space-based laser systems for _rapid_ and _controlled_ NEO orbit modification / deflection.

– "Local" laser ablation system using rendezvous spacecraft with laser/power system payload (orbiting or station-keeping with NEO – "small" standoff distance from object).

- Provide background on laser ablation fundamentals and research.
- Determine feasibility and identify system requirements and performance.
- Characterize the range of NEOs (size, distance, etc.) that this deflection technique could be applicable for and examine the potential for "billiard ball" option using small NEAs.
- Compare the benefits and effectiveness of laser ablation vs. other non-disruptive techniques (e.g., rendezvous system providing direct thrust to NEO).
- Identify and compare potential laser, sensor, power, & propulsion technologies.
- Identify enabling technologies, determine current level of development, and estimate required technology development in the future.



– "Remote" laser ablation system (range less than ~ 2.0 AU).

- Determine feasibility of a permanent fixed laser system and identify the requirements and performance of system and compare to "local" system defined above.
- Compare location options (orbiting vs. surface based system) to determine trades and drivers.
- Identify enabling technologies, determine current level of development, and estimate required technology development in the future.