NEAR-EARTH OBJECTS (NEOS)—STATUS OF THE SURVEY PROGRAM AND REVIEW OF NASA'S 2007 REPORT TO CONGRESS

HEARING

BEFORE THE

SUBCOMMITTEE ON SPACE AND AERONAUTICS

COMMITTEE ON SCIENCE AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

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NEAR-EARTH OBJECTS (NEOS)—STATUS OF THE SURVEY PROGRAM AND REVIEW OF NASA'S 2007 REPORT TO CONGRESS

THURSDAY, NOVEMBER 8, 2007

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON SPACE AND AERONAUTICS,
COMMITTEE ON SCIENCE AND TECHNOLOGY,
Washington, DC.

The Subcommittee met, pursuant to call, at 10:07 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Mark Udall [Chairman of the Subcommittee] presiding.

U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE & TECHNOLOGY
SUBCOMMITTEE ON SPACE AND AERONAUTICS

Hearing on

Near-Earth Objects (NEOs)—
Status of the Survey Program and Review of NASA's 2007 Report to Congress

Thursday, November 8, 2007
10:00 a.m. – 12:00 p.m.
2318 Rayburn House Office Building

WITNESS LIST

Panel 1

Rep. Luis Fortuño
Resident Commissioner
Puerto Rico

Panel 2

Dr. James Green
Director
Planetary Science Division
NASA

Dr. Scott Pace
Associate Administrator
Office of Program Analysis and Evaluation
NASA

Dr. Donald Yeomans
Manager
Near Earth Object Program Office
Jet Propulsion Laboratory

Dr. Donald Campbell
Professor, Cornell University
Former Director
Arecibo Observatory

Dr. J. Anthony Tyson
Professor, University of California, Davis
Director
Large Synoptic Survey Telescope Project

Mr. Russell "Rusty" Schweickart
Chairman and Founder
B612 Foundation

HEARING CHARTER

SUBCOMMITTEE ON SPACE AND AERONAUTICS
COMMITTEE ON SCIENCE AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES

Near-Earth Objects (NEOs)—Status of the Survey Program and Review of NASA's 2007 Report to Congress

THURSDAY, NOVEMBER 8, 2007
10:00 A.M.–12:00 P.M.
2318 RAYBURN HOUSE OFFICE BUILDING

Purpose

On Thursday, November 8, 2007 at 10:00 a.m., the House Committee on Science and Technology's Subcommittee on Space and Aeronautics will hold a hearing to examine the status of NASA's Near-Earth Object survey program, review the findings and recommendations of NASA's report to Congress, *Near-Earth Object Survey and Deflection Analysis of Alternatives,* and to assess NASA's plans for complying with the requirements of Section 321 of the *NASA Authorization Act of 2005.*

Witnesses

Panel 1

- The Honorable Luis G. Fortuño, Resident Commissioner, Puerto Rico

Panel 2

- Dr. James Green, Science Mission Directorate, NASA
- Dr. Scott Pace, Program Analysis and Evaluation, NASA
- Dr. Donald K. Yeomans, Jet Propulsion Laboratory
- Dr. Donald B. Campbell, Cornell University
- Dr. J. Anthony Tyson, University of California, Davis
- Mr. Russell "Rusty" Schweickart, B612 Foundation

Potential Issues

- What is the current status of NASA's Near-Earth Object (NEO) search program, and how urgent is the need to move ahead with the expanded search that was directed in the 2005 *NASA Authorization Act*? Is the timeline for achieving the goal appropriate or would changes in the "deadline" provide benefits in terms of technical approaches or costs?
- What are the most important priorities to address relative to detecting, characterizing, and developing the means to deflect NEOs?
- NASA submitted a 2007 report to Congress on NEO search and deflection options, but the report doesn't provide a recommended option, as required in the 2005 *NASA Authorization Act.* What approach does NASA recommend for complying with the legislated mandate and what steps has NASA taken to begin implementing any of the options identified in the report?
- NASA's report to Congress mentions search options that would rely on planned ground-based telescopes that have been proposed for development under the auspices of other agencies. What role, if any, should NASA play in supporting the NEO-related operations of those telescopes? What alternatives exist if those assets are not funded and developed?
- Planetary radar facilities have been cited as critical for providing more precise orbital determinations of potentially hazardous NEOs. However, the two radar facilities currently being used to obtain data on NEOs [Arecibo and Goldstone] may not be available in the future. What are the implications should existing planetary radar facilities become unavailable?

- A NEO object, Apophis, has been identified and could pass as close as 23,100 kilometers from the Earth's surface in 2029 and return again for a close approach in 2036. What threat does this object pose in terms of a potential impact with Earth, and what is needed to improve our understanding of the threat?
- How much time would be required to prepare a mitigation approach if a hazardous object were discovered to be on a collision course with Earth? How much time would likely be available?
- How well understood are the potential approaches to deflecting asteroids? What is the confidence level in the technologies that would be required? What information is needed to assess the various approaches, and how will decisions be made on which mitigation strategy to take?
- What is the degree of international involvement in searching for, characterizing, and studying deflection options for NEOs? What steps, if any, has NASA taken on potential collaboration or coordination of NEO-related initiatives?
- How will policy and legal issues involved in addressing NEOs—e.g., when and how to warn the public and whether to use nuclear explosives to deflect an asteroid—be handled on national and international levels? What steps have NASA and other federal agencies taken to date to address such issues?

Background

Astronomers estimate that millions of asteroids, comets, meteoroids, and other cosmic debris orbit within the vicinity of Earth and the Sun. The Earth is continually bombarded by these remnants from the formation of the solar system. Small objects ranging from the size of a dust particle up to a size of about 50 meters in diameter do not pose impact threats to Earth, because they burn up and disintegrate upon entry to the Earth's atmosphere. However, larger objects pose potentially catastrophic threats because they would not disintegrate before impacting the Earth. Near-Earth Objects (NEOs) are defined as asteroids and comets whose trajectories bring them within 45 million kilometers (km) of the Earth. NEOs larger than about 140 meters, whose orbits about the Sun bring them within 7.5 million km of the Earth's orbit, are classified as potentially hazardous objects (PHOs). Most of these objects are asteroids. According to NASA, there are currently 900 known Potentially Hazardous Asteroids (PHAs). NASA scientists estimate that the population of PHOs is about 20,000 objects.

The literature on NEOs is not entirely consistent on the threats posed by various sizes of objects. Information from NASA's Near-Earth Object Program webpage [*http://neo.jpl.nasa.gov*] and other sources indicates the following:

- Objects larger than 50 meters can survive entry through the Earth's atmosphere, and could cause local disasters or events such as tsunamis upon impact. Estimates of the frequency of impacts of objects of this size range from once every 100 years to once every 500 years.
- Objects larger than one km in diameter that impact Earth would cause disasters on a global scale, and *"the impact debris would spread throughout the Earth's atmosphere so that plant life would suffer from acid rain, partial blocking of sunlight, and from the firestorms resulting from heated impact debris raining back down upon the Earth's surface."* Estimates of the frequency of these range from once every few hundred thousand years to once every million years.
- "Extinction-class" objects (10 km or greater in size) are estimated to occur on average once every 50 million to 100 million years.

Past NEO Impacts and Events

Evidence from past major NEO impacts or aerial explosions illustrates the catastrophic consequences that these objects can have:

- The impact of a NEO on the north side of Mexico's Yucatan Peninsula some 65,000,000 years ago that is thought to have helped bring about the extinction of the dinosaurs and to have destroyed 75 percent of life on Earth. Scientists estimate the frequency of an impact event of this magnitude to be about once every 50–100 million years.
- The Barringer Meteor Crater in Arizona is about one kilometer wide and is estimated to be 50,000 years old. The impact was caused by a nickel-iron meteorite, weighing about 300,000 tons and whose size was roughly 45 meters in diameter. The impact explosion was comparable to 20 million tons of TNT

and created a hole 174 meters deep. Scientists estimate these types of impacts to occur once every 250–1,000 years.

- The Tunguska Event took place in Siberia in 1908 when a NEO estimated to be 50–100 meters in size disintegrated about five-ten kilometers above the Earth's surface. That event unleashed energy comparable to an estimated 10–15 million tons of TNT. The explosion flattened trees and other vegetation over an area of roughly 2,000 square kilometers [about 500,000 acres]. Scientists estimate that this scale of impact would occur about once every 250–1,000 years.

Within the last two decades, instances of objects that passed near Earth brought increasing interest in identifying NEOs and exploring options to protect Earth from a potential NEO impact. For example:

- On March 23, 1989, the 1989 FC asteroid with an estimated diameter of 0.3 miles came within 430,000 miles of Earth. 1989 FC carried the energy estimated to be more than 1,000 one-megaton hydrogen bombs. The asteroid was only discovered after it had made its closest approach to Earth.
- Asteroid 99942 Apophis, discovered in 2004, is estimated to be roughly 300 meters in diameter, and could pass as close as 29,470 km [about 18,300 miles] from the Earth's surface [i.e., about the altitude that geosynchronous communications satellites orbit the Earth] in 2029. Radar observations conducted at the Arecibo Observatory in January 2005 significantly improved the understanding of the asteroid's orbit. The probability of impact in 2036, when the asteroid makes another close approach, is currently estimated to be 1/45,000. Scientists hope to use Arecibo again in 2012 to further refine the orbital coordinates when the asteroid is expected to be in a favorable viewing position.

Determining the population of NEOs, including those in the PHO category, can only be achieved by conducting a search campaign using ground-based or space-based telescopes, or a combination of the two.

Previous Congressional Actions Related to NEOs

Congress has taken a number of steps since 1990 to promote increased understanding of NEOs and the potential threat they pose, as well as potential options for protecting Earth from hazardous NEOs. The *National Aeronautics and Space Administration Multi-year Authorization Act of 1990* directed NASA to conduct two workshop studies on NEO detection and interception. In 1993 the House Science and Technology Committee held a hearing to review the results of the two reports, and in 1994 [by means of House Report 103–654, which accompanied the *National Aeronautics and Space Administration Authorization and Space Policy Act for Fiscal Year 1995*] gave further direction to NASA to coordinate with the Department of Defense and international space partners on identifying and cataloging NEOs greater than one kilometer in diameter that are in an orbit around the Sun that crosses Earth's orbit within the next decade. In 1998, NASA established a Near-Earth Object Program Office at the Jet Propulsion Laboratory and established its Spaceguard Survey. The Survey had the goal of detecting and cataloging 90 percent of NEOs one km or larger by the end of 2008.

NASA's Current NEO Survey Program and Budget

The Spaceguard Survey was housed in NASA's Exploration Systems Mission Directorate in recent years, but earlier this year it was moved to the Science Mission Directorate. NASA's report to Congress states that the current budget for the program is $4.1 million per year for Fiscal Years 2006–2012. NASA officials report that the annual budget is allocated as follows: $3 million are used to support the search teams and ground-based telescope facilities, $500,000 is allocated to JPL for studies on near-Earth objects, $400,000 is provided to the Minor Planets Center at the Smithsonian Center for Astrophysics to refine the orbital coordinates of NEOs that have been detected, and the remainder is allocated to additional NASA-funded studies.

NASA's report to Congress states that as of December 2006 the Spaceguard Survey had identified 701 of the estimated 1100 NEOs larger than one km that are believed to exist.

Recent Congressional Action on NEOs

Section 321 of the 2005 *NASA Authorization Act* directed NASA *"to plan, develop, and implement a Near-Earth Object Survey program to detect, track, catalogue, and characterize the physical characteristics of near-Earth objects equal to or greater* *than 140 meters in diameter in order to assess the threat of such near-Earth objects to the Earth. It shall be the goal of the Survey program to achieve 90 percent completion. . .within 15 years after the date of enactment of this Act."* Section 321 also directed NASA to report to Congress on an analysis of ground-based and space-based alternatives to conduct the Survey; a recommendation on which Survey option to pursue and a proposed budget; and an analysis of options to divert an object that threatens impact with Earth.

NASA's Near-Earth Object Survey and Deflection Analysis of Alternatives Report to Congress

NASA's report, *Near-Earth Object Survey and Deflection Analysis of Alternatives, Report to Congress,* prepared in response to Sec. 321 of the NASA Authorization Act of 2005, was submitted to Congress in March 2007. The study was led and managed by NASA's Office of Program Analysis and Evaluation. The report is a condensed version of a longer, un-circulated version that included the analysis on which findings of the report to Congress were based. The 2007 report to Congress provides options for meeting the Survey goals by 2020, as required in the Act, and options for meeting the goals on a longer timeframe. However, the report does not provide Congress with NASA's recommended option for conducting the Survey or provide a cost estimate for that Survey.

The report's basic conclusion is that *"NASA recommends that the program continue as currently planned, and we will also take advantage of opportunities using potential dual-use telescopes and spacecraft—and partner with other agencies as feasible—to attempt to achieve the legislated goal within 15 years. However, due to current budget constraints, NASA cannot initiate a new program at this time."*

In addition, the report contained a number of additional findings, including:

- *"The goal of the Survey Program should be modified to detect, track, catalogue, and characterize, by the end of 2020, 90 percent of all Potentially Hazardous Objects (PHOs) greater than 140m whose orbits pass within 0.05 AU of the Earth's orbit (as opposed to surveying for all NEOs).*
- *The Agency could achieve the specified goal of surveying for 90 percent of the potentially hazardous NEOs by the end of 2020 by partnering with other government agencies on potential future optical ground-based observatories and building a dedicated NEO survey asset assuming the partners' potential ground assets come online by 2010 and 2014, and a dedicated asset by 2015.*
- *Together, the two observatories potentially to be developed by other government agencies could complete 83 percent of the survey by 2020 if observing time at these observatories is shared with NASA's NEO Survey Program.*
- *New space-based infrared systems, combined with ground-based assets, could reduce the overall time to reach the 90 percent goal by at least three years. Space systems have additional benefits as well as costs and risks compared to ground-based alternatives.*
- *Radar systems cannot contribute to the search for potentially hazardous objects, but may be used to rapidly refine tracking and to determine object sizes for a few NEOs of potentially high interest. Existing radar systems are currently oversubscribed by other missions.*
- *Determining a NEO's mass and orbit is required to determine whether it represents a potential threat and to provide required information for most alternatives to mitigate such a threat. Beyond these parameters, characterization requirements and capabilities are tied directly to the mitigation strategy selected."*

The NASA report also describes the general advantages and disadvantages of using ground versus space-based search systems and analyzes an approach that includes a combination of ground-based and space-based NEO search capabilities:

- *Ground-based Optical Systems.* Ground-based telescopes are relatively easy to maintain and offer the flexibility for upgrades. They are limited by their nighttime or early morning viewing periods as well as the atmosphere's effects on observations.
- *Space-Based Optical Systems.* These systems can take advantage of proven space technologies, are not restricted in viewing hours and atmospheric interference, and can observe objects in inner Earth orbits or orbits similar to Earth's more easily than can ground-based systems. Space-based survey approaches however require access to space, data downlinks, and replacement spacecraft.

- *Space-Based Infrared Systems.* The technology for space-based infrared systems is less mature than space-based optical technology, however the infrared systems would require smaller aperture telescopes and could provide greater accuracy on the sizes of NEOs they detect.

The NASA report suggests that the goals of the Congressionally-mandated survey could be met by acquiring shared access to a proposed ground-based NSF/DOE, telescope system, the Large Synoptic Survey Telescope (LSST) and a potential Air Force telescope system, the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS). In addition, this exemplar search program would require an additional LSST-type telescope dedicated to the NEO survey effort.

LSST is proposed as a large-aperture, wide-field telescope. According to literature from the LSST project, the telescope will *"Conduct a survey over an enormous volume of sky; do it with a frequency that enables repeat exposures of every part of the sky every few nights in multiple colors; and continue this mode for ten years to achieve astronomical catalogs thousands of times larger than have ever previously been compiled."* LSST was recommended as a high priority initiative in the 2001 National Academies Astronomy and Astrophysics Decadal Survey. In addition, the 2003 National Academies Solar System Exploration Survey included the following recommendation: *"The SSE* [Solar System Exploration] *Survey recommends that NASA partner equally with the National Science Foundation to design, build, and operate a survey facility, such as the Large Synoptic Survey Telescope (LSST). . .to ensure that LSST's prime solar system objectives are accomplished"* LSST has not yet been approved as new project start by the National Science Foundation.

The Director of the LSST project is expected to testify that LSST could complete the mandated survey within 12 years from the start of the telescope operations. This goal would involve modifications to the observing strategy and to the data processing procedures. The LSST project estimates that the cost of an LSST NEO survey over 12 years would be about $125M.

Pan-STARRS is being developed by the University of Hawaii with funding from the U.S. Air Force. A main goal of Pan-STARRS is to detect potentially hazardous objects. Pan-STARRS is planned to be a system of four individual telescopes that will survey large areas of the sky at a high degree of sensitivity. The prototype one-mirror Pan-STARRS telescope is complete; a full four-telescope system has not yet been approved.

The NASA report to Congress also indicates that by using a space-based infrared telescope [along with the LSST and Pan-STARRS systems], NASA could exceed the mandated requirement and detect an estimated 90 percent of the PHO population by 2017.

An additional capability that could be brought to bear on the NEO survey task is NASA's Wide-field Infrared Survey Explorer (WISE), which is scheduled for launch in 2009. The WISE spacecraft will survey the sky in the infrared band at high sensitivity. Asteroids, which absorb solar radiation, can be observed through the infrared band. NASA officials told Committee staff that NASA plans to use WISE to detect NEOs, in addition to performing its science goals. NASA expects that WISE could detect 400 NEOs [or roughly two percent of the estimated NEO population of interest] within the spacecraft's six month—one year mission.

It should be noted that the National Academies' 2001 report *New Frontiers in the Solar System* [the solar system exploration decadal survey] commented on the potential value of ground-based observatories for detecting near-Earth objects: *"The SSE Survey's Primitive Bodies Panel endorses the concept of a large telescope capable of an all-sky search strategy that would reveal large numbers of near-Earth objectsalso endorses a telescope that would enable the physical study of such objects by spectroscopic and photometric techniques. The panel heard recommendations for the Large Synoptic Survey Telescope (LSST) and the Next Generation Lowell Telescope (NGLT). . .Other options, including the Panoramic Optical Imager concept, should be explored and a choice made that NASA can support in the next decade.*

According to the NASA report to Congress, once a NEO is identified, further characterization of its mass and orbit are required to *"assess the threat"* as required in the Act. Characterization involves observations that provide details on an object's structure, whether it is a single or binary NEO, its porosity, rotation rate, composition, and surface features. NASA's report to Congress discusses the need to characterize an object to inform decisions on mitigation.

According to NASA officials, characterization is usually focused on those objects that are identified as posing a potential threat. Both optical and radar ground-based systems can be used, however radar provides precise orbital determinations more quickly than optical systems. A dedicated in-situ mission to observe the object would provide the greatest detail on the character of the object and, according to the NASA report to Congress, help to *"confirm the probability of impact and characterize the potential threat if deflection is necessary."*

The report presents two broad strategies for diverting asteroids from a collision path with Earth. "Impulsive" options would involve the use of conventional or nuclear explosives and have immediate results. "Slow push" options would achieve deflection results over a period of time.

- *"Impulsive"* options include:
    - Surface conventional explosive (detonating on impact)
    - Subsurface conventional explosive
    - Standoff nuclear explosive (detonate on flyby with proximity fuse)
    - Surface nuclear explosive (detonate via impact with surface fuse)
    - Delayed nuclear explosive (surface lander, detonate at chosen time)
    - Subsurface nuclear explosive
    - Kinetic impact (high speed impact)
- *"Slow push"* approaches include:
    - Focused solar (focused beam to burn-off surface material)
    - Pulsed laser (rendezvous mission that burns-off material using laser)
    - Mass driver (rendezvous mission mines and ejects material)
    - Gravity tractor (large rendezvous mission flies in proximity to "pull" object off course)
    - Asteroid tug (rendezvous mission attaches to and pushes object)
    - Heating of surface material

The report includes the following findings on deflection alternatives:

- *"Nuclear standoff explosions are assessed to be 10-100 times more effective than the non-nuclear alternatives. . .. Other techniques involving the surface or subsurface of nuclear explosions may be more efficient, but they run the risk of fracturing the target NEO. They also carry higher development and operations risks.*
- *Non-nuclear kinetic impactors are the most mature approach and could be used in some deflection/mitigation scenarios, especially for NEOs that consist of a single, small solid body.*
- *"Slow push" mitigation techniques are the most expensive, have the lowest level of technical readiness, and their ability to both travel to and divert a threatening NEO would be limited unless mission durations of many years to decades are possible.*
- *30–80 percent of potentially hazardous NEOs are in orbits that are beyond the capability of current or planned launch systems. Therefore, planetary gravity assist swing-by trajectories or on-orbit assembly of modular propulsion systems may be needed to augment launch vehicle performance, if these objects need to be deflected."*

Critics of NASA's analysis of deflection options argue that NASA's report focuses on atypical asteroid threats rather than the objects of size ranges that have a much higher probability of actually impacting the Earth. They argue that NASA's focus on the less likely scenarios results in a set of deflection requirements that are skewed towards nuclear explosives. If the focus would be placed on addressing the deflection requirements of the smaller, more common PHOs, the critics of NASA's analysis would assert that *"over 99 percent of them can be deflected using non-nuclear means."* One of the witnesses at the hearing, Mr. Russell "Rusty" Schweickart, will discuss issues related to NASA's analysis of deflection options, as well as identify what he believes are serious technical flaws in NASA's report to Congress.

Planetary Radar Facilities

Arecibo Observatory

The Arecibo Observatory in Puerto Rico, which has been described as *"the largest and most sensitive"* ground-based radar telescope on Earth, has been used to reduce the uncertainty of NEO collision estimates and refine the time period of when a NEO may pass near Earth. In addition, radar observations are more precise than data from optical telescopes in identifying details on the mass, shapes, trajectories, sizes, and on whether the NEO is a single object or part of a binary system. In 2005, Arecibo observations improved the estimates of the trajectory for the object, Apophis, which is on a path that will take it close to Earth in 2029. Research using the Arecibo Observatory also helps improve our understanding of how solar radiation influences near-Earth objects.

Arecibo is operated by Cornell University under a cooperative agreement with the National Science Foundation. A 2006 independent review of all NSF ground-based astronomy facilities recommended that *"The National Astronomy and Ionosphere Center [Arecibo Observatory] . . .should seek partners who will contribute personnel or financial support to the operation of Arecibo. . . by 2011 or else these facilities should be closed."* At present, the planetary radar facility at Arecibo is funded through FY 2008. Funding beyond that date is uncertain.

NASA's Goldstone Deep Space Tracking Station

The only planetary radar facility other than Arecibo is NASA's Goldstone Deep Space Tracking Station in Goldstone, California. Goldstone is less sensitive than Arecibo, however its steerable antenna allows it to see a larger portion of the sky. NASA is planning to replace the current Deep Space Network antennas and is looking at a number of options, including phased array antennas. The current replacement options do not appear to provide a planetary radar capability comparable to that of the existing Goldstone facility.

The 2003 National Academies Solar System Exploration Survey report contained the following recommendation: *"In addition, NASA should continue to support ground-based observatories for planetary science, including the planetary radar capabilities at the Arecibo Observatory in Puerto Rico and the Deep Space Network's Goldstone facility in California. . .as long as they continue to be critical to missions and/or scientifically productive. . ."*

NEO Contributions to Science, Human Exploration, and Resource Utilization

The NASA report notes that an increased search for and characterization of NEOs will benefit scientific discovery and study of Kuiper Belt Objects, as well as in determining whether certain comets originated in the Kuiper Belt. Further data on NEOs could also provide information that could be used to consider extracting and using asteroid resources and for considering a potential human mission to an asteroid. A 1998 National Academies Report on *The Exploration of Near-Earth Objects* notes that:

> *"Although it would be difficult to justify human exploration of NEOs on the basis of cost-benefit analysis of scientific results alone, a strong case can be made for starting with NEOs if the decision to carry out human exploration beyond low Earth orbit is made for other reasons. Some NEOs are especially attractive targets for astronaut missions because of their orbital accessibility and short flight duration. Because they represent deep space exploration at an intermediate level of technical challenge, these missions would also serve as stepping stones for human missions to Mars. Human exploration of NEOs would provide significant advances in observational and sampling capabilities."*

NEO-Related Activities at the United Nations

The United Nation's Committee on the Peaceful Uses of Outer Space (COPUOS), Scientific and Technical Subcommittee has discussed and considered the issue of NEOs. In 2006, the subcommittee established a Working Group on Near-Earth Objects to focus on the issue over the 2006–2007 timeframe and also formed an Action Team. Over the next one to two years, the subcommittee plans to continue to obtain reports on NEO activities and to address the need for more international coordination on observations and follow-up studies. The subcommittee also plans to work on international procedures for handling NEO threats.

Space Science Missions to Comets and Asteroids

In addition to its ground-based Spaceguard Survey program, NASA and non-U.S. space agencies have launched, or are planning to undertake a number of space science missions to study asteroids and comets. NASA's report to Congress notes that information gained from these missions benefits the agency's current NEO program. A number of past, current, and future missions of note include:

- NASA's Near-Earth Asteroid Rendezvous (NEAR) mission, launched in 1996, flew by two asteroids and studied one, Eros;
- The Stardust mission collected dust samples from comet Wild 2;
- Deep Impact, launched in 2004, penetrated comet Tempel 1;

- The Dawn mission, launched in late September 2007 is en route to study, Ceres and Vesta, two of the largest known asteroids located in the main asteroid belt between Mars and Jupiter;
- Japan's Hayabusa mission had the objective of collecting a sample from the near-Earth asteroid Itokawa, and the sample carrier is en route back to Earth; and
- The European Space Agency's Rosetta mission to comet Churymov-Gerasimenko in late 2014 will rendezvous with and land on the comet.
- In addition, the European Space Agency has conducted studies on a potential space mission that could test and validate technologies for deflecting an asteroid.

Chairman UDALL. Good morning. This hearing will come to order. I would like to extend a particular welcome to our witnesses, and in particular, recognize Congressman Luis Fortuño's presence here with us today.

As many of you may recall, today's hearing on Near-Earth Objects was originally scheduled for October 11, but we postponed it in the wake of our good friend Rep. Jo Ann Davis' untimely death.

Thus, before we proceed any further, I would like to express my appreciation to each of the witnesses for your willingness to accommodate that postponement, and appear before us today. Your testimony will be invaluable to us as we consider how best to proceed in getting a better understanding of the potential threats of Near-Earth Objects, NEOs, as well as options for dealing with them.

Today's hearing is the latest in a series that stretches back to the early 1990s. We have come a long way since the late George Brown, former Chairman of the Science and Technology Committee, led the first efforts to focus Congressional attention on the potential threat posed by Near-Earth asteroids and comets.

It has been a bipartisan effort over the intervening years, and a lot has been accomplished. In that regard, I want in particular to salute the dedication of Mr. Rohrabacher in pushing for continued federal initiatives to detect, track, and catalog NEOs, as well as to examine ways to deflect them if necessary. He has been an effective catalyst for action, and I look forward to continuing to work with him on this issue.

As we will hear from our witnesses, much progress has been made in detecting and cataloging the largest NEOs over the last decade. However, as we will also hear, much more remains to be done. In particular, we need to survey potentially hazardous asteroids that are smaller than the ones cataloged to date, but which could do significant damage if they impact or explode above the Earth's surface near populated areas.

That is why Congress directed NASA to "plan, develop, and implement" a NEO survey program for objects as small as 140 meters in size, in the *NASA Authorization Act of 2005.* As a result, I am disappointed and concerned that NASA's report to Congress failed to provide a recommended option and budget plan for such a survey, as directed by the Act. In fact, the report says NASA has no plans to do anything beyond the current Spaceguard program at this time.

Equally troubling, one of the NASA witnesses will testify that "NASA would be pleased to implement a more aggressive NEO program, if so directed by the President and Congress," with the implication that Congress has not yet done so. I believe section 321 of the *NASA Authorization Act,* which I quoted earlier, is unambiguous. Congress, in fact, has directed NASA to "plan, develop, and implement" such a program, and we would hope that the President would send over a NASA budget request that reflects that Congressional direction.

Today, I want to focus on where we go from here. Given the lack of a clear plan in NASA's report to Congress, I hope that our witnesses today will be able to provide some guidance to the Committee on the best and most cost-effective path forward for meeting the goal of surveying NEOs down to 140 meters in size. In that regard, there are a number of related questions that need to be addressed.

First, I would like to hear from each of the witnesses about the planetary radar capabilities at Arecibo and Goldstone. How important are they to addressing the NEO task? Second, how can we make the most effective use of capabilities being planned or developed by other federal agencies, such as LSST and Pan-STARRS, and what role should NASA play in supporting them?

NASA's testimony indicates that it has been providing funds to the Air Force's Pan-STARRS project, so that it will be capable of providing data on NEO detections. That is an interesting development, and it raises the question of whether NASA should also be providing funds to other facilities, such as Arecibo, and the proposed LSST project, if doing so will materially contribute to meeting the NEO survey objectives in a responsible, cost-effective manner.

Third, I would like to know if there are adjustments to either the timetable or scope of the NEO survey called out in the *NASA Authorization Act* that would make sense, either by allowing more cost-effective approaches on a slightly longer timetable, or by focusing on just potentially hazardous objects, rather than on all NEOs.

Fourth, surveying NEOs is just part of the task. If we find one that is headed towards Earth, we will need to have good options for deflecting it. What priorities should be given to developing deflection technologies versus NEO survey systems in the coming years?

And finally, the potential threat posed by Near-Earth Objects is not isolated to the United States. What contributions are other national and international bodies making to the effort? Should more be done?

Well, as you can see, we have a lot to consider today. Fortunately, we have a very distinguished set of witnesses to assist us in our oversight task, and I again want to welcome all of you, and I look forward to your testimony.

At this point, the Chair now recognizes my friend, the Ranking Member, Mr. Feeney from Florida, for his opening remarks.

[The prepared statement of Chairman Udall follows:]

PREPARED STATEMENT OF CHAIRMAN MARK UDALL

Good morning. I'd like to extend a welcome to our witnesses and in particular recognize Congressman Luis Fortuño's presence here with us today.

As many of you may recall, today's hearing on Near-Earth Objects was originally scheduled for October 11th, but we postponed it in the wake of Rep. Jo Ann Davis's untimely death. Thus, before we proceed any further, I'd like to express my appreciation to each of the witnesses for your willingness to accommodate that postponement and appear before us today.

Your testimony will be invaluable to us as we consider how best to proceed in getting a better understanding of the potential threats posed by Near-Earth Objects—NEOs, as well as options for dealing with them.

Today's hearing is the latest in a series that stretches back to the early 1990s. We have come along way since the late George Brown—former Chairman of the Science and Technology Committee—led the first efforts to focus congressional attention on the potential threat posed by Near Earth asteroids and comets. It has been a bipartisan effort over the intervening years, and a lot has been accomplished.

In that regard, I in particular want to salute the dedication of Mr. Rohrabacher in pushing for continued federal initiatives to detect, track, and catalog NEOs, as well as to examine ways to deflect them if necessary. He has been an effective catalyst for action, and I look forward to continuing to work with him on this issue.

As we will hear from our witnesses, much progress has been made in detecting and cataloging the largest NEOs over the last decade. However—as we will also hear—much more remains to be done.

In particular, we need to survey potentially hazardous asteroids that are smaller than the ones cataloged to date, but which could do significant damage if they impact or explode above the Earth's surface near populated areas. That is why Congress directed NASA to *"plan, develop, and implement"* a NEO survey program for objects as small as 140 meters in size in the NASA Authorization Act of 2005.

As a result, I'm disappointed and concerned that NASA's report to Congress failed to provide a recommended option and budget plan for such a survey, as directed by the Act. In fact, the report says NASA has no plans to do anything beyond the current Spaceguard program at this time.

Equally troubling, one of the NASA witnesses will testify that *"NASA would be pleased to implement a more aggressive NEO program if so directed by the President and Congress,"*—with the implication that Congress has not yet done so. I think Sec. 321 of the *NASA Authorization Act,* which I quoted earlier, is unambiguous—Congress has in fact directed NASA to *"plan, develop, and implement"* such a program. And we would hope that the President would send over a NASA budget request that reflects that congressional direction.

Today, I want to focus on where we go from here. Given the lack of a clear plan in NASA's report to Congress, I hope that our witnesses today will be able provide some guidance to this committee on the best and most cost-effective path forward for meeting the goal of surveying NEOs down to 140 meters in size.

In that regard, there are a number of related questions that need to be addressed. First, I'd like to hear from each of the witnesses about the planetary radar capabilities at Arecibo and Goldstone. How important are they to addressing the NEO task?

Second, how can we make the most effective use of capabilities being planned or developed by other federal agencies, such as LSST and Pan-STARRS, and what role should NASA play in supporting them? NASA's testimony indicates that it has begun providing funds to the Air Force's Pan-STARRS project *"so that it will be capable of providing data on NEO detections. . ."*

That's an interesting development, and it raises the question of whether NASA should also be providing funds to other facilities such as Arecibo and the proposed LSST project if doing so will materially contribute to meeting the NEO survey objectives in a responsible, cost-effective manner.

Third, I'd like to know if there are adjustments to either the timetable or scope of the NEO survey called out in the *NASA Authorization Act of 2005* that would make sense—either by allowing more cost-effective approaches on a slightly longer timetable or by focusing on just potentially hazardous objects rather than on all NEOs.

Fourth, surveying NEOs is just part of the task. If we find one that it is headed towards Earth, we will need to have good options for deflecting it. What priority should be given to developing deflection technologies versus NEO survey systems in the coming years?

Finally, the potential threat posed by Near-earth objects is not isolated to the United States. What contributions are other national and international bodies making to the effort? Should more be done?

Well, as you can see, we have a lot to consider today. Fortunately, we have a very distinguished set of witnesses to assist us in our oversight task.

I again want to welcome all of you, and I look forward to your testimony.

Mr. FEENEY. Well, thank you, Mr. Chairman, and I appreciate you calling this morning's hearing, although I did tell you as I greeted you this morning that this is just one more thing for us to worry about, that hadn't been on my list until a couple weeks ago, when I saw the original notice of hearing.

And I want to echo your remarks. We are very grateful to the witnesses, because we had to reschedule the hearing on short notice, and we thank you, and we are very appreciative that you are here today, so that we can accommodate that emergency change.

NASA's Near-Earth Object program, though very modest in scale compared to many of the agency's multi-billion dollar endeavors, is vitally important, and NASA has been doing an exemplary job standing up an office and managing the Nation's and world's only survey for potentially hazardous Earth-crossing asteroids and comets. I find it distressing that other nations haven't, to date, taken a more active role, and I note that we have some visitors from Germany here today. We are very grateful for their interest.

NASA began the NEO survey, called the Spaceguard program, in 1998, and I note that my colleague, Dana Rohrabacher, who is here, was instrumental in advocating that, with the goal of detecting and cataloging 90 percent of all potentially hazardous asteroids and comets larger than one kilometer in diameter within a decade, and it appears to be relatively on track to meet that target. Subsequently, a 2003 NASA-chartered team of scientists recommended that the survey seek all NEOs of 140 meters in diameter or larger, reasoning that the smallest of these could still inflict large regional impacts if they struck the Earth.

Their recommendations were made part of the 2005 NASA authorization legislation, directing NASA to "plan, develop, and implement a Near-Earth Object survey program to detect, track, catalog, and categorize Near-Earth Objects equal to or greater than 140 meters in diameter."

The goal was to get 90 percent completion within 15 years. This change in mission is no small matter. As the universe of potentially hazardous objects, PHOs, to be detected and cataloged increased by a factor of 20, from 1,000 to approximately 20,000. The bill also required NASA to complete an analysis of alternatives to meet this ambitious goal, and to report back with a recommended option. NASA provided such a report earlier this year, but did not indicate a preferred choice, instead urging the current Spaceguard program be allowed to continue its survey for one kilometer and larger Near-Earth Objects, that will allow the agency to take advantage of opportunities using potential dual use telescopes and spacecraft to achieve the goals outlined in the 2005 authorization.

Although the 15-year timeline may not be met in all cases, NASA's rationale is purely budget-driven, arguing that current resources are too constrained. While disappointed, I certainly can't disagree or argue with their reasoning.

At this morning's hearing, it is my hope that we get a clearer understanding of NASA's plans to proceed with utilizing dual use telescopes and spacecraft, their potential costs and schedules, and other facilities that may be utilized, including the Arecibo Observatory.

I hope to hear concrete steps taken by NASA to develop cooperative relationships necessary to ensure the requirements laid out in the 2005 NASA authorization are met. We will also hear about the future of the Arecibo Radio Observatory in Puerto Rico, the largest and most powerful such facility in the world. Arecibo is operated by the Cornell University under a contract with the National Science Foundation (NSF). It appears very likely that NSF will significantly reduce its financial support, such that Arecibo will have to shut down its radar facility. This, I think, would be a mistake. Arecibo has the capability of making very precise orbital calculations in a short amount of time, a critical feature that optical telescopes simply cannot match. And the sum of money at stake is on the order of several million dollars a year, an investment I think is well worth the return. While NSF may be outside the purview of this subcommittee, the ramifications of Arecibo's loss to the NEO program begs the discussion.

I want to first welcome my good friend, Luis Fortuño, to today's hearing. I want to also thank all of our guests once again, express my appreciation for changing their schedule to accommodate our schedule, and I want to thank my Chairman, Mr. Udall, and with that, look forward to the discussion.

[The prepared statement of Mr. Feeney follows:]

PREPARED STATEMENT OF REPRESENTATIVE TOM FEENEY

Thank you, Mr. Chairman, for calling this morning's hearing. And I want to echo Mr. Udall's comments, acknowledging that our originally scheduled hearing was postponed on very short notice. I greatly appreciate that all of our scheduled witnesses were able to accommodate the date change, and I hope notice got out quickly enough to save you from unnecessary travel.

NASA's Near-Earth Object (NEO) program, though very modest in scale compared to many of the agency's multi-billion dollar endeavors, is vitally important, and NASA has been doing an exemplary job standing-up an office and managing the Nation's—and world's—only survey for potentially hazardous Earth-crossing asteroids and comets. I find it distressing that other nations haven't, to date, taken a more active role.

NASA began the NEO survey, called the "Spaceguard" program, in 1998 with the goal of detecting and cataloguing 90 percent of all potentially hazardous asteroids and comets larger than one kilometer in diameter within a decade, and it appears to be on track to meet that target.

Subsequently, in 2003 a NASA-chartered team of scientists recommended that the survey seek all NEOs of 140 meters in diameter or larger, reasoning that the smallest of these could still inflict large regional impacts if they struck Earth. Their recommendations were made part of the 2005 NASA authorization legislation, directing NASA to "plan, develop and implement a Near-Earth Object Survey program to detect, track, catalogue, and characterize. . .near-Earth objects equal to or greater than 140 meters in diameter. . .," with the goal of 90 percent completion within 15 years. This change in mission is no small matter, as the universe of potentially hazardous objects (PHOs) to be detected and catalogued increased by a factor of twenty (from 1000 to 20,000). The bill also required NASA to complete an analysis of alternatives to meet this ambitious goal and to report back with a recommended option.

NASA provided such a report earlier this year but did not indicate a preferred choice, instead urging the current "Spaceguard" program be allowed to continue its survey for 1 kilometer and larger near-Earth objects, and to allow the agency to take advantage of opportunities using potential dual-use telescopes and spacecraft to achieve the goals outlined in the 2005 authorization, although the 15 year timeline may not be met in all cases. NASA's rationale is purely budget driven, arguing that current resources are too constrained. While disappointed, I certainly can't disagree with their reasoning.

At this morning's hearing, it is my hope that we get a clearer understanding of NASA's plans to proceed with utilizing dual-use telescopes and spacecraft, their potential costs and schedules, and other facilities that may be utilized, including the Arecibo Observatory. I hope to hear of concrete steps being taken by NASA to develop cooperative relationships necessary to ensure the requirements laid out in the 2005 NASA authorization are met.

We'll also hear about the future of the Arecibo Radio Observatory in Puerto Rico, the largest and most powerful such facility in the world. Arecibo is operated by Cornell University under a contract with the National Science Foundation (NSF). It appears very likely NSF will significantly reduce its financial support such that Arecibo will have to shut down its radar facility. This, I think, would be a mistake. Arecibo has the capability of making very precise orbital calculations in a short amount of time, a critical feature that optical telescopes cannot match. And the sum of money at stake is on the order of about $2 million a year, an investment that I think is well worth the return. While NSF may be outside the purview of this subcommittee, the ramifications of Arecibo's loss to the NEO program begs the discussion.

I want to welcome my friend, Rep. Fortuño, to today's hearing. I also want again to say thanks to our excellent panel of expert witnesses for taking time from their busy schedules to be here.

Thank you, Mr. Chairman.

Chairman UDALL. Thank you, Congressman Feeney. If there are Members who wish to submit additional opening statements, your statements will be added to the record. Without objection, so ordered.

And in addition, I would also like to include a statement for the record from the Planetary Society into today's hearing. Without objection, so ordered. [*See Appendix 2: Additional Material for the Record.*]

At this time, I would like to go ahead and recognize our first panel. And we are delighted to have Representative Luis Fortuño, the Resident Commissioner of Puerto Rico, with us here today, who will be testifying, I think, before the Committee for the first time.

Congressman Fortuño, the floor is yours.

Panel 1

STATEMENT OF REPRESENTATIVE LUIS FORTUÑO, RESIDENT COMMISSIONER, PUERTO RICO

Mr. FORTUÑO. Thank you. Thank you, Mr. Chairman. Chairman Udall, Ranking Member Feeney, distinguished Members of this subcommittee.

Every day, an enormous quantity of cosmic material falls to the Earth. Most burn up on reentry in a harmless way. However, NASA predicts that more than 20,000 large, potentially dangerous objects pass by the Earth in close proximity, and given the proper circumstance, could threaten or severely impact our existence. Although the chances of a major impact are slim, the consequences are too great to disregard.

I believe we should continue to advance our knowledge of Near-Earth Objects and their potential consequences for life on Earth. I commend Congressman Rohrabacher on his effort to continue funding for Near-Earth Objects surveillance programs. Since 1992, the Spaceguard program's goal was to discover 90 percent of the NEOs with one kilometer diameter potential by 2008. Although the success of this program will be substantial, there will still be thousands of objects, ranging from 200 to 500 meters in diameter, that will be overlooked. We must enhance our understanding of this phenomenon by studying and assessing the threats posed to our environment and to our national security.

According to Director Michael Griffin, NASA does not have the funds to carry out a more extensive program. There have been suggestions that NASA and the National Science Foundation should cooperate to fund the construction of a new ground-based telescope to perform tracking functions of Near-Earth Objects and other astronomy surveys. I do not think we need to take on such a burden, when there is still a great deal of information to be gained by utilizing the unique capabilities of the Arecibo Observatory in Puerto Rico.

As the world's largest and most powerful radio telescope, the Arecibo Observatory is essential to monitoring and surveying NEOs. However, the National Science Foundation has threatened to close the observatory in 2011, and NASA has, so far, been unwilling to assume funding of the radar required for tracking NEOs.

Closing the observatory will severely limit our ability to quickly and accurately refine the orbits of newly emerging threats, and reduce our monitoring capabilities.

This is why I have introduced H.R. 3737, which directs the National Science Foundation and NASA to work together to ensure continued full funding of the Arecibo Observatory, and in particular, the radar. It is my recommendation and the recommendation of 19 of my colleagues, that these agencies start working in collaboration and reconsider how they allocate their funding.

Mr. Chairman and Ranking Member Feeney, the Arecibo Observatory's radar is the world's most powerful instrument for post-discovery characterization and orbital refinement of Near-Earth asteroids. Observations performed with the radar are critical for identifying asteroids that might be on a collision course with Earth.

I respectfully urge the Committee to consider continuing the important work performed by the Arecibo observatory, and consider, as well, H.R. 3737, as one potential solution to this challenge. The unique capabilities of radar are critically important as we work towards fulfilling the 2005 Congressional mandate of detecting and characterizing 90 percent of NEOs down to 140 meters in diameter.

A potentially dangerous collision of an asteroid or comet is a very real threat. We must take action now to enhance our awareness to prevent a catastrophe. A better understanding of our skies will not only help us to comprehend the wonders of the Earth's environment, but is essential to assessing the dangers that may threaten our society.

The world's most sensitive radio telescope at Arecibo Observatory must not be closed. By the way, we don't have final numbers, but NSF is determining the cost of dismantling this facility and bringing the area back to a greenfield, but it is around $200 million. We are dealing with a $4 million gap a year, so the numbers are certainly there as well.

Mr. Chairman and Ranking Member Feeney, thank you for the opportunity to provide my views on this issue. I will now ask permission to show, in the Committee's flatscreen, some images of the Arecibo Observatory, that would help understand the size and magnitude of this extraordinary science resource.

Chairman UDALL. Please proceed.

Mr. FORTUÑO. Thank you.

That is an aerial picture of the radio telescope. As you see, it is embedded in a number of mountains. That is another angle. It is a massive facility. It really is.

It is visited every year by 300,000 people, 25,000 of them are K–12 students. That is it.

Thank you again, Mr. Chairman.

[The prepared statement of Mr. Fortuño follows:]

PREPARED STATEMENT OF CONGRESSMAN LUIS G. FORTUÑO

Chairman Udall and Ranking Member Feeney,

Every day an enormous quantity of cosmic material falls to the Earth. Most burns up on re-entry in a harmless way, however NASA predicts that more than 20,000 large, potentially dangerous objects pass by the Earth in close proximity and, given the proper circumstance could threaten or severely impact our existence. Although the chances of a major impact are slim, the consequences are too great to disregard.

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This is why I have introduced H.R. 3737, which directs the National Science Foundation and NASA to work together to ensure continued full funding of the Arecibo Observatory and in particular, the radar. It is my recommendation that these agencies start working collaboratively and reconsider how they allocate their funding.

Mr. Chairman and Ranking Member Feeney, the Arecibo Observatory's radar is the world's most powerful instrument for post-discovery characterization and orbital refinement of near-Earth asteroids. The observations performed with the radar are critical for identifying asteroids that might be on a collision course with Earth. I respectfully urge the Committee to consider continuing the important work performed by the Arecibo Observatory and consider, as well, H.R. 3737 as one potential solution to this challenge. The unique capabilities of radar are critically important as we work towards fulfilling the 2005 congressional mandate of detecting and characterizing 90 percent of near-Earth Objects down to 140 meters in diameter.

A potentially dangerous collision of an asteroid or comet is a very real threat. We must take action now to enhance our awareness to prevent a catastrophe. A better understanding of our skies will not only help us to comprehend the wonders of the Earth's environment, but is essential to assessing the dangers that may threaten our society. The world's most sensitive radio/radar telescope at Arecibo Observatory must not be closed.

Mr. Chairman and Ranking Member Feeney, thanks for the opportunity to provide my views on this issue.

DISCUSSION

Chairman UDALL. Thank you, Resident Commissioner Fortuño. This testimony has been very helpful, and I want to pay particular note to the costs that might be involved in decommissioning this site, and we look forward to getting firmer numbers, because the obvious argument would be you would take the money that would be used in decommissioning the site, and actually operate it for a certain number of years or even decades into the future.

At this time, I would be happy to recognize Mr. Feeney, if he has any questions for his colleague, Mr. Fortuño.

IMPACT OF SHUTTING DOWN ARECIBO

Mr. FEENEY. Well, thank you, Mr. Chairman, and thank you for your testimony, Congressman. You know, as I read through the materials and the different NSF and NASA projections, and discussion of this important issue, all of them suggest that Arecibo is very important to our capabilities.

Any decision to close it down seems to be purely budget-driven, and so that I hope, as we get the numbers and the estimates for what it would cost, and what the impact would be of shutting it down, that you will immediately provide this committee, and also, the Committee with jurisdiction over NSF, with those numbers. Because if this is entirely cost-driven, then we need to, as we are understanding the advantages that everybody acknowledges, we also need to know that the, of keeping it open, that the disadvantages of closing it also will have a significant cost many, many times what it costs on an annual basis to keep it alive.

Our next panel includes some very distinguished witnesses. One of them, for example, Mr. Yeomans' testimony will tell us that Arecibo and Goldstone complement one another and provide two very different functions. That is very important, because while the one telescope is capable of identifying Near-Earth Objects that may be a threat, it is Arecibo that helps us determine the exact threat to the Earth. And the fascinating thing is that we have the capability with Arecibo, at least with the large objects that we have now proceeded to catalog, and we are very near our goal, or at least we are on track. Mr. Yeomans will testify that once we find the vast majority of them, they can be tracked, cataloged, and then ruled out or in as threats during the next 100 years or so.

I think the people of the world would be very grateful to know, especially with 100 years notice, that there may be a catastrophe, driven by a Near-Earth Object. But most importantly, we have the technological capabilities to actually deflect or to eliminate the damage with that type of notice, and again, Mr. Yeomans and our other witnesses will testify to that.

So, Mr. Fortuño, I know that Congressman Rohrabacher had a question. I wanted to yield a few minutes to him, but if you could tell us the impact, because probably uniquely you are able to tell us this question, the impact on Puerto Rico if we shut Arecibo down, in the next year or two, what the local impact would be. We will get to the technical experts. I had assumed you are not an astrophysicist. Neither am I. Don't feel bad about that. Go ahead and tell us the impact on Puerto Rico.

Mr. FORTUÑO. Thank you, and thank you for your comments. Certainly. The impact, we are estimating that it will be about $50 million for the Arecibo area, actually. On top of that, the impact on those kids that may have an interest in science and technology, that will not be able, otherwise, to visit a facility like this one. If I may add, the Arecibo radio astronomy led to the first discovery of a planet outside of our own solar system, to the first discovery of a binary pulsar, resulting in a Nobel Prize, and the first detailed, three dimensional mapping of how galaxies are distributed in the universe.

So, it is really, from the scientific point of view, it will be priceless to our young students, that have an interest in this area.

GEORGE BROWN

Mr. FEENEY. Any remaining time, I would be pleased to yield to Congressman Rohrabacher.

Mr. ROHRABACHER. Thank you very much. And thank you, Mr. Chairman, for your kind words, and bipartisan words, and holding the hearing. I can't help but notice George Brown's picture right back there. I don't know how many people in this room knew George Brown. I knew him. He was the Chairman here when I came here 20 years ago, and he was a wonderful human being. He was a man of integrity, and I am very pleased that some of the work that I have done in this area actually bore the name of George Brown, because he was just a fine person, and had that very same bipartisan spirit that Mr. Udall has been trying to demonstrate here today.

And hopefully, when we are talking about things that might threaten the entire planet, that may well motivate Congress to be bipartisan, if nothing else does. I mean, after all, it is just the entire planet that may be destroyed. But George Brown really gave me personal guidance, and his integrity was very much appreciated.

IMPORTANCE OF ARECIBO WITH REGARD TO COST

When we are talking about Arecibo, I want to, of course, recognize the hard work that Congressman Fortuño is actually putting into this effort. It is a heroic effort. I am very pleased to be assisting him. But of course, we are not trying to do anybody any favors here. This isn't an issue of doing anyone a favor.

First and foremost, the Arecibo telescope is doing work currently that would cost us more, even outside of the area of Near-Earth Objects. Even outside the area of Near-Earth Objects, the Arecibo telescope is doing work that would be more costly to do if, for example, we would send satellites. I understand we sent a mission to Venus that cost a certain amount of money, but the actual images that we got back from Arecibo were better than sending the probe up to Venus. Now, how much did that cost us? I mean, it probably cost us enough to keep Arecibo going for a decade.

And clearly, also, when you look at the shutdown costs, which has been mentioned here, if you take all of that together, well, you could probably put that in the bank, and the interest on that money would probably keep the Arecibo telescope going. And this exemplifies sort of the screwball nature of the way we do business up here on Capitol Hill sometimes. And if we let this asset be set aside and closed down, it would be a tragedy, but also, as I say, very symbolic of the fact that we can't even do our job in Capitol Hill enough to take a very cost-effective asset, and something that is doing a mission that is vitally important to our security, that we can't even get ourselves together enough to get a limited amount of money to keep that project going. So, I think this is very symbolic, and that we should all be working together on this, and we are working on this.

Just a question. Now, you mentioned the kids that there are, and you mentioned how this would affect your economy. Tell me, if we didn't know that a Near-Earth Object was coming, and thus, one snuck by and landed in the Caribbean, would it be possible that Puerto Rico would be wiped out?

Mr. FORTUÑO. Well, actually, anything can happen, but certainly, you could have the East Coast of the United States, not just the Caribbean, affected by something like that. And again, the cost-effectiveness of this facility has to be highlighted, and I thank you, Mr. Rohrabacher, for your leadership on this issue, not just on Arecibo, the issue in general.

I think it is an issue that we need to devote resources and time to it, and again, I thank the Chairman and all the Members of this subcommittee.

Mr. ROHRABACHER. Shutting down Arecibo means that we are intentionally putting ourselves in a position of ignorance of potential threats, and with that ignorance may come bliss for a while. However, let us note it also not only gives us ignorance, but it also prevents us from having any chance of deflection if there is a threat. So, we are putting ourselves in a position of being ignorant of a potential threat, and also, making ourselves incapable of responding to the potential threat. And Arecibo is in the middle of this. No one should take us seriously about watching out for the long-term interests if we let this asset go.

So, I thank you very much, and I am looking forward to working with you, working with the Ranking Member, and working with the Chairman. We need to work on this, and show that we can actually—if we can't get this done, we can't get anything done. I mean, it is as simple as that.

Mr. FORTUÑO. Thank you.

Mr. ROHRABACHER. And thank you for your hard work.

VISITING ARECIBO

Chairman UDALL. I thank the gentleman from California. I would note, for the record, that my colleague from Texas, Mr. Lampson, is here. There is nobody more passionate an advocate for NASA and all that NASA does. I do believe he does not have a question——

Mr. LAMPSON. No, I don't.

Chairman UDALL.—for his colleague from Puerto Rico. Resident Commissioner, if you——

Mr. LAMPSON. I do look forward to visiting, however.

Chairman UDALL. I am sorry, you——

Mr. LAMPSON. I do look forward to visiting the facility some time.

Chairman UDALL. That is an open offer, I am sure.

Mr. FORTUÑO. It is a beautiful facility, but actually, some time between December and March is the best time to visit.

Chairman UDALL. Well, I again want to thank the Resident Commissioner, and at this time, would be pleased to excuse you. I know you have other responsibilities and a busy schedule. Thank you again for joining us.

Mr. FORTUÑO. Thank you, Mr. Chairman.

Chairman UDALL. At this time, as the Resident Commissioner departs, we will pause, while the second panel can take your seats and get comfortable, and then, we will begin the presentations from the second panel in a few minutes.

I want to welcome the panel, and at this time, it seems appropriate to introduce all of the witnesses that have joined us. I would, before I do so, just let the panel know, and the others who are here with us, that there are votes pending at some point in the next 25 to 30 minutes. We will, I think, have a series of at least two votes, and we will do all we can to move the testimony forward, and then we will recess for 40 minutes, and then reconvene the hearing.

Let me begin here, on my left to the audience's right, with Dr. James Green, who is the Director of the Planetary Science Division at NASA. Next to him is, moving from left to right again, is Dr. Scott Pace, who is the Associate Administrator of the Office of Program Analysis and Evaluation at NASA. Third on the panel, Dr. Donald Yeomans, who is the manager of the Jet Propulsion Laboratory's Near-Earth Object Program Office. Proceeding down the line, Dr. Campbell, Dr. Donald Campbell, who is a Professor of Astronomy at Cornell University, and a former Director of the Arecibo Observatory. Next to Dr. Campbell, Dr. J. Anthony Tyson, who is a Professor of Physics at the University of California, Davis, and a Director of the Large Synoptic Survey Telescope Project. And our last witness on the second panel, we have Mr. Russell "Rusty" Schweickart, former Apollo astronaut, Lunar Module pilot on Apollo IX, and the Chairman and Founder of the B612 Foundation.

Welcome, gentlemen, to all of you. We are really pleased to have you here today. I think all of you know, I think many of you have been before the Committee before, that your spoken testimony is limited to five minutes each, after which the Members of the Subcommittee will have five minutes each to ask questions.

So, Dr. Green, we will begin with you. The floor is yours.

Panel 2

STATEMENT OF DR. JAMES L. GREEN, DIRECTOR, PLANETARY SCIENCE DIVISION, SCIENCE MISSION DIRECTORATE, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA)

Dr. GREEN. Thank you, Mr. Chairman and Members of the Committee, for the opportunity to present information on NASA's important efforts to find Near-Earth Objects or NEOs.

At the request of Congress, NASA currently conducts a very successful NEO search program designed to find 90 percent of the NEOs greater than one kilometer in diameter. Since the program started in 1998, NASA has funded over $30 million in NEO search efforts. During this time period, NASA has found, as of Monday, I checked, 727 one kilometer or larger Near-Earth asteroids and 65 Earth-approaching comets, as well as 4,198 smaller NEOs.

At the current discovery rate, we will have discovered more than 50 large NEOs by the end of 2008, bringing us very close to achieving our 90 percent discovery goal, according to our current estimate of roughly 940 greater than one kilometer size NEOs.

NASA currently funds four teams that operate eight ground-based telescopes, of mostly one meter class, dedicated to searching the skies and detecting NEOs. All NEO observations that are collected are sent to an international clearinghouse for small bodies. This organization is called the Minor Planet Center. The Minor Planet Center determines the initial orbit for any newly discovered NEO, so that observatories worldwide may observe the object and confirm its existence. Once an NEO's orbit has been determined, its potential for impacting the Earth is assessed. Over 99 percent of the objects discovered by our search efforts so far have no potential for Earth impacts over many millennia, but a smaller number, which do, are tagged potentially hazardous objects.

Now, more detailed and refined analysis of potentially hazardous objects' orbits is then conducted by NASA's NEO Program Office at the Jet Propulsion Laboratory. Observations on potentially hazardous objects are also automatically received, their orbits updated to determine the level of probability of impacting the Earth in the next 100 to 200 years. The results of this analysis is constantly updated and published on our NEO program website.

Now, the National Science Foundation's Arecibo Radio Telescope, although it has no use in detecting NEOs, does indeed provide us important observations for NEOs that pass within 20 million miles of the Earth. Arecibo plays that important role in refining the orbit, allowing us to obtain information about the object's size, its shape, and its spin rate. The only other facility currently being used by NASA for routine planetary radar is NASA's own Goldstone facility, which is part of our Deep Space Network. To date, no international facilities are capable of performing this feat on a regular basis.

Previous planetary spacecraft missions have not contributed directly to detecting NEOs. NASA missions, such as the Near-Earth Asteroid Rendezvous, Stardust, Deep Impact, and the Japanese Hayabusa 1 missions, have all brought us fascinating information on NEO composition, origin, and migration into the inner solar system. The recently launched Dawn mission will travel past the orbit of Mars and into the main asteroid belt, observing both Vesta and Ceres, which are the largest objects in that region. The asteroid belt has been shown to be the most probable region where these objects are coming from, that we now classify as NEOs.

In our report to Congress, requested by the 2005 Act, NASA recommended that the current program be continued, and that we would look at opportunities for potential dual use ground-based telescopes, spacecraft, and also, partner with other agencies as feasible. For example, we are actively planning to use the Air Force Panoramic Survey Telescope and Rapid Response System, also referred to as Pan-STARRS, after it becomes operational with its very first telescope next year. When Pan-STARRS is completed, and with its intended four telescope configuration, by 2011, this system alone could discover up to 70 percent of the potentially hazardous objects larger than 140 meters by 2020.

It is important to note that no significant NEO detection efforts are currently conducted outside of NASA. However, there is growing interest in international communities to contribute. Most recently, the United Nations Committee on the Peaceful Uses of Outer Space recently established a working group on NEOs, to encourage more international work on the issue.

Other opportunities are beginning to materialize; that can help us in these detection efforts. NASA's own Wide-Field Infrared Survey Explorer, which is being developed for a late 2009 launch, is an astrophysics mission designed to map the infrared sky. However, it is also capable of detecting many asteroids, in which a portion will indeed be NEOs.

We have also been discussing with the Canadian Space Agency how their upcoming Near-Earth Orbit Surveillance Satellite (NEOSSat) mission would be able to contribute to NEO research and detection, and other important missions like these are being planned by the European Space Agency, the Japanese Aerospace Exploration Agency, and for which we are in close communications with.

In closing, let me again thank you for the opportunity to appear at this hearing, and I would be happy to respond to any of your questions.

[The prepared statement of Dr. Green follows:]

PREPARED STATEMENT OF JAMES L. GREEN

Mr. Chairman and Members of the Subcommittee, thank you for the opportunity to appear today to discuss the goals and accomplishments of NASA's Near-Earth Objects (NEOs) Observation Program. The Subcommittee's invitation to testify identified a series of six questions, and I have structured my testimony around your specific concerns.

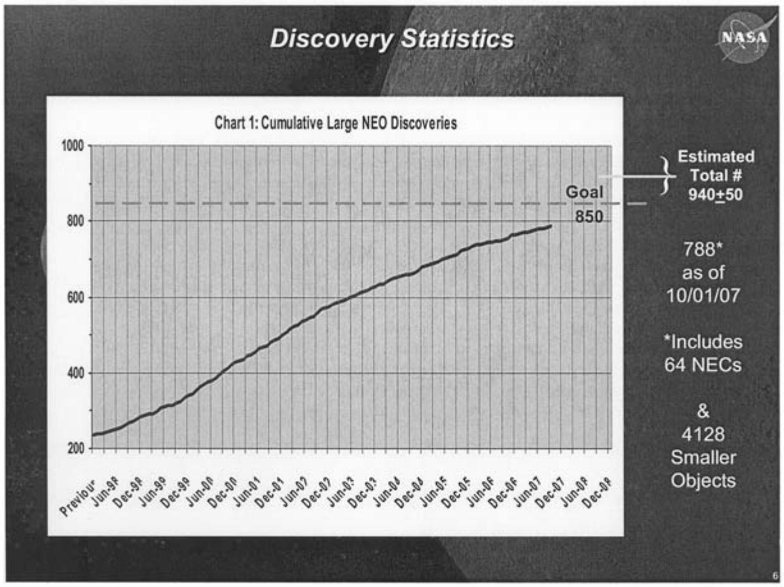
Question 1: *Please describe NASA's NEO Program and the infrastructure and operations in place to support the ongoing Survey (e.g., use of observatories, survey processing and NEO databases, analysis of identified objects, research, and sensor development)?*

To achieve NASA's stated goal of finding over 90 percent of the NEOs greater than one kilometer in diameter, the Agency's NEO Observation Program currently funds four survey teams that operate eight ground-based telescopes of mostly one meter class apertures essentially dedicated to the NEO search effort. Two of the teams are sponsored by the University of Arizona Lunar and Planetary Laboratory, Tucson, Arizona, one by Lowell Observatory in Flagstaff, Arizona, and one by the Massachusetts Institute of Technology Lincoln Laboratory. Each team conducts independent operations for 14 to 20 nights per month, as weather permits, avoiding approximately a week on either side of the full moon when the sky is too bright to detect these extremely dim objects from the ground.

All collected observations believed to be of known or previously unknown NEOs are sent to the international "clearinghouse" for small body observation data, the Minor Planet Center (MPC). The MPC maintains the database of observations and orbits on all known small bodies (asteroids, comets, dwarf planets, Kuiper Belt Objects (KBO), etc.) in the Solar System under the sanction of the International Astronomical Union. It is hosted by the Smithsonian Astrophysical Observatory's Center for Astrophysics in Cambridge, Massachusetts, but is largely funded by NASA. The MPC verifies and validates the observations by determining if they are of an already known object (by comparing them to the known orbits), or are indeed a new discovery. The MPC then determines and publishes an initial orbit for the new discovery so that observatories world-wide may look for the object and confirm its existence. Sometimes it takes a few nights of additional observations to adequately determine, or "secure," the orbit of a new object so that it may be regularly observed.

Once a new object's orbit is secured, its potential for impacting the Earth is assessed. Well over 99 percent of all objects discovered (which also include Main Belt Asteroids, comets, Trojans, Centaurs and KBOs) have no potential for Earth impact even over many millennia, but the small fraction which do are tagged as Potentially Hazardous Objects (PHOs). More detailed and refined analysis of a PHO's orbit is conducted by NASA's NEO Program Office at the Jet Propulsion Laboratory in Pasadena, California, which also aids in coordinating the activities and operations of NASA's NEO projects. Observations on PHOs are automatically forwarded to JPL and their orbits updated with high precision analysis to determine a level of probability of the object impacting the Earth in the next 100 to 200 years. The results of this analysis is constantly updated and published on the NEO Program website at *http://neo.jpl.nasa.gov*.

Since the program's inception in 1998, NASA has funded over $30M in NEO search efforts using funds from the Science Mission Directorate's Research and Analysis program. To date, these efforts have found the vast majority of the 724 one-kilometer Near Earth Asteroids and 64 Earth approaching comets now known, as well as the 4,128 known smaller NEOs. At the current discovery rate, we will have found about 50 more NEOs larger than one kilometer by the end of 2008, bringing us very close to achieving our 90 percent goal, measured against the current estimate of about 940 total one-kilometer objects. This work has retired the majority of the risk that Earth could be struck by a large asteroid in the foreseeable future.



Question 2: *What roles do other U.S. Government institutions, universities, private and not-for-profit organizations, and international entities play in contributing to the NEO Survey and how is NASA coordinating with these institutions?*

As discussed above, NASA does not directly own or operate any of the NEO Survey assets, but fully or partially funds several universities and private institutions to conduct the necessary elements of the survey using existing ground-based astronomical facilities. The University of Arizona (UofA) operates most of the search telescopes, either directly or in partnership with others. Two telescopes are operated at Kitt Peak by the UofA Spacewatch project, while the UofA Catalina Sky Survey operates two telescopes at Mt. Lemmon Observatory and one in partnership with the Australian National Observatory at Siding Spring Observatory in New South Wales, Australia, which is currently our only southern hemisphere survey site. Lowell Observatory, a private institution, operates a smaller search telescope outside Flagstaff, Arizona. The remaining search team, funded by NASA at MIT/Lincoln Laboratory, operates on two U.S. Air Force-owned one-meter class telescopes at the Stallion Air Force Station on White Sands Missile Range near Socorro, New Mexico. The Minor Planet Center is operated by the Smithsonian Astrophysical Observatory using mostly NASA funding, and the NEO Program Office is at the Jet Propulsion Laboratory, managed by the California Institute of Technology.

No significant NEO detection efforts are currently conducted by the international community. Less than two percent of NEOs detected in the last ten years were found by systems other than those funded by NASA.

Currently, the only organized work in the international community that is significant to the NEO Survey is the NEO Dynamics Site (NEODyS), operated by the University of Pisa in Italy. NEODyS conducts independent analysis on NEO orbits similar to that performed by NASA's NEO Program Office at JPL. JPL and NEODyS constantly compare results they obtain for PHO orbits and predicted impact probabilities. If the results from one vary significantly from the other, they redo their analyses until they can resolve the discrepancy. This work offers a completely independent check of impact prediction results prior to an announcement of any significant threat.

Also worth noting is the current significant role for new discovery follow-up observations conducted world-wide by a dedicated amateur astronomer community. Through its website, the MPC supplies position information on newly discovered objects and solicits observations needed to improve the orbit from anyone who may want to attempt the work. Much of these follow-up observations are obtained by amateur astronomer individuals or clubs with relatively sophisticated but smaller telescope systems. However, once NASA moves the search to objects much smaller than one kilometer, this work quickly becomes beyond the capabilities of these amateur systems.

Coordination of efforts is largely voluntary through the use of information published on the MPC and NEO Program Office websites. The competitive nature of the grant program used to finance the search teams has encouraged them to make improvements in their systems and data processing to maintain their detection rates. This community meets either in the U.S. or internationally annually, on average, to discuss progress and improvements to the survey effort. In addition, last year the United Nations Committee on the Peaceful uses of Outer Space (COPUOS) established an Action Team on NEOs within its Scientific and Technical Subcommittee to encourage more international work on this issue. The Action Team is focused on identifying gaps in efforts and coordination within the international community, as well as recommending improvements. NASA is charter member of this new group.

Question 3: *How do spacecraft missions to comets and asteroids, as well as other scientific spacecraft, contribute to the NEO program?*

Currently, spacecraft missions do not contribute to the detection of NEOs. However, space missions do provide the most significant and detailed information on what we know about the character and composition of them. NASA Discovery missions such as the Near-Earth Asteroid Rendezvous (NEAR), Stardust, Deep Impact, and the Japanese Hyabusa mission have contributed important information to our understanding of the origin of comets and asteroids, providing insight on their evolution into the inner Solar System near the Earth, their structure and physical properties, and their composition. The recently launched Dawn mission will travel to the two largest objects in the Main Belt of Asteroids—Vesta and the dwarf planet Ceres. This area of the Solar System has been shown to be the region of origin for most of the objects that now are near Earth, and the Dawn mission will tell us many things about their nature. Other significant contributions by spacecraft include studies by the Hubble Space Telescope, Spitzer, Galileo, and other asteroid and comet flybys performed by several Solar System exploration missions.

Not only are these data important to the development of concepts to deal with any impact threat an NEO may pose, but they are also critical to an understanding of the nature NEOs for possible destinations and resources in our future exploration of the Solar System.

While NASA does not have any formal responsibility for the task of mitigation, scientific missions such as Deep Impact and the current Dawn mission to Vesta and Ceres provide information that may be critical to planning an asteroid deflection. Likewise, many of the systems and technologies that are being developed for exploration missions are directly applicable to mitigation missions. These capabilities are the hallmarks of a robust, space-faring nation.

Question 4: *What is the Arecibo facility's role in the detection, tracking, and characterization of Near-Earth Objects, and what alternatives, if any, exist to carry out its role if the facility is shut down? How do the capabilities of those alternatives compare to those of the Arecibo facility?*

The National Science Foundation's Arecibo Radio Telescope facility has had no useful role in the detection of NEOs—its technical characteristics make it incapable of conducting searches for these relatively small and distant objects. However, once we know the position of an object is accessible by a focused radar beam, Arecibo plays an important role in the quick refinement of the orbit to a precision not obtainable by other means, and for understanding the object's size, shape and spin rate. Arecibo also aids in the detection of possible binary objects, (~15 percent of NEOs), which in turn provides data that can be used to determine their mass. When an object passes close enough to the Earth to achieve a measurable radar return (about 20 million miles depending on the size), the use of radar is one of several valuable tools for obtaining additional information about these objects.

The only other facility currently being used by NASA for routine planetary radar is NASA's own Goldstone facility, part of our Deep Space Network (DSN) for communication with spacecraft on missions beyond Earth's orbit. No international facility is capable of performing this feat on a regular basis.

There are significant differences with the planetary radar capability at Arecibo compared to Goldstone. The Goldstone radar is a 70-meter steerable dish, allowing it to access objects significantly lower to the horizon than the more limited sky area accessible to the limited pointing capability of the Arecibo radar. However, Arecibo is twice as powerful as Goldstone and has a much larger (304 meter) collection dish, which allows it to observe objects significantly farther away than Goldstone.

Question 5: *Will NASA's current NEO program satisfy the requirement established in Sec. 321(d)(1) of the* NASA Authorization Act of 2005, *and if not, what is NASA's plan for satisfying that requirement?*

Although the current systems funded by NASA are capable of detecting objects smaller than one kilometer in size, the objects must come significantly closer to the Earth than a one kilometer object needs to in order to be detected. It would take timescales much longer than 15 years to observe 90 percent of these objects with the systems we currently use.

As outlined in the report NASA submitted to Congress on March 7, 2007, pursuant to direction in section 321 of the *NASA Authorization Act of 2005* (P.L. 109–155), the Agency recommended that the current survey program, funded at approximately $4M annually, be continued. In addition, NASA indicated that the Agency would look for opportunities using potential dual-use telescopes and spacecraft—and to partner with other agencies as feasible—to attempt to achieve the legislated goal within 15 years. Several alternatives as to how this might be accomplished were presented and analyzed in the March 7 report. However, due to current budget constraints, it is not possible for NASA to initiate a new program. The costs for the alternative programs ranged from $470M to in excess of $1.0B over 10 to 19 years, depending on how aggressive of a timeline would be pursued.

The current NEO program is fully funded through 2012. In addition, NASA is initiating plans to use other survey systems to increase the survey's detection sensitivity and rates. For example, NASA has begun providing funds to the Air Force Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) project so that it will be capable of providing data on NEO detections after it starts operations on its first telescope in the next year. If the Air Force continues to fund this project to its intended four telescope configuration by 2010, this system alone could discover over 70 percent of the potentially hazardous objects larger than 140 meters by 2020. NASA is also assessing the upgrades that must be instituted at the Minor Planet Center to absorb the substantial increase in new detection data that this system will provide.

Finally, NASA is also assessing what already planned spacecraft might contribute to the detection effort. A leading example for possible dual-use is the Wide-field Infrared Survey Explorer (WISE). Currently being developed for a late 2009 launch for a six-month astrophysics mission to map the infrared sky, the WISE instrument is also capable of detecting many asteroids, of which a portion will be NEOs. We are investigating improvements to the timeliness of the spacecraft's data down-link and archival plans to increase its utility for NEO detections, as well as a possible extended mission to double the time available to detect these objects. The science community may propose a NEO survey mission under the competitively-selected Discovery program.

Question 6: *What plans, policies, or protocols does NASA have in place in the event that a previously unknown object on a near-term impact trajectory is detected?*

NASA has an NEO contingency notification plan to be utilized in the very unlikely event an object is detected with significant probability of impacting the Earth. The plan establishes procedures between the detection sites, the Minor Planet Center, the NASA NEO Program Office at JPL, and NASA Headquarters to first quickly verify and validate the data and orbit on the object of interest, and then up-channel confirmed information in a timely manner to the NASA Administrator. These procedures were first exercised with the discovery of the object now known as Apophis, which was found in December 2004 in a hazardous orbit but determined to not have a significant probability of impacting the Earth in the near-term. NASA will continue to refine this internal contingency plan, and begin work with other U.S. Government agencies and institutions when directed.

Again, thank you for the opportunity to testify today, and I look forward to responding to any questions you may have.

Biography for James L. Green

Dr. Green received his Ph.D. in Space Physics from the University of Iowa in 1979 and began working in the Magnetospheric Physics Branch at NASA's Marshall Space Flight Center (MSFC) in 1980. At Marshall, Dr. Green developed and managed the Space Physics Analysis Network, which provided many scientists, all over the world, with rapid access to data, other scientists, and specific NASA computer and information resources. In addition, Dr. Green was a safety diver in the Neutral Buoyancy tank making over 250 dives until he left MSFC in 1985.

From 1985 to 1992 he was the Head of the National Space Science Data Center (NSSDC) at Goddard Space Flight Center (GSFC). The NSSDC is NASA's largest space science data archive. In 1992 he became the Chief of the Space Science Data Operations Office until 2005 when he became the Chief of the Science Proposal Support Office. While at GSFC, Dr. Green was a co-investigator and the Deputy Project Scientist on the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) mission. From 1992 to 2000 he was also the Deputy Project Scientist for Mission Operations and Data Analysis for the Global Geospace Science Missions WIND and POLAR. He has written over 110 scientific articles in referred journals involving various aspects of the Earth's and Jupiter's magnetospheres and over 50 technical articles on various aspects of data systems and computer networks.

In August 2006, Dr. Green became the Director of the Planetary Science Division at NASA Headquarters. Over his career, Dr. Green has received a number of awards. In 1988 he received the Arthur S. Flemming award given for outstanding individual performance in the federal government and was awarded Japan's Kotani Prize in 1996 in recognition of his international science data management activities.

Chairman UDALL. Thank you, Dr. Green. Dr. Pace.

STATEMENT OF DR. SCOTT PACE, ASSOCIATE ADMINISTRATOR, PROGRAM ANALYSIS AND EVALUATION, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA)

Dr. PACE. Thank you, Mr. Chairman. Members of the Committee, thank you for the opportunity.

I would like to review some of the findings and recommendations of the report that we provided to the Congress in response to the Authorization Act of 2005. The principal findings of the report to Congress were the result of a study led by my Office. The Study Team conducted an analysis of alternatives, with inputs from several government agencies, international organizations, and representatives of private organizations. I think that we covered a wide spectrum of views of the scientific and technical community in the effort.

NASA recommended that the existing Spaceguard survey program continue, as currently planned. NASA would also take advantage of opportunities using potential telescopes, such as the Large Synoptic Survey Telescope, and the proposed Panoramic Survey Telescope, otherwise known as Pan-STARRS, that you heard mentioned, along with potential dual use spacecraft, some partnerships with other agencies, as feasible, to make progress toward achieving the legislative goal.

However, I have to say that due to budget constraints, NASA cannot initiate a new program beyond Spaceguard at this time, and however, as also was noted, that NASA, it is fair to say, would be pleased to implement a more aggressive Near-Earth Object program if, in fact, so directed by the President and Congress. Given the constrained resources and strategic objectives that the agency has already been tasked with, I would have to say that NASA cannot place a new NEO program above current scientific and exploration missions. But I imagine that will be the subject of dialog and discussion with you, and see how we can move forward.

The goal of finding 90 percent of potentially hazardous objects 140 meters in diameter and larger is one to two orders of magnitude more technically challenging than the existing Spaceguard mission. To reach the goal within 10 to 15 years would require at least one new dedicated ground or space observatory, and we can share with other folks, but to really hit the goal, you need a dedicated facility.

Cataloging the number of total objects, say 100,000, at the rate they would be discovered, around 30 to 50 a day, would require a new tracking and data management infrastructure, whose ongoing operation may constitute a sizable portion of the total cost. A delay of five to 10 years in achieving the legislation goal, we think, carries little additional risk when the impact interval for 140 meter objects is about once every 5,000 years. We think there is time to do the survey right. This rate of impact indicates the system may need to operate, conducting searches, tracking objects, for an extended period of time before identifying a credible threat, and I would like to describe really three periods in that process.

Today, we know where a few 140 meter objects are, but we know little about when or if they will impact. We are ignorant. For the initial 10 to 20 years the survey is progressing, the average warning time will rise, the unwarned impact risk will gradually decline, and during this period, potentially decades of warning will become likely.

After 10 to 20 years of the survey, a steady state period will be reached, where unwarned impacts of potentially hazardous objects would be highly unlikely. Centuries of warning time become possible in a steady state period.

The NASA identified, in its report, an exemplar NEO survey program, with estimates for its architectural costs that, if funded, could achieve the specified goal of surveying 90 percent of potentially hazardous objects by the end of 2020. This would occur by constructing or funding a dedicated survey asset, combined with NASA partnerships with other agencies on future optical ground-based observatories. Details of the exemplar program were provided in our report, and again, we would be happy to discuss them.

I want to caution, however, that the budget estimates in the report are what we call architecture costs, and a lot more rigorous analysis would be needed before a program to be assessed for implementation. So, more work needs to be done on those cost estimates.

Finally, the current NEO Spaceguard survey program, really without any augmentation, would not be able to satisfy the requirements of the Authorization Act. In the Act right now, the requirements of the survey program are to find only NEOs greater than a kilometer in diameter, and therefore, if we focused on things smaller than that, 140 meters, it would require additional effort. Without major augmentation, NASA estimates that we could detect 14 percent of the 140 meter or larger potentially hazardous objects by 2020.

In our cooperative efforts with Air Force, the Pan-STARRS program, it would be capable of providing data on NEO detections after operations start. We think that this system alone could discover about 70 percent of potentially hazardous objects larger than 140 meters by 2020. So, we think there are some promising approaches.

While NASA does not have any formal responsibility for the task of NEO mitigation, as mentioned, scientific missions such as Deep Impact and Dawn provide information that may be critical to planning and asteroid deflection, and likewise, many of the systems and technologies that are being developed for exploration are directly applicable to mitigation missions. These capabilities are the hallmarks of a robust and spacefaring nation, capable of the many tasks that may be assigned to it.

Thank you, Mr. Chairman. I would be pleased to respond to any questions.

[The prepared statement of Dr. Pace follows:]

PREPARED STATEMENT OF SCOTT PACE

Mr. Chairman and Members of the Subcommittee, thank you for the opportunity to appear today to review the findings and recommendations of NASA's report to Congress in response to the *NASA Authorization Act of 2005* (P.L. 109–155). Below, I have addressed the questions posed by this Subcommittee in your invitation to testify.

Question #1: What were the principal findings and recommendations of NASA's Near-Earth Object Survey and Deflection Analysis of Alternatives: Report to Congress, *March 2007, and what was the basis for those findings and recommendations?*

The principal findings were the result of a study team, led by NASA's Office of Program Analysis and Evaluation (PA&E) that conducted an analysis of alternatives with inputs from several other U.S. Government agencies, international organizations, and representatives of private organizations. The team developed a range of possible options from public and private sources and then analyzed their capabilities and levels of performance including costs, development schedules, and technical risks. In order to meet the congressional goal of completing the survey by 2020, the study team assumed primary project elements would have started their development by October 1, 2007.

NASA recommended that the existing "Spaceguard Survey" program continue as currently planned, and that NASA would also take advantage of opportunities using potential dual-use telescopes[1] and spacecraft—and partner with other agencies as feasible—to make progress toward achieving the legislative goal of discovering 90 percent of all potentially hazardous objects 140 meters in mean diameter and greater. However, due to budget constraints, NASA cannot initiate a new program beyond the Spaceguard Survey program at this time.

NASA would be pleased to implement a more aggressive NEO program if so directed by the President and Congress. However, given the constrained resources and strategic objectives the Agency has already been tasked with, NASA cannot place a new NEO program above current scientific and exploration missions.

For ease of following the findings and recommendations, simplified definitions are as follows:

- *"Detection"* is the act of finding the objects;
- *"Tracking"* is the act of determining their orbits;
- *"Characterization"* is the act of determining their physical properties;
- *"Cataloging"* is the act of maintaining a data base of the orbits and physical properties of known objects and predicting potential impacts with the Earth; and
- *"Mitigation"* is the act of deflecting, destroying, or reducing the impact consequences of a specific object that is predicted to strike the Earth.

Key Findings for the Survey Program

- The goal of the Survey Program should be modified to detect, track, catalogue, and characterize, by the end of 2020, 90 percent of all Potentially Hazardous Objects (PHOs) greater than 140 meters whose orbits pass within 0.05 AU (Astronomical Units) of the Earth's orbit (as opposed to surveying for all NEOs).
- The Agency could achieve the specified goal of surveying for 90 percent of the potentially hazardous NEOs by the end of 2020 by partnering with other gov-

[1] The proposed Large Synoptic Survey Telescope (LSST) and Panoramic Survey Telescope And the Rapid Response System (Pan-STARRS) present possible future opportunities, if they are funded by other agencies. Another possible opportunity would be the Lowell Discovery Channel Telescope (DCT), but its contribution would be less than LSST or Pan-STARRS.

ernment agencies on potential future optical ground-based observatories and building a dedicated NE0 survey asset, assuming the partners' potential ground assets come online by 2010 and 2014, and a dedicated asset by 2015.

- Together, the two observatories potentially to be developed by other government agencies could complete 83 percent of the survey by 2020 if observing time at these observatories is shared with NASA's NE0 Survey Program.
- New space-based infrared systems, combined with shared ground-based assets, could reduce the overall time to reach the 90 percent goal by at least three years. Space systems have additional benefits as well as costs and risks compared to ground-based alternatives.
- Radar systems cannot contribute to the search for potentially hazardous objects, but may be used to rapidly refine tracking and to determine object sizes for a few NEOs of potentially high interest.
- Determining a NEO's mass and orbit is required to determine whether it represents a potential threat and to provide required information for most alternatives to mitigate such a threat. Beyond these parameters, characterization requirements and capabilities are tied directly to the mitigation strategy selected.

Key Findings for Diverting a Potentially Hazardous Object (PHO)

The study team assessed a series of approaches that could be used to divert a NEO potentially on a collision course with Earth. Nuclear explosives, as well as non-nuclear options, were assessed.

- Nuclear standoff explosions are assessed to be 10–100 times more effective than the non-nuclear alternatives analyzed in this study. Other techniques involving the surface or subsurface use of nuclear explosives may be more efficient, but they run an increased risk of fracturing the target NEO. They also carry higher development and operations risks.
- Non-nuclear kinetic impactors are the most mature approach and could be used in some deflection/mitigation scenarios, especially for NEOs that consist of a single small, solid body.
- "Slow push" mitigation techniques are the most expensive, have the lowest level of technical readiness, and their ability to both travel to and divert a threatening NEO would be limited unless mission durations of many years to decades are possible.
- 30–80 percent of potentially hazardous NEOs are in orbits that are beyond the capability of current or planned launch systems. Therefore, planetary gravity assist swing-by trajectories or on-orbit assembly of modular propulsion systems may be needed to augment launch vehicle performance, if these objects need to be deflected.

Question #2: How were the cost estimates and technical options contained in the report arrived at, and was any independent assessment of the cost estimates and technical options conducted?

Technical Options

The technical options contained in the report were developed through a systematic exploration of the trade space for feasible alternatives, followed by a conceptual design of selected options. Concepts were selected to represent the available range of cost, performance, and acceptable technical risk to complete the detection, tracking, cataloguing, and characterization missions. Concepts were based on historical and existing projects and on white papers presented at a NASA-sponsored workshop of national experts.

Trade trees were developed to describe the technical options. The detection and tracking trade tree consisted of existing and new ground-and space-based observatories operating in the visible and infrared spectra; ground based radars were considered for tracking. The characterization trade tree contained existing, proposed, and new remote and in-situ observing assets. Cataloguing considered a range of operations and data management options based on historical, proposed, and new information systems.

Cost Estimates

Life cycle costs were calculated as the total architecture cost in fiscal year 2006 billions of dollars including development, production, deployment, and operation of the alternatives. Life cycle costs for the detection, tracking, and data management options were calculated both for a fixed period (through 2020) and until the objective of cataloguing 90 percent of specified threats was complete. For some options that rely on existing systems or available technology, operational costs were much higher than the development costs over the 15–20 year life cycle. In order to meet the Congressional goal of completing the survey by 2020, the study team assumed primary project elements would have started their development by October 1, 2007.

For space-based systems, the total life cycle costs included estimated costs for program management, systems engineering, mission assurance, launch vehicle, spacecraft, scientific instruments, mission specific ground data systems, mission operations, and data analysis. Ground-based systems included the cost of development, production, and operations. Operations costs were calculated over either the survey period for detection, tracking, and cataloguing missions or the predicted duration of characterization missions.

The cost estimates for the space vehicles relied on multiple methods including historical analogies and prior cost-estimating experience. Cost-risk analyses were performed using these data as inputs and assumed that every cost element could be represented by statistical characteristics such as mean, standard deviation, and mode. A cumulative probability distribution of total cost was generated for this analysis by combining cost distributions from the different cost elements, and costs were estimated at the 65 percent cost confidence level when applicable. Programmatic costs were based on historical actual costs and applied as a percentage of the space vehicle costs. Launch vehicle costs were based on recent, publicly released estimates for commercial launch vehicles.

Ground-based observatory costs were based on reported expenses for currently operating systems or based on estimates for systems currently in development. For several ground based options, concepts of operations postulated utilizing (sharing) data that would be collected on existing or planned systems without materially affecting the primary mission of these systems. For these systems, it was assumed that the NEO program would fund only a small portion (or none) of the development costs, but that an equitable portion of the annual operations costs would be funded by NASA. In cases where the ground based systems were expected to be copies of systems that are currently in development, only the production and operation costs of the NASA-acquired systems were considered—substantially reducing their development costs and cost-risk.

Although multiple cost-estimating methodologies, databases, and organizations were used, truly independent cost estimates were not generated as these are typically not within the scope of a conceptual, architecture-level study. Likewise, assessments of the technical options were carried out using an experienced team of personnel from several organizations, but fully separate evaluations of the concepts were not performed.

Question #3: What is the "recommended option and proposed budget to carry out the Survey program pursuant to the recommended option," as called for in Sec. 321(d)(2)?

NASA recommended that the existing "Spaceguard Survey" program continue as currently planned, and that NASA would also take advantage of opportunities using potential dual-use telescopes[2] and spacecraft-and partner with other agencies as feasible-to make progress toward achieving the legislative goal of discovering 90 percent of all potentially hazardous objects 140 meters and greater.

The goal of finding 90 percent of potentially hazardous objects 140 meters and larger is one to two orders of magnitude more technically challenging than the Spaceguard mission. To reach this goal within 10–15 years requires at least one new dedicated ground or space observatory.

Cataloging the number of total number of objects—approximately 100,000—at the rate they would be discovered, which is between 30 and 50 per day, requires a new tracking and data management infrastructure whose ongoing operations may constitute a sizable portion of total costs.

A delay (e.g., 5–10 years) in achieving the legislative goal carries little additional risk when the impact interval for 140m objects is about once every 5,000 years. This rate of impacts also indicates that the system may need to operate (searching and tracking) for an extended period before identifying a credible threat. There are three epochs to the problem of detection and tracking:

- Now: We know where few 140m objects are and when/if they will impact.

[2] The proposed Large Synoptic Survey Telescope (LSST) and Panoramic Survey Telescope And the Rapid Response System (Pan-STARRS) represent possible future opportunities, if they are funded by other agencies. Another possible opportunity would be the Lowell Discovery Channel Telescope (DCT), but its contribution would be less than LSST or Pan-STARRS.

- Initial 10–20 years of the survey: Average warning time will rise, unwarned impact risk gradually decline. Decades of warning become likely.
- Steady-state: After 10–20 years of the survey, unwarned impacts of 140m objects would be highly unlikely. Centuries of warning become possible.

Currently, NASA carries out the "Spaceguard Survey" to find NEOs greater than 1 kilometer in diameter, and this program is currently budgeted at $4.1 million per year for FY 2006 through FY 2012. We also have benefited from knowledge gained in our Discovery space mission series, such as the Near-Earth Asteroid Rendezvous (NEAR), Deep Impact, and Stardust missions that have expanded our knowledge of near-Earth asteroids and comets. Participation by NASA in international collaborations such as Japan's Hayabusa mission to the NEO "Itokawa" also greatly benefited our understanding of these objects. NASA's Dawn mission, launched on September 27, 2007, will increase our understanding of the two largest known main belt asteroids, Ceres and Vesta, between the planets Mars and Jupiter. NASA conducts survey programs on many celestial objects—the existing Spaceguard program for NEOs, surveys for Kuiper Belt Objects, the search for extra-solar planets, and other objects of interest such as black holes to understand the origins of our universe. The science community could propose such a NEO survey mission under the competitively-selected Discovery program.

NASA also identified an exemplar NEO Survey Program and estimates for its architectural costs that, if funded, could have achieved the specified goal of surveying 90 percent of the PHOs by the end of 2020 by constructing or funding a dedicated survey asset combined with NASA partnerships with other government agencies on potential future optical ground-based observatories: the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS–4 or PS4) and the Large Synoptic Survey Telescope (LSST). Details of the exemplar program were provided in NASA's report. Note that budget estimates in the report are rough "architecture costs" and would require more rigorous analysis before a program could be assessed for implementation.

Question #4: Will NASA's current NEO program satisfy the requirement established in Sec. 321(d)(1) of the NASA Authorization Act of 2005, *and if not, what is NASA's plan for satisfying that requirement?*

The current NASA NEO "Spaceguard Survey" program, without any augmentation, would not be able to satisfy the requirements outlined in section 321(d)(1) of the *NASA Authorization Act for 2005.* The requirements for the Spaceguard Survey program are to find only NEOs greater than one kilometer in diameter, and its funding is currently budgeted at $4.1 million per year. NASA estimates that the current program, if continued without major augmentation, would detect 14 percent of the 140 meters or larger potentially hazardous objects by the end of 2020. However, NASA is initiating plans to use other survey systems to increase the survey's detection sensitivity and rates. For example, NASA has begun providing funds to the Air Force Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) project so that it will be capable of providing data on NEO detections after it starts operations on its first telescope in the next year. If the Air Force continues to fund this project to its intended four telescope configuration by 2010, this system alone could discover over 70 percent of the potentially hazardous objects larger than 140 meters by 2020.

NASA recommended that the existing "Spaceguard Survey" program continue as currently planned, and that NASA would also take advantage of opportunities using potential dual-use telescopes and spacecraft—and partner with other agencies as feasible—to make progress toward achieving the legislative goal of discovering 90 percent of all potentially hazardous objects 140 meters and greater.

NASA would be pleased to implement a more aggressive NEO program, if so directed by the President and Congress. However, given the constrained resources and strategic objectives the Agency has already been tasked with, NASA cannot place a new NEO program above current scientific and exploration missions.

Question #5: How is progress on meeting the requirements of Section 321 being measured and monitored?

Survey performance is tracked continuously by the NEO Program Office at JPL, and reported monthly on NASA's NEO Program website at *http://neo.jpl.nasa.gov/stats.* This database shows the performance of each survey team and reports the number of NEOs, including Earth approaching comets, found each month by orbit and size (larger or smaller than one kilometer) class. It also breaks out the objects which are potentially hazardous by size class. Specific orbit and estimated size information for each discovered NEO can also been found on the website, as well as probability of impact statistics for Potentially Hazardous Objects.

The discovery statistics information is rolled up each year and reported by the Science Mission Directorate as part of our *Government Performance Reporting Act* (GPRA) submittal.

In closing, NASA recommends that the existing "Safeguard Survey" program continue, as planned, and that the Agency take advantage of opportunities using potential dual-use telescopes and spacecraft, as well as partner with other agencies, to make progress toward achieving the legislative goal.

Mr. Chairman, I would be pleased to respond to any questions you or the other Members of the Subcommittee may have.

BIOGRAPHY FOR SCOTT PACE

Scott Pace is the Associate Administrator for Program Analysis and Evaluation at NASA. In this capacity, he is responsible for providing objective studies and analyses in support of policy, program, and budget decisions by the NASA Administrator. He previously served as Chief Technologist for Space Communications in NASA's Office of Space Operations where he was responsible for advising senior NASA management on issues related to space-based information systems. He participated in the negotiations that resulted in the 2004 GPS–Galileo Agreement between the United States and the European Commission. Pace also previously served as the Deputy Chief of Staff to NASA Administrator Sean O'Keefe. His primary areas of responsibility included oversight of the President's Management Agenda in Human Capital, Competitive Sourcing, Expanding e-Government, Financial Management, and Integrating Budget and Performance.

Prior to NASA, Pace was the Assistant Director for Space and Aeronautics in the White House Office of Science and Technology Policy (OSTP). There he was responsible for space and aviation-related issues and coordination of civil and commercial space issues through the Space Policy Coordinating Committee of the National Security Council. Pace served on the Bush-Cheney Transition Team for NASA and the National Science Foundation.

Prior to his White House appointment, Pace worked for the RAND Corporation's Science and Technology Policy Institute (STPI)—a federally funded research and development center for the Office of Science and Technology Policy. In addition to his extensive research into space policy, technology policy, and international competitiveness at RAND, Pace also was a key member of a successful international effort to preserve radio navigation satellite spectrum at the 1997 World Radiocommunication Conference (WRC97) and the addition of new spectrum for satellite navigation at WRC–2000. He also was a member of the Department of Defense Senior Review Group on Commercial Remote Sensing and the National Research Council's Committee on Earth Sciences.

From 1990 to 1993, Pace served as the Deputy Director and Acting Director of the Office of Space Commerce (OSC), in the Office of the Deputy Secretary of the Department of Commerce. Among his many responsibilities at OSC, Pace coordinated space policy issues across the Department and participated in efforts affecting export controls for space technologies; space trade negotiations with Japan, Russia, China, and Europe; the licensing process for private remote sensing systems; missile proliferation; and the U.S. space industrial base.

Pace received a Bachelor of science degree in physics from Harvey Mudd College in 1980; Master of science degrees in aeronautics and astronautics and technology and policy from the Massachusetts Institute of Technology in 1982; and a doctorate in policy analysis from the RAND Graduate School in 1989. His dissertation was entitled "U.S. Access to Space: Launch Vehicle Choices for 1990–2010."

Chairman UDALL. Thank you, Dr. Pace. Dr. Yeomans.

STATEMENT OF DR. DONALD K. YEOMANS, MANAGER, NEAR-EARTH OBJECT PROGRAM OFFICE, JET PROPULSION LABORATORY

Dr. YEOMANS. Mr. Chairman and Members of the Subcommittee, thank you for the opportunity to appear today.

Chairman UDALL. Dr. Yeomans, I think you should turn on your microphone, if you can.

Dr. YEOMANS. Thank you for the opportunity to appear today to discuss the potential threats of Near-Earth Objects, progress toward meeting the discovery goal articulated in the *NASA Authorization Act of 2005,* the role of the Arecibo Planetary Radar within the Near-Earth Object Program, and the response options available if a Near-Earth Object is found to be on an Earth-threatening trajectory.

Near-Earth objects are comets and asteroids that can pass within about 45 million kilometers of the Earth's orbit. While some showy naked eye comets may occasionally pass close to Earth, it is the difficult to find, but the far more numerous asteroids are of the most concern in near-Earth space today. About one-fifth of the near-Earth asteroids can approach the Earth's orbit even closer, to within seven and a half million kilometers, and these so-called potentially hazardous asteroids are of most concern for near-term hazard avoidance.

As part of the *NASA Authorization Act of 2005,* NASA was asked to consider options for extending the search down to objects as small as 140 meters in diameter, and to find and catalog them within 15 years of the Act becoming law. By finding and cataloging 90 percent of this population of potentially hazardous asteroids, the statistical or actuarial risk to Earth from potentially hazardous asteroids of all sizes would be reduced by 99 percent from pre-survey levels. We can speak of risk reduction in this case, because once an object is discovered and cataloged, its future motion can accurately be predicted, and in the unlikely case where it does threaten Earth, there would be sufficient time to deflect it, thus saving the enormous costs due to fatalities and/or infrastructure damage.

According to a 2003 NASA Near-Earth Object science definition team study that undertook a cost-benefit analysis for the discovery of potentially hazardous asteroids, the risk reduction accruing from this next generation potentially hazardous asteroid search would pay for itself in the first year of operations.

While an impact by a 140 meter sized object would not generate global physical consequences, its impact energy would still be about 100 megatons of TNT explosive, and the likelihood of one of these impacts is 100 times greater than an impact by one of the less numerous one kilometer size potentially hazardous asteroids.

With regard to the uncertainty associated with threats from potentially hazardous asteroids, the largest factor, by far, is the large number of undiscovered objects in the size ranges that are small enough to be very numerous, yet large enough to easily penetrate the Earth's atmosphere. For example, we have only discovered about four percent of the 20,000 potentially hazardous asteroids larger than 140 meters, and less than one percent of the 200,000 objects larger than 50 meters.

The solution to this uncertainty is to continue and hopefully accelerate the search for potentially hazardous asteroids. Once we find the vast majority of them, they can be tracked, cataloged, and then ruled out or in as threats during the next 100 years or so.

The current NASA Near-Earth Object goal is focused upon the discovery and tracking of objects one kilometer in diameter and larger. It is not realistic to expect the current survey program, with its modestly sized telescopes, to efficiently find 140 meter sized objects that are nearly 50 times fainter compared to the one kilometer sized objects at the same distance and with the same reflectivity.

Because all potentially hazardous asteroids do eventually come very close to the Earth, the current ongoing surveys could complete the goal outlined in the *2005 NASA Authorization Act,* but it would likely take over a century to do so. We simply cannot afford to wait that long.

At least two next generation ground-based wide-field search telescope surveys are in development. Pan-STARRS is under development at the University of Hawaii, with Air Force funding, and will have one of its 1.8 meter telescopes operational in Hawaii in early 2008. If the planned four telescope version of Pan-STARRS is completed by 2010, it could help reach the goal by about 2040.

Likewise, the 8.4 meter aperture LSST telescope that is under development with funding from NSF, DOE, and other partners, could help reach the goal by about 2034, if it began operation in 2014.

If we assume that both the Pan-STARRS four telescope system and the LSST operate in their planned shared mode, which includes many observations unrelated to potentially hazardous asteroids, then the goal could be reached by about 2026. The potentially hazardous asteroid discovery rate could be increased beyond the results shown in the NASA report, if the observing times and sequences of Pan-STARRS and LSST were optimized for potentially hazardous asteroid observations.

Both positional data for potentially hazardous asteroid orbit determination and trajectory predictions are based upon optical, plane-of-sky observations. Because the radars provide line of sight, velocity, and range information to about one millimeter per second and 10 meter accuracy levels, this data, when used in conjunction with the optical data, provide a secure orbit and trajectory far more rapidly than if only optical data are available. With only a limited amount of optical data to work with, the orbit of a newly discovered potentially hazardous asteroid is often not accurate enough to immediately rule out a future Earth impact.

However, with radar data in hand, the orbit of a newly discovered potentially hazardous asteroid can be quickly and more precisely determined, its motion accurately projected far into the future, and future impact possibilities can usually be quickly ruled out. Likewise, in the rare situation when an object is actually on an Earth-impacting trajectory, radar observations will be critical in quickly identifying this case.

A number of existing technologies can deflect an Earth-threatening asteroid if there is time. The primary goal of the potentially hazardous asteroid survey programs is to discover them early and provide the necessary time. An asteroid that is predicted to hit Earth would require a change in its velocity of only three millimeters per second, if this impulse were applied 20 years in advance of the impact itself. The key to a successful deflection is having sufficient time to carry it out, whether it is a slow, gentle drag of a gravity tractor, or the more impulsive shove from an impacting spacecraft or explosive device. In either case, the verification process will be required to ensure the deflection maneuver was successful, and to ensure the object's subsequent motion would not put it on yet another Earth-impacting trajectory.

While suitable deflection technologies exist, none of them can be effective if we are taken by surprise. It is the aggressive survey efforts and robust radar systems that must ensure that the vast majority of potentially hazardous objects are discovered and tracked well in advance of any Earth-threatening encounters.

The first three steps in any asteroid mitigation process are find them early, find them early, and find them early.

Thank you.

[The prepared statement of Dr. Yeomans follows:]

PREPARED STATEMENT OF DONALD K. YEOMANS

Mr. Chairman and Members of the Subcommittee, thank you for the opportunity to appear today to discuss the potential threats of near-Earth objects (NEOs), our progress toward meeting the discovery goal articulated in the *NASA Authorization Act of 2005,* the role of the Arecibo planetary radar within the NEO program and the response options available if a NEO is found to be on an Earth impacting trajectory.

The Near-Earth Object Population: When the Earth was young, frequent collisions of comets and asteroids likely delivered much of the water and carbon-based molecules that allowed life to form, and once life did form, subsequent collisions may have punctuated the evolutionary process and allowed only the most adaptable species to progress further. We may owe our very existence atop the world's food chain to these objects. As the Earth's closest neighbors (some pass within the Moon's distance), these icy comets and rocky asteroids have been termed near-Earth objects. Their proximity to Earth presents an opportunity to utilize their vast metal, mineral and water ice resources for future space structures and habitats. Their water resources can be broken down into hydrogen and oxygen—the most efficient form of rocket fuel. These near-Earth objects may one day be the resources, fueling stations and watering holes for human interplanetary exploration. While these objects are of extraordinary scientific interest, likely enabled the origin of life itself, and may loom large for the future development of space exploration, their proximity to Earth also presents a potential horrific threat should a relatively large near-Earth object once again strike Earth without warning.

Potentially Hazardous Asteroids: Near-Earth objects are comets and asteroids that can pass within 45 million kilometers of the Earth's orbit. While some showy, naked-eye comets may occasionally pass close to Earth, it is the difficult to find (but far more numerous asteroids) that are of most concern in near-Earth space today. About one fifth of the near-Earth asteroids can approach the Earth's orbit even closer (to within 7.5 million kilometers), and these so-called potentially hazardous asteroids (PHAs) are of most concern for near-term hazard avoidance.

Celestial debris hits the Earth all the time, but the vast majority of it is so small that it does not survive passage through the Earth's atmosphere. The debris is created over millions of years, as asteroids inevitably run into each other, producing smaller fragments, which themselves collide yielding even more debris. Over time, the fragments and debris spread out, and some of it migrates into Earth approaching orbits. The Earth is pummeled with more than 100 tons of impacting material each day but almost all of it is far too small to cause anything other than a harmless meteor, or shooting star, or the occasional fireball event. Larger objects are less numerous than smaller objects and hit the Earth less often. While a basketball-sized object strikes the Earth's atmosphere daily, larger car-sized impactors hit only a few times each year, and even these generally break up into smaller pieces as they streak through the atmosphere. Occasionally a fragment of a larger impactor will reach the Earth's surface—one such hit may have occurred less than two months ago when a reported asteroid fragment perhaps one meter in diameter struck in southern Peru creating a 13-meter crater near Lake Titicaca.

Larger impactors with diameters in the 50 to 140 meter range, while they do not usually impact the ground, can result in damaging air blasts that cause significant destruction. For example, on June 30, 1908, an impactor with a diameter of about 50 meters detonated over the Tunguska region of Siberia and leveled trees for 2,000 square kilometers. Its impact energy has been estimated at about 10 million tons of TNT explosives (10 megatons or 10 MT), comparable in energy with a modern nuclear weapon. Roughly speaking, PHAs that have diameters larger than 140m can punch through the Earth's atmosphere and cause regional damage if they strike land or create a harmful tsunami should they impact into an ocean. There are thought to be about 20,000 PHAs in this size range, each with a potential impact energy of 100 MT or more. On average, one of these objects would be expected to strike Earth every 5,000 years and therefore would have a one percent probability of impact in the next 50 years. Although their mean impact frequency would be about once every 500,000 years, PHAs larger than a kilometer in diameter could cause global consequences due to not only the extraordinary blast itself (50,000 MT) but also the dust and debris thrown into the air, and the subsequent firestorms and acid rain. The extinction of the dinosaurs and a sizable fraction of the Earth's other species some 65 million years ago is thought to be due to an impactor with a diameter of about 10 kilometers that created an impact energy of as much as 50 million MT. Over very long time intervals, PHAs with diameters greater than one kilometer are statistically the most dangerous objects because their impacts would cause global consequences.

NASA Responses to the PHA Issues: In 1998, before the Subcommittee on Space and Aeronautics, a NASA representative outlined the goal to discover and catalog 90 percent of the NEOs larger than one kilometer by the end of 2008. There are currently thought to be over 900 of these objects, and about 80 percent of them have already been found and cataloged. Roughly the same percentage of PHAs in this size range has also been found. When this goal has been reached, 90 percent of the global risk from PHAs would be retired. Almost all of these discoveries have come by way of NASA supported search programs.

As part of the *NASA Authorization Act of 2005,* NASA was asked to consider options for extending the search down to objects as small as 140 meters in diameter, and to find and catalog them within 15 years of the Act becoming law (i.e., by the end of 2020). By finding and cataloging 90 percent of this population of PHAs, the statistical or actuarial risk to Earth from PHAs of all sizes would be reduced by 99 percent from pre-survey levels. We can speak of risk reduction in this case because once an object is discovered and cataloged, its future motion can accurately be predicted and, in the unlikely case where it does threaten Earth, there would be sufficient time to deflect it, thus saving the enormous costs due to fatalities and/or infrastructure damage. According to a 2003 NASA NEO Science Definition Team study that undertook a cost/benefit analysis for the discovery of PHAs, the risk reduction accruing from this next generation PHA search would pay for itself in the first year of operations. While an impact by a 140 meter-sized object would not generate global physical consequences, its impact energy would still be about 100 MT, and the likelihood of one of these impacts is 100 times greater than an impact by one of the less numerous one kilometer-sized PHAs.

With regard to the uncertainty associated with threats from PHAs, the largest factor, by far, is the large number of undiscovered objects in the size ranges that are small enough to be very numerous but large enough to easily penetrate the Earth's atmosphere. For example, we have discovered only about four percent of the 20,000 PHAs larger than 140 meters and less than one percent of the 200,000 objects larger than 50 meters. The solution to this uncertainty is to continue and hopefully accelerate the search for PHAs. Once we find the vast majority of them, they can be tracked, cataloged and then ruled out (or in) as threats during the next 100 years or so. This process can continue year after year so the window of safety is always at least 100 years. There are other, less significant, uncertainties dealing with the refinement of a particular object's size, mass and structure as well as the dynamical model that is used to accurately predict the object's motion over 100 year time scales. For example, over long time intervals, the minute pressure of sunlight and its thermal re-radiation can significantly affect a PHA's motion. For a select number of Earth approaching objects, we will need the use of the planetary radars, or possibly rendezvous spacecraft missions, to better understand their sizes, shapes, masses, surface properties, and possible binary natures.

The Next Generation of Search: As noted, the current NASA NEO goal is focused upon the discovery and tracking of objects one kilometer in diameter and larger. It is not realistic to expect the current survey program, with its modestly sized telescopes, to efficiently find the 140 meter-sized objects that are nearly 50 times fainter compared to a one kilometer-sized object at the same distance and with the same reflectivity. Because all PHAs do eventually come very close to the Earth, the current ongoing surveys could complete the goal outlined in the 2005 *NASA Authorization Act* but it would likely take over a century to do so. We cannot afford to wait that long.

In the report to Congress requested by the 2005 *NASA Authorization Act,* several options were outlined, both ground-based and space-based, that could meet the goal of finding 90 percent of the PHAs larger than 140 meters by the end of 2020. For example, a one-meter aperture infrared telescope in a heliocentric orbit near Venus could do the job three years early. Within this report, NASA noted that it did not have the resources to carry out a survey option that would meet the 2020 deadline set by the 2005 Act and that, in an attempt to achieve the legislative goal by the end of 2020, it would seek to continue the current survey programs and look for opportunities to use dual use telescope facilities and spacecraft along with partnering with other agencies as feasible.

At least two next-generation, ground-based, wide-field search telescope surveys are in development. The Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), under development at the University of Hawaii with Air Force funding, will have one of its four 1.8 meter telescopes operational in Hawaii in early 2008. If the planned, four telescope version of Pan-STARRS is completed by 2010, it could help reach the goal by about 2040. Likewise the 8.4 meter aperture Large Synoptic Survey Telescope (LSST) that is under development with funding from NSF, DOE and other partners, could help reach the goal by about 2034 if it began operation in 2014. If we assume that both the Pan-STARRS four telescope system and the LSST operate in their planned shared modes, which includes many observations unrelated to PHAs, then the goal could be reached by about 2026. The PHA discovery rate could be increased beyond the results shown in the NASA response to the 2005 Act if the observing time and sequences of Pan-STARRS and LSST were optimized for PHA observations.

In terms of actual discoveries of new PHAs, there has been little success beyond the survey programs supported by NASA. However, the international community, including many sophisticated amateur astronomers, is very active in providing the follow-up observations necessary to secure an object's orbit once it has been found. The NEODyS program in Pisa, Italy works closely with, but independent of, the NEO Program Office at JPL to compute impact probabilities for predicted Earth close approaches for at least 100 years into the future. It is also encouraging to note the activities of a NEO Action Team within the UN Committee on the Peaceful Uses of Outer Space (COPUOS) includes an effort to encourage more international efforts on the NEO issues.

The importance of Radar Observations: There are only two planetary radars in existence (and no alternatives) that can routinely observe close Earth approaching asteroids, and both of them are critically important for investigating the nature of these objects and for rapidly refining their trajectories. The 70-meter Goldstone antenna in California's Mojave desert is fully steerable, can track an asteroid and can cover large regions of sky while the larger 305-meter Arecibo antenna in Puerto Rico has twice the range but only observes within a 40-degree zone centered on the overhead position (20 degrees on either side of zenith). The capabilities of these two telescope complement one another and often a significantly better and longer set of observations can be achieved using both radars on a close approaching target asteroid.

Most positional data for PHA orbit determination and trajectory predictions are based upon optical, plane-of-sky observations. Because the radars provide line-of-sight velocity and range information accurate to about the one mm/s and 10 meter levels, these data when used in conjunction with the optical data provide a secure orbit and trajectory far more rapidly than if only optical data are available. With only a limited amount of optical data to work with, the orbit of a newly discovered PHA is often not accurate enough to immediately rule out a future Earth impact. However, with radar data in hand, the orbit of a newly discovered PHA can be quickly and more precisely determined, its motion accurately projected far into the future and future impact possibilities can usually be quickly ruled out. Likewise, in the rare situation when an object is actually on an Earth threatening trajectory, radar observations will be critical in quickly identifying this case.

Unfortunately the Arecibo radar program is not funded by the NSF beyond FY 2007 and the planetary science community is in danger of losing one of its instrumental crown jewels. As a measure of this radar facility's importance, note that 65 percent of all radar experiments to characterize near-Earth asteroids were performed at Arecibo, 47 percent of all binary near-Earth asteroids were discovered at Arecibo and 85 percent of the near-Earth asteroids with the critical astrometric radar data for orbit improvement have data from Arecibo. All of this was accomplished with only five percent of this instrument's time. The superior sensitivity of the giant Arecibo radar can determine the sizes, shapes, rotation characteristics, surface characteristics and binary nature for many PHAs. All of these physical characteristics are important criteria to understand before a deflection mission is considered. Radar observations are responsible for the best physical characterization of any PHA as large as a kilometer (i.e., the binary asteroid 1999 KW4). Radar observations reduce a PHA's orbit uncertainties quickly and dramatically so that future impact possibilities can be quickly knocked down thus reducing the odds that we will need to invest in a spacecraft investigation to characterize the PHA's nature in preparation for a precautionary deflection mission. Thus the relatively modest costs of maintaining the Arecibo radar in a robust state could prevent the future need for 100's of millions of dollars per case for spacecraft reconnaissance of an object to determine whether or not it is an actual threat.

What Should be Done in the Event of an identified NEO Threat? A number of existing technologies can deflect an Earth threatening asteroid—if there is time. The primary goal of the PHA survey programs is to discover them early and provide the necessary time. An asteroid that is predicted to hit Earth might require a change in its velocity of only three millimeters per second if this impulse were applied twenty years in advance of the impact. The key to a successful deflection is having sufficient time to carry it out, whether it is the slow, gentle drag of a gravity tractor or a more impulsive shove from an impacting spacecraft or explosive device. In either case, a verification process would be required to ensure the deflection maneuver was successful and to ensure the object's subsequent motion would not put it on yet another Earth impacting trajectory. While suitable deflection technologies exist, none of them can be effective if we are taken by surprise. It is the aggressive survey efforts and robust planetary radars that must ensure that the vast majority of potentially hazardous objects are discovered and tracked well in advance of any Earth threatening encounters. The first three steps in any asteroid mitigation process are: Find them early, find them early, and find them early!

BIOGRAPHY FOR DONALD K. YEOMANS

At the Jet Propulsion Laboratory in Pasadena California, Donald K. Yeomans is a Senior Research Scientist, supervisor of the Solar System Dynamics Group, and manager of NASA's Near-Earth Object Program Office. His group is responsible for providing position predictions for the solar system's planets, natural satellites, comets and asteroids. For the comets and asteroids that can approach the Earth, his group monitors their motions and provides predictions and impact probabilities for future Earth encounters.

Dr. Yeomans was the Radio Science team chief for NASA's Near-Earth Asteroid Rendezvous (NEAR) mission. He is currently the NASA Project Scientist for the Joint Japanese and U.S. mission to land upon, and return a sample from, a near-Earth asteroid (Hayabusa) and he was a scientific investigator on NASA's Deep Impact mission that successfully impacted comet Tempel 1 in July 2005. He provided the accurate predictions that led to the recovery of comet Halley at Palomar Observatory on October 16, 1982 and allowed the discovery of 164 BC Babylonian observations of comet Halley on clay tablets in the British Museum.

He is a graduate of Middlebury College in Vermont and received his doctorate degree in astronomy from the University of Maryland in 1970. He has written numerous technical papers and four books on comets and asteroids. He has been awarded 15 significant achievement awards by NASA including an Exceptional Service Medal and a Space Act Award. To honor his work in planetary science, asteroid 2956 was renamed 2956 YEOMANS.

Chairman UDALL. Thank you, Dr. Yeomans. You all heard the bells ringing. One vote has been called on the Floor of the House, so we are going to continue the hearing. Congressman Lampson will come back and relieve me, so we can make the best use of your time and the Committee's time.

So, thank you, Dr. Yeomans. We will move to Dr. Campbell. Looking forward to your testimony, sir.

STATEMENT OF DR. DONALD B. CAMPBELL, PROFESSOR OF ASTRONOMY, CORNELL UNIVERSITY; FORMER DIRECTOR, ARECIBO OBSERVATORY

Dr. CAMPBELL. Mr. Chairman and Members of the Committee, thank you for this opportunity to address you on the role of radar, and specifically, the radar system on the giant Arecibo Telescope in Puerto Rico, in the tracking and characterization of NEOs, and the current state of funding of this National Science Foundation facility.

Dr. Yeomans has just described the importance of precision radar measurements in predicting the future orbits of NEOs, and determining which NEOs are really hazardous to Earth. For these hazardous objects, additional precision radar measurements are extremely important to assess the impact probability and the need to take action to mitigate the threat.

Near-Earth asteroids form a very diverse population, encompassing a large range of sizes, shapes, rotation states, densities, internal structure, and binary nature. It is important to understand the range of these characteristics in order to design suitable mitigation strategies. While a very small number of NEOs have been visited by spacecraft, radar provides by far the best means to survey these characteristics for a large number of objects. For an object that we know poses a direct threat to Earth, radar can provide vital input to mitigation planning.

As you have heard, there are only two very high powered radars in the world capable of studying solar system bodies including NEOs. One is on the NSF's Arecibo Telescope, and the other is on NASA's Deep Space Network 70 meter antenna in California. The Arecibo radar is over 20 times more sensitive than the one on the Goldstone antenna, and has been the dominant contributor to near-Earth asteroid characterization and orbit prediction. However, the Goldstone antenna can look at more of the sky than Arecibo, making the two systems very complementary. They should both be preserved.

In 2005 and 2006, the NSF Division of Astronomical Sciences undertook a Senior Review to examine the balance of its investments in various astronomical facilities the Division supports, including the Cornell University-based National Astronomy and Ionosphere Center, which operates the Arecibo Observatory for the NSF. The report was submitted to the NSF in November 2006. Despite considerable input to the Committee from both the National Astronomy and Ionosphere Center and the planetary community, the Arecibo Planetary NEO Radar Program is essentially ignored in the Committee's report.

The report recommended that NAIC's operating funds provided by the NSF's Division of Astronomical Sciences be reduced over the following three years from approximately $10.5 million to $8 million, and then in Financial Year 2011, be halved again to $4 million. At the $8 million level, budgetary pressures are likely to make the termination of the radar and NEO program unavoidable, unless additional funding is found. In the slightly longer-term, if Cornell cannot find the additional funding needed to keep the Observatory open, then, in the report's words, "The Senior Review recommends closure after 2011 if the necessary support is not forthcoming."

If the Arecibo radar system is decommissioned, it would leave the lower sensitivity NASA Goldstone system as the only radar in the world capable of precise orbit determination for NEOs and measurements characterizing their physical properties. It will probably be unable to fill the void, especially with the large number of NEOs likely to be detected over the next decade or more.

Replacing the Arecibo Telescope and radar system with a mission-specific facility of equal sensitivity would cost several hundred million dollars. Given its contributions to the NEO program and other research areas, and the relatively small budget needed to keep it operating, closing Arecibo does not make sense.

In answer to the question as to how much it would cost to support Arecibo for NEO activities, independent of any other use of the telescope, the budget would probably need to be very roughly the same as the Observatory's current budget, about $10 million per year. Most of the operating costs of large telescopes are fixed costs, relating to such things as maintenance, independent of the science mission.

In summary, Earth-based radar provides critical information related to NEO orbit prediction and characterization. Arecibo is the primary radar involved in this activity, and will remain so for at least the next 10 years provided that both the Observatory and its radar system are adequately funded.

If the Arecibo Observatory is closed, a unique research capability will be lost that makes valuable contributions not only to the study of Near-Earth Objects, but in other areas of astronomy and atmospheric science. One of Puerto Rico's main research facilities, and a spectacular structure as you saw earlier, the Arecibo Telescope is important to local education and tourism. Its closing would be a major loss to both science and the island.

Thank you for your attention.

[The prepared statement of Dr. Campbell follows:]

PREPARED STATEMENT OF DONALD B. CAMPBELL

Mr Chairman and Members of the Committee, thank you for this opportunity to address you on the important issue of near-Earth objects and their potential threat to Earth.

I have been asked to address issues related to the use of radar systems to track and characterize near-Earth objects (NEOs) and, specifically, to address the role of the radar system on the giant Arecibo telescope in Puerto Rico in this activity and the current state of funding for this National Science Foundation facility. I will address these questions in turn.

- *What role do Earth based radars play in the tracking and characterization of Near Earth Objects (NEOs)? What role, if any, do they play in providing information about specific hazardous objects?*

Radar plays an important role in predicting the future orbits of NEOs and measuring many of their physical characteristics such as size, shape, rotation state and, in the case of binary objects, their mass and density. Radar can measure distances to NEOs to an accuracy of about 10m (30 ft) and their line-of-sight velocity to an accuracy of about one mm per second (12 ft per hour), orders of magnitude better than the equivalent optical measurements. For potentially hazardous objects (PHOs), optical observations based on measuring their changing position on the sky over days or weeks in many instances cannot rule out a possible future impact with the Earth. To do so can require optical positional measurements spanning years or decades. For future searches, radar astrometry, the measurement of distance and line-of-sight velocity, can be used to help cull the number of PHOs—not all the newly detected NEOs will be observable with radar—so that we can concentrate on the few that really are potentially hazardous. For these objects, additional precision radar measurements are extremely important to assess the impact probability and the need to take action to mitigate the threat.

The more we know about NEOs in general and about specific ones that pose a threat to Earth, the easier it will be to design effective mitigation strategies. "Know your enemy" would seem to be good advice in this instance. NEOs form a very diverse population encompassing a large range of sizes, shapes, rotation states, densities, internal structure and binary nature. While a very small number of NEOs have been visited by spacecraft, radar provides by far the best means to survey these characteristics for a large number of objects. Knowing the range of characteristics facilitates the design of effective mitigation techniques that can be applied to an object with any of these characteristics. For an object that we know poses a direct threat to Earth, radar can provide vital input to mitigation planning including planning for any precursor space mission.

Over the past few years, the accuracy of the Earth impact prediction based on precision radar astrometry for a few PHOs has been limited not by the accuracy of the radar measurements but by the inability to accurately model all of the very small forces on these objects in addition to that due to the Sun's gravity. One of these forces, the Yarkovsky effect, is related to sunlight absorbed by the body and its re-emission as heat. Precision radar astrometry over several years of a small asteroid, Golevka, demonstrated in 2003 that this effect can modify the orbits of small asteroids over very long periods of time. This has revolutionized our understanding of how small asteroids in the main asteroid belt between Mars and Jupiter are transported into the inner solar system to become NEOs and, some, PHOs. This new understanding resulting from a basic science driven project will also help in refining PHO Earth impact probabilities for the few objects that may be of real concern.

- *What role has the Arecibo Observatory played in surveying NEOs and what are the impacts to the NEO program should Arecibo be decommissioned?*

The radar system on the NSF's Arecibo Telescope in Puerto Rico is one of only two very high powered radars in the world that are used for studying solar system bodies including NEOs. The other one is on NASA's Deep Space Network 70m antenna at Goldstone in California's Mojave desert. With its 300m (1,000 ft) diameter telescope and radiated power of one megawatt, the Arecibo radar is over 20 times more sensitive than the one on the Goldstone antenna. However, because of its limited steerability, Arecibo can only observe about half the sky observable with the Goldstone antenna making the two systems very complementary.

Because of its greater sensitivity and availability, the Arecibo radar system has carried out 65 percent of all radar observations characterizing NEOs, 47 percent of the known binary NEOs were discovered with Arecibo (most of the rest were discovered with optical telescopes), and data from Arecibo was used for 85 percent of the NEOs for which precision radar distance and velocity astrometric measurements have been made for orbit determination.

If the Arecibo radar system is decommissioned it would leave the lower sensitivity radar system on the NASA 70m Goldstone antenna as the only radar system in the world capable of precise astrometry of NEOs and measurements characterizing their physical properties. A tremendous amount of basic science related to NEOs and other solar system bodies would be lost and the highest sensitivity radar would no longer be available to provide precision astrometry and characterization data just as the NEO search programs are ramping to a new level. Given the pressures on the 70m Goldstone antenna in carrying out its prime mission, its lower sensitivity and the large number of NEOs likely to be detected over the next decade or more, it seems unlikely that this system could come close to filling the void. Replacing the Arecibo telescope and radar system with a mission specific facility of equal sensitivity would cost several hundred million dollars. Given its contributions to the NEO program and other research areas in radio astronomy and ionospheric physics and the relatively small budget needed to keep it operating, closing Arecibo does not make sense. In the words of Bill H.R. 3737, recently submitted by Congressman Fortuño on behalf of himself, Congressman Rohrabacher and other Members of the House of Representatives, "The Arecibo Observatory is an invaluable and unique asset in warning and mitigating potential hazards posed by near-Earth objects."

- *Did the recent National Science Foundation (NSF) Senior Review of Arecibo evaluate the facility's role in surveying NEOs and the impact of Arecibo's potential decommissioning on the NEO survey program? If not, why not?*

The National Astronomy and Ionosphere Center (NAIC), the formal name for the Arecibo Observatory located in Puerto Rico, is one of the four National Astronomy Centers plus the U.S. component of the international Gemini observatory, funded through the Division of Astronomical Sciences at the NSF and is operated by Cornell University under a Cooperative Agreement with the NSF. NAIC is unique among the Centers in that it supports research in three diverse areas, radio astronomy, planetary radar astronomy including the study of NEOs, and ionospheric physics. The first two are supported through funding from the Division of Astronomical Sciences at the NSF while the ionospheric program, about 15 percent of the budget, is funded through the Division of Atmospheric Sciences at the NSF. NAIC has about 120 people working at the Arecibo Observatory in Puerto Rico. In addition to providing research facilities for its scientific user community, it operates a visitor center that attracts about 120,000 visitors a year most from Puerto Rico including about 25,000 school children.

In 2005–2006 the Division of Astronomical Sciences of the National Science Foundation (NSF) undertook a "Senior Review" to examine the balance of its investments in the various astronomical facilities that the Division supports. The review was motivated by a combination of the budget outlook at that time for the Foundation and the ambitions of the astronomical community to invest in new facilities to address fundamental questions as recommended in the previous Astronomy Decadal Survey and other reports such as "Connecting Quarks with the Cosmos." The Senior Review committee submitted its report to the NSF in November, 2006.

The aims of the Senior Review were widely supported by the astronomical community and it is not my intention to criticize its major findings. However, its charge was to look at the "big picture" and in such a process small, high quality programs that are not central to the priorities of the committee or the NSF can end up becoming a casualty on the way to the main goal. Such seems to be the case for the planetary/NEO radar program at the Arecibo Observatory. During the review process, Cornell University and NAIC provided considerable input to the committee about the Observatory's research programs including the planetary/NEO radar program. Many planetary astronomers, especially those interested in NEOs, wrote to the Committee strongly supporting the Arecibo radar program. However, the Arecibo planetary/NEO radar program was essentially ignored in the committee's report with the only explanation I have heard being that the program was too small in funding terms to be individually considered. There were no planetary astronomers on the committee.

I should emphasize that the Senior Review report did not recommend that the Arecibo planetary/NEO radar program be canceled but that is likely to be the outcome of its budgetary recommendations vis-à-vis NAIC. It recommended that NAIC's operating funds provided by the NSF Division of Astronomical Sciences, about 85 percent of its yearly budget with the rest coming from the NSF Division of Atmospheric Sciences, be reduced over the following three years from approximately $10.5M to $8M and then, in FY 2011, be halved again to $4M. By early 2009 Cornell is required to have definite commitments from other entities for the additional operating funds needed to keep the observatory open. If it cannot get these commitments then, in the Senior Review report's words "The Senior Review recommends closure after 2011 if the necessary support is not forthcoming."

The planetary/NEO radar program is scheduled to continue in operation at a reduced level of activity through FY 2008 compared with its normal use of about 400 hours of telescope time per year. If the NSF implements the Senior Review's recommendations to reduce NAIC's budget for astronomical research to the $8M level, budgetary pressures and deferred maintenance are then likely to make termination of the radar/NEO program unavoidable unless additional funding is found. Since the planetary/NEO radar system has significant operational and maintenance costs associated with the transmitting system, terminating it is the only identifiable way to save about $1M in operating costs short of canceling the observatory's entire radio astronomy program. The NSF has said that they will not augment NAIC's budget to provide support for the planetary radar/NEO program and has indicated that this area of research should be supported by NASA. Until a few years ago, NASA did provide partial support for the Arecibo radar program. In the slightly longer-term, if additional operating funds are not found well before the projected FY 2011 NSF/AST reduction to $4M then the Arecibo Observatory will possibly be closed definitely terminating its contributions to the tracking and characterization of NEOs.

- *What level of funding and technical support would be required to carry out the NEO-related activities of Arecibo, independent of any other astronomy-related activities? Will any upgrades to the facility or its instruments be required?*

The current yearly cost for operating Arecibo's planetary radar system for about 400 hours a year is close to $1M. About 60 percent of this time is devoted to NEO research. This covers the cost of the operation and maintenance of the high powered transmitting capability plus several engineers and a small scientific staff. It does not cover major maintenance items for the transmitting system. It also does not cover the cost for the operation and maintenance of the telescope and the general support for grounds, buildings, etc., needed to keep the observatory operating as a facility. Prorating these costs based on the observing hours used would raise the current costs of the planetary radar program to close to $2M/yr.

No study has yet been done of the precise role of the Arecibo radar and how many hours of NEO observations will be needed when the new, high sensitivity searches commence starting with Pan-STARRS. This needs to be done. The demand for the use of the Arecibo radar will undoubtedly increase significantly but whether by a factor of two or five is uncertain. While maintaining the observatory's multi-disciplinary program, some increase in the use of the radar system for NEO observations can certainly be accommodated. A program using about 500 hours a year for NEO observations and, perhaps, 100 hours for radar studies of other solar system bodies would cost $2M to $3M including its share of general observatory support costs. The costs would prorate roughly with observing time.

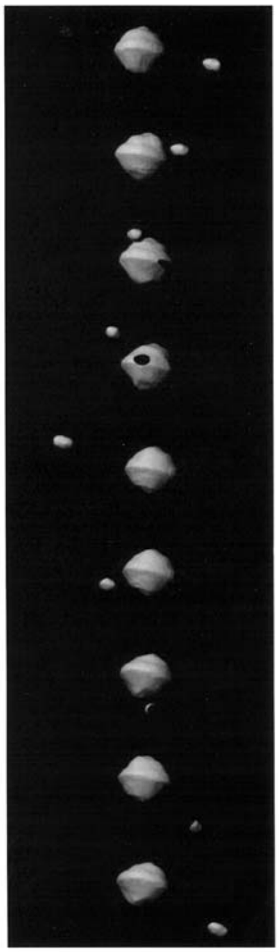
In answer to the question as to how much it would cost to support Arecibo for NEO activities independent of any other use of the telescope, the budget would need to be very roughly the same as the observatory's current budget, about $10M per year. Most of the operating costs of large telescopes are fixed costs related to maintenance, etc., independent of the science mission. However, I want to emphasize that any NEO radar program is unlikely to utilize all, or even a majority, of the observing time available on the telescope.

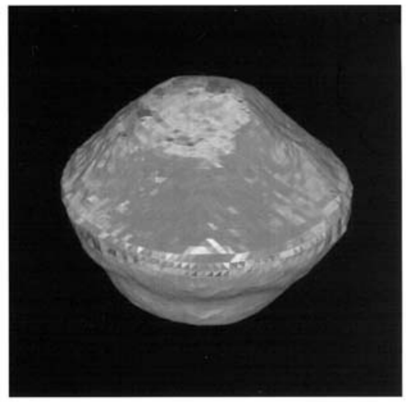
The Arecibo telescope and radar system underwent a major NSF and NASA funded upgrading about ten years ago. At this time some major components of the transmitting system need refurbishment or replacement and some of the data handling equipment used for the NEO program needs updating. Total costs of this are estimated to be about $2M.

- *What are your perspectives on NASA's* Near-Earth Object Survey and Deflection Analysis of Alternatives Report to Congress*?*

NASA's report was a comprehensive discussion of the issues related to the detection of 90 percent of all NEOs larger than 140m by 2020, the requirement to determine their orbits, understand the broad characteristics of different classes of asteroids in order to be able to design mitigation strategies, and, of course, the range of possible mitigation strategies. Staying within my area of expertise, the report's discussion on the usefulness of determining orbits with radar versus with optical means and the best means to characterize these objects to, in the report's words, "inform mitigation" should be revisited. For orbit determination the issue is whether a relatively quick refinement of at least some percentage of the orbits of newly discovered PHOs is preferable to waiting the 10 to 20 years that optical means require for orbit determinations that will as stated in the report "nearly match the accuracy of radar-improved orbits."

The role of the radar systems in surveying the broad range of NEO types could also have been given more emphasis in the report. Radar is currently the only Earth or Earth-orbit based technique that has the resolution needed to provide information about a wide range of physical properties important to mitigation planning. The images below show the detailed shape model of the main component of the binary NEO 1999 KW4 and a simulation of the binary system, results obtained by Steven Ostro of JPL and colleagues from observations using the Arecibo and Goldstone radars. The work was described in the cover article of *Science* magazine last November. We now know KW4's size, about 1.5 km (one mile) for the main body, shape, rotation rate, mass, density and that it is a binary object. The low density of the main body, about twice that of water, tells us that it is rubble pile rather than a single large "rock." This is all information that is critical to "informing mitigation."





Binary Near-Earth Asteroid 1999 KW4

Top image: A detailed shape model derived from Arecibo and Goldstone radar observations of the 1.5 km (1 mile) diameter main body of the binary NEO 1999 KW4. Its low density, about twice that of water, indicates that it is an unconsolidated "rubble pile" kept together by gravity. Color indicates the apparent slope of the surface.

Left image: A computer generated simulation of the ~0.5 km (0.3 mile) "moon" in its 17 hour orbit about the main body. Its orbital distance from the center of the main body is about 2.5 km. The black areas on the main body in the 3rd and 4th images are the shadow of the moon in this simulation.

See Science magazine and its cover image from 24 November, 2006 for a detailed description of this work. Images courtesy of S. Ostro (JPL) and D. Scheeres (University of Michigan).

Chairman UDALL. Thank you, Dr. Campbell.

Next on the panel is Dr. Tyson, and I would, as a preface to his remarks, mention that as a Member of the Armed Services Committee, I am used to many, many acronyms, and I used one earlier in my comments to begin the hearing, about the LSST, which is the Large Synoptic Survey Telescope Project, and Dr. Tyson is a key part of that effort.

So, Dr. Tyson, welcome, and the floor is yours.

STATEMENT OF DR. J. ANTHONY TYSON, PROFESSOR OF PHYSICS, UNIVERSITY OF CALIFORNIA, DAVIS; DIRECTOR, LARGE SYNOPTIC SURVEY TELESCOPE PROJECT

Dr. TYSON. Thank you, Mr. Chairman and Members of the Committee. It is an honor to be asked to testify before you today on this important subject.

The House Committee on Science has been a leader, on a bipartisan basis, over two decades, in focusing attention on the need to detect, characterize, and catalog near-Earth asteroids. The passage of the George E. Brown Near-Earth Object Survey Act was a landmark piece of legislation that sets a goal of cataloging 90 percent of NEOs of 140 meters in diameter and larger within 15 years.

The Committee is properly looking at the existing and future capabilities of carrying out this goal and expanding the existing Spaceguard program. LSST adopted the goal of surveying NEOs at the outset as one of its major science capabilities. I have attached to the statement a nine page summary of the capabilities of LSST for detecting NEOs and obtaining their orbits.

Until recently, the discussion of risk associated with an impact of NEOs has been statistical. In other words, what is the probability? This is similar to considerations of risk in many other areas, such as weather and traffic accidents. What if it were feasible to deploy a system that would alert me of an impending traffic accident well in advance? That would change the very nature of that risk from a probabilistic worry to a deterministic, actionable situation. The ability to detect virtually every potentially hazardous near-Earth object and determine its orbit with precision transforms that statistical threat into a deterministic prediction. We face many threats, and virtually all of them are either so complex or unpredictable that they are treated probabilistically, even though the social and financial consequences are legion. With a comparatively small investment, the NEO risk can be transformed from a probabilistic one to a deterministic one, enabling mitigation.

Ground-based optical surveys are the most cost-effective tool for comprehensive NEO detection, determination of their orbits, and subsequent tracking. Radar, as we have heard, also plays an important role once the threatening NEO has been found, in refining its orbit when the NEO is near. The first job is to find the NEOs which are potentially hazardous, so-called potentially hazardous objects, or potentially hazardous asteroids, actually, from among the swarm of 10 million other asteroids.

A survey capable of extending these tasks to NEOs with diameters as small as 140 meters, as mandated by Congress, requires a large telescope, a large camera, and a sophisticated data acquisition, processing, and dissemination system. This Congressional mandate drives the requirement for an eight meter class telescope with a 3,000 megapixel camera and a sophisticated and robust data processing system. These requirements are met by the LSST.

The LSST is currently, by far, the most ambitious proposed survey of the sky. With initial funding from the National Science Foundation, Department of Energy laboratories, and private sponsors, the design and development efforts are well underway at many institutions.

Fortunately, the same hardware and software requirements are driven by science unrelated to NEOs. LSST reaches the threshold where different science drivers, and therefore, different agencies, NSF, DOE, and NASA, can work together to efficiently achieve seemingly disjoint but deeply connected goals. This broad range of science has earned LSST the endorsement of a number of committees commissioned by the National Academy of Sciences. Because of this synergy, the Congressional mandate can be reached at only a fraction of the cost of a mission dedicated exclusively to NEO search.

We have carried out over 100 computer simulations of the LSST operations for a variety of NEO optimized scenarios. The planned LSST baseline survey cadence on the sky, that is to say, the way you tile the sky with time, during the night, is capable of providing orbits for 82 percent of potentially hazardous asteroids larger than 140 meters after 10 years of operation, and is 90 percent complete for objects larger than 230 meters. This baseline cadence assumes that five percent of the total observing time is spent on NEO specialized observing. This is what is currently planned.

By increasing this fraction of NEO specialized surveying to 15 percent, that is to say, from five to 15 percent, and by running the survey longer, the Congressional mandate of 90 percent completeness for potentially hazardous asteroids of 140 meters and greater size, can be fulfilled after 12 years of operation, with 60 percent completeness level reached after only three years. These specialized observations would be of limited use to other science programs, and they require 15 percent of the observing time.

The current cost estimate for LSST in 2006 dollars is $389 million for construction, and $37 million per year for operations. For a 12-year long survey, 15 percent of this total cost is $125 million. Thus, we could deliver the performance of a full NEO dedicated LSST to NASA and to the world at a small fraction of the total cost to build and operate such a system. This cost is equivalent to 30 percent of operations, which would commence in 2014.

Note that by operating LSST in this special NEO optimized mode, we would have the performance equivalent of an LSST fully dedicated to NEO serving. By supporting only 15 percent of the total cost, NASA would be essentially getting an NEO dedicated LSST. This is a key new insight, relative to the costing model in the 2007 NASA NEO report to Congress.

Thank you.

[The prepared statement of Dr. Tyson follows:]

PREPARED STATEMENT OF J. ANTHONY TYSON

Mr. Chairman and Members of the Committee. It is an honor to be asked to testify before you today on this important subject. By way of identification, I am an astrophysicist and Professor of Physics at the University of California, Davis, and

Director of the Large Synoptic Survey Telescope (LSST) project; before coming to UC–Davis four years ago I did research and development at Bell Labs for 34 years.

The House Committee on Science has been a leader on a bipartisan basis for over two decades in focusing attention on the need to detect, characterize, and catalog near-Earth asteroids. The passage of the "George E. Brown Jr. Near-Earth Object Survey Act" was a landmark piece of legislation that sets a goal of cataloging 90 percent of NEOs of 140 meters in diameter and larger within 15 years. The Committee is properly looking at the existing and future capabilities for carrying out this goal and expanding the existing Spaceguard program. LSST adopted the goal of surveying NEOs at the outset as one of its major science capabilities.

Until recently, the discussion of risk associated with an impact of a NEO has been statistical; what is the probability? This is similar to considerations of risk in many other areas such as weather and traffic accidents. What if it were feasible to deploy a system that would alert me of an impending traffic accident well in advance? That would change the very nature of that risk from a probabilistic worry to a deterministic actionable situation. The ability to detect virtually every potentially hazardous Near-Earth object and determine its orbit with precision transforms that statistical threat into a deterministic prediction. We face many threats, and virtually all of them are either so complex or unpredictable that they are treated probabilistically even though the social and financial consequences are legion. With a comparatively small investment the NEO risk can be transformed from a probabilistic one to a deterministic one, enabling mitigation.

The First Job: Finding the NEOs

Ground-based optical surveys are the most efficient tool for comprehensive NEO detection, determination of their orbits and subsequent tracking. (Radar also plays an important role once a threatening NEO has been found, in refining its orbit when the NEO is near.) The first job is to find the NEOs which are potentially hazardous (so-called Potentially Hazardous Asteroids) from among the swarm of ten million other asteroids. A survey capable of extending these tasks to NEOs with diameters as small as 140m, as mandated by Congress, requires a large telescope, a large camera, and a sophisticated data acquisition, processing and dissemination system. The Congressional mandate drives the requirement for an eight-meter class telescope with a 3000 Megapixel camera and a sophisticated and robust data processing system. These requirements are met by the LSST.

Why is a large telescope required? A typical 140-meter NEO appears very faint (visual magnitude of 25). Multiple NEO detections in a single night are required to estimate its motion, so that its future or past detections can be linked together. This linkage has to be done exceedingly robustly because the near-Earth objects will be outnumbered nearly a thousand to one by main-belt asteroids (between Mars and Jupiter) which present no threat to Earth. By reliably linking detections on multiple nights, the NEO's orbit can be reconstructed and used to compute its impact probability with Earth. Despite their name, NEOs are typically found far from Earth. In principle, very faint objects can be detected using long exposures, but for objects moving as fast as typical NEOs, the so-called trailing losses limit the exposure time to about 30 seconds. In order to detect 140-meter NEOs in 30 seconds, an eight-meter class telescope is required.

Why is a large camera required? The need for a very large field of view comes from the requirement that the whole observable sky should be observed at least every four to five nights. For comparison, we need a field of view thousands of times larger than the Hubble Space Telescope's Advanced Camera for Surveys. With its 10 square degree field of view, LSST will be able to reach the mandated high NEO completeness.

Finding Near-Earth Objects with Ground-based Surveys

Ground-based optical surveys are a very cost effective tool for comprehensive NEO detection, determination of orbits, and subsequent tracking. A survey capable of extending these tasks to NEOs with diameters as small as 140m, as mandated by Congress, drives the requirement for a large telescope, a large camera, and a sophisticated data acquisition, processing and dissemination system.

To find a significant fraction of the faint NEOs one must essentially make a movie of the deep sky. Each faint asteroid must be captured in many separate exposures in order for computers to distinguish it from the numerous other asteroids and then piece together its orbit. A large area of the sky (ideally all the sky visible from some location on Earth, at least 20,000 square degrees) must be surveyed rapidly and deeply in order to survey a large volume for these faint asteroids. The ability of a telescope and camera to take rapid deep repeated images of the entire sky is proportional its "throughput." Throughput (sometimes called etendue) is simply the product of the telescope light collection area (units: square meters) times the camera field of view in a single snapshot (units: square degrees). Thus throughput of a survey facility is measured in units of square meters square degrees. The throughput of LSST is 320 square meters square degrees. High throughput is a necessary condition for such a facility to carry out its mission, but not a sufficient condition: one must also arrange to have high observing efficiency (access to the sky) and highly efficient optics and imaging detectors in the camera, as well as superb image quality.

For an efficient NEO survey, the whole observable sky should be observed at least every four to five nights, with multiple observations per night. In order to do so with exposure time of about 30 seconds per observation, a 10 square degree large field of view is required. Such a large field of view, with pixel size sufficiently small to fully sample the image at a good observing site, implies a multi-billion pixel camera. Indeed, at the time of its completion, the 3.2 billion pixel LSST camera will be the largest astronomical camera in the world.

With a 3.2 billion pixel camera obtaining images every 15 seconds (individual 30 second exposures are split into two 15 second exposures for technical reasons), the data rate will be about 20 thousand gigabytes per night. Not only is this a huge data rate, but the data have to be processed and disseminated in real time, and with exquisite accuracy. It is estimated that the LSST data system will incorporate several million lines of state-of-the-art custom computer code.

State of the LSST project

The Large Synoptic Survey Telescope (LSST) is currently by far the most ambitious proposed survey of the sky. With initial funding from the U.S. National Science Foundation (NSF), Department of Energy (DOE) laboratories and private sponsors, the design and development efforts are well underway at many institutions, including top universities and leading national laboratories. The main science themes that drive the LSST system design are Dark Energy and Dark Matter, the Solar System Inventory, Transient Optical Sky and the Milky Way Mapping. It is this diverse array of science goals that has generated the widespread excitement of scientists ranging from high-energy physicists to astronomers and planetary scientists, and earned LSST the endorsement of a number of committees commissioned by the National Academy of Sciences.

Fortunately, the same hardware and software requirements are driven by science unrelated to NEOs: LSST reaches the threshold where different science drivers and different agencies (NSF, DOE and NASA) can work together to efficiently achieve seemingly disjoint, but deeply connected, goals. Because of this synergy the Congressional mandate can be reached at only a fraction of the cost of a mission dedicated exclusively to NEO search.

The scientific priority for constructing a large aperture ground based survey telescope was recommended in the astronomy and astrophysics Decadal Survey 2000 report entitled *Astronomy and Astrophysics in the New Millennium.* Since then, LSST has reached a high state of design maturity. LSST has recently passed the NSF Conceptual Design Review for construction, which puts it on track for transition to Readiness in spring 2008. LSST is a public-private project. To date $44M in private funding has been raised. Twenty two institutions have joined the effort and have contributed significant in-kind technical labor. LSST R&D continues for another three years under NSF support along with in-kind contributions. The project is on track for first light in 2014. It is proposed that the DOE (because of the importance of LSST for addressing the mystery of dark energy) support the $80M cost of constructing the camera. Foreign support now appears likely, and this in-kind would offset the camera cost.

Method of Study: the LSST Operations Simulator

The LSST Operations Simulator was developed to be able to do just the sort of assessment described in this document. It contains detailed models of site conditions, hardware and software performance, and an algorithm for scheduling observations which will, eventually, drive the robotic LSST observatory. The resulting sky coverage for the LSST baseline cadence is shown in Figure 1.

For the currently planned LSST baseline cadence, objects counted as cataloged are observed on 20 different nights on average. A more stringent requirement could decrease the completeness by up to three percent. The completeness is also a function of the assumed size distribution: the flatter the distribution, the higher the completeness. If the latest results for the NEO size distribution by A. Harris are taken into account, the completeness increases by one to two percent. Due to these issues, the completeness estimates have a systematic uncertainty of two percent. Our analysis assumes that no NEOs are known prior to LSST. Current surveys make a negligible contribution to the 90 percent completeness for NEOs of 140m and up.

The NEO survey completeness achievable with LSST

The LSST system is the only proposed astronomical facility that can detect 140-meter objects in the main asteroid belt in less than a minute. The LSST system will be sited at Cerro Pachon in northern Chile, with first light scheduled for 2014. In a continuous observing campaign, LSST will cover the entire available sky every four nights, with at least two observations of an NEO per night. Over the baseline survey lifetime of 10 years, each sky location would be observed over 800 times. Two NEO detections in a single night are required to estimate its motion, so that its future or past detections can be linked together. This linkage has to be done exceedingly robustly because the near-Earth objects will be outnumbered a hundred to one by main-belt asteroids which present no threat to Earth. By reliably linking detections on multiple nights, the NEO's orbit can be reconstructed and used to compute its impact probability with Earth.

The currently planned LSST baseline observing cadence on the sky, described in the Major Research Equipment and Facilities Construction proposal submitted to NSF, is simultaneously optimized for all four main science drivers: Characterizing Dark Energy and Dark Matter, the Solar System Inventory, Transient Optical Sky, and the Milky Way Mapping (see Figure 1). Computer simulations of LSST observing show that the data stream resulting from this baseline cadence on the sky is capable of providing orbits for 82 percent of Potentially Hazardous Asteroids (PHA) larger than 140 meters after 10 years of operations. The completeness curve as a function of time since the start of the survey is shown in Figure 2 (second curve from top). This baseline cadence spends five percent of the total observing time on NEO-optimized observations in the north region of the ecliptic (plane of the solar system).

Various adjustments to this baseline cadence can boost the completeness for 140m and larger PHAs to 90 percent. Based on about 100 different simulations, we find that such adjustments to the baseline cadence or filter choices can have unacceptably large impact on other science programs, if the 90 percent completeness is to be reached within 10 years from the beginning of the survey. However, with a minor adjustment of the baseline cadence and additional specialized observing for NEOs, this completeness level can be reached with a 12-year long survey, and with a negligible effect on the rest of science goals.

These specialized observations would be of limited use to other science programs, and they require 15 percent of the observing time. The dependence of completeness for 140m and larger objects on time is shown in Figure 2. For LSST, Figure 2 shows the baseline survey and the special NEO-optimized survey. In addition, we also show completeness curves for the same observing cadence and under the same assumptions regarding seeing and efficiency for smaller versions of LSST of less throughput. The lowest curve (black line) in Figure 2 shows the completeness for current NEO assets (ca. 2014–) for comparison.

Conclusions

The ability of LSST to reach the mandated 90 percent completeness for 140m and larger PHAs in 10 years by the so-called "dedicated" option described in the 2007 NASA NEO report is supported by our detailed and realistic simulations. An important additional insight from these simulations is that we can deliver the performance of a "dedicated" system by spending 85 percent of the total observing time on a general survey useful for all LSST science programs, and by specializing only about 15 percent of the total observing time for NEO surveying. If such an NEO-optimized program is executed for 12 years, the 90 percent completeness for 140m and larger PHAs can be reached without a significant negative impact on other science programs.

The current cost estimate for LSST in 2006 dollars is $389M for construction and $37M per year for operations. For a 12-year long survey, 15 percent of the total cost is $125M. Thus, we could deliver the performance of a full NEO-dedicated LSST to NASA at a small fraction of the total cost to build and operate such a system. This cost is equivalent to 30 percent of operations, which would commence in 2014. To assure LSST keeps on schedule, about $5M should be spent on optimized NEO orbit software pipeline development in the last phase of R&D and the construction phase, 2009–2014.

Executive Summary

In December 2005 Congress directed NASA to implement a near-Earth object (NEO) survey that would catalog 90 percent of NEOs larger than 140 meters in 15 years. In order to fulfill the Congressional mandate using a ground-based facility, an eight-meter class telescope equipped with a 3200 Megapixel camera, and a sophisticated and robust data processing system are required. These criteria are met by the Large Synoptic Survey Telescope (LSST). We have carried out over 100 simulations of the LSST operations for a variety of NEO-optimized scenarios. The planned LSST baseline survey cadence on the sky, simultaneously optimized for all main science drivers, is capable of providing orbits for 82 percent of PHAs larger than 140 meters after 10 years of operation, and is 90 percent complete for objects larger than 230 meters. This baseline cadence assumes that five percent of the total observing time is spent on NEO-specialized observing. This is what is currently planned. By increasing this fraction to 15 percent and by running the survey longer, the Congressional mandate of 90 percent completeness for NEOs of 140m and greater size can be fulfilled after 12 years of operation, with 60 percent completeness level reached after only three years.

Note that by operating LSST in this special NEO-enhanced mode we would have the performance equivalent of an LSST fully dedicated to NEO surveying. By supporting only 15 percent of the total cost, NASA would be essentially getting a NEO-dedicated LSST. This is a key new insight relative to the costing model in the 2007 NASA NEO report to Congress.

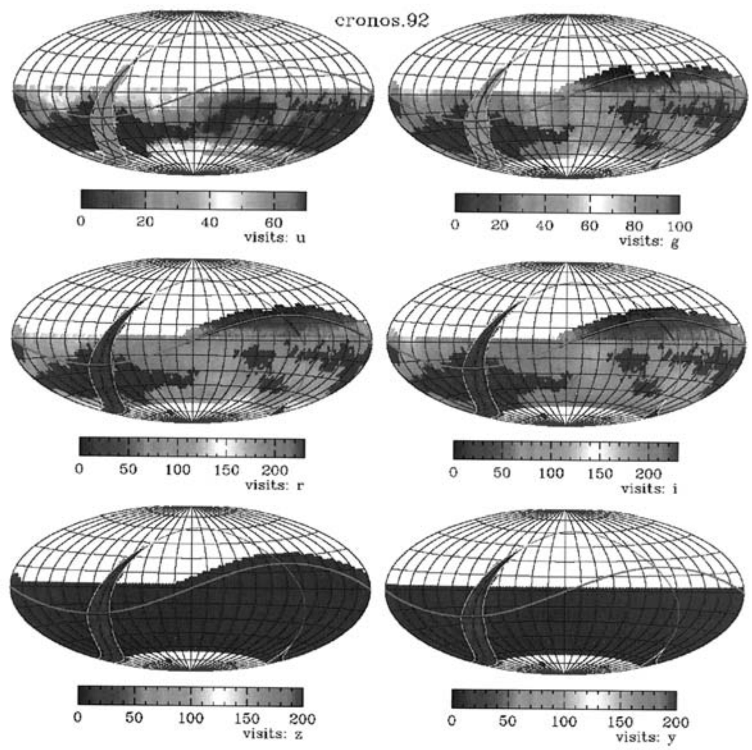


Figure 1. The result of computer simulations of planned LSST operations. Plots of LSST's coverage of the sky are shown for each of the 6 colors (wavelength bands from the ultraviolet to the near infrared), denoted ugrizy. These simulations are fully realistic in that they incorporate real weather data from the LSST site and detailed LSST system behavior. The number of visits per field in each filter for the simulated 10-year long baseline survey is shown. The blue area seen in the upper right part of the griz panels represents observations optimized for NEO survey in the planned baseline survey. However, all the displayed observations contribute to the NEO completeness. Although the baseline survey achieves a completeness of 82% after 10 years, additional NEO-dedicated observing can achieve 90% in 12 years as shown in Figure 2.

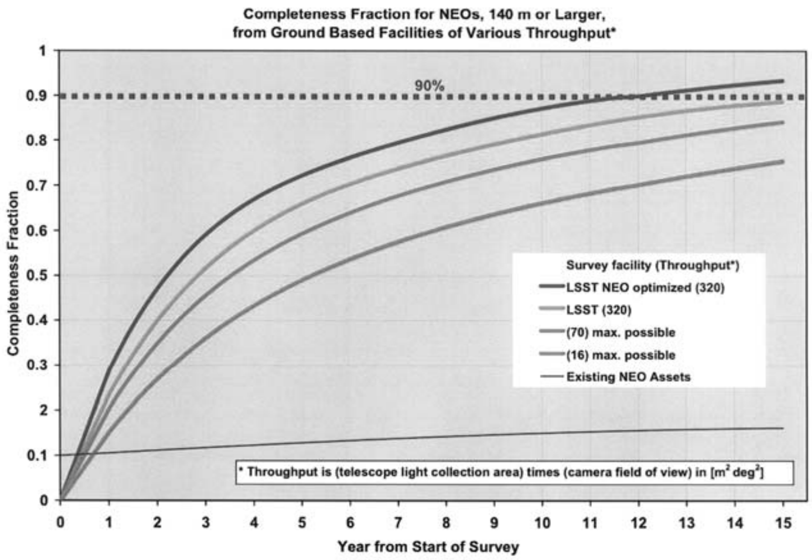


Figure 2. The completeness of several NEO surveys, based on LSST baseline cadence on the sky, is shown vs time from the start of the survey. The top two curves, with 15% and 5%, correspond to the LSST special NEO-optimized and the baseline LSST plan. The other curves represent the maximum possible completeness for less capable systems with smaller throughput. The top curve, based on 15% of the observing time spent in an NEO optimized mode, reaches the Congressional goal of 90% completeness for NEOs larger than 140m after 12 years of surveying. Given the timeline for agency approval of construction funding, it is likely that the LSST will have first light in 2014 and the sky survey will begin in 2015. With the survey start in 2015, the completeness for 140m and larger objects achieved in 2020 would be 70%, with 90% completeness for 350m and larger objects. Facilities with throughput smaller than LSST's 320 square meters square degrees have corresponding less completeness as shown in the lower curves.

BIOGRAPHY FOR J. ANTHONY TYSON

J. Anthony "Tony" Tyson, distinguished Professor of Physics at University of California, Davis, is an experimentalist interested in gravitational physics. His current research is in cosmology: dark matter distribution, gravitational lens effects, cosmic shear, and the nature of dark energy. These investigations involve software for pattern recognition, detection of transients in images, large database handling and processing, and new instrumentation for optical astronomy. He directs a national effort to build a new kind of telescope/camera called the Large Synoptic Survey telescope (LSST). With its large aperture and wide field of view, LSST promises to shed light on the mysterious "dark energy" that is considered to be the most urgent problem in the physics of our universe.

Tony Tyson received his B.S. in Physics from Stanford in l962 and a Ph.D. from University of Wisconsin at Madison in 1967, and a postdoctoral fellowship at the University of Chicago. He is a Fellow of the American Physical Society and the American Academy of Arts and Sciences, and a member of the National Academy of Sciences and the American Philosophical Society.

Mr. LAMPSON. [Presiding] Thank you, Dr. Tyson. Mr. Schweickart.

STATEMENT OF MR. RUSSELL "RUSTY" L. SCHWEICKART, CHAIRMAN AND FOUNDER, B612 FOUNDATION

Mr. SCHWEICKART. Mr. Chairman, Mr. Ranking Member Feeney, and Members of the Committee, Mr. Lampson, I thank you for giving me the opportunity here to testify on the Near-Earth Object situation, on NASA's report to Congress on the matter, and on where we need to go from here.

With very limited time, I will jump right into the four questions I was asked to address, and our six specific recommendations pertaining to it. We were asked first to provide our perspectives on NASA's report to Congress, and whether we agree or disagree with the report's findings and recommendations.

The first two elements of the Congress' directive related to analyzing ways of meeting the new goal, as we have heard, and a specific directive to recommend a program and a budget to support it. NASA completely ignored Congress' direction to recommend a search program and supporting budget. I want to emphasize here, picking up on Chairman Udall's earlier comment that not only did the Congress direct NASA to make a recommendation and a budget to support it, but the President signed that into law, so it is in law by both the President and the Congress.

So, our first recommendation is that Congress should again direct NASA, in the clearest language possible, to comply with the law, and recommend a search program and supporting budget.

With regard to Congress' directive, the third task of NASA, that they analyze possible alternatives that could be employed to divert an object on a likely collision course with Earth, we highlight only two of the many technical flaws in NASA's report to Congress. The first of those, NASA misinterpreted the Congressional intent, and elected to consider forward deflection, to look at what would be required, only a set of very large, very improbable Near-Earth Objects, rather than the far more frequent but still devastating impacts which we are much more likely to encounter.

Assuming, therefore, this extraordinary demand, NASA naturally came up with an extraordinary response, namely, the use of nuclear explosives. In fact, 99 percent of the NEOs most likely to trigger a call for deflection can be diverted by non-nuclear kinetic impacts, that is, simply running into the Near-Earth Object with a spacecraft, similar to what was done by NASA on July 4, 2005, in the Deep Impact crash into Comet Tempel 1.

In a letter clarifying the Congressional intent, Congressman Dana Rohrabacher stated that: "The first order of business is to ensure that we have a clear understanding of what the options are for the situations we are most likely to encounter." When shown this letter, NASA's comment to us, in a June 18, 2007 meeting was, to paraphrase it: "If we had seen this letter at the time we began the study, we might have come out with a different report." Bottom line, nukes are not necessary, except in extremely rare and unusual circumstances.

The second serious flaw in NASA's report is that NASA failed to understand and address the fact that whenever an asteroid passes near the Earth, for example, as the result of a deflection, it passes through a region in which are scattered hundreds of impact keyholes, small areas through which, if the asteroid passes, it will return in a few years to impact the Earth. Any deflection which causes an impacting asteroid to avoid hitting the Earth will end up, instead, passing through this minefield of impact keyholes. A successful deflection, therefore, depends upon the use of both a primary deflection, that is, to miss the Earth, using an appropriate impulsive technique, that is, a kinetic impact, or in exceptional cases, a nuclear explosion, and a potential secondary deflection, if it is headed for a keyhole, using a slow push capability, to ensure that the NEO both misses the Earth and misses the keyholes, therefore avoiding placing it on a return trajectory with an impact in a few years.

Again, in our meeting on June 18, 2007 with NASA, they acknowledged that at the time the analysis was done, it did not understand the importance of this issue. Bottom line, both strength and precision are necessary for a successful deflection.

Moving on, the second question I was asked to address was which relevant factors, data, or options are not addressed in the report, and how should NASA investigate those areas. Given the two serious flaws in NASA's report, which I just cited, as well as many others that are outlined in detail in my written testimony, we recommend, number two, that NASA should produce a supplement to its report to Congress, based on new knowledge which has come to light since it began its analysis.

The third question Congress asked me to respond to was what does NASA need to do now to understand and mitigate the risks of potential NEO impact? Absent someone in NASA going beyond the search and discovery challenge, and thinking through the complex issues of NEO deflection, we stand justly accused of focusing on numeric goals for the sake of meeting an abstract quota, that is, 90 percent of so many objects, et cetera, et cetera. We therefore recommend that NASA, our third recommendation, that NASA should assign someone in its NEO program to the specific task of thinking through, analyzing, and understanding the NEO deflection challenge.

And in addition, our fourth recommendation, based on this question, is that NASA should validate the basic NEO deflection capability, through the execution of a demonstration asteroid deflection mission. That is, we should not be put in the position of doing a deflection mission for the first time when lives actually count on it.

Finally, we were asked what governance structure should be established to address potential NEO threats. This is, by far, the most important question that I was asked by the Congress. NASA, as the U.S., and arguably the world's premier space agency, should have the responsibility for both fully understanding the NEO deflection challenge and developing and testing deflection technology. It does not have that responsibility now.

Therefore, our fifth recommendation is that the Congress expressly assign to NASA the technical development elements of protecting the Earth from NEO impacts as a public safety responsibility. That is, without NASA having the specific responsibility assigned to it to develop the technical means of protecting the Earth from NEO impacts, it will not be done. They must be assigned this responsibility. Otherwise, there will not be action in this regard.

The larger question, however, is to which agency of government should the overall responsibility for protecting the Earth from NEO impacts be assigned, not just the technical development aspects, but the policy and political responsibility. This inherently international issue will involve complex and very sensitive coordination and negotiation, and the U.S. involvement will place in the hands of the agency responsible the lives and property of potentially the entire population.

We, therefore, recommend as our final and sixth recommendation that the Congress study the issue of overall governmental responsibility for protection of the Earth from NEO impacts, perhaps with the assistance of specialized policy entities, and ultimately, to hold public hearings to engage a wide perspective on this issue.

The logical candidates, obviously, for this overall responsibility are the Department of Homeland Security, the Department of Defense, and of course, NASA itself.

This has been, of necessity, a very cursory review of a very important set of issues and questions. I thank you for the opportunity to discuss them with you, and I look forward to responding to any questions you may have.

[The prepared statement of Mr. Schweickart follows:]

PREPARED STATEMENT OF RUSSELL L. SCHWEICKART

Mr. Chairman and Members of the Committee:

Thank you for the opportunity to testify on this important subject; an issue of increasing interest regarding the protection of life and property around the planet.

I represent B612 Foundation (B612), a private non-profit corporation founded in 2002 by a group of astronauts, astronomers, planetary scientists and engineers to advocate and develop the means of diverting a near-Earth object (NEO) threatening an impact with Earth. B612 has developed several alternative concepts for deflecting NEOs and we have actively urged NASA, the Congress, and others to pursue the NEO challenge beyond search and discovery and into mitigation and prevention.

I will start by commending the Committee for its efforts since the early 1990s in seeing that this public safety issue is responsibly addressed. The impact of near-Earth objects with the Earth is properly described as a cosmic natural hazard of potentially unprecedented dimension, threatening both life and property. Unlike other natural hazards, however, we can in this instance, using current space technology, both predict and prevent the occurrence of such a disaster.

No other natural hazard presents such a wide range of potential destruction, but in no other case are we fortunate enough to have at hand the advanced technology and creative imagination to mitigate such a catastrophic event. The range of explosive impacts we may be called on to prevent extend from the "Tunguska Event" of 1908, approximately a five megaton (MT) explosion over Siberia (equivalent to over 300 Hiroshima bombs) up to impacts 100,000 times larger—large enough to destroy civilization and threaten the survival of humanity. We intend to prevent such infrequent but devastating events by slightly and precisely modifying the orbit of a threatening NEO, causing it to pass harmlessly by the Earth. Stated differently, we intend, using available space technology, to slightly alter the workings of the solar system in order to enhance human survival on planet Earth.

To realize such a bold claim we must put in place three critical components of a response system. They are: advanced notice (i.e., an early warning system), a demonstrated deflection capability, and a standing decision process to enable timely action.

The Congress, NASA, and other key global players are to be congratulated for their excellent work in implementing the first phase of the early warning system, the Spaceguard Survey, which has been in operation since 1998. The Congress is to be further commended for its vision in mandating that NASA take the next critical steps as expressed in the *George E. Brown, Jr. Near-Earth Object Survey Act of 2005* (the Act). The Act extends the Spaceguard Survey goal, directing NASA to "detect, track, catalogue, and characterize . . . near-Earth objects equal to or greater than 140 meters in diameter. . ." and to "achieve 90 percent completion of [the survey] within 15 years after the date of enactment of this Act."

The Congress also directed that "The Administrator shall transmit to Congress not later than one year after the date of enactment of this Act an initial report that provides the following:

(A) An analysis of possible alternatives that NASA may employ to carry out the Survey program, including ground-based and space-based alternatives with technical descriptions.

(B) A recommended option and proposed budget to carry out the Survey program pursuant to the recommended option.

(C) Analysis of possible alternatives that NASA could employ to divert an object on a likely collision course with Earth."

It is NASA's mixed response to these three directives which prompts my testimony here today.

I have been specifically requested to address the following four questions;

1. What are your perspectives on NASA's Near-Earth Object Survey and Deflection Analysis of Alternatives Report to Congress? Do you agree or disagree with the report's findings and recommendations?
2. Which, if any, relevant factors, data, or options are not addressed in the report and how should NASA investigate those areas?
3. What does NASA need to do now to understand and mitigate the risks of potential NEO impacts?
4. What governance structures should be established to address potential NEO threats?

1. Perspectives on the NASA Report

My response to the first question is in three parts, corresponding to the three components of the Congressional direction to NASA.

a) Analysis of Survey Program Alternatives:

I believe that NASA did a very good job (with the exception of the NASA life cycle cost estimation for the several survey alternatives) in developing and comparing a set of alternative Survey designs to meet the 140-meter goal. While I am not personally qualified to comment on the NASA costing I note that knowledgeable Pan-STARRS and LSST personnel challenge the NASA figures used. These experts claim that the actual costs for both cooperative and dedicated use of such telescopic facilities are considerably lower than those projected by NASA.

One factor not addressed in NASA's analysis of options to meet the revised Survey goal was the capability of various search system options for NEO tracking vice NEO discovery. While all of us in the NEO community strongly support moving aggressively to meet Congress's 140-meter discovery goal the fundamental intent of this enterprise is to protect the Earth from NEO impacts. This ultimate purpose is achieved by both the discovery of NEOs which might pose a threat AND also by tracking them accurately to determine whether or not a deflection campaign is necessary.

It is an unfortunate reality that ground-based telescopic tracking produces, for many challenging NEOs, discontinuous information; data dropouts may last for several years at a time. Should such a critical data dropout occur just as a NEO is found to threaten an impact, the decision on mounting a deflection campaign may well have to be made on the basis of uncomfortably "stale" tracking data. The well-known NEO Apophis, which currently has a one in 45,000 probability of collision with the Earth in 2036, is in such a data dropout period at this time. We were last able to see Apophis in August 2006 and we will not see it again until 2011–2012. For Apophis this data interruption is uncomfortable, but not critical since we will see it again before we need to decide on a deflection campaign. This is, however, simply a matter of chance and in many instances in the future we will not be so fortunate.

The orbital phasing responsible for this interrupted tracking can be eliminated by selecting any of several space-based search options in NASA's analysis to augment the ground-based systems. While NASA reports that overall costs for space and ground tracking are comparable (a controversial claim), the tracking quality provided by a telescope in a Venus-like orbit, in particular, is vastly superior. The dual-band IR telescope is especially preferable since it also improves greatly our estimates of NEO mass (and thus impact energy).

In summary, NEO search and discovery is extremely important. NEO tracking, however, is equally important for deciding whether and when to mount a deflection campaign. The dual-band IR telescope in a Venus-like orbit offers both discovery and tracking advantages at a cost comparable to the best ground-based telescopic options.

b) Recommended Program and Supporting Budget:

With respect to the second Congressional charge to recommend a program to meet the 140-meter search goal and a budget to support it, NASA failed to respond. NASA opted instead to state the obvious, that ". . . due to current budget constraints, NASA cannot initiate a new program at this time." Of course NASA's tight fiscal situation is precisely why the Congress requested not only a recommended program but also a proposed budget necessary to carry it out.

One can sympathize with NASA's fear of the dreaded "unfunded mandate" from Congress while decrying the Agency's decision to defy the Congressional directive and to delay the initiation of this critical search program. Congress, however, must also recognize and confront the dilemma it imposes on NASA (and other agencies) when it directs action without the specific identification of funds to support the work. Yet given that Congress explicitly directed in its mandate that NASA provide it with a proposed budget to support the program NASA cannot be excused.

I can only urge that **the Congress should again direct NASA in the clearest language possible to comply with the law and recommend a search program and supporting budget. (Recommendation 1)** It is time for the Nation to aggressively pursue this urgent NEO program.

c) Analysis of Deflection Alternatives:

B612 Foundation believes that NASA's analysis of deflection alternatives, as reported to the Congress, has serious technical flaws. NASA's findings and recommendations misunderstand, mischaracterize, and misrepresent many of the critical issues and options involved in the diversion of a threatening NEO. Furthermore the NASA Report fails to address a number of crucial issues which lie at the very heart of the deflection challenge.

An analysis of the errors of both commission and omission are too numerous and detailed to include in this testimony. I have therefore attached to this written testimony, and urge the Members and their staff to read, several documents which address these errors in depth. These documents include:

1. An exchange of correspondence with Congressman Dana Rohrabacher regarding clarification of the intent of the Congress in the nature of the NEOs to be considered for diversion (attachments 1 & 2),
2. An *"Independent Analysis of Alternatives that could be employed to divert a NEO on a likely collision course with Earth."* (attachment 3; also available at *http://www.b612foundation.org/press/press.html*, #15), and
3. Two detailed critiques of the NASA Report addressing on a point-by-point basis specific errors in the NASA analysis. (attachments 4 & 5; also available at *http://www.b612foundation.org/press/press.html*, #16).

To appreciate the depth of the technical errors in the Report, I strongly urge that these appended documents be reviewed in detail. I will summarize here a few of the key points.

Size matters

In examining the technical alternatives for diverting threatening NEOs, NASA selected ". . . a set of five [note: there were actually 7] scenarios representing the likely range of threats." In fact, the set of impact scenarios NASA chose as "typical" were extraordinarily challenging, resulting in a preference for a deflection concept delivering extraordinary capability, i.e., nuclear explosives.

The *least* challenging of the NEOs NASA considered in its analysis is part of a group that comprises just two percent of the potential impact cases. The impact frequency of such an object is once every 35,000 years. The remaining objects considered by NASA range upward to a one kilometer asteroid (one impact per million years) and a one-kilometer, long-period comet (even more rare).

In fact, objects which hit much more frequently and yet deliver considerable impact energy make up 98 percent of the likely impact threat. The most likely of these objects to impact is comparable to the Tunguska event of 1908 in Siberian Russia. That event is estimated to have exploded with the force of about five megatons of TNT equivalent, or over 300 Hiroshima bombs. Had the Tunguska event been instead the "London event," or "Moscow event," it would have destroyed not just 800 square miles of forest and a few reindeer but an entire city and its population.

As Congressman Dana Rohrabacher stated in his clarification letter to B612 on this subject, "While it is important to understand what technology exists or needs to be developed to divert the larger and more devastating NEOs the first order of business is to insure that we have a clear understanding of that the options are for the situations we are most likely to encounter."

A random impact occurring directly over a major city is, of course, highly unlikely. Yet when the possibility of such an event and the means of preventing it from occurring are known to exist by the general population it is reasonable to conclude that public pressure on the international community will successfully demand that we initiate a deflection.

Given then a cohort of "most likely NEOs to be deflected" ranging from a Tunguska-like object at the smallest and most frequent end of the scale up to events 100 times less frequent, we find that over 99 percent of them can be deflected using non-nuclear means.

The need for the availability of nuclear explosions for deflection in extreme cases cannot currently be ruled out, but the likelihood of such a demand materializing over the next several decades is extremely small. Furthermore our search efforts will make the need for such a solution increasingly unlikely over time.

Precision matters

NASA uses the word "effectiveness" in its Report purely as a measure of how much momentum change can be imparted to the asteroid. e.g., in its "Key Findings for Diverting a Potentially Hazardous Object," the first sentence of the first finding states "Nuclear standoff explosions are assessed to be 10-100 times more effective than the non-nuclear alternatives analyzed in this study." The technical term for NASA's undefined word "effectiveness" in this instance is "total impulse," i.e., the amount of momentum imparted to the asteroid in the process of the deflection.

Without doubt the total impulse available is a key measure of any deflection concept. However all of the impulsive (i.e., relatively instantaneous as juxtaposed with slow) deflection techniques evaluated are, while quite powerful, highly uncertain with regard to predicting the precise total impulse delivered. Experts in the field estimate uncertainties ranging from factors of two to five or even higher in the resulting total impulse delivered by either the nuclear or kinetic impact deflection concepts.

Certainly "strength" may well be needed in the deflection of an object on an impact trajectory. The first order of business is, without question, to ensure that the NEO is deflected sufficiently that it miss the planet.

What NASA totally missed however is that whenever an asteroid passes near the Earth (or any planet) it passes through a region in which are scattered hundreds of small impact "keyholes," small areas in Earth's proximity through which if the asteroid passes it will return within a few years and impact the Earth. Any deflected asteroid which misses the Earth must transit this minefield of impact keyholes.

Because the percentage of space taken up by such keyholes is small compared with the space between them the probability of the NEO passing through one is fairly low. However the consequences of passing through such a keyhole are severe. Thus, whether or not a deflected NEO misses the keyholes cannot be left to chance. A successful deflection must therefore be defined as one which causes the potentially impacting asteroid to not only to miss the Earth but also to miss all impact keyholes. Without this constraint any deflecting agency would be limited to declaring, "we successfully deflected the asteroid away from an impact with Earth. . . and it is unlikely that it will return for an impact any time soon."

A successful deflection requires both adequate strength and high precision. Immediately following an impulsive deflection the new orbit of the asteroid must be precisely determined and examined for a future keyhole transit. if headed for a keyhole then a small "trim" maneuver can be executed using a weak but precise "slow push" (as NASA refers to it) deflection to avoid that critical passage.

This combination of imprecise strength and precise adjustment is both necessary and sufficient to declare to the world that a fully successful deflection has been achieved. NASA completely missed this essential point in its analysis.

These two key flaws are illustrative of the quality of the analysis on deflection alternatives in the NASA Report. I again refer you to the attachments for greater detail.

2. How should NASA now proceed on these issues?

I believe that **NASA should produce a supplement to its Report to Congress based on new knowledge which has come to light since it began its analysis. (Recommendation 2)** The state of knowledge of the NEO deflection challenge is increasing very rapidly and NASA has not stayed abreast of recent developments. This is not entirely NASA's fault since it has no assigned responsibility in this critical area. Nevertheless given the Congressional request for an analysis of alternatives, and the urgent need for a legitimate understanding of these options, I urge that NASA revisit this matter. I list below, inter alia, a few suggestions in this regard.

a) NASA should re-examine the NEO deflection challenge utilizing the most likely set of threatening NEOs that we will likely confront. The lower bound of this cohort should lie in the range of the 1908 Tunguska event. (Note: This does not imply a change in the 140 meter search goal. In meeting the 140-meter goal NASA will discover a large fraction of the Tunguska sized NEO cohort as well.)

b) NASA should examine the need for precision and control in the deflection process taking particular account of the role impact keyholes play during a deflection.

c) NASA should further review and analyze its current (and future) database of NEOs to determine the frequency with which close gravitational encounters occur between the time of NEO discovery and the time of potential impact. In the case where such encounters occur (e.g., Apophis, the most threatening NEO in the current database) analysis shows that a single mission can often be employed to both determine if an impact is indeed threatened and take "slow push" preventive action if necessary. We must understand this class of prospective impacts and capitalize on the potential for a simple and less costly deflection mission.

d) NASA should fully assess the value of a dual-band IR telescope in a Venus-like orbit for search and tracking purposes. NASA has already analyzed this instrument's search capability, but it should extend its thinking to evaluate how to use such an instrument to support our impact prevention capability.

e) NASA should correct its faulty analysis of the cost and technological readiness of the Gravity Tractor.

3. What needs to be done to mitigate the risks of potential NEO impacts?

There are two key actions to be taken that would make significant progress toward protecting the Earth from the potential devastation of NEO impacts. Neither of them is expensive yet both of them are extremely important, even urgent, in light of the anticipated rapid rise in the NEO discovery rate in the near future.

a) **NASA should assign someone in its NEO Program to the specific task of thinking through, analyzing and understanding the NEO deflection challenge. (Recommendation 3)** So long as the NASA effort, and therefore thinking, is restricted to the NEO discovery process only, the government will lack the critical information and understanding needed to protect the Earth from NEO impacts. There is critical linkage between the upstream process of NEO search and orbit analysis and the downstream information needed to deflect NEOs. Absent someone explicitly thinking this through we stand justly accused of focusing on numeric goals for the sake of meeting an abstract quota. I hasten to point out that NASA cannot make such an assignment without being given the explicit responsibility for this critical function.

b) **NASA should validate a basic NEO deflection capability through the execution of a demonstration mission. (Recommendation 4)** While deflection concepts can and indeed must first be worked out conceptually, in an endeavor as critical to public safety as deflecting an asteroid bound for an impact, our ultimate success in such a vital undertaking cannot depend solely on a paper analysis. A demonstration program can be performed on a non-threatening asteroid at a cost no more than that of a typical small scientific mission. This effort need not, and perhaps should not, be undertaken as a U.S. mission per se. The European Space Agency (ESA) has already performed the initial feasibility and design phase of such a mission (though it should be modified to validate the "slow push" component). Were an international partnership agreement negotiated a reasonable cost estimate for a complete NEO deflection demonstration campaign could be performed for about the cost of a single scientific mission.

4. What governance structures should be established to address potential NEO threats?

I believe this to be the single most important question of this hearing. Until and unless an explicit assignment of responsibility within government is made to protect the Earth from NEO impacts, no significant advances in our capability will be made, and the US public, and indeed the world public, will remain unnecessarily at risk.

Ironically and somewhat counter intuitively, the full cost of assigning such responsibility and paying for its operations is almost vanishingly small. It is, nevertheless, a sobering responsibility, and an historic one. The very concept of being able to slightly alter the workings of the cosmos to enhance the survival of life on Earth is staggeringly bold. Yet this very capability lies within our technical means today. The missing element, the fatal missing element, is a governmental assignment of responsibility.

I would break this charge into two logical pieces.

a) First it seems to me that there exists today a single logical entity that should be responsible for the analysis, design, manufacturing and testing of a NEO deflection capability. That entity is NASA. NASA is our national space agency and is clearly charged with the development of our national space capability. This is, I believe, a clear and obvious choice.

   NEO work in NASA is, however, administratively in an orphaned status. Protecting the Earth from NEO impacts is neither space science nor exploration, although there are elements of both involved. Protecting the Earth from NEO impacts is a public safety activity. Yet today within NASA and its supporting space science and exploration communities the strong perception is that a dollar spent on NEO work is a dollar taken from space science or exploration. This "zero-sum game" presumption cannot be allowed to persist. Yet until explicit responsibility and funding for NEO research, as a public safety responsibility, is assigned to NASA by the Congress, this terrible conflict will persist. I therefore recommend **that the Congress expressly assign to NASA the technical development elements of protecting the Earth from NEO impacts as a public safety responsibility. (Recommendation 5)**

b) The second element is considerably more challenging and controversial. That is, to which agency of government should fall the overall responsibility for protecting the Earth from this infrequent, but devastating natural hazard? This responsibility is greater than and somewhat separate from the technical issues discussed above.

   While we have not addressed this matter above I will simply state unequivocally that the NEO mitigation decision process and the policies embedded within it are inherently international. Any NEO deflection will necessarily shift risk, however temporarily, between people and property across the planet. As we move a NEO away from an Earth impact, we necessarily shift its impact point from one region to another until we complete the deflection.

   Given this characteristic, and I ask that you grant this arguendo, the response to a threatening NEO will involve complex and very sensitive international coordination and probably negotiation. This is a planetary challenge, not a national one. The policies, procedures, criteria, thresholds, and agreements which must be addressed are international political challenges and the U.S. involvement will place in the hands of the agency responsible the lives and property of the world's entire population.

   It would frankly be presumptuous of me to make a specific recommendation here. Obvious candidates for such a responsibility include the Department of Homeland Security (DHS), the Department of Defense (DOD), and of course NASA. Many other agencies will clearly need to be involved in the decision processes given the potential of evacuation, migration (including cross border), and potentially unprecedented property destruction.

   I therefore recommend **that the Congress study the issue of overall governmental responsibility for protection of the Earth from NEO impacts, perhaps with the assistance of specialized policy entities, and ultimately hold public hearings to engage a wide perspective on the issue. (Recommendation 6)**

In closing I would suggest a personal perspective based on having spent the last six years of my life studying this issue. NEOs are part of nature. A NEO impact is a natural hazard in much the same way as are hurricanes, tsunamis, floods, etc. NEO impacts are deceptively infrequent, yet devastating at potentially unimaginable levels. NEOs are however not our enemies. We do not need to "defend" against NEOs, we need to protect ourselves from their occasional impact, as we do with other natural hazards.

Unlike other natural hazards, however, NEO impacts can be predicted well ahead of time and actually *prevented* from occurring. If we live up to our responsibility, if we wisely use our amazing technology, and if we are mature enough, as a nation and as a community of nations, there may never again be a substantially damaging asteroid impact on the Earth. We have the ability to make ourselves safe from cosmic extinction. If we cannot manage to meet this challenge, we will, in my opinion, have failed to meet our evolutionary responsibility.

Thank you.

Attachment 1

Russell L. Schweickart | Chairman, B612 Foundation

Letter to Congressman Rohrabacher requesting clarification of Congressional intent with respect to Initial Report (Sec 321 (4)(C), George E. Brown, Jr. Near-Earth Object Survey Act)... Excerpt from email message from R. Schweickart to G. Hanover (staff to D. Rohrabacher), 13 June 2007.

Dear Congressman Rohrabacher:

Clark Chapman, Tom Jones and I are scheduled to meet with key personnel at NASA HQ on Monday, 18 June. This meeting is in response to an exchange of correspondence between Administrator Mike Griffin and Clark Chapman and I. Clark and I are both board members of the B612 Foundation and all three of us are part of the professional NEO community and took part in NASA's NEO Workshop in Vail, Colorado last year.

The meeting on Monday is via Mike Griffin's invitation and is intended to resolve what both we and Mike are concerned with, namely possible technical errors in NASA's response to the Congress. Clarification of a specific issue from Congressman Dana Rohrabacher (as then principal author of the language) would go a long way to helping resolve these issues.

As you know B612 Foundation and other professionals in the NEO community have had substantial disagreement with NASA over the report and recommendations they provided the Congress in response to requirement for an "Initial Report" contained within the George E. Brown Jr. Near-Earth Object Survey Act. In relevant part the act required an "Analysis of possible alternatives that NASA could employ to divert an object on a likely collision course with Earth."

In its response to Congress, and in particular as specified in the NASA Final Report (technical backup to the summary provided Congress) NASA defined a set of "Possible Scenarios - Application of the Alternatives" (Sec. 6.13, pg 93) which they then subsequently used to analyze diversion alternatives. This set of scenarios NASA employed are large to very large NEOs (and a long-period comet) which are very improbable and would occur very infrequently (one scenario would happen statistically once in 80,000 years, the rest at less than once in 200,000 years).

B612 Foundation and others interpreted the language to require an analysis of diversion alternatives most likely to be called for within the next several decades, i.e. from those Tunguska-like objects and up which will occur most frequently and do substantial damage on the Earth's surface. These objects, from 45-50 meters in diameter and up, will statistically occur once every 600-800 years and hence would be approximately 100 times more frequent than those that NASA selected.

Clearly the diversion alternatives recommended will depend on the set NEOs to be diverted. It would be of substantial help if Congressman Rohrabacher were to clarify whether he intended the analysis to respond to large and infrequent objects or to possible alternatives that could be used to divert the smaller, far more frequent objects that nevertheless impact with 10 or more megatons of TNT equivalent energy and would devastate a city (i.e. Tunguska-like objects and larger).

Thank you for your help in clarifying this language. Our goal is to insure that the best information possible is provided to the Congress in regard to this critical issue.

Sincerely,

Rusty Schweickart
Chairman, B612 Foundation

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Russell L. Schweickart
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Sonoma, CA 95476 fax: 707-343-1628
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<>--- ---<>--- ---<>--- ---<===>--- ---<>--- ---<>--- ---<>

Attachment 2

DANA ROHRABACHER
46th District, California

Committees:
FOREIGN AFFAIRS
Ranking Republican, Subcommittee on International Organizations, Human Rights and Oversight
Subcommittee on Asia, the Pacific, and the Global Environment
SCIENCE AND TECHNOLOGY
Subcommittee on Space and Aeronautics
Subcommittee on Investigations and Oversight

Congress of the United States
House of Representatives

WASHINGTON OFFICE:
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Washington, DC 20515–0546
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South Bay: (310) 377-9493

http://rohrabacher.house.gov

June 14, 2007

Dr. Russell L. Schweickart
Chairman, B612 Foundation
760 Fifth St. East
Sonoma, CA 95476

Dear Dr. Schweickart:

Thank you for your request for clarification regarding the requirement in the George E. Brown, Jr. Near-Earth Object Survey Act that NASA provide Congress with an "Analysis of possible alternatives that NASA could employ to divert an object on a likely collision course with Earth."

The intention, in the writing of the language, was to gain an understanding of the technical options that could be used to divert the most likely near-Earth objects that would threaten an impact with Earth over the next several decades. While it is important to understand what technology exists or needs to be developed to divert the larger and more devastating NEOs the first order of business is to insure that we have a clear understanding of what the options are for the situations we are most likely to encounter.

Thank you for your request and I look forward to hearing the results of your meeting.

Sincerely,

Dana Rohrabacher

Dana Rohrabacher
Member of Congress

Attachment 3

Russell L. Schweickart — Chairman, B612 Foundation

Independent Analysis of Alternatives that could be employed to divert a NEO on a likely collision course with Earth

Summary Findings:

1. There are three current NEO deflection concepts which I consider in this analysis to be essentially ready for development, testing and deployment if needed; the gravity tractor, the kinetic impactor, and nuclear explosion, in ascending order of total impulse available. I therefore limit this analysis to these available options.
2. 98% of the pragmatic NEO threat can be diverted by the use of the gravity tractor and kinetic impactor concepts. I.e. 98% of the realistic threat posed by NEO impacts will require no more total impulse for diversion than is available using the combination of kinetic impactor and gravity tractor.
3. The use of the sufficient capability of the kinetic impactor/gravity tractor combination is highly valued not simply because the nuclear explosion capability is excessive but because the precision of the resulting deflection provides full assurance to a concerned world public that the deflection has been successful and has not resulted in the possibility of a near-term return of the NEO.
4. The statistical probability of having to resort to the use of nuclear explosives to divert a threatening NEO in the next 100 years is approximately 1 in 1000. Stated differently, the frequency at which a NEO requiring the use of nuclear explosives for diversion would otherwise impact the Earth is approximately 1 in 100,000 years. Nevertheless it is available should such an improbable need arise.
5. The characteristics of the gravity tractor and kinetic impactor are such that they nicely compensate for each others' limitations. Most importantly the combined use of the kinetic impact/gravity tractor provides not only the capability to divert over 98% of the threat but also the ability to state with confidence that a NEO once deflected will not be left on a trajectory with a near term return impact.
6. With the exception of testing the nuclear explosion option all three concepts should be analyzed in detail. Consideration should be given in the future to flight testing the kinetic impactor/gravity tractor combination to validate the capability and provide confidence to the world public. The further development of deflection concepts not considered in this analysis should also be encouraged.
7. Attention should be given to the importance of timely decision-making. If timely decisions are not made when a NEO threat arises the window of opportunity for the use of non-nuclear means for deflection can irrevocably be passed thereby leaving the world with the Hobson's choice of using nuclear explosions in space for deflection or taking the chance of a devastating impact. This timing challenge applies even for the case of very small NEOs.
8. Considerable information characterizing the nature of the NEO threat is available in the current Spaceguard Survey database and should be extracted from it to more fully understand both the frequency of resonant return impacts and the decision timing challenge in the light of episodic tracking opportunities.

Definitions, abbreviations, etc.

For the purpose of this analysis I will use the following terms for brevity.

Congressional report – *The Near-Earth Object Survey and Deflection Analysis of Alternatives*, Report to Congress., March 2007
Final report – *2006 Near-Earth Object Survey and Deflection Study*, Final Report, Dec 2006 (internal distribution only, access denied to public and outside experts)
KI – kinetic impact or kinetic impactor; a deflection method utilizing the energy and momentum of a spacecraft directly impacting a NEO to achieve a change in its orbit.
GT – gravity (or gravitational) tractor; a deflection method utilizing the mutual gravitational attraction of a spacecraft "hovering" immediately in front of or behind a NEO to affect a desired change in its orbit.
Nuclear – any deflection method using a nuclear explosion to affect a desired change in the orbit of a NEO.
Beta – the multiplier of the KI impact momentum resulting from the ejecta of NEO material from the NEO surface. Based on data presented at the recent PDC07 (AIAA Planetary Defense Conference) I will conservatively assume the value range of 4 +/- 2 for this key variable.
Total impulse – the change in momentum required to deflect a NEO or the momentum change available from any given deflection method. (units; kg-m/s or Ns)
PoR – the Path of Risk. The narrow corridor across the face of the Earth within which a specific NEO will impact IF it does indeed collide with the planet.
PDC07 – The recent (5-8 Mar 07) AIAA Planetary Defense Conference held in Washington, DC
The world – this phrase is used as a proxy for the yet to be determined process by which nations will ultimately chose what action is appropriate in consideration of a NEO threatening an impact. As in "the world will not likely opt to "take the hit" for objects of Tunguska size."
Pragmatic threat – that range of NEOs which the world will likely opt to deflect, assuming prior knowledge of a potential impact and the capability for deflecting it. This definition of NEO threat breaks strongly from the actuarial risk which is heavily biased toward the largest undiscovered NEOs. The pragmatic threat is characterized by the observation made at PDC07 that "a hit is a hit is a hit" vs. the actuarial measure of annualized lives lost globally. As pointed out by Alan Harris at PDC07, in an actuarial sense the annualized lives lost will always be dominated by that fractional large NEO that has not yet been discovered.

<u>What deflection concepts are available and should be considered?</u>

There are three concepts for deflecting NEOs which employ currently available technology and which require a minimum of additional analysis, development, and for the non-nuclear options, testing and demonstration. These three are, in ascending order of total impulse capability, the gravity tractor, kinetic impact, and nuclear explosions, and are the only three options dealt with in this analysis.

Several other deflection concepts have been put forward but these are not considered due either to the need for considerable advancement in technological capability or the requirement for specific, currently unavailable knowledge about NEOs themselves such as how attach securely to the surface of an asteroid. In this category are large space mirrors or powerful lasers for ablating NEO surface materials, the Asteroid Tugboat which attaches to and pushes directly on the asteroid, mass drivers in a variety of configurations which must also attach to the NEO and require considerable in situ construction, and suggestions of deflection by altering the coloration and thermal characteristics of the NEO surface.

Gravity Tractor Of the three concepts considered viable in the near term, the gravity tractor (GT) offers the least total impulse but imparts that limited impulse in a fully controlled manner. The gravity tractor (Nature, November 2005) must execute a full rendezvous with the NEO (velocity matching) and then actively "hover" either immediately in front of the NEO or behind it in order to either increase or decrease the NEO's velocity respectively. Since a gravity tractor spacecraft, in any configuration, will carry aboard an active radio transponder its position and velocity are very well known before, during and following the deflection maneuver. These characteristics of the GT provide a dramatic improvement in the knowledge of the NEO orbit both prior to any deflection maneuver and, if a deflection is required and performed, precise knowledge of the resultant NEO orbit.

Of note is the fact that through the use of its transponder a GT, deployed to a NEO with a high probability of impact, will discover in many instances that there is no need for a deflection. In those instances where a deflection is indeed found to be required, either the GT itself can be used to provide the required deflection, or if the total impulse required is outside its capability, observe the deflection impulse provided by a kinetic impactor (KI) and subsequently determine precisely the result and even "trim" the outcome if necessary. This synergetic use of the GT and KI offers a very powerful combination.

Kinetic Impactor The KI imparts a desired change in a NEO's orbit by crashing into it, in the desired direction and with a predetermined impact velocity and impactor mass. The change in velocity of the NEO is controlled by two factors; the momentum directly transferred to the NEO by the KI and the additional momentum provided by the mass and velocity of the NEO material ejected from the impact site per se. In many if not most cases the ejecta component of the momentum change exceeds that due directly to the momentum transferred directly by the KI. The ratio of the total momentum realized to the momentum of the KI at impact is expressed as the parameter beta, or the momentum multiplier.

The specific value of beta for any given impact is known very imprecisely. Recent work by Keith Holsapple and others indicates that beta increases with the energy of the impactor but is highly dependent on the specific characteristics of the particular NEO being impacted. For relative impact velocities typically between 5 and 15 km/s beta appears likely to have values no lower than 2 and not likely higher than 10. For the purposes of this analysis beta is considered to have a value of 4 +/- 2. Since beta is a very powerful influence on deflection performance and its maximum value could be much higher it should be a priority for further research, both analytic and (hopefully) empirical. In summary the total impulse imparted to the NEO for a KI is equal to beta x the impactor momentum. Given that the total impulse delivered to a NEO can vary by a factor of at least 3 the resultant orbit of the NEO is uncertain. This unavoidable uncertainty in the result of the deflection is the reason a KI (or nuclear) deflection is described here as uncontrolled.

There is, as was presented at PDC07, an opportunity for the use of a series of KI impacts should the total impulse required exceed that available in a single KI mission. Nevertheless the uncertainty in the resulting NEO orbit due to the variability in beta remains whether for a single or multiple impact deflection.

A further consideration of the KI employed alone, is that since it does not rendezvous with the NEO but rather simply crashes into it, it cannot determine whether or not, in fact, a deflection is required. For this reason the European Space Agency (ESA) in the development of its Don Quijote mission, has come to believe that a precursor rendezvous mission with a transponder is needed prior to the launch of an impactor, both to collapse the uncertainty in the NEO orbit (and therefore determine whether a deflection is in fact required) and to determine post-impact the resultant NEO orbit. ESA's position is that a KI should not be used as a stand-alone but rather in combination with a precursor spacecraft which first rendezvous with the NEO and provides both pre- and post-impact precision tracking. I fully concur in this finding and see the KI as a viable deflection concept only in combination with a transponder-bearing spacecraft which plays this crucial pre- and post-impact role.

It is clear, based on the above, that the performance of the KI is considerably enhanced, both prior to and post impact, by the presence of a supporting transponder mission. Later in this analysis I show an even greater value in the KI/GT combination in the potential for the GT subsequent to the KI impact to not only determine the precise result of that impact but also to "trim" or slightly modify the deflection to insure that the NEO does not end up in an orbit with a resonant return impact within the next few decades.

Nuclear explosive The use of nuclear explosives for NEO deflection has been proposed in several forms ranging from subsurface emplacement to stand-off explosion. There are many technical unknowns about all of these configurations and I will not in this analysis attempt to delve into them. Suffice to say, for the purposes of this analysis, that while there are many unknown technical factors to be examined the nuclear explosives option offers a larger total impulse capability than any other available concept albeit with a very high uncertainty as to the momentum transfer achieved. Once again, as with the KI, the deflection is uncontrolled with considerable uncertainty in the post-deflection NEO orbit. Whether a stand-off GT could be used to serve both the pre- and post-deflection functions listed above for the KI would depend on it being able to survive the nuclear explosion itself.

The other obvious considerations re the nuclear option are the international legal prohibitions and the world-wide public concern with most things nuclear and especially weapons. The challenge of obtaining widespread international agreement that a nuclear explosion should be used in deflecting a NEO will be daunting, to understate it. Nevertheless, if the world is unable to come to agreement in time to utilize a non-nuclear deflection method the final option, due to its greater total impulse capability, will be nuclear. The ultimate alternative to using a nuclear device for diverting a NEO is "taking the hit". This is an ominous choice given the psychological and physical implications of mass evacuations, refugees, destruction of infrastructure and the like. This reality should put strong emphasis on the world dealing early with the challenge of making timely NEO deflection decisions.

JUXTAPOSITION with NASA's Congressional Report

The conclusions in NASA's Congressional Report regarding the technological readiness and costs of a variety of deflection concepts appear to be seriously flawed. Without access to the Final Report however it is not possible to specifically examine the basis for these judgments. The primary differences between this analysis and NASA's are the more limited set of deflection concepts considered (I consider only those which I believe will be available for use within the next several decades), and the extreme underestimate of the technological readiness level and equally extreme overestimate of the cost of the gravity tractor. While not available for detailed review without access to the Final Report, it appears from graphics shown briefly during PDC07 that the Report has erroneously equated the GT concept with the extremely expensive and technically immature Prometheus spacecraft. (NASA cancelled this program two years ago, largely for run-away cost reasons) The GT concept, as presented in NASA's NEO Workshop held in Vail, Colorado in June-July 2006, is adaptable to any size spacecraft and was specifically presented and evaluated in White Paper 42 (the only professional paper presented on the gravity tractor) based on NASA's Deep Space 1 spacecraft flown successfully from 1998-2000 and costing (based on the official NASA website, http://nmp.nasa.gov/ds1/quick_facts.html) $149.7 million (FY 95-99). Given that the presentations at NASA's Vail Workshop explicitly presented and evaluated the GT concept based on the Deep Space 1 mission technology, and not on the cancelled Prometheus, it is mystifying why, in NASA's Report to Congress the GT was presented as technically immature and extremely costly. Without access to the Final Report it cannot be stated with certainty but it appears that NASA inappropriately used the low technological readiness level and extreme cost of the cancelled Prometheus spacecraft as a proxy for the GT. In this analysis I use the GT as it was presented to the NASA study team in the NASA NEO workshop in Vail, Colorado.

What is to be deflected?

In order to analyze the efficacy of any NEO deflection method one must first determine or define the challenge being addressed. In this instance it is the range of total impulse required to deflect the NEOs most likely to trigger a deflection decision.

The bottom of this range is assumed herein to be a Tunguska-like NEO based on the assumption that nations, knowing that a Tunguska class object is threatening an impact, and knowing that the means to deflect it are available, will not sit idly by and "take the hit". While the consequences of such an impact are, from an actuarial point of view, not likely to kill many people, the public presumption will be that the NEO will impact in the worst possible spot along the PoR where it crosses the territory of concern. For many of these small NEOs the PoR will not have resolved to a specific local area, let alone a point, by the time a decision to deflect it will have to be made. The image of Tunguska entering over London vs. Siberia will not be dispelled by probabilistic assurances of how unlikely it would be that any particular city would be located at "ground zero".

From recent work by Mark Boslough of Sandia National Laboratory presented at PDC07 the most likely impact energy of the Tunguska asteroid is ~ 5 MT. His impressive simulations indicate that due to a finite "pancake" form (vs. a point source) of the NEO, and its downward momentum, past analysis of damage done on the ground at Tunguska has been overestimating the impact energy by a factor of 3 to 4. Further consultation with Alan Harris convinces me to use 5 MT as the current best estimate of the Tunguska impact energy.

Using Alan Harris' most recent analysis of the size-frequency plot for NEOs we see (Fig. 1) that a 5 MT impact energy equates to a NEO 45 meters in diameter with an impact frequency of just under 1 in 1000 years. The population of objects this size is estimated at 400,000 according to the most recent size-frequency plot.

[note: The best estimate of the size-frequency distribution of NEOs is judged (by Alan Harris and others) to be represented in Fig. 1 by the observations below the constant power law line (long blue dash) which Harris believes best represents the actual size-frequency distribution. For this reason I have conservatively chosen to use the "dip" vs. the constant power law distribution in this analysis. Were I to use the constant power law line the population of Tunguska-like NEOs would be over 1 million (vs. 400,000) and the frequency of impact 1 in 500 years (vs. 1 in 1000 years)]

With this defining the lower bound for the analysis of total impulse required, I then determine the upper bound of the most likely 99% of NEOs to be deflected by decreasing the population by two orders of magnitude (i.e. 4,000) which corresponds with a 400 meter diameter object with an impact energy of 3500 MT and an impact frequency of just under 1 in 100,000 years.

99% of the pragmatic threat then originates with objects between 45 and 400 meters in diameter, and it is heavily skewed toward the much larger numbers of the smallest objects.

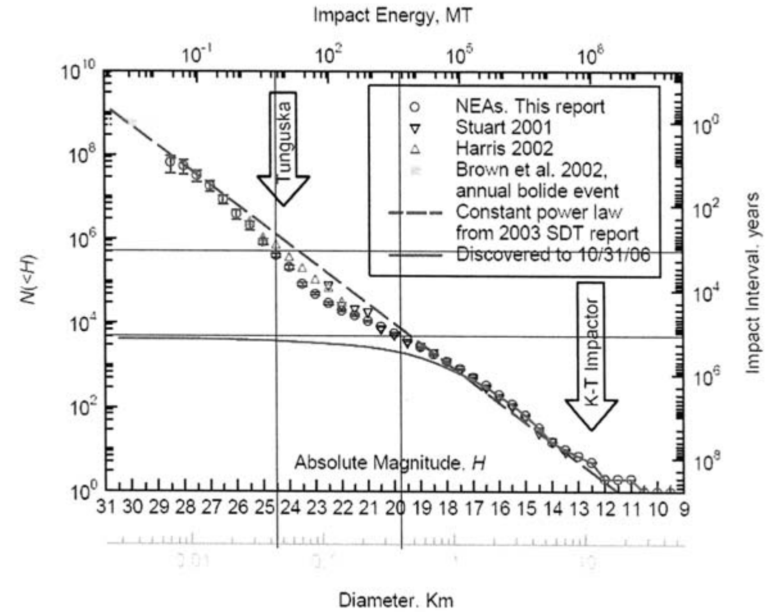

Figure 1. Size-frequency diagram for near-Earth objects, courtesty Alan Harris. The superposed intersecting lines bound the 99% of NEO impacts most likely to be encountered and trigger a call for deflection. These NEOs range from 45 – 400 meters in diameter. The left vertical line reflects the most recent estimate of the impact energy (5 MT) associated with the Tunguska event in 1908.

JUXTAPOSITION with the NASA Congressional Report:

The Congressional report assumes a set of 7 challenging cases (1A through 6) which are highly improbable if one considers the most likely deflections to be called for. All but the Apophis 1A & 1B cases (addressed below) lie within the least likely 10% of potential NEO impacts that statistically threaten the world. My analysis determines the most likely 99% of NEOs to call for deflection and evaluates the deflection options against this challenge.

The Congressional Report presentation of the Apophis 1A and 1B scenarios is, on plain reading of the description, erroneous. It is likely that the Full Report goes into greater detail in the definition of these scenarios, but absent access to it no detailed critique can be made. However, in addressing the Apophis case de novo, it is an extremely moderate deflection challenge and lies well within the capability of the most modest GT. Furthermore, in employing a GT for such a deflection the uncertainty in the outcome of the deflection is very low due to the transponder availability on the GT. Therefore a deflection resulting in a 2036 Earth miss distance of 3 Earth radii (from the geocenter) is more than adequate to reach a collision probability in 2036 of less than e-6.

The selection of scenarios used in the NASA Congressional Report drive the conclusions. It would seem to go without question that if one selects for the evaluation scenarios exceptional challenges (challenges requiring exceptionally high total impulse) then the inevitable conclusion will be that nuclear explosions are the preferred response. Clearly this is circular reasoning and the basis for the selection of hypothetical scenarios must be examined. In this analysis I identify what I believe to be the minimum sized NEO likely to trigger a deflection decision and then extend the analysis to include the deflection of NEOs 100 times less frequent, i.e. the most likely 99% of deflections likely to be called for. Nuclear explosions may be needed in certain extreme and unlikely circumstances, but excessive force is not to be valued when more than adequate and far less controversial means are available. The nuclear option should be the choice of last resort.

What is the range of total impulse required for deflection of the pragmatic threat?

The lower bound is defined by the smallest NEOs of concern; those ~45 meters in diameter. The mass of such an object is roughly 130,000 metric tons. The total impulse required for deflection requires mass to be multiplied by the change in velocity needed to divert the object, and this number is highly variable, depending on the circumstances. In this portion of the analysis I will consider only the case of a direct impact with Earth, i.e. no intervening close gravitational encounter between the discovery of the threat and the nominal impact. The very powerful effect of such close gravitational passes on the velocity change required for deflection of a NEO will be dealt with separately below.

The velocity change required in a direct impact is strongly dependent on the time between the deflection maneuver and the nominal impact and somewhat weakly dependent on the particular orbit of the NEO. The goal of the Spaceguard Survey is to provide the world with "decades of early warning" of a pending impact and for the purposes of this analysis I will assume that a deflection will be executed 10-20 years prior to impact. Considering the change in velocity required for several known cases (Apophis and 2004 VD17) I will consider, for this analysis, the typical delta v required for each Earth radius of deflection to be 0.1 – 0.3 cm/s, and therefore use the average of 0.2 cm/s as representative.

The lower bound then on the total impulse for deflecting the smallest objects considered is approximately 2.6e5 kg-m/s per Earth radius of deflection. The comparable value for NEOs 100 times less likely to impact Earth, i.e., those ~400 meters in diameter is 1.8e8 kg-m/s. The remaining cohort of NEOs larger than 400 meters (i.e. less than 1 % of the pragmatic threat) are simply considered to require greater than this total impulse.

What is the range of total impulse available using the two non-nuclear deflection methods?

The GT performance is dependent on the mass of the GT spacecraft and the distance at which it hovers ahead of or behind the NEO center of mass. For the purposes of this analysis I will consider only a very modest GT based primarily on hardware already flown and tested, specifically the Deep Space 1 mission of 1998-2001. Assuming the spacecraft mass at 1 metric ton and hovering at 1.5 NEO radii above the center of mass of a 45 meter diameter NEO, I arrive at a total impulse applied of 658 kg-m/s per day, or a deflection period of 395 days to cause the NEO impact point to be displaced by 1 Earth radius. Since an actual deflection will need to be targeted to miss impacting the Earth by 3 or more Earth radii (see below), the minimum sized asteroid of concern would require a 1 metric ton GT to "tow" it for more than three years to accomplish a deflection. This is then a marginal case.

For a KI the calculation is simple but leaves one with a large uncertainty. A one metric ton KI with a relative velocity at impact of 15 km/s will impart a direct momentum transfer of 15e6 kg-m/s. Assuming a nominal beta of 4 this results in a nominal total impulse capability of 6e7 kg-m/s or a range of 3-9e7 kg-m/s. Translated this results in a more than adequate capability to deflect a 45 meter NEO or, at the upper end of the distribution the need for 6 KI impacts of this capability to deflect a 400 m NEO by 3 Earth radii assuming a minimum value of 2.0 for beta

I assume, albeit without any specific evidence or knowledge, that some form of the nuclear option may be able to divert a 400 meter object with a single explosion. In any event, whether single or multiple nuclear explosions are required the end result will be a priori highly uncertain. Furthermore whether or not this can be accomplished without fragmentation of the NEO is an unknown requiring further study.

<u>Targetting considerations</u>

A key question to be answered is what should the end target be when deflecting an asteroid? The worst case challenge is if the nominal impact point for the NEO of concern is located at the midpoint of the PoR.. the locus of potential impact points across the Earth. A deflection of 1 Earth radius, assuming the PoR lies near the equator would cause the deflected NEO to skim the Earth's atmosphere.

Clearly this is an unacceptable lower bound for a deflection. More realistically one would want to deflect a threatening NEO to take it outside the Roche limit, the minimum distance at which the asteroid would not fragment into several pieces. While the calculation of the Roche limit is a complex one a value of 2.5 Earth radii from the geocenter is roughly correct. Therefore for the purposes of this analysis a reasonable minimum target for the NEO miss distance will be assumed to be 3 Earth radii from the geocenter.

<u>Conclusion re NEOs on a direct impact course</u>

For NEOs on a direct impact trajectory the GT is inappropriate for use with even the smallest NEOs (45 meters) in the pragmatic threat cohort. Were a GT to be used to deflect a 45 meter NEO to a distance of 3 Earth radii it would require a deflection duration of 1185 days or 3.25 years.

The KI method, using a single KI, would however be adequate for NEOs up to 220 meters in diameter using the nominal value of beta or objects of 155 meters diameter using the minimum value of 2. Multiple KI impacts could extend this capability.

In conclusion then while the GT is impractical for diverting any asteroids of concern on a direct impact trajectory with Earth, the KI can deflect objects up to 155 meters in diameter with a single impact and the minimum value of beta. If one considers multiple impacts it would require 3 in order to successfully deflect a 225 meter asteroid by 3 Earth radii with a beta of 2.0. Were a beta of 6.0 assumed a single KI impact could deflect a 225 meter NEO by 3 Earth radii or, with three impacts, a 325 meter NEO.

These performance numbers result in a single KI mission of 1 metric ton and relative velocity at impact of 15 km/s and a minimum beta value of 2 being able to deflect by 3 Earth radii 97% of the pragmatic NEO threat with a single impact or 98% with three impacts. If a NEO in the largest 2% of the pragmatic threat were to threaten an impact a nuclear explosive may have to be used.

JUXTAPOSITION with the NASA Congressional Report:

6 of the 7 "hypothetical scenarios" of NEO impacts used in NASA's Congressional Report require greater total impulse for deflection than is available using the highest beta KI deflection. In this analysis, using the pragmatic threat cohort of NEOs all but approximately 1% of the threat can be deflected by use of a 1 metric ton KI with a relative impact velocity of 15 km/s.

How is this analysis affected by taking into account resonant return trajectories and associated keyholes?

This issue, dealt with specifically in White Paper #39 presented at NASA's NEO workshop in Vail, has a very powerful influence, not only on the total impulse required to deflect an incoming NEO, but also on deflection targeting and the ability of a deflecting agency to assure the world that the deflection has been successful. For reasons not evident in the Congressional Report it appears that none of these influences were taken into account in the NASA analysis.

Resonant returns and their associated keyholes are defined by the NEO returning to the impact intersection an integral number of years later if it passes through the keyhole. E.g. for the asteroid Apophis, which will make a very close pass by the Earth on 13 April 2029 there is a keyhole close to its point of closest approach to the Earth such that if it passes within that very narrow region (in this case 600 meters wide) it will end up in an orbit with a period of 426.125 days and therefore return 7 years later (6 Apophis orbits around the Sun) and impact Earth.

If one looks at the NEOs with a non-zero probability of impacting Earth and travels backward in time from the potential impact one finds that in many cases there is a prior close pass by the Earth which sets the asteroid onto a course leading to the potential impact. The potential impact of Apophis in 2036 is such a case. In this instance if Apophis were to impact the Earth in April 2036 it would first have had to pass through the 7/6 keyhole as it passed the Earth in 2029.

The good news about keyholes is that if one deflects a threatening NEO prior to it passing through the keyhole the total impulse required to insure that it misses the Earth is reduced by orders of magnitude. Just how much lower the required total impulse is for deflection depends strongly on the specific orbital dynamics but it commonly ranges from 1 to 4 orders of magnitude and occasionally more, such as in the case of Apophis.

The effect of this is that for threatening NEOs that must pass through a keyhole prior to impact considerably less total impulse is required for deflection in order to avoid an impact, provided the deflection is performed prior to keyhole passage. E.g. while a 1 metric ton GT cannot deflect a small 45 meter diameter NEO on a direct impact trajectory in less than approximately 3 years, it can deflect the 280 meter Apophis in less than 40 days.

The relevant question then is what percentage of the population of Earth impactors will have first had to pass through a keyhole prior to impact, and how great a reduction in total impulse required for deflection is realized? Unfortunately the answer to this question is not known, though data mining of the current NEO database could provide us an excellent statistical answer. This research should be done but it is not on NASA's work plan primarily because no one is currently funded to work on the issue of deflection in the NASA/JPL program.

What can be said however is that the incidence of close prior encounters with the Earth prior to impact (another way of saying passage through a keyhole) are not uncommon and may range up to 30% of cases or higher. Again, for the purposes of this analysis the fraction of these instances is assumed to be 30%.

Integrated into this analysis this factor reduces by 30% the number of NEOs which otherwise would require a nuclear explosion for deflection making them available for deflection by either the GT or KI. Indeed it further translates into a number somewhat below 30% of the entire pragmatic threat that are available to the GT alone, e.g. Apophis.

In summary the cohort of NEOs in the pragmatic threat category that can be deflected by non-nuclear means exceeds about 98% and many of them can be deflected by the GT alone.

JUXTAPOSITION with the NASA Congressional Report:

The NASA Congressional Report makes no specific mention of resonant returns or keyholes. The only implied recognition of their existence is found in "hypothetical scenario" A (Apophis) which uses the phrase "before its close approach to Earth in 2029" in describing the case. This in combination with the low total impulse required for Example A2 in Figures 4 and 5 leads one to the conclusion that this case assumes a predicted keyhole passage and a deflection prior to that event. The scenario then specifies however that Apophis must be deflected by 5 km to achieve a probability of collision less than e-6. The basis for this targeting goal (the only targeting addressed in the Report) is presumably contained within the NASA Final Report, but not available here for analysis. However, if taken as the deflection targeting miss distance (from the center of the 2029 keyhole) this requirement would result in a miss distance in 2036 of 17 Earth radii! Given that the Roche limit is at approximately 2.5 Earth radii and a very precise deflection of Apophis can easily be accomplished using a 1 metric ton GT (~a 40 day deflection maneuver), a deflection to 3 Earth radii is more than adequate. If, on the other hand, an uncontrolled deflection with a substantial uncertainty re the final Apophis orbit is assumed then, depending on the specific assumptions used the 17 Earth radii miss distance may be necessary.

In other words, if one assumes that the GT is not used for the A2 case and that it is not available to trim an uncontrolled deflection by either a KI or nuclear explosion, then the uncertainty in the result of the deflection may well require a very large targeted miss distance. However a very modest 1 metric ton GT can precisely deflect Apophis prior to its keyhole passage with a target of only 3 Earth radii. This is completely missed in the Congressional report.

Further implications of resonant returns and keyholes

One further consideration alluded to earlier is the issue of keyholes along the deflection path and their significance for uncontrolled deflections.

If one considers any deflection by a KI and assumes that the minimum value of beta is used to target the deflection so that the entire range of possible results lies at 3 Earth radii or greater, then clearly the outer limit of possibilities ranges out to 9 Earth radii. Along that very long path between 3 and 9 Earth radii lie thousands of resonant returns and keyholes through any one of which, albeit with low probability, the deflected NEO may pass. A significant percentage of these keyholes have uncomfortably short return times and, in the limit, can result in return impacts in less than 5 years.

Unless some means is employed to insure that a deflected NEO has not been "dropped" into one of these keyholes the world may find itself having avoided one impact only to have caused there to be another even more challenging impact by the same NEO. Despite the probability of this risk being fairly low (again, this can and should be specifically analyzed) without some means to positively control the deflection the best that can be said is "Yes, we deflected the NEO and it probably will not come back". However, when dealing with the world public, especially after the anxiety surely to have accompanied the initial deflection, to not be able to assure positively that it was not dropped into yet another keyhole will certainly be difficult for the world to accept.

For this reason it is highly desireable that any uncontrolled deflection be immediately followed by a precise determination of the result and a means to adjust the deflection to avoid all keyholes if necessary.

Both of these conditions can be met with the combination of KI/GT. I.e. if a GT is always used as the precursor mission to a KI, then it is also in place to determine precisely (with its transponder) the actual result of the KI deflection and to determine whether or not the actual residual uncertainty includes a keyhole. In general it will not, but should this be the case then the GT can quite easily tow the asteroid slightly toward or away from the Earth in order to insure that there are no keyholes within the residual uncertainty of the deflection. In other words, the GT is there to both precisely determine the outcome of the KI deflection and, if necessary to trim it, thereby guaranteeing the world that the deflection will not result in a short term resonant return.

Thus the modest total impulse capability of the GT can easily compensate for the uncertainty in the KI deflection and the greater total impulse capability of the KI can be used with precision via the transponder and impulse trim capability of the GT.

JUXTAPOSITION with the NASA Congressional Report:

The NASA Congressional Report makes no mention of the possibility of a deflection placing the deflected NEO on a resonant return impact course. While the probability of such an eventuality is low it is by no means zero. The unavoidable consequence of an uncontrolled deflection is that the best that can be said, post deflection, is that the immediate impact has been avoided and that it is unlikely to return any time soon. With the use of a controlled deflection one will be able to provide positive assurance to an anxious world that there will be no short term resonant return.

In summary

On the order of 98% of the total pragmatic threat posed by NEOs impacting the Earth can be diverted from impact by the use of either the GT alone (for some resonant return NEOs) or the KI/GT combination. Only the least likely 1% of the threat (on the order of 1 in 100,000 years) will require the use of nuclear explosives for a successful deflection.

JUXTAPOSITION with the NASA Congressional Report:

Because of the "hypothetical scenarios" presented in the NASA Report to Congress the nuclear options are either best suited to the task or absolutely required. This selection of specialized scenarios is not, however, representative of the deflection cases most likely to be encountered. The highest probability impacts will always correlate with the smallest NEOs and, based on the assumption that the world will not choose to "take the hit" of a Tunguska-like object if its potential impact is known ahead of time, this cohort of NEOs is selected in this analysis as the lower limit of the pragmatic threat cohort. 99% of the NEOs in this cohort are more likely to call for deflection than those cases selected in the NASA Congressional Report. If those cases considered as examples require the use of nuclear explosions for deflection than it follows logically that the analysis will conclude that indeed nuclear explosives are required. There is no basis for arguing that excessive capability (i.e. nuclear explosion) is to be preferred over adequate capability, especially when the result of its application yields an uncertain and potentially dangerous result (the small but real risk of a short term return impact) and that there are many legal and social challenges to its use.

Russell L. Schweickart

Attachment 4

Technical Critique of NASA's Report to Congress and associated of "2006 Near-Earth Object Survey and Deflection Study: Final Report" Published 28 Dec. 2006

Russell L. Schweickart
Chairman, B612 Foundation
And
Chairman, Association of Space Explorers Committee on NEOs
1 May 2007

General Comments:

The *2006 Near-Earth Object Survey and Deflection Study* published in December 2006 served as the technical background report for NASA's Report to Congress, *Near-Earth Object Survey and Deflection Analysis of Alternatives* submitted to the Congress on or about 9 March 2007.

This background technical report (the Final Report), held from public release, has nevertheless circulated through the NEO "community." The analytic source of many of the objectionable conclusions contained in the Report to Congress are to be found in this document. The comments contained herein identify the most egregious technical errors in the Final Report but by no means reflect the full scope of errors scattered throughout the document. A full and exhaustive technical critique would be a major undertaking and is probably of limited value given the key errors addressed below.

The fact that NASA has submitted such a flawed report to the Congress and adamantly denied access to its antecedent technical analysis for review by the professional community is troubling, to understate the issue. The public safety issue of NEO impacts and the capability to prevent them by the use of space technology is one in which the value of public trust cannot be overemphasized. Absent NASA opening its full analysis to professional scrutiny and review, the public trust in the integrity and technical competence of NASA is in jeopardy.

The four technical errors identified below are then just a sampling of the problems associated with NASA's handling of the Congressional mandate to address this issue. It is hoped that by openly publishing these and other shortcomings in the two NASA documents a serious review will be initiated by NASA and a revised and accurate report will be provided the public and the Congress.

Technical Errors:

1. **Failure to consider the size/frequency distribution of the NEOs which NASA would most likely be called on to divert from an Earth impact.**

The NASA analysis of possible alternatives to divert an object on a likely collision course with Earth is based on a set of "Possible Scenarios" which are not representative of the NEO population most likely to require deflection. The NEOs in the NASA analysis represent the 1-2% least likely cohort of the NEO threat which will, assuming an impact, create substantial damage on the ground. (Fig. 1)

Because the NEOs NASA selected to analyze are large they require a large total impulse to deflect thereby biasing the result to the nuclear deflection option.

Conversely had NASA considered the far more likely NEOs impacts ranging from Tunguska-like asteroids upward, the analysis would have indicated that approximately 98% of the threat could be handled by the kinetic impact option.

The basis for NASA's selection of scenarios was an early proposal made prior to the first AIAA Planetary Defense Conference in 2004. These hypothetical deflection challenges (Athos, Porthos, etc.) were understood to be "challenging", not representative of the most likely NEOs to be deflected. Furthermore the steering committee for the AIAA conference strongly criticized them as unrealistic and recommended that they not be used. In the end they were modified by the steering committee and ultimately largely disregarded by those who wrote papers and attended the conference. They in no way represent the NEO profile most likely to require deflection in the real world.

2. **Failure to take into consideration, or even recognize, the existence and implications of multiple resonant returns and associated keyholes distributed along the deflection path (the Targeting issue).**

The NASA analysis makes the assumption that deflecting an approaching NEO consists only of causing it to miss the planet at the time of the nominal impact. The analysis does not account for the fact that there are hundreds of resonant return points and associated impact keyholes located along the path of deflection. If a deflection fails to account for these keyholes the NEO may miss the Earth at the time of impact only to return in one or a few years for another impact.

NASA's analysis therefore assumes that the stronger the deflection the better. In fact, in order to assure the world that a deflection has been successful the NEO must not only miss the Earth at the anticipated time of impact but it must also pass by the Earth such that its +/- 5 sigma error ellipse (equivalent to 1 chance in 1 million) passes cleanly between impact keyholes. This requires precision in the deflection, not simply strength (i.e. total impulse). A NEO deflection for which the public cannot be assured that it will not be returning for an impact in just a few years is not a desirable outcome.

This requirement can be achieved using the combination of a kinetic impact (or possibly nuclear explosion) primary deflection followed immediately by a precision orbit determination and possible final "trim" maneuver to positively place the error ellipse between keyholes. This trim maneuver requires very little total impulse but rather continuous closed loop tracking such as would be available with a gravity tractor or other slow deflection technique.

3. **The gravity tractor concept, which is independent of any specific spacecraft hardware, has erroneously been directly tied to the very expensive and technologically immature Prometheus spacecraft (or more generally, nuclear electric propulsion (NEP)).**

White paper #42 *Threat Mitigation: The Gravity Tractor*, presented at NASA's Vail NEO workshop, explicitly and repeatedly identified the flight tested Deep Space 1 mission hardware in its presentation and performance analysis of the gravity tractor concept.

Despite the concept being clearly identified as independent of any specific spacecraft technology and despite most of the examples given (including the capability of deflecting Apophis) referring to a slight modification of the already flown Deep Space 1 hardware, NASA in its "Final Report" ties the gravity tractor technology readiness level and cost with NEP (see Figures 56, 57, and 58). Given that the cost of Deep Space 1 is reported at $147M and the cost of NEP (in the NASA report) at $10B, this is no small error.

4. The development and use of incorrect information on asteroid 144898 2004 VD17.

Asteroid VD17 is one of the most extensively tracked NEOs on the JPL risk tables (over 5 years of tracking) and it offers an excellent example of the incidence and influence of close gravitational encounters preceding a potential Earth impact. This asteroid, along with Apophis, was highlighted in White Paper 039, *Threat Characterization: Trajectory Dynamics*, presented at NASA's NEO Workshop in Vail, CO as an example of the influence of close gravitational approaches prior to a potential Earth impact.

In addition to the text in the White Paper describing the influence of close gravitational approaches, a figure was included (Figure 3, attached here as well), along with a reference, illustrating the 3 orders of magnitude decrease in the delta V required to deflect this asteroid, if done early, due to the presence of three successive close approaches to the Earth prior to the nominal 2102 impact.

In the NASA Final Report (Figure 47., pg 103) the plot for delta V required to deflect asteroid VD17 ignores these three close gravitational encounters with Earth. It therefore shows the delta V required to be approximately 5×10^{-3} meters/sec 90 years prior to the nominal impact. The plot in White Paper 39 (Carusi, Milani) indicates three close gravitational encounters with Earth prior to impact resulting in a required delta V of 90 years prior to impact of approximately 5×10^{-6} meters/sec.

This factor of 1000 is a very significant error in the example given in the NASA Final Report and one which illustrates the criticality, and frequency, of close gravitational approaches in the analysis of NEO deflection requirements. (Figs. 2 & 3)

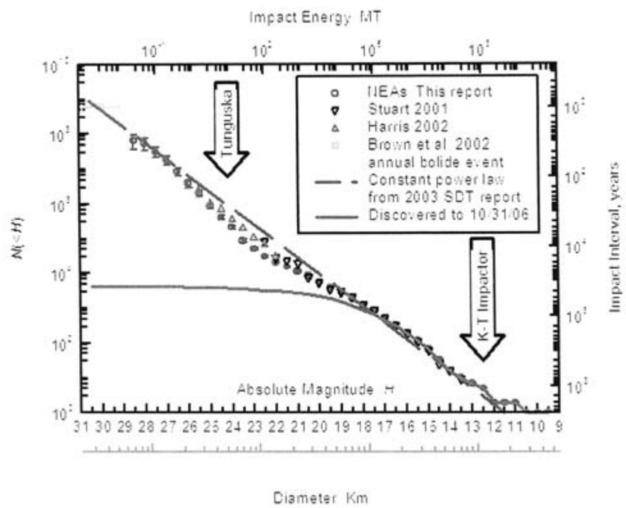

Fig. 1 The current size-frequency plot for near-Earth objects, presented at the March 2007 AIAA Planetary Defense Conference in Washington, DC by Alan W. Harris. This is an updated version of Fig. 2-3 from the 2003 NEO SDT study published by NASA in August 2003. For the purposes of this critique the differences between the 2003 and 2007 versions of this plot are insignificant.

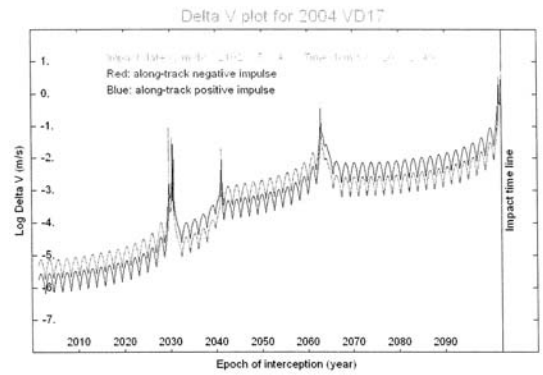

Fig. 2 The delta V plot developed by Carusi, Milani, et al. showing the change in velocity required to deflect asteroid 144898 2004VD17 from an Earth impact in 2102. This plot was incorporated into White Paper #39 presented at NASA's 2006 NEO Workshop in Vail, Colorado to illustrate and emphasize the role of close gravitational encounters in shaping NEO deflections. The three discontinuities in this plot each represent a close pass of the NEO by the Earth in the decades prior to its potential impact with Earth in 2102.

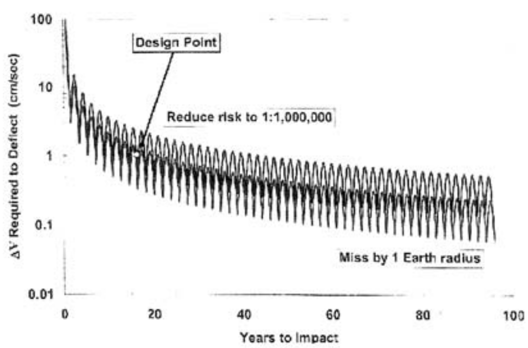

Figure 47. ΔV Required to Deflect Asteroid VD17

Fig. 3 The comparable plot from NASA's *2006 Near Earth Object Survey and Deflection Study* showing the absence of close gravitational encounters prior to impact and the resultant factor of 1000 higher delta ' required for deflection as a result of this omission.

Attachment 5

Critique of "2006 Near-Earth Object Survey and Deflection Study: Final Report"
Published 28 Dec. 2006 by NASA Hq. Program Analysis & Evaluation Office

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and
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2 May 2007

Introduction

This "Final Report" (called "Report" hereafter) was distributed to a select group of people just prior to the Planetary Defense Conference (PDC), held at George Washington University, March 5-8, 2007. It was rumored that less than 100 copies were printed. There were oral presentations at the PDC about the Report (on March 5 and 6) by two NASA officials involved in the Study, Lindley Johnson and Vern Weyers. It was said that the Report would be delivered to Congress imminently. In fact, a report was delivered to Congress on 9 March; although it appears to be based on the Report critiqued here, it is only about 10% as long. Attempts by individuals involved in the Study, like myself, to obtain copies of the longer Report were rebuffed by the NASA Administrator, who claimed that the Report consisted of "internal pre-decisional materials." Nevertheless, copies of the full, 272-pg., full-color, bound report (with artwork on the front and back covers) have circulated, so I have had a copy to study for the past month.

The Study was undertaken at the direction of Congress, which passed an amendment to the Space Act, which was signed by the President and became law at the end of 2005. Among its provisions was a requirement that the NASA Administrator deliver by the end of 2006 an analysis of NEO detection and deflection options along with a "recommended option and proposed budget" to carry out an NEO survey down to 140-meter diameter. Although wording in the 272-pg. Report suggests that it *is* the requested report and says that the Administrator is hereby "submitting" it, the actual report submitted to Congress (more than two months late) is just a brief digest of this Report, excising most of the analysis on which the conclusions are based.

I was among many individuals who responded to NASA's public "Call for Papers" (12 May 2006) via the NASA NSPIRES system; I was subsequently invited to a meeting in Vail, Colorado, "NASA Near-Earth Object Detection and Threat Mitigation Workshop," 26-29 June 2006. (The Report repeatedly refers to this as a "public workshop," but, in fact, it was by invitation only, and a member of the news media was expelled from the meeting.) I participated in two ways in the workshop: (a) my abstract was "accepted" as input to the workshop, although not for oral presentation, and I was thus invited to attend the workshop; (b) I was subsequently invited by the Study Group to present an Introductory Briefing on one aspect of NEO studies. (Indeed, my name, affiliation, and abstract title are given in a list of Vail workshop attendees, pg. 155 of the Report.) Nevertheless, despite my input to the Study, I was refused formal access to this Report.

General Comments

One of the major issues about this Report is the fact that it appears to have been published with the intention that it be submitted to Congress, but it was instead withheld from all but a handful of the Report's authors. Thus it appears that it has been NASA's intent to hinder the ability of the public to assess the analyses that form the basis for the summary of conclusions that was in the much shorter report actually submitted to Congress. Moreover, even the "accepted" abstracts submitted to the Vail Workshop are apparently not available for public scrutiny. This is incompatible with traditional openness in science and with NASA's previous policies about what began as -- and is even called in the Report -- a "public" process.

A major failure of the Report is that it does *not* appear to offer "a recommended option and proposed budget," as required by the law. (However, one could argue that preferences regarding options and budgetary estimates are offered implicitly, throughout the Report.) Instead, as widely reported in the press and debated in subsequent editorials and op-eds, the shorter report to Congress rebuffs this provision of the law and claims that NASA cannot recommend a program because it lacks the funding to implement such a program.

The most serious problem with the substance of the Report is that it uses an absurd metric to assess the relative merits of approaches to NEO deflection and thus arrives at the problematic conclusion that the use of nuclear weapons is the preferred approach for deflecting any kind of NEO that would otherwise strike the Earth. While it is certainly a fact of physics that nuclear weapons are the only potentially available technology for dealing with an exceptionally large (>> 1 km) asteroid or comet, or for dealing with a smaller NEO if the warning time is unusually short (years rather than decades), these are very rare cases. Much simpler, non-nuclear methods, some based on technology that has already flown in space, are quite sufficient for handling the overwhelming proportion of plausible NEO impact scenarios...despite being downweighted by the misbegotten criteria applied in this Report.

This Report is of very uneven quality. The detection analysis is fairly good, perhaps because it represents an updating of the excellent Science Definition Team (SDT) report of 2003. The characterization analysis, however, is absurd and incompetent. And the analysis of deflection technologies is based on erroneous assumptions, misunderstandings of fundamental technical issues, and obsolete information. The Report is replete with small errors to such an extent that one must guess that it was never proofread by anyone. A whole Section is out-of-place (Sect. 5.18, except for Table 17, should precede Sect. 5.12). Perhaps final proofreading was suspended when it was decided to replace this Report with the much shorter version actually submitted to the Congress. Conceivably, and hopefully, the Report was withheld from wider distribution because of a realization within NASA that it contains egregious errors; in this case, one may hope that the intention is to fix the errors, release the Report, and submit it to Congress -- emphasizing that significant conclusions in the March report have had to be revised. If so, then I hope that my discussion of the errors below will prove to be useful. (I cannot, as a single individual, claim that I have deep expertise concerning all matters that I discuss, below...but I am sure that the vast majority of my criticisms are technically valid.)

Specific Issues (main body of Report, generally ordered by page number)

* Pg. 12, pg. 15 (4th bullet in "Summary of Findings"), and generally in Sects. 5.12-5.14: "If detection systems must characterize the catalog...". This sentence in the Executive Summary illustrates one absurdity about the characterization evaluation. It is obvious that we generally (a) *want* (but don't require) to maintain or enhance our current *scientifically motivated* characterization approaches (including current groundbased techniques and occasional space missions to interesting NEOs) and (b) *require* that detailed in situ characterization mission/s be flown (if possible) to any genuinely threatening object that might need to be deflected. This Report fails to make this distinction, and spends much effort evaluating new and costly groundbased or spacebased systems that would characterize significant fractions of discovered NEOs. It talks frequently of "validating models," which makes only a little sense in terms of scientific understanding of

NEOs, and no sense in the deflection context. (The Report does offer "Option 7" which would characterize only threatening objects, though I object to how it is framed: see below.)

Furthermore, the Report takes a totally backwards approach to characterization, saying that we first need to determine what deflection system we will use before addressing what characterization option we will try to build and implement. The "logic" is not what it should be, namely that we will select (from a tool-kit of relevant technologies) what deflection approach would be appropriate for an *identified* threatening NEO of a particular size; rather, it says (specifically in the last paragraph of pg. 73) that we will soon select a one-approach-fits-all deflection system (e.g. stand-off nuclear) as the preferred generic deflection scheme and only then design a characterization effort that will address the needs of that sole deflection approach. (The seriousness of this error is illustrated by the fact that the Report seems to select stand-off nuclear as the preferred approach -- because it is "most effective" -- and then ridiculously concludes that we need to know *less* about the physical nature of the NEO for stand-off nuclear than for all other deflection options! [This absurd argument is "developed" in the middle paragraph of pg. 61.].)

The logical approach, instead (and of course!), is to have a tool-kit of deflection approaches that will address the range of feasible cases, then characterize any threatening NEO that is found, and finally fold the results of that characterization into designing the appropriate deflection mission (which may involve more than one deflection technique) from among the techniques in our tool-kit.

As indicated by the naive Fig. 27, and by the naive statement on pg. 61 about there being about 8 different asteroid "types", it appears that there is no understanding in the Study about what specific physical properties of asteroids need to be characterized and for what purpose. I suppose that the "8 types" might refer to the more common taxonomic classes; but those taxa are related to mineralogy, which is of very minor relevance to this topic compared with other parameters; in various permutations, the other parameters (wide variations in size, rubble pile vs monolith, spin rate, whether binary or not, whether covered with regolith or not, etc.) result in far more than 8 relevant types. This unsupported number "8" turns out to be very important, because this is what is used as a multiplier to arrive at the ridiculously high cost for characterization in the $2 - $7 Billion range (see Table 17)! Since there are many more than 8 relevant types, the logic of using this number (whatever its value) as a multiplier is obviously seriously flawed. As I discuss below, very useful characterization can be done *much* more cheaply; generally what is needed is one or a few characterization missions directed toward the particular NEO that threatens to collide with Earth.

* Pg. 14 (Exec. Summary of deflection analysis): First, it states that the analysis is based on "five scenarios representing the likely range of threats over million-year timescales." Unfortunately, the Study Group has *not* considered the cases that are actually most likely. While it is appropriate to consider an extreme outlier (a comet or large NEA), so we can set a bound on our deflection options, the size-frequency curve (Fig. 2) evidently did not prominently play into evaluation of the appropriate elements of the tool-kit of mitigation alternatives.

A major error is adoption of the phrase "most effective" (meaning most energetic) as the criterion-of-merit for evaluating deflection systems. Application of this criterion appears to result in selection of stand-off nuclear as the preferred option, which is then married to the absurd judgement (mentioned above) that no characterization is required for this approach. The absurdity of this metric of "effectiveness" can be illustrated by an analogy. It is as if automobiles were ranked by the sole metric of how fast they can go. To be sure, an occasional car might be valued for its ability to go 700 km/h (if the goal is to race it on the Bonneville flats), but for the vast majority of car-buyers, the mix of relevant metrics includes more practical issues related to the most common uses of cars (fuel efficiency, safety, etc.).

The 8th bullet in "Summary of Findings" on pg. 15 concludes that "slow push deflection techniques are the most expensive" and that mission durations must be "many decades". To be sure, the Mass-Driver approach must be quite expensive. But why would the Gravity Tractor be expensive? The information presented on Gravity Tractor (and Space Tug) to the Study at the Vail Workshop concerned a concept based on the already-flown Deep Space One; instead the Study has used the already obsolete (abandoned by NASA), and much more expensive, Nuclear Electric Propulsion approach of Prometheus and JIMO. And the "many decades" evaluation is wrong in the highly relevant keyhole context.

The 8th bullet seems to be a "red herring" by contrasting the required reliability of a "deflection campaign" with the reliability of a single launch (see also 6.3.2 on pg. 73 and 6.12.1 on pg. 88).

* Pp. 17, 32, 78, 79, and elsewhere: "June 2006 NEO Public Workshop". Reference is made several times in this Report to the "public" workshop. There was nothing "public" about it! It was by invitation only and the one member of the news media who showed up was expelled.

* Pg. 19, first sentence: "The Administrator of NASA submits this report...". No he didn't! This Report was *not* submitted, but rather was withheld from the public. Instead, a summary roughly 10% as long was submitted to Congress.

* Pg. 23 and 27: The Study appears to have misunderstood the conclusion of the SDT report about the importance of comets. The SDT regarded comets as about 1% of the *hazard*. This is misinterpreted here as "the total number of near-Earth comets...is estimated to be smaller than 1% of [NEAs]." If you are speaking of numbers, you'd better speak of sizes, which they don't.

* Pg. 26, Fig. 5: The Report mixes apples and oranges in this erroneous figure. The figure states the estimated total of NEA's >1 km is 1,100 but that only 689 have been discovered as of Oct. 2006. The correct number is about 840. The 689 comes from the revision of criteria by JPL for assessing the magnitude of a 1 km NEA. If you are going to use the number 689, then you must also use a number more like 950, not 1100, for the total number of 1 km NEAs.

* Pp. 26-27: "air blast limit" is a strange and potentially misleading term.

* Pg. 30 and subsequently. At the top of pg. 30, it appears that the Report defines "mitigation options" to be "deflection options" and nothing else. (This is explicitly denied on pg. 71, where it says that these terms "are not used interchangeably"; but see the third-from-last bullet on pg. 70.) This use is a gross distortion of the meaning of "mitigation" as used in the disaster and hazard reduction community; moreover, it certainly would be regarded by such experts as dramatically incomplete, since it takes no account of mitigating impacts by NEOs not detected or not deflected (e.g. by evacuation, amassing food supplies, and disaster response and recovery). This information was submitted to the Study (in my own accepted abstract) but has been ignored.

* Pg. 30. This states that Apophis will make close approaches to the Earth in 2013, 2022, 2029, and 2036. This is not quite right. Approaches in 2013, 2021 (not 2022!), and 2036 are not especially close. Of course, Apophis might (with very small probability) make a much closer approach in 2036, but only if it passes near the 2036 keyhole in 2029 (when it makes its *very* close pass by Earth).

* Pp. 30-31. I'm not an expert, but I think it is wrong or at least highly misleading to say that "few objects have nearly resonant orbits that lend themselves to keyholes." It may be true for NEAs generally, but NEOs that actually hit the Earth have *good* chances of having passed through a keyhole during earlier years and decades. Also, it states that "if an object [passes] through a keyhole, very little time will usually be available to mitigate the threat." The JPL NEO Risk Page shows numerous cases of future possible impacts by objects resulting from passage through keyholes decades earlier. I sense that, in later sections of the Study, there is little technical appreciation of keyholes and how they affect mitigation strategy.

* Pg. 34 and Sect. 5.13.2 (incl. Fig. 27). This Report seems to have a fundamental misunderstanding of the utility of 10/20 micron radiometry as a remote-sensing technique. There are strange words on pg. 34 about how the atmosphere prevents accurate determination of NEO sizes by this technique, which may be the reasor

radiometry is wholly omitted from the variety of groundbased characterization techniques shown in Fig. 27. Radiometry using groundbased telescopes (augmented, of course, by IRAS and Spitzer) has long been a central approach for determining asteroid sizes and continues to be employed. Polarimetry, strangely, *is* included in Fig. 27 (although it is a technique that is now rarely used because it is much more cumbersome and time-consuming, and no better than radiometry for determining albedos and sizes). Of course, many groundbased characterization observations are difficult for small objects, unless they are very close and brighter than normal.

* Pg. 37, Table 4. The Report considers various data management alternatives, including enhancement of the MPC, or adopting "Aerospace Corp.'s Space Systems Engineering Database," but fails to mention utilization or augmentation of the data management systems already being designed by Pan-STARRs and by LSST (Google). Why weren't these considered as options?

* Pg. 40 (Table 5), Fig. 10, and Sect. 5.10.3 (pp. 54-55): Arecibo is treated very strangely in this Report. I would think that it should have been considered an integral element of the system. At first I thought that it was omitted from Table 5 because the title of Table 5 considers only "detection" and "tracking" (where "tracking" is earlier defined as tracking during a single night). But Fig. 10 includes "catalog" in addition to tracking (which is a longer-term kind of tracking). Obviously, for purposes of this Report, long-term, precise tracking of NEOs should be viewed as greatly assisted by radar; instead, this Report downplays that in several misleading ways. I'm guessing that exclusion of radar at this early stage is symptomatic of the incomplete consideration given to radar throughout this Study.

There is an analysis (e.g. Fig. 22) that shows radar being no better than optical in defining orbits over a long duration, and it is stated that this is the usual case. But for cases of potential impactors, this *is not* the usual case. I expect that a fairly large fraction of objects that actually strike the Earth would be available during earlier years and decades for dedicated radar opportunities. I suspect that the minimal consideration of the role of keyholes in this Report is related to downplaying radar. Radar is especially useful during the years immediately after an NEO is discovered and in cases involving keyholes.

The Study appears to believe (cf. pp. 50-51, top of pg. 52) that when Spaceguard 2 (the recommended survey down to 140 m diameter) is complete, PHO's will have orbits known for centuries into the future (and without radar). Despite the repeated caveat about "assuming no close planetary encounters occur in the interim," I don't think the Study Group "gets it". The Report states that such close planetary encounters are "rare for any given object on human timescales." But such close planetary encounters are *not* so rare for the objects that might actually hit. Indeed, to satisfy the Study's "1-in-a-million" criterion (the application of which they seem to limit to deflection systems alone, not to the larger planetary defense system, which includes detection and tracking), attention *must* be paid to those that have close planetary encounters, even if they are moderately uncommon. After all, the rare ones that are going to hit us are the ones that matter! Instead, this Report dismisses them.

* I also wonder why the Discovery Channel Telescope is dismissed in this Report. While it can't do the whole job, of course, neither (according to this Report) can other single groundbased telescopes. Why was it excluded from being paired with others in the options study? It was definitely presented at the Vail meeting. And it is hardly conjectural: it is already being built by an institution (Lowell Observatory) that is already deeply involved in Spaceguard.

* Pg. 50, there is a strange citation to "Fig. 19 from Ref. 17," which is a Schweickart et al. abstract for the Vail meeting. Certainly 19 figures could not have been fit into this page-limited abstract. Presumably the wrong abstract is cited.

* Pg. 51, Table 12, and associated text: This is not a convincing analysis of various minor forces acting on asteroids. The Study hasn't considered the gravitational effects of main-belt asteroids, for instance. And it

appears, from their casual dismissal of 10 meters per year as a meaningful effect by Yarkovsky or YORP, that they are considering the dimensions of the Earth rather than the dimensions of keyholes...a difference of many orders-of-magnitude.

* Top paragraph, pg. 54: The Report seems to believe that "amateur astronomers" will be the folks doing "precovery" searches when Spaceguard 2 gets underway. This is ridiculous. The existing databases currently being used (in part by amateurs) will be almost totally useless in the era of Spaceguard 2, which will be finding NEAs too faint to have shown up in surveys by 1-meter class telescopes. It will be the elements of Spaceguard 2 itself that will have to undertake the responsibility for archiving their data and for searching for precovery images in their own records. The idea that we need to fund amateur astronomers to do this in the future is nuts.

* Pg. 59: Lightcurves are omitted as a method of searching for asteroidal satellites, despite being one of the most productive techniques.

* Pg. 66, Table 17: This is a nutty summary of characterization options. Option 1 (do little), and Option 2 (dedicate some groundbased telescopes for NEO characterization) are plausible options. But Options 3-6 are nutty in a planetary defense context. And Option 7 (send missions to "8 potential threats at 5 years intervals") is totally absurd, although it takes one small step toward doing what's important: concentrating on an actual threatening NEO. Instead of studying the highest-ranking threats every 5 years, however, the requirement should be to study *any* threatening NEO that rises above some threshold of really being a threat that we need to know about. It will take some careful analysis and judgement-calls to determine what that threshold is, but this Report doesn't even begin to go there.

* Bottom of pg. 68: Two strange statements here. First, it suggests that we will use NEO resources to supplement Earth's diminishing resources! That is the stuff of science fiction and the distant future. NEO resources will be used in support of operations *in space* (of course!). Then there is the puzzling statement that "this study has also identified several funded efforts to survey and characterize the NEO population, which likely will come about with minimal NASA contribution." Where are these mysterious sources of funding? I and my astronomy colleagues would like to know!

* Pp. 69-70 "5.21 Findings": There are 15 bullets here. Bullet #9 repeats the absurd suggestion of paying amateur astronomers to do precovery analysis. Bullet #10 advocates dedicated facilities to follow-up discoveries (I think in a characterization context); this is a nice idea, but not required. Bullet #11 repeats the misleading conclusion that we will have centuries of warning about any potential impact (or 99% of them) once Spaceguard 2 is complete (true for most, but not true for many that might hit during the next decades). Bullet #12 again downgrades radar by falsely saying that it is applicable to only "a few" objects. Bullet #13 repeats the backwards logic that we must choose a one-approach-fits-all deflection strategy before determining what kind of characterization is required.

* Pg. 73, 6.3.1: The phrase "deflected a distance to reduce its probability of impact to 1 in 1 million," apparently incorporates the erroneous idea that there is one-to-one correspondence between distance and safety. There is not. There may be a keyhole capable of a resonant return at a particular distance.

* Pg. 75: Fig. 34 is a case *not* involving a keyhole, hence provides no insight about that very different and relevant situation.

* Pg. 76, 6.6 "Figures of Merit". Here is the core of the fatal flaw in this document. It defines a figure-of-merit as being the fraction of the PHO population for which a deflection approach can provide sufficient momentum *or more*. Obviously, from such a criterion, the most energetic approach wins. The appropriate

figure-of-merit is to evaluate the fraction of expected deflections required during the next century which can be satisfied by a deflection system that is (a) sufficient (with appropriate margin), (b) most precise and controllable (so we know what we are doing and what we have done, such as *not* placing the NEO into a keyhole), and (c) most gentle (so that the NEO, if a rubble pile or other loose assemblage, will not come apart unpredictably).

* Pg. 79-80, 6.8.2 "Overall Effectiveness." Once again, there is a false definition that considers the widest range of applicability as best, ignoring more appropriate figures-of-merit and failing to weight toward the most likely cases (very small NEOs with very long warning times). In addition to being based on the wrong criteria, Tables 21 and 22 show unjustified bias towards the nuclear alternatives. How can nuclear alternatives, for example, be said to have *high* readiness when none have ever been flown in space, hence no proximity blast in space on the surface of (or adjacent to) an NEO has ever been attempted, while the elementary Gravity Tractor (based on the already flown Deep Space One) is rated *medium* in readiness?

* Pg. 80, center: The Report states, "knowing the statistical distribution of rotation rates is a key development parameter" for the Space Tug. This is absurd. We already know the statistical distribution of rotation rates for NEOs. What we need to know, probably for any deflection scheme (except, perhaps, the Gravity Tractor) is "what is the spin state of the particular NEO we are trying to deflect?"

* Pg. 81, Tables 23 and 24. There are absurd entries in these tables. Estimates of the coupling efficiency of a nuclear standoff blast vary widely, and obviously depend on the composition and density of the surface material. Why is "No" put in Table 23 for density and material properties for nuclear standoff? For the nuclear subsurface case, why is it suggested that it is only "helpful" to know density and material properties? If you don't know them (and they could vary between solid iron-nickel alloy to talcum powder), how will the device be placed subsurface with any reliability? In Table 24, why is knowledge of the spin required for the Gravity Tractor?

* Pg. 82, Table 25. This contains yet more unsupportable biases about there being no need for characterization (beyond the modest existing groundbased observations) in order to enable any nuclear (or Kinetic Impactor) deflection scheme. This is wholly irresponsible. And yet the Space Tug is ridiculously said to require the full-up, multi-billion-dollar, >8 missions every 5 years characterization extravaganza, when all it actually requires is one good characterization mission flown to the specific NEO that needs to be deflected. I believe that most of the rationales (a) - (j) (pp. 82-83) for the entries in this table are wrong.

* Pg. 83, 6.11.2, 3rd bullet. This vital assumption that a PHO will "not experience large-scale fracturing" by an impulsive deflection strike rules out, from the beginning, what could be the majority of cases requiring deflection of especially dangerous NEOs. Most NEOs 150 - 300 m in size are probably rubble piles and one of the major concerns is that they would be disrupted by a KI impact. Asteroids in general, and rubble piles in particular, are weak; they can be thought of more like eggs than golf balls: if you strike them, they are likely to rupture before you can move them very much.

* Pg. 85. This final paragraph describes an obvious fact of physics, but it is wholly inappropriate as a measure of merit for proposed deflection schemes.

* Pg. 88, 6.12.2: "more robust"? What is meant by this? I fear that the authors of the Study mean more "effective" (hence more powerful) when the opposite might be the case, for example if keyholes are nearby.

* Pp. 93-97: Case A1 makes no sense whatsoever. Why would one want to deflect Apophis by 1 Earth radius from its current miss-distance in 2029 of about 5 Earth radii? The issue is to deflect it reliably away

from the 2036 keyhole, and any other keyhole. There are other keyholes in the vicinity of 1 Earth radius, so the argument is fallacious that greater distance improves safety.

* Pg. 93: It should be noted that of the 6 (or 7) cases listed, Cases E & F are extremely unlikely to happen, although they do serve to bound the problem. The most likely case (a 50-100 m NEO with a warning time of many decades) is not among the cases analyzed.

* Pg. 100: Instead of using a more relevant design, such as that presented to the Study, they have employed the obsolete JIMO concept. There is no comment in the analysis of cases A1 and A2 that the fact that nuclear methods exceed the required performance by many orders of magnitude (Tables 27 and 28) suggests that they are *inappropriate*.

* Pg. 102-103: The analysis of VD17 is wrong. It has been well-known for some time that VD17 encounters keyholes decades before 2102 and that the deflection requirement is orders-of-magnitude less than calculated here.

* Pg. 106-108: "Since the asteroid is predicted to hit Earth 11 years after detection...". I thought that the hypothetical Athos was discovered at least 20 years before impact. Although a central feature of this case is the presence of a moon orbiting around Athos, the Study addresses this vital issue in only very general terms, and concludes that the specific outcomes of different deflection scenarios "are beyond the scope of this study." In fact, a large fraction of small NEOs (20% - 40%) are expected to have such moons, and it is hardly a peripheral issue about how to deal with them. As the report briefly mentions before declaring the topic "beyond scope", slow-push techniques are less likely to strip a moon away from its parent. The dismissal of this vital topic appears to be yet one more bias against slow-push techniques.

* Pg. 111: Comets are not "activated by interaction with the solar wind."

* Pp. 111-112: There is an inconsistency. Porthos is said to have a diameter of 1 km on pg. 111 but a radius of 1 km on pg. 112.

* Pg. 117: The "cost-performance" measure is totally bogus. The relevant measure of cost would be the *least* costly approach that is *sufficient* to *safely* do the required deflection. And nuclear options do *not* meet that criterion, except for those very rare cases where they are the *only* options that are sufficient.

* Pg. 117, first finding: This is false in several respects. The vast majority of cases do not require nuclear. Standoff blasts do *not* minimize the possibility of fracturing (the minimal possibility of fracturing is certainly the Gravity Tractor case), although they are less than some other cases. And nuclear standoff certainly *does* require knowledge about the target asteroid.

* Pg. 117, third finding: Slow push techniques are not, generically, the most expensive. The Study has used an inappropriate model for the Gravity Tractor, for example. G.T. could very well be the cheapest approach; a tandem Kinetic Impactor with G.T. observer and back-up would be a very cost-effective approach for diverting the vast majority of threatening NEOs. It is also false to say that "their ability to divert an object is very limited unless one assumes very long action times." The question is whether their ability is *sufficient* and whether the action times are reasonable (e.g. several years or less); clearly for cases involving small NEOs and keyholes, the G.T. often is capable.

* Pg. 133: Many of the "findings" simply repeat the errors noted above.

BIOGRAPHY FOR RUSSELL L. SCHWEICKART

Russell L. (Rusty) Schweickart is a retired business and government executive and serves today as Chairman of the Board of the B612 Foundation. The organization, a non-profit private foundation, advocates the development of a space system to protect the Earth from future asteroid impacts. The Foundation's goal is "to significantly alter the orbit of an asteroid, in a controlled manner, by 2015."

Schweickart is the founder and past president of the Association of Space Explorers (ASE), the international professional society of astronauts and cosmonauts. .He currently serves as Chairman of the ASE's Committee on Near-Earth Objects. The organization promotes the cooperative exploration and development of space and the use of space technology for human benefit. The ASE has a current membership of over 390 astronauts and cosmonauts from 31 nations. The Association's first book, *The Home Planet,* with a preface by Schweickart, was published simultaneously in 10 nations in the Fall of 1988 and was an immediate international best seller.

In 1987–88, Schweickart chaired the United States Antarctic Program Safety Review Panel for the Director of the National Science Foundation (NSF) in Washington, DC. The resulting report, *Safety in Antarctica,* a comprehensive on-site review of all U.S. activities in Antarctica, led to a restructuring of the program, increasing the safety of operations in that hazardous environment. At the request of the National Science Foundation, Schweickart also served on the 1997–1998 United States Antarctic Program Outside Review Panel, which reported to the White House (OSTP) and Congress on the future of U.S. facilities in Antarctica. The U.S.' Amundson-Scott South Pole station is currently being fully rebuilt as a result of this work.

In 1977 Schweickart joined the staff of Governor Jerry Brown of California, and served in the Governor's office for two years as his assistant for science and technology. In 1979 Schweickart was appointed to the post of Commissioner of Energy for the State of California and served on the Commission for five and a half years. The Commission, which was chaired by Schweickart for three and a half years, was responsible for all aspects of energy regulation in the state other than rate setting, including energy demand forecasting, alternative energy development, power plant siting and energy performance regulation for appliances and buildings.

Schweickart joined NASA as one of 14 astronauts named in October 1963, the third group of astronauts selected. He served as lunar module pilot for Apollo 9, March 3–13, 1969, logging 241 hours in space. This was the third manned flight of the Apollo series and the first manned flight of the lunar module. During a 46 minute EVA Schweickart tested the portable life support backpack which was subsequently used on the lunar surface explorations. On the mission with Schweickart were commander James A. McDivitt and command module pilot David R. Scott.

Schweickart served as backup commander for the first Skylab mission which flew in the Spring of 1973. Following the loss of the thermal shield during the launch of the Skylab vehicle, he assumed responsibility for the development of hardware and procedures associated with erecting the emergency solar shade and deployment of the jammed solar array wing, operations which transformed Skylab from an imminent disaster to a highly successful program.

After the Skylab program, Schweickart went to NASA Headquarters in Washington, DC as Director of User Affairs in the Office of Applications. In this position he was responsible for transferring NASA technology to the outside world and working with technology users to bring an understanding of their needs into NASA.

Prior to joining NASA, Schweickart was a research scientist at the Experimental Astronomy Laboratory of the Massachusetts Institute of Technology (MIT). His work at MIT involved research in upper atmospheric physics, star tracking and the stabilization of stellar images. His thesis for a master's degree at MIT was an experimental validation of theoretical models of stratospheric radiance.

Schweickart served as a fighter pilot in the U.S. Air Force and the Massachusetts Air National Guard from 1956 to 1963. He has logged over 4000 hours of flight time, including 3500 hours in high performance jet aircraft.

Schweickart was awarded the NASA Distinguished Service Medal (1969) and the Federation Aeronautique Internationale De La Vaux Medal (1970) for his Apollo 9 flight. He also received the National Academy of Television Arts and Sciences Special Trustees Award (Emmy) in 1969 for transmitting the first live TV pictures from space. In 1973 Schweickart was awarded the NASA Exceptional Service Medal for his leadership role in the Skylab rescue efforts.

He is a Fellow of the American Astronautical Society and the International Academy of Astronautics, and an Associate Fellow of the American Institute of Aeronautics and Astronautics. Schweickart is a Trustee and a Fellow of the California Academy of Sciences.

Schweickart was born on 25 October 1935 in Neptune, NJ. He is married to Nancy Ramsey of West Hartford, CT. He has seven children and eleven grandchildren. He graduated from Manasquan High School, NJ; received his Bachelor of Science degree in 1956 and his Master of Science degree in 1963, both from the Massachusetts Institute of Technology.

His hobbies include golf, bicycling, and hiking.

DISCUSSION

Mr. LAMPSON. Thank you, sir, very much. Thank all of you, the whole panel. It is really been a pretty fascinating topic for us to be taking up.

At this time, each Member will be given five minutes to question the panel, and I will yield myself, as Chairman, the first five minutes.

IMPORTANCE OF SURVEYING OBJECTS LARGER THAN 140M

And Dr. Yeomans, is it correct that you pretty much agree with the importance of surveying all potentially hazardous objects, down to 140 meters in size?

Dr. YEOMANS. Yes. I think that is the next step. By doing so, by finding 90 percent of these objects, we would effectively reduce the risk of all Near-Earth Objects to Earth by 99 percent. Now, Rusty mentioned the smaller objects still, but that could be the subject of a third generation search. But the 140 meter and larger objects are primarily, necessarily the focus of the next survey.

Mr. LAMPSON. Well, the Authorization Act of 2005 directs NASA to implement a program to catalog 90 percent of all the 140 meter or larger NEOs by the end of 2020. Is that still a realistic goal, or should the scope or timetable be adjusted, and if so, what would you recommend that new goal to be?

Dr. YEOMANS. Well, I think the 2020 timeline was selected because we needed some sort of a metric to judge progress by, but it has been pointed out that the impact interval for a 140 meter sized object is about 5,000 years, so my personal opinion would be that we could afford to wait another couple of years, and perhaps do the survey by the end of 2030 or thereabouts, and explore some options that would be easier and less expensive to carry out within that timeframe.

RISK OF CHANGING THE PROJECT TIMELINE

Mr. LAMPSON. Maybe our technology even would have grown more, and we will be able to do it more effectively, or at a lesser cost.

Dr. Tyson indicates that the LSST could meet the 90 percent goal by 2026, at an average cost to NASA of about $10 million a year for 12 years. From a risk reduction standpoint, how serious would a 6-year delay in meeting that Congressional goal be, and would anybody else after that, after your comment, would anybody else like to make a comment on it?

Dr. TYSON. I think that the risk reduction is significant, if one is able to go down to these small sizes. In 12 years, as opposed to 10 years, my personal opinion is the same as Don's. I think that one has to just get on with it and do these surveys, and if it takes

12 years instead of 10 years to reach 90 percent, then we should just do that.

Mr. LAMPSON. Dr. Yeomans, would you comment also, please?

Dr. YEOMANS. I agree with what Tony said. I would like to see, perhaps, an extension of our report to Congress, whereby a few options are looked at in far more detail, in a more rigorous fashion, and costing is done in a more rigorous fashion. And perhaps one of the options, one of the few options that would be examined, would be the LSST, working in cooperation with Pan-STARRS, and also one, perhaps two space-based options. Infrared surveys are still very effective, but that would be my suggestion.

NON-U.S. NEO CHARACTERIZATION

Mr. LAMPSON. Anybody else want to make a comment on that before I ask my next question? Okay, let me go on, because we are going to get to all of you.

Dr. Yeomans, what if any contributions are non-U.S. organizations or agencies providing to the detection, tracking, and characterization of NEOs?

Dr. YEOMANS. Well, as was pointed out, in terms of discovering them, NASA is doing the lion's share of the work, certainly more than 98 percent of all discoveries are by NASA-supported facilities. But there are international efforts underway to characterize these objects. Our colleagues in ESA, the European Space Agency, are making strides. The Japanese have a mission currently underway to visit a Near-Earth asteroid and bring a sample back, so that is important.

We have a group at Pisa, Italy, that is also working with us very closely to determine independently impact probabilities for various objects, and so, we are constantly in touch with those folks to verify our results, and they are doing the same, and verifying their results with us, and if we come up with interesting objects like Apophis, for example, the object that will get very close to the Earth in 2029, we wait until we have verified our results with our colleagues in Italy before we make any formal announcements. So, that is working very well.

INCREASING INTERNATIONAL NEO COLLABORATION

Mr. LAMPSON. Is there more that should be done? And if so, what steps ought to be being taken? Can we build greater relationships, obviously through science we can, but is this one of those areas?

Dr. YEOMANS. I think it is. We should continue to encourage our international colleagues to participate more in the discovery area, more in the characterization area. And those activities are ongoing, through the Action Team that was mentioned, the UN Action Team 14, for the Peaceful Uses of Outer Space. So, those international discussions are going on. We certainly would appreciate more international efforts in these areas.

Mr. LAMPSON. Dr. Green, what if any plans does NASA have to engage other nations or international entities in efforts to direct and characterize NEOs?

Dr. GREEN. Currently, through our bilateral discussions with many of the other space agencies, such as ESA, such as the Canadian Space Agency, this is, indeed, a topic that comes up on every agenda. And indeed, we do see, as I mentioned in my testimony, growing international interest in this area. There are several missions that ESA has been studying, and most recently, in what they call Cosmic Visions, there is another mission called Marco Polo, that does have a much better chance now of making it through their budgetary process, that will also add information that is important for us.

The Canadians will be launching a spacecraft called NEOSSat. We have been discussing about how it can be utilized, and making the data more available. So, indeed, in summary, that interest now is becoming more international. It is getting into the plans, future plans of our space agency partners. And as I mentioned, it is, indeed, a topic that we will continue to discuss and promote.

Mr. LAMPSON. Anyone else want to—Mr. Schweickart.

PUBLIC SAFETY

Mr. SCHWEICKART. Yes, Mr. Lampson. Let me simply second what has been said, but go a bit beyond it. I think one of the most important things that can come out of this hearing is to explicitly recognize that what we are discussing here is not science. What we are talking about here is public safety. This is not a subject in which relatively small amounts of money, frankly, should be traded off with the scientific research that goes on in NASA and elsewhere.

We are talking here about two separate things, and they should not be mingled and seen as a zero-sum game, which is the way in which expenditures for issues related to Near-Earth Objects are seen by many people today. This is not a zero-sum game. We are talking about two things. One is science and exploration. Another is public safety. And we should not sacrifice public safety for science. These things are very important.

I think when you go to the international community for additional support, it would be very helpful if the U.S., in its presentations in COPUOS, in the United Nations, were to appeal for additional support, on the basis that we are talking about, public safety on a worldwide basis. I think that may make a real difference.

Thank you.

Mr. LAMPSON. Thank you very much for your comments. Anyone else? Thank you very much. I will yield the next five minutes to Mr. Feeney, the Ranking Member.

Mr. FEENEY. Well, thank you, Mr. Chairman, and I am struck by your remark, Mr. Schweickart, that the way to appeal for international support on this is through safety and security, and I happen to agree with that. I mean, a lot of exploration, especially space exploration, is not a zero-sum game, but there are winners and losers. There are property rights issues. There are capabilities, in terms of geopolitics. But certainly, when you are talking about the potential to deflect a threat to the entire Earth, it seems to me that had the dinosaurs had the capability to deflect these things 65 million years ago, they might still be around. And maybe we can convince some of our international partners to bear some of the load; this is a win-win for everybody involved.

NEO DEFLECTION TECHNOLOGY

So, because there are so many fascinating parts of this, Dr. Yeomans, your remarks did not specifically talk about the technology that Mr. Schweickart did. You said that existing technologies can deflect an Earth-threatening asteroid if there is time. Can you describe those technologies, and can you give us your assessment of Mr. Schweickart's discussion of nuclear versus kinetic and the size of the objects?

Dr. YEOMANS. Well, there is basically two groups of mitigation techniques. There is the fast, flyby, or impacting techniques. You run into it, as we did with the Deep Impact mission, back in July of 2005, and simply slow the object down, if it is small enough to do that, and you have time enough, so that in 20 or 30 years time, when it was predicted to hit the Earth, its orbit would have been changed, so that it wouldn't hit. So, there is the fast or impulsive techniques, where you run into it, or if it is a large object, you would use nuclear explosives, perhaps.

And then, there is the slow push techniques, where you rendezvous with the object, fly alongside it, and you do a number of techniques, possibly. A gravity tug has been suggested, where you just take your spacecraft, and put it up next to your asteroid, and just use the gravitational attraction between the two to move them just a little bit. Now, that is a technique that, as Rusty pointed out, can be used for so-called trim maneuvers. That is not what you would do primarily, but you would use that as a secondary device to alter the orbit of the object, in the event that your primary technique, the impulsive technique, perhaps didn't do the job, or knocked it into one of these subsequent keyholes that he talked about, where a subsequent impact would be likely.

So, in any event, you need a spacecraft nearby to verify the result. That is clear, so—or that would be the optimal technique. So, again, you have to find them early to allow that to happen.

Mr. FEENEY. Mr. Schweickart, staying on the deflection capabilities for a second. You know, NASA says the slow push mitigation techniques are the most expensive, and we are furthest behind in technological capabilities. You seem to have a very different view from NASA's preference for a nuclear device.

In terms of whether we use the slow push versus nuclear, in terms of where we could intercept a Near-Earth Object, is there a difference, in terms of when we can intercept the object in the two techniques, and what are the relative advantages and disadvantages, depending on size of the NEO?

Mr. SCHWEICKART. Yes, thank you very much for the question.

First, let me endorse everything that Don just said in response to your earlier question. I don't think we have any daylight between us, frankly. I think the daylight is between what Don just said and what I also believe, and what the NASA report to Congress said. There is quite a bit of difference in there.

Mr. FEENEY. Let me say that NASA knows we have nuclear capabilities, and they know that they had a mission with one kilometer NEOs. What they did was to take the limited number of threats that they knew how to deal with very comfortably, but they avoided the more complex and more numerous problems. Is that maybe——

Mr. SCHWEICKART. Yes, I think that is a fairly good representation. Let me give you an idea that the nuclear, I would not, our organization would not suggest that nuclear can be ruled out. However, statistically, if you look at the probability of needing to use nuclear, as opposed to nonnuclear means, the frequency of that occurrence would become necessary about once every 100,000 years. So, you are talking about a very improbable frequency of need, and it is that issue which we have with what appeared in the NASA report.

And let me emphasize, again, that as I stated in my report, that NASA in our discussions with them after they submitted their report, acknowledged that they did not fully understand this issue at the time the report was written. Don has now reflected, in fact, a current, and I believe a view which we totally support and agree with.

Let me go to something which you mentioned, which is an extremely important, let me say misperception, and that is that in some way, what we are talking about is a slow push technique versus nuclear or kinetic impact. The thrust of my, no pun, the thrust of my testimony is to point out that both strength and precision are needed for a successful deflection when an asteroid is headed, let me say, for a direct impact with the Earth. You need the strength of a kinetic impact, in general or under exceptional conditions, a nuclear explosion, but you need to follow that up, potentially, if in fact, the deflection has now caused the asteroid to head for a keyhole which will cause it to come back, you need now this trim capability of the slow technique, gravity tractor or other slow technique, which can make a precision correction, to ensure that you don't have that asteroid coming back and hitting. Those two things are necessary for a successful deflection.

Now, the one final thing which you mentioned, and we have not addressed it yet, but it is very important, and that is that NASA did not, in completing its report on the deflection capabilities, understand that the precision deflection that we are talking about could be done with existing space hardware. They used, for their analysis, the assumption of a very large, very complex spacecraft for a gravitational tractor, and that was incorrect. It was a misunderstanding, and in fact, that error should be corrected. Existing ordinary technology can be used, it is very mature, and it is very inexpensive, in fact.

DEFLECTION OF NEOs INTO KEYHOLES

Mr. FEENEY. Just very briefly, with my colleagues' indulgence. I am fascinated by these keyholes. So we are successful with the deflection for the time being, we miss, and it, for whatever reason, it comes into a keyhole. Don't we get a second shot to play ping pong with the thing?

Mr. SCHWEICKART. The basic sequence, which Don outlined, and which we advocate, is that any, first of all, we don't talk about a deflection mission. We should be talking about a deflection campaign, because one of the things that you need to have in place at the asteroid that you intend to deflect is a transponder, a spacecraft that has rendezvoused with it that has a transponder, so that we can do precise radio tracking. Number one, we need to determine, in fact, is that asteroid headed for an impact with the Earth. Number two, if it is, then you send up a deflection mission, a strong one, a kinetic impact, to make the primary deflection so that it misses the Earth.

The next thing you do is go over to it with that same spacecraft which has now been observing that impact, to again precisely determine the success of that primary deflection, and very important, is it now going to pass through one of these nearby keyholes. If, and it is improbable, but if it is heading now for a keyhole, then you need to make a small adjustment in the deflection, using that same spacecraft with the transponder that has a gravity tractor capability, to make a small adjustment to make it miss that keyhole. Now, you have missed the Earth and all return keyholes, and therefore, you have a successful mission.

That is a deflection campaign, involving basically two spacecraft.

MORE ON INTERNATIONAL COLLABORATION

Mr. FEENEY. Mr. Rohrabacher.

Mr. ROHRABACHER. Thank you very much, and I have certainly found this hearing to be fascinating, as I expected it to be, and I would hope that we attract enough attention from the general public and from decision-makers, to understand that there are some things that we have to do, and I certainly agree with Rusty when he suggests that this is a safety issue and not a science issue. I would call it planetary defense, for lack of a better description, and I would hope that as we do enlist others, our European allies and the Japanese and others, I would hope that we also include the Russians in this equation as well. No one mentioned the Russians. I think a Russian-American partnership in this endeavor, I think they have a lot to contribute, and I think it would go a long way towards establishing the type of cooperation we need in space with the Russians.

PROBABILITY OF A 10KM NEO HITTING EARTH IN THE NEAR FUTURE

And with that, I see Arecibo, when we talked about, is a short-term issue in what we are talking about here. I mean, Arecibo is step number one, and we've got to get that done, and then, we are talking about this further threat. I understand that the object that hit the Earth and now is being credited with eliminating the dinosaurs happened about 65 million years ago, but I understand that they say that an object like that, odds-wise, would be about every 50 million years. So, are we not now in a cycle that would put us in the probability that there is another such object that may head to the Earth, not in the near future in terms of our lifetime, but in terms of the lifetime of the planet? Is that accurate to say?

Dr. YEOMANS. If I may respond. Statistically, the likelihood of an object that size happening, first of all, that was a 10 kilometer sized object, and there currently are no potentially hazardous asteroids that are that size. The largest is Toutatis, which is 5.4 kilometers, so we are not likely to see another dinosaur-like event.

And the probabilities are such that an impact of an object of a particular size could happen tomorrow. It could happen in 5,000 years. So, they are not really on cycles, as such.

Mr. ROHRABACHER. Well, but we are just talking about the levels of probability or likelihood, and people chart out what these objects are, you know, every so many thousand years, you can expect something to happen, just with the likelihood of the objects that are out. I think we are just talking about mathematical likelihood, and not necessarily anything else.

APOPHIS NEO

I would like to note that just a few years ago, there was a Near-Earth Object that passed between, or at least as close to the Earth as would have been between the Earth and the Moon, it was that close, and we didn't actually see it until it was actually past. And when you are talking about Apophis, it is a Near-Earth Object, that as we say, and I think Rusty mentioned it, in 2029 is when it will come close to the Earth.

Is it true that we do not know if that object will, after it goes past the Earth the first time, that we do not know if the Earth's gravity will actually impact its trajectory to the point that it then becomes a threat? Is that correct?

Dr. YEOMANS. That is correct. Apophis will make a close approach on April 13, 2029, Friday the 13th.

Mr. ROHRABACHER. Friday the 13th.

Dr. YEOMANS. It is within 4.5 Earth radii of the surface, well within the geosynchronous altitude of our satellites.

Mr. ROHRABACHER. So, it is actually closer than some of our satellites.

Dr. YEOMANS. It is.

Mr. ROHRABACHER. And we don't know what the Earth's gravity will do to that trajectory, and so, it may, 10 years later, we may, as Rusty is talking about a campaign, we may be facing a second onslaught that may be even more dangerous 10 years later.

Dr. YEOMANS. Well, it has a one in 45,000 chance of passing through one of these keyholes that Rusty mentioned, and hitting us in April 13, 2036, but with the help of radar, Arecibo and Goldstone in 2013, we have a 95 percent chance of eliminating that threat altogether. So, it is a very unlikely situation, and one that we can drive to zero, probably.

UNDERSTANDING THE THREAT POSED BY NEOS

Mr. ROHRABACHER. Now, I will tell you that unlikely is, I remember the very first hearing we had on this, and I keep remembering, maybe it was one of you, we suggested the chances of anyone ever being hurt on this planet by a Near-Earth Object is, you know, about the same chance as you getting a royal straight flush in Las Vegas, and it just happens that I had gone to Las Vegas and got a royal straight flush once, and so, that is really actually what made it real for me, is when someone said that. And also, now, I have three children at home that are three years and three and one-half years old. We are not just talking about my lifetime or your lifetime, we are talking about their lifetime as well.

So, I think that Rusty calculated right. However, let me just note, from what you said, Rusty, that you know, this is, when we are dealing with people, we have got to deal with this as a safety issue. It shouldn't be a tradeoff for science. That works internationally, maybe, and it may not work, in terms of getting the job done here. But that may be the only type of trading game that we can do here on Capitol Hill and still get the job done.

And this issue is a priority for me. As far as I can see, we need to understand the threat, and that is what we are talking about right now. We don't even fully understand the threat yet. Then we need to know what we should do, which is a matter of discussion, and we have not even come close to that yet.

FUTURE RESPONSIBILITY

And finally, we need to know who is going to be in charge of doing what needs to be done. And so we need a lot of discussion on this, and make those determinations. We are just now at the "should we even take the steps necessary to understand the threat" stage, and I think there is no question about that.

Rusty, do you want to comment?

Mr. SCHWEICKART. Yes. I think it is very important, your last point, Congressman Rohrabacher. What we know now is that NASA is responsible. NASA is in charge of discovering, tracking, cataloging, et cetera, Near-Earth Objects. What we also know, but we don't seem to acknowledge, is that no one is in charge of protecting the Earth from impacts.

Mr. ROHRABACHER. Right.

Mr. SCHWEICKART. So, that next step is extremely important. At the moment, NASA has not yet adequately thought through the deflection issues. They have not, because they have not been told to. They do not have that responsibility. Until NASA or someone is given the responsibility to think through all of the implications and decisions and international cooperation, et cetera, for protecting the Earth from impacts, not just finding them, that job will not be done.

So, this is extremely important.

Mr. ROHRABACHER. All right. Mr. Chairman, I would suggest that that is our job, that is our job as Congress, is to designate who is going to be responsible for that, what Rusty was just talking about, and we should do that in this session of Congress. It is that important an issue, and if another Near-Earth Object sneaks up on us, and we don't even know who we are going to, what procedure we are going to use to try to thwart the threat, then we haven't done our job.

Thank you very much, and I appreciate you, Mr. Chairman, and yield back.

Chairman UDALL. Thank you, Mr. Rohrabacher. We, as you all know, have another vote underway. I am going to recess the Committee for a very short period of time, given it is one vote, and we will return as quickly as we can, and continue the questioning. We will have another round. I know Mr. Feeney intends to return, and I will see if Rohrabacher wants to ask another round of questions when we reconvene the Committee.

So, the Committee stands in recess.

[Whereupon, at 11:40 a.m., the Subcommittee was recessed, to reconvene at 12:08 p.m.]

Chairman UDALL. The hearing will reconvene. Again, I want to thank the panel for your forbearance with all the votes. We do, I believe, have another vote in an hour, so I understand that we can probably conclude the hearing in the hour we have left to us.

POTENTIAL NASA PARTNERSHIPS

At this time, the Chairman will yield himself five minutes. And I would like to focus, Dr. Green, on the testimony, as delivered by you and Dr. Pace, recommends that NASA continue the existing Spaceguard survey and also take advantage of opportunities using potential dual use telescopes and aircraft, and partner with other agencies, as feasible, to make progress toward achieving the legislative goal.

We have heard today at least two examples of potential partnerships with other agencies supporting the planetary radar at Arecibo and funding the NEO operations of the LSST, that would make significant progress toward achieving the legislative goal for NEO detection and tracking at, I believe, a modest annual cost to NASA.

What, specifically, is NASA doing to take advantage of either of these two potential partnership opportunities?

Dr. GREEN. Indeed, we do want to continue on with our discussions with NSF for the use of the LSST. We have, certainly, an infrastructure in place with the Minor Planet Center, and our ability to utilize that data for NEO detection and orbit determination.

Also, I had mentioned in my testimony the importance of using the Pan-STARRS system that the Air Force is currently putting into place, and in fact, we have provided them with a small amount of funds to be able to upgrade their software such that they are able to do some tracking, which is extremely important, and they have been very receptive. And that relationship is also quite strong.

So, our intent is, indeed, to leverage these two important facilities as they are available, and as they come online.

NASA FUNDING NEO PARTNERSHIPS

Chairman UDALL. Thank you, Dr. Green. To follow on, I wanted to ask if you have entered into any concrete discussions with NSF or DOE on potential partnerships addressing this Congressionally directed NEO survey task, and if not, why not?

Dr. GREEN. Okay. Indeed, as I mentioned, we have concrete discussions with the Air Force, utilizing the Pan-STARRS system, and they are fully aware of what our intent is. NSF, indeed, is aware of our interest in using the LSST, and I anticipate that within this next year, that those discussions will become more firm, as we do understand how the funding becomes available for them to be able to actually build that system.

Chairman UDALL. Thank you, Dr. Green. To continue this line of inquiry, you mentioned that you are providing funding to the Air Force for Pan-STARRS. Did NASA do an analysis of the relative merits of providing NASA funding for Pan-STARRS, versus funding for the LSST or the Arecibo Planetary Radar, before deciding to give these resources to the Air Force? And if not, why not, and how much money is being provided, and where is it coming from in NASA?

Dr. GREEN. The funding that we are utilizing to support small upgrades in the software for Pan-STARRS is a fairly modest amount. I would have to come back to the record to give you the exact amount, but it is within the $100,000 to $200,000 range.

[The information follows:]

MATERIAL REQUESTED FOR THE RECORD

The NASA Near Earth Objects (NEO) Program started limited funding to the Pan-STARRS project in 2007 with a partial award to a proposal submitted to the program by the University of Hawaii, who manages the Pan-STARRS development for the Air Force. This partial award was a one-year grant to the University of Hawaii of $450,000. Any future funding will depend on the success of pending and future proposals Pan-STARRS submits to competitive opportunities of the NEO Program that NASA announces through its annual Research Opportunities in Space and Earth Sciences.

Indeed, what we have arranged, with time, has been utilizing the funding for our NEO search opportunities with NSF, as Arecibo's telescope, by allowing us to increase the number of observers on utilizing that facility, with time. And then NSF taking over more of the operational activities. And then, we are following the National Academy report that did, indeed, suggest that NSF should support their ground-based facilities, and that allows us to better utilize the funding that we have available.

Chairman UDALL. Is NASA prepared to consider providing funding to Arecibo or the LSST project, as is being done with Pan-STARRS? And again, if not, why not, and if I can add a comment, why wouldn't it be logical to support those other activities, if you are prepared to support Pan-STARRS?

Dr. GREEN. Well, currently, our arrangement with NSF has been to follow the NRC report that came out in 2001, which delineated roles and responsibilities for the funding of infrastructure. Indeed, we have worked with NSF in the past to be able to develop Arecibo capability for its radar use, and therefore, we leveraged that, as the rest of the community does, for that kind of research.

So, with respect to that, I believe we have a working relationship is what it boils down to. NSF is funding their infrastructure capability. We are able to, with time, as I mentioned with Arecibo and also with the Pan-STARRS system, that the Air Force provide incrementally small amounts of funds to be able to meet and satisfy our requirements and needs, and that has worked extremely well, and we will continue to pursue that approach in the future.

The LSST activity, of course, is one that needs to be resolved, in terms of whether they will have sufficient funding, and be able to put together the capability before we can begin to figure out how to work with them and leverage that system.

Chairman UDALL. Dr. Yeomans or anybody else on the panel, would you care to comment?

Dr. YEOMANS. I would just like to add that the modest funding to Pan-STARRS was done under a peer review process. They submitted a proposal to the Near-Earth Object Observations Program in NASA Headquarters, which is a modest program in and of itself, and it was thought at the time that their proposal was of sufficient merit that it should be awarded this modest sum. So, that was the process by which Pan-STARRS was funded at a modest level.

Chairman UDALL. Anybody else on the panel would like to comment? Dr. Campbell.

Dr. CAMPBELL. If I may, I would, just on the Arecibo situation, like to comment that perhaps the NSF hasn't read the NRC report, but it is my understanding they feel strongly that the solar system research, and especially research related to the NEO issue, is a NASA responsibility, and that they are very reluctant to provide additional funding to carry out that activity.

Their plans to act on the recommendations of the Senior Review to reduce Arecibo's operating budget to $8 million, the concern, as Dr. Green just pointed out, is that NASA feels that they shouldn't really be supporting the operations of a National Science Foundation facility, as opposed to supporting some of the science which makes use of it. And what we are talking about here are the operational costs of the radar system at Arecibo.

Chairman UDALL. Dr. Tyson.

USING LSST FOR NEO DETECTION

Dr. TYSON. Yes, thank you. I would like to make a couple of comments. First of all, the progress, we are on schedule on LSST towards a first light in 2014. We have a grant already from the National Science Foundation for R&D. We are about two-thirds of the way through that. We have put in, earlier this year, a construction grant, a construction proposal to the NSF. We just had this review, a very good positive result from that, and we are going towards readiness, into the National Science Board. So, we are on schedule, actually, for a 2014 first light.

What is needed here to address this modified mission, beyond what we intend to do, this extra 15 percent of Near-Earth asteroid observing, is some extra support, starting now, with the collaborating with the computer science community on new ways of linking the small tracklets that one has when you take multiple images. Each one of these, LSST will see about 150, each one of these small asteroids, about 150 times. You have to link all of these little tracks together.

The problem is, the challenge is this. I just wish we had special glasses that we could put on when we look out at the night sky, and we only see the nearby Earth-threatening asteroids. Unfortunately, when you look out deeply in the night sky for things that are moving, you are confusion limited by this huge cloud of 10 million main belt asteroids, and you actually have to track all of those guys. You actually have to know each one of those orbits in order to separate out the Earth-threatening ones. So, that is the challenge, and that takes a lot of, millions of lines of computer code. There are some clever computer scientists out there that think they have a solution to some of those problems, and we need to get on with it. That is about $1 million a year, starting in next year or the year after, four or five years, and then we will have the software in place. And then, that extra 15 percent effort would cost us somewhere around $12 million a year during operations.

Radar Versus Optical NEO Detection

I wanted to make a comment, if I may, about radar versus optical. I think you need both. One is not the replacement for the other. Radar is not a method of discovering all of these things, and winnowing down this 10 million objects into the few that are threatening. But once you have done that with optical, then radar is absolutely critical on the ones that you are really concerned with, to refine the orbit.

Importance of Arecibo Radar

Chairman UDALL. Mr. Schweickart.

Mr. SCHWEICKART. Yes, Chairman Udall. I would like to just pick up on where Tony left off, and give slightly different language, perhaps, or perspective on the Arecibo radar and its criticality.

As Tony said, these two are not, I mean the Arecibo radar is not simply another thing to look for asteroids with. Number one, radar is not a good instrument to find or discover, to meet the quota that you guys have essentially dumped on NASA, you know, a certain number by a certain year. However, when what you are looking at or thinking about is protecting the Earth from impacts, picture yourself with a few hundred baseballs headed for your head. If you willingly take your pen and poke out one eye, you are now left with monocular vision. You don't have binocular vision. And if you want to get depth perception, you need both eyes. And yet, what we are doing is we are about to head into a serious decision-making process over the next 15 years on do we or do we not have to deflect something, and what you have done is, if you eliminate Arecibo, is you wiped out, willingly, your binocular vision.

Now, that is extremely important. It is a little different way of thinking about the essential nature of Arecibo. It complements the optical view, and the most critical decisions we are going to make, or the most frequent ones, are the relatively small objects, which are numerous, which we are going to have to make decisions about. Those are the very ones that you get the least amount of data on, and where the Arecibo contribution is extremely critical. Because the next time you see that asteroid, it may be on final approach, and that first vision you get of it needs both optical and radar, you need both eyes.

So, that is a different take on it. But it is not meeting the search goal which NASA has been assigned. It doesn't help in that, but it does help if what you are interested in is protecting the Earth.

Chairman UDALL. Thank you. That is very, very helpful to get that perspective.

The Chair now recognizes, as we begin another round, the Ranking Member, Mr. Feeney.

Mr. FEENEY. Thank you, Mr. Chairman.

Radius of NEO Surveys

This first question is for Dr. Tyson, Mr. Schweickart, Dr. Yeomans, and Dr. Campbell. The NASA recommendations are that we survey objects that come within .05 AU of Earth's orbit, instead of 1.3 AU, as required by the 2005 authorization. Do you agree or disagree with that recommendation, and why don't you give us some comments? If we need to change our recommendation, this is a place to start discussing it.

Dr. TYSON. Congressman, I do agree with that. If you are calculating, if you are interested in, as I think we are, completeness in a survey of Earth-threatening objects, then you should have a survey of Earth-threatening objects, and those are the ones that come within——

Mr. FEENEY. Is .05 the number? Do you think that is a reasonable number?

Dr. TYSON. That is right.

Mr. FEENEY. Okay.

Dr. TYSON. I agree with that.

RAMIFICATIONS OF AN ASTEROID HITTING EARTH

Mr. FEENEY. Okay. And no dissension? Okay. If anybody has an opinion, they agree with you, Dr. Tyson. I want to get an idea of the potential ramifications from a strike of Earth. A couple of months ago, we had a one meter object strike in Peru, roughly. We think it created about a 13 meter crater. Is that impact, I mean, if I am looking at a 100 meter object, am I looking at, you know, 1.3 kilometer crater? If I am looking at a kilometer object, am I looking at, you know, 13 kilometers?

And outside the actual kinetic strike, and the damage done by things being broken apart by the actual collision, are there other things, like radiation or heat, or damages that would impact the environment or humans? This is for anybody who wishes to——

Mr. SCHWEICKART. Mr. Feeney, a relatively easy number is a 100 meter object is about 100 megatons of explosive energy, or picture it as 100 one megaton nuclear bombs going off in one place without the radiation, without the nuclear radiation issue. But the explosive force is tremendous. Now, the other effects, I mean, the detailed effects of shock and that sort of thing, or even if there is a crater in the ground, are not as significant. When you talk about an explosion in the low atmosphere equivalent to 100 megatons, the impact on the ground is tremendous. The Tunguska event is thought today to have been about a five megaton explosion.

Mr. FEENEY. That was in 1908?

Mr. SCHWEICKART. 1908. We are celebrating the hundredth anniversary of that event next year, celebrating——

Mr. FEENEY. We are very familiar with floods and hurricanes in Florida. We refer to things as a 10 year event, a 20 year event, a 100 year event. What was the 1908 event, in your estimate? Is that one in 5,000 years, one in 100?

Mr. SCHWEICKART. Well, it is about a one in 600 to 800 year event, something like that. The size estimates have recently come down, so the frequency at which it occurs has gone up slightly. But I think the point is that that explosion, which flattened 2,000 square kilometers of forest and set them afire in Siberia. Luckily, it didn't kill anyone, maybe one person, that was only about a five megaton event, and it never got to the ground, there is no crater. But the impact would have wiped out all of London or Moscow or Washington, D.C., or any other city, had it unfortunately come, or exploded over one of those cities.

So, the impact of these things does not necessitate a crater in the ground, but they are extremely powerful, even down to objects as small as, say, 40, 45 meters in diameter.

Mr. FEENEY. Dr. Tyson.

Dr. TYSON. Yes. I would like to point out that it certainly would ruin my afternoon if one of these things hit close to my house. But most of the Earth's surface is covered by water, and studies of the actual physical damage from objects that are less than about a few hundred meters in size come really from the tidal waves that are set off when these objects would hit the ocean. There is much more danger that all coastal cities would experience a huge tsunami from such objects.

The actual physics of what happens with larger objects is different. They are so large, these several kilometer size rocks are so large that they actually go down to the bottom, all the way through the water, and punch a hole into the ocean floor, and put all of that mud up into the stratosphere, creating nuclear winter. It is a very different scenario. So, for these smaller objects, it is a different and a somewhat scarier scenario, because there are so many more of them. As somebody pointed out, there is a factor of 100 more of these things. And there is a problem with, you know, I have a problem with probability. You know, you can say——

Mr. FEENEY. Probably.

Dr. TYSON. Well, most likely. You can say that, well, actually, maybe we should spend $1 million on something else, because actually, the probability of this is rather low. But if a 100 meter object could be on its way towards Earth right now, and hit next week, for example, even though its probability, the probability per unit time is very low. So, I think what we need to do is to get on with these discovery surveys, which find virtually all of the Earth-threatening asteroids, and find their orbits, and then it changes the whole equation.

Mr. FEENEY. Thank you, Mr. Chairman. I yield back.

Chairman UDALL. Thank you. I am not sure, Dr. Tyson, you ruined my afternoon with that image, but that is a very powerful image and very compelling reason to do the work we are talking about here today.

The Chairman recognizes the gentleman from California, Mr. Rohrabacher.

Mr. ROHRABACHER. Let us see. It is going to create a huge wave. I think I am the only surfer on this panel. One hand, we got another one here. All right.

Now, let me see if I have got this right, Rusty, that the one, the object that exploded over this, was it Tunguska?

Mr. SCHWEICKART. Tunguska, yes, sir.

Mr. ROHRABACHER. Okay, was only the equivalent of a five megaton? And the one——

Mr. SCHWEICKART. Yes, sir. The most recent analytic work at Los Alamos indicates it was about five megatons, about 45 meters.

Mr. ROHRABACHER. And you are saying the ones we are looking for are 140, would be the equivalent of 140 megatons, if it is a 140 meter object. Is that right?

Mr. SCHWEICKART. Approximately, yes, sir.

NEO SURVEY OBJECTIVES

Mr. ROHRABACHER. So, you are talking about something that would be 100 times more powerful than the one at Tunguska, is what we are just trying to observe?

Mr. SCHWEICKART. Yes, sir. That is correct. But let me emphasize, sir, that the 140 meter search goal is, in fact, at this time, the correct goal. Because, among other things, it is extremely difficult to find things as you get smaller and smaller. So 140 meters is a good goal, and in the process of finding 90 percent of the 140 meter objects, we are also going to find something on the order of 40 to 50 percent of the objects down to 45 or 50 meters. So, we will not have, let me say, a complete survey of those things which can do serious damage on the ground, but we will learn a great deal about them in the process of meeting this appropriate goal.

Mr. ROHRABACHER. Right. From what you said, we are talking about a huge potential destructive power. I mean, we are talking about something beyond, I think, the imagination of any of us here. What is the estimate of the number of undiscovered asteroids that are of 140 meter range? How many have we yet to discover? What are we talking about?

Mr. SCHWEICKART. Don has probably got the best number, but——

Dr. YEOMANS. The 140 meter sized objects, we think there is approximately 20,000 that are in the category of potentially hazardous asteroids, and we have discovered less than four percent of them.

Mr. ROHRABACHER. So, there are 20,000, and we have actually charted only about four percent of them? And it is 100 times stronger than what flattened all of that territory up in Russia?

Dr. YEOMANS. It is like your statement, sir, ignorance is bliss.

Mr. ROHRABACHER. Yes, sir. Dr. Tyson.

Dr. TYSON. Just to add a data point. It is hard to comprehend the destructive force of something like this, but a 300 meter asteroid, of which there are many, has the potential to wipe out entire countries.

Mr. ROHRABACHER. Well, obviously, there is a need for us to be prepared to try to do what we could. If we could mitigate that, we are talking about minimal expense, as compared to what, the cost of actually having to absorb this type of damage.

PLANETARY DEFENSE RESPONSIBILITIES

I would like to talk a little bit about that. Who should be in charge? NASA is obviously involved with the efforts of identifying this, and with the Jet Propulsion Laboratory, and the assets that we are talking about. And NASA has been tasked with this. Once we determine that there is a threat, Rusty is suggesting that this is no longer a science issue. This is a defense issue at that point. Should the Defense Department be the ones who are then tasked with immediately taking over responsibility? Do you have some ideas as to who should, then, be the entity that is responsible for planetary defense? To start with NASA, and then work our way down.

Dr. PACE. Thank you, sir. Well, as you probably know, there is no one who is tasked specifically with that responsibility right now. That is not a settled policy question. And I think it is also fair to say that it would be something that would take the resources and capabilities of multiple federal agencies, if they were to be so tasked.

So, as Mr. Schweickart says about, these things are safety issues versus sort of science issues, I would also submit this is really a policy question as to where you want to assign policy responsibilities for this, and what sort of importance you want to give to it.

I think NASA's traditional role certainly is stronger in the science and in the technology side of it, and therefore, you know, it wouldn't be obvious that we would be the lead agency for something like that, although if so directed, we would certainly participate with other federal agencies who were assigned.

Mr. ROHRABACHER. Does anyone else have a thought on that?

Dr. TYSON. Mr. Rohrabacher, I would like to comment just a bit, and I thank you very much for highlighting that issue, because as I said, I believe this is really the most important single issue before the world, frankly. It is not only the United States, the Congress, and the Administration, but every, this is a global issue. It is not a national issue.

Mr. ROHRABACHER. Well, the first part of it is, are we going to do what is necessary to identify the threat, and then, the issue is who is going to do it?

Dr. TYSON. Right. And I think that the identification of the threat has been relatively well dealt with. NASA has explicit responsibility, in terms of discovering. The identification of a threat comes right up to the point of warning, and issuing warnings has not been assigned to anyone, including NASA. So, that assignment has not been made.

And I think that, in fact, it probably was avoided at the time, several years ago, because of this fundamental policy question. Who is to make these large international policy decisions, and I think that it is important that we look at the logic of it, and who should be involved? NASA clearly is the world's premier agency for developing and testing and demonstrating space capability, and space capability is the sine qua non of protecting the Earth against asteroid impacts.

However, the policy issues are a larger issue, which involves cooperation between nations, agreements, tradeoffs of risk and many, many other things. And so, the policy issue is somewhat separable. Now, the Department of Homeland Security, it would seem, on plain reading of the language, might be one logical agency. The Department of Defense is clearly another potential agency, and NASA itself has many international responsibilities, for example, the International Space Station, in which it makes policy decisions on behalf of the Nation. So, to me, those three agencies are the prime candidates.

I, frankly, because of the need for international cooperation and worldwide public confidence, would argue against the Department of Defense being the principal agency. The Department of Homeland Security certainly has a large responsibility, but it seems to me that the Congress needs to hold hearings to allow many, many people and perspectives and issues to be openly aired in this regard. But it is extremely important, because these international decisions are being forced on us by the very search programs that we have been talking about.

In the next 10 to 15 years, we are going to discover hundreds of thousands of asteroids, and some of them, probably in the hundreds, will look as though they are headed for an impact. And somebody is going to have to make a decision, within the next 15 years, of do we or do we not take protective action?

Now, those decisions are going to involve tradeoffs between nations and national policy issues, and it seems to me we need to get on with this critical decision, so that we are in a place to contribute.

Mr. ROHRABACHER. Thank you very much, and Mr. Chairman, I appreciate your holding this hearing, and I would like to personally thank the witnesses. This has been very illuminating, if not hair-raising. Thank you.

Chairman UDALL. I thank the gentleman from California, and I know within his political party and his circles, there is a lot of debate about the prefix NEO, and to which words you then apply it, but since Mr. Rohrabacher may be more of a neo-internationalist now than he perhaps has been in the past, when it comes to supporting a worldwide effort to make sure that the planet doesn't suffer from one of these impacts.

GOLDSTONE ANTENNA UPGRADES

We are approaching another vote. I would like to ask a couple of additional questions of the panel, and then, we will, my questions will conclude the hearing. And I wanted to start with Dr. Green. NASA is planning to replace the existing deep space antennas at Goldstone with an upgraded system. Will NASA maintain the current planetary radar capability at Goldstone as part of the upgrade, and if not, why not?

Dr. GREEN. Indeed, the organization in NASA that manages the Deep Space Network is the Space Operations Mission Directorate. They have the responsibility for developing an evolutionary plan for that system. It is used for communications, in addition to the science that we utilize that system for, and our radar requirements have been given to that organization as they develop their plan. In the near future, we anticipate seeing those requirements met in the newly redesigned Deep Space Network.

Chairman UDALL. Dr. Yeomans, how important is it?

Dr. YEOMANS. How important is it to maintain the radar with the DSN? I think it is very important. As was mentioned by a number of folks on the panel here, the Goldstone radar and the Arecibo radar are the only two we have, in terms of planetary observations, and they are very complementary. Goldstone covers a large area of sky. It can actually track the objects, whereas Arecibo is fixed, and can track 20 degrees on either side of directly overhead, so very often, an object will come into the Arecibo window, pass out of it, and pass into the Goldstone window and vice versa. So, it is important to keep both of these facilities robust.

FUTURE STEPS IN NEO DETECTION AND DEFLECTION

Chairman UDALL. I would like to follow another line of questioning, but start with Dr. Yeomans again, and just give the panel a heads-up, and invite each one of you to comment before we conclude the hearing. And the focus will be where do we go from here? NASA submitted its report to Congress on options for the expanded NEO program for approaches to deflect NEOs.

What do you believe, Dr. Yeomans, the relative priority for resources should be between NEO detection, tracking, cataloging, characterizing, and development of deflection approaches? In other words, what is most important to do next, and what specifically should NASA do next? Easy question, I know.

Dr. YEOMANS. Well, I am a bit biased. We have to find them early was my first, second, and third priority. And I do think finding them is the first priority. Obviously, we can't mitigate if we don't find them. We can't characterize if we don't find them.

Having said that, we do need to characterize, because there is an enormous diversity amongst Near-Earth asteroids. They range all the way from a fluffy, wimpy, ex-cometary fluff ball to a rubble pile, to a slab of solid rock, to a slab of solid iron. So, you wouldn't mitigate each of those objects with the same technique, perhaps. So, we do need to characterize these objects, and we do need to at least study techniques for mitigation. There is computer simulation work that needs to be done to understand how an impact or an explosion would interact with a rubble pile, with a slab of iron. So, we do need to understand the mitigation and the characterization, but I think discovery is still the most important.

ORBITAL DETERMINATION

Chairman UDALL. Dr. Campbell, Dr. Tyson, Mr. Schweickart in turn, would you each like to comment on the question of priorities?

Dr. CAMPBELL. I think there is little doubt that discovery is the most important thing. If you haven't found them, you certainly can't track them and characterize them. It is clear, though, that there is little point in just making a catalog of a lot of objects in the sky, with poorly defined orbits. And therefore, I think that the two, orbit determination and discovery have to go hand-in-hand. And it seems to me the most important thing to do is to cull the number of objects that you have found as quickly as possible, so that you can actually concentrate on the ones that actually do pose a threat. We have already got thousands of potential objects here, we are going to be finding tens of thousands. We need to know which ones of these are a potential threat to Earth, and for the very smallest objects, we have potentially very little time to do that, in terms of the fact that they will be rather close to the Earth in orbits, and pass rather quickly, and not be detectable in the future.

Chairman UDALL. Dr. Tyson.

Dr. TYSON. Thank you, Chairman. Discovery involves obtaining orbits. You can find a rock that is in the sky and then lose it, and it is of no use, and that doesn't count as a discovery. So, with LSST, one sees each one of these asteroids 100 to 200 times, even more. So, it is possible to derive a pretty good orbit for those, and distinguish them from the background.

So, that facility would get orbits for the Earth-threatening, so-called potentially hazardous asteroids. What is not widely known is that we observe the whole sky every several nights. We just repeat the whole sky every several nights, often in a different color band. So, we have a huge amount of color information in a six color system on each one of these Earth-threatening asteroids, and that, it turns out, as you might imagine, tells you a fair amount of information about the character of its surface and what it is made out of. So, we will gain some knowledge for characterization as well from this data.

But I think we need, actually, the bottom line, I think, is we need to start this process of discovery. I agree with Don that one has to actually discover these things and get their orbits first, and that involves a multi-agency cooperation in these new facilities. I am thinking of the Department of Energy Office of Science, NASA, and the National Science Foundation.

Chairman UDALL. Mr. Schweickart.

MORE ON DETECTION AND DEFLECTION

Mr. SCHWEICKART. Yes, Mr. Chairman. Thank you.

I would like to suggest that your, the way in which you have posed the question is somewhat purist, I guess I would use the word. Like most things in life, we are confronted with things which are, they can be posited as either/or, but the reality is that they are usually not, and I would suggest that this is the case here.

There is absolutely no question that finding them is absolutely the highest priority. Finding them early is very critical. At the same time, the most important thing to keep in mind is that we are finding them in order to protect the Earth from impacts, and so, I would also suggest that at the same time that we are spending money on finding them, we can also direct JPL or NASA to put one or two people to thinking about and working through and understanding the ultimate issue of protecting the Earth, mitigating ones that would be coming at us. And right now, unfortunately, that additional task of thinking through the deflection issue is not there.

And all that takes is a clever person, which JPL has lots of, frankly, thinking about it. But right now, no one is assigned to that, because their job is to find them. And so, I suggest that we do both. And I don't think it's either/or.

Chairman UDALL. Knowing your history, and also having viewed with Mr. Feeney the movie Armageddon, I am sure you would be willing to volunteer for one of those missions, because the spirit is still willing.

Thank you.

Mr. SCHWEICKART. Well, luckily, we don't have to have a human mission to one of these things.

Chairman UDALL. Thank you again for your testimony, for appearing here today. I want to turn to the representatives of NASA and Dr. Green and Dr. Pace. Would you care to comment as well, and well, you will have the final word today.

Dr. PACE. Yes, I just wanted to address a point that any of these sort of mitigation techniques that one would want to use, of course, depends on the situation. As I said, many, many of these different objects have different technical characteristics, and different mitigation techniques may be appropriate.

And so, in that regard, I just, I wanted to go back and clarify one point, that our report, I hope, did not give the impression that we had a preference for use of nuclear explosives. So, those are simply one of the items in the toolkit, and people can disagree over whether it is appropriate or not, depending on the situation. I just want to stress that we did not want to express a preference.

The second thing is that we are trying to not only find objects, and obviously, more can be done, but that characterizing these objects is really also part of our science program. The missions, such as Dawn, that are being done, our international cooperation, what we learn about these objects with our science missions, we think is also directly helpful, should and if a mitigation mission ever be necessary.

And then, finally, I wanted to agree with Dr. Tyson's point about the importance of turning a probabilistic threat into a deterministic one. That is, with a survey effort, and one can go faster or slower, depending on available resources, that one can get to a point where you know where these things are, and whether or not you have thousands of threats, hundreds of threats, one, or none. And that is also achievable. Progress is being made in ground-based optical telescopes at an amazing rate. LSST is one particularly notable one. And that if we simply proceed on the path we are on, we will, in fact, get good survey information. We will get good characterization of objects with our existing science program, and make progress, you know, toward the legislative goal.

Thank you.

Chairman UDALL. Dr. Green, did you have anything else to add?

IMPORTANCE OF NEO CHARACTERIZATION

Dr. GREEN. I certainly would echo a number of things that have been stated here. We know enough about the asteroids to know that not all are created equal. They are very heterogeneous, not only in composition in size, but also in their structure. Some are rubble piles. Some are, indeed, irons and quite different in shapes. And therefore, that characterization aspects, which is important from the scientific point of view, understanding their origin and their evolution, is extremely important for any, the next step, which would be consideration of mitigation, provided we understand that they are potentially hazardous objects, and when they might pose an important threat to us.

So, I believe we have started that first baby step. We are moving out with existing assets. And we are excited about the near-term future, with new assets coming online. We will definitely step up our effort, in terms of utilizing those, and I believe, as we learn more about them, both from in situ observations, but continuing to utilize our radar facilities, not only in NASA, but we sincerely hope that NSF will continue to support the Arecibo radar, that that will enable us to then take more of those steps, which will lead up to some sort of mitigation information necessary to avoid these hazards in the future.

Chairman UDALL. Thank you, Dr. Green. I think I speak on behalf of Congressman Feeney, the Ranking Member, in offering my thanks to all of you for taking your valuable time today to appear before us, both panels, including Congressman Fortuño, have been very, very useful to the Committee.

I would like to make note if there is no objection, the record will remain open for additional statements from the Members, for answers to any followup questions the Subcommittee may ask of you all on the panel. Without objection, so ordered.

The hearing is now adjourned.

[Whereupon, at 12:50 p.m., the Subcommittee was adjourned.]

Appendix 1:

Answers to Post-Hearing Questions

ANSWERS TO POST-HEARING QUESTIONS

Responses by James L. Green, Director, Planetary Science Division, Science Mission Directorate, National Aeronautics and Space Administration (NASA)

Questions submitted by Chairman Mark Udall

Q1. NASA submitted a 2007 report to Congress on NEO search and deflection options, but the report doesn't provide a recommended option, as required in the 2005 NASA Authorization Act. *What approach does NASA recommend that complies with the legislated mandate and what steps have NASA taken to begin implementing any of the options identified in the report?*

A1. NASA will look for opportunities using potential dual-use telescopes and spacecraft—and partner with other agencies as feasible—to attempt to achieve the Congressional goal outlined in Section 321 of the *NASA Authorization Act of 2005* (P.L. 109–155). The Agency has already begun work with Pan-STARRS to ensure its capability for use in the NEO survey effort, and is beginning work to assess what might be done with the Wide-field Infrared Survey Explorer (WISE), and to upgrade the capabilities of the Minor Planet Center (MPC).

Q1a. NASA's report to Congress mentions search options that would rely on planned ground-based telescopes that have been proposed for development under the auspices of other agencies. What role, if any, should NASA play in supporting the NEO-related operations of those telescopes? What alternatives exist if those assets are not funded and developed?

A1a. Maximizing use of the Pan-STARRS and eventually the LSST, if they are developed by other agencies, may be a very cost-effective way for NASA (though perhaps not the Federal Government as a whole) to meet the 90 percent goal, though not on the timeline outlined in Section 321 of the *NASA Authorization Act of 2005* (P.L. 109–155). At the present time NASA does not have a commitment from the sponsoring agencies that the assets will be developed. However, the Agency has begun discussions with the University of Hawaii regarding use of the Pan-STARRS prototype telescope and will continue to monitor its further development, as well as the possible eventual support of LSST by the National Science Foundation, in order to insert at the appropriate time capabilities and commitments for their use in the NEO survey effort. In fact, LSST (or a generic equivalent) is expected to be reprioritized by the National Academies in its upcoming astronomy and astrophysics decadal survey process, and this report will play a significant role in future prospects for LSST within the Foundation's broader set of priorities.

Q2. Dr. Yeomans testified that optical observations alone are often not "accurate enough to immediately rule out a future Earth impact" *once a potentially hazardous asteroid is detected. Dr. Campbell testified that the Goldstone antenna alone would be unlikely to fill the void if Arecibo were to be shut down. What specifically are NASA's plans for calculating the risk of potentially hazardous objects in a timely fashion, especially given the expected increase in NEOs detected from an expanded survey with Pan-STARRS or LSST? Do those plans involve either Arecibo or Goldstone?*

A2. The Spaceguard System, which was setup and supported by NASA, will continue to process NEO observations for impact prediction analysis by the Agency's NEO Program Office in a near real-time manner through the established procedures with the Minor Planet Center of obtaining timely follow-up optical observations and reviewing archived data and photographic records for "pre-discovery observations." As the proposed expanded survey efforts (potentially with assets like Pan-STARRS and LSST) come on line to detect significantly fainter (i.e., smaller) NEOs, these types of instruments will have the coverage capacity to essentially be responsible for obtaining their own optical follow-up observations.

Although the radar capabilities of both Arecibo and Goldstone are able to provide precise refinement of NEO orbits, their observations are only available on a limited subset of NEOs—those that happen to be passing close enough to Earth to be within their range. NASA will use these observations when available, but by far the majority of NEOs orbits must still be determined via optical observations. Once a NEO has been initially detected and its approximate position determined, a whole host of other optical assets can be brought to bear on that NEO's location to determine the orbit as precisely as our orbit models allow. Over time periods significantly smaller than the average impact rate (a few years versus hundreds of years between significant impacts) a collection of optical observations will approach the accuracy that can be obtained via radar observations.

Q3. What are the requirements for data management to support the expanded Survey? How big a job is it likely to be?

A3. Data throughput required as an expanded Survey reaches peak discovery productivity is estimated to reach as much as 100 times the current discovery and observation rates, with the associated needs for expanded data archives. The current Minor Planet Center computer systems are at least two generations obsolete, and will therefore need to be upgraded. However, the anticipated capabilities needed are well within the capabilities of modern desktop computer network systems.

Q3a. Your testimony indicates that NASA has started to evaluate the needs of the Minor Planet Center to accommodate the increase in detection that will result from an expanded survey. What, in specific terms, are NASA's plans for the Minor Planet Center and any changes that may be required to support the expanded survey? What, if any, costs are associated with those plans? How do those plans relate to options on data management presented in the report to Congress?

A3a. In 2008, NASA's Science Mission Directorate plans to solicit for proposals from the small Solar System bodies community for management and operations of the Minor Planet Center—first to modernize the current computer systems and operations, and then to accommodate expanded data throughput for an anticipated expansion of the Survey effort. Costs will be determined based on the proposals received, but NASA does not anticipate costs beyond $1.0 million per year initially. Later options may look at back-up facility needs. This approach most closely relates to the "Scale Existing Data Management Systems" alternative outlined in the NASA report on NEOs submitted to Congress in March 2007.

Q3b. Does NASA have any plans to compete the data management task for the expanded search?

A3b. The Minor Planet Center solicitation will be a full and open competition.

Q4. The European Space Agency (ESA) has conducted a study for a mission (Don Quixote) that would test NEO deflection technologies. Has ESA expressed any interest in international cooperation on a mission, if it were to go forward? If so, has NASA explored the possibility of contributing?

A4. The Don Quixote mission concept has been discussed at bilateral meetings with ESA as a potential area for cooperation. However, NASA understands that further development of this mission has been placed on hold by ESA.

Q4a. Your testimony noted that "ESA has been studying . . . another mission called Marco Polo, that does have a much better chance now of making it through their budgetary process, that will also add information that is important for us." *Could you please describe the potential Marco Polo mission and how it would benefit NASA's NEO search and/or the characterization of NEO's? What is the status of any discussions between NASA and ESA on collaboration or access to data from this potential mission?*

A4a. Marco Polo is a proposed near-Earth object sample return mission to a primitive asteroid whose objective is to return samples that are otherwise not available among known meteorites. Primitive bodies are leftover building blocks from the earliest era of Solar System formation and may have contributed water and organics to Earth, thereby providing a foundation for life. Primitive meteorites are among the least frequently sampled by falling to Earth and all samples received are biased by their ability to survive atmospheric passage. Direct investigation of both the fresh regolith and fresh lithospheric fragments is also impossible by any means other than sample return. Marco Polo will conduct a broad in situ analysis of the target and the geologic context for the samples prior to their acquisition. Sample return enables the power of the Earth's laboratories to identify major chronological events in solar system history, to search for pre-solar material yet unknown in meteorite samples, and to characterize in depth the nature of organic compounds that may be present. Thus, Marco Polo will provide extensive information for the characterization of NEOs. A participating scientist proposal has been submitted by a team of U.S. scientists to the ESA Cosmic Vision solicitation for this mission and we are in the preliminary stages of the process to award to this proposal.

Q4b. You also testified that "The Canadians will be launching a spacecraft called NEOSSat. We have been discussing about how it can be utilized and making the data more available." *Could you please describe the NEOSSat mission and how the data would benefit NASA's NEO search and/or characterization effort? What is the status of any discussions between NASA and the Canadian Space Agency on collaboration or access to data from this potential mission?*

A4b. The Canadian Space Agency (CSA) Near Earth Object Surveillance Satellite (NEOSSat) is a small satellite with a 0.15 meter aperture visible sensor which we understand will be launched sometime in 2009. The small aperture of the sensor means it will have little advantage over current ground based capabilities to detect and track NEOs. However, the continuous access offered by a space-based asset may provide some advantage to augment our capabilities, perhaps in the area of obtaining follow-up observations. NASA is in preliminary discussions with the CSA about collaboration or access to the data.

Q5. Dr. Tyson testified that the estimated the cost for a 12-year long survey would be $125 million. You testified that "The LSST activity, of course, is one that needs to be resolved, in terms of whether they will have sufficient funding, and be able to put together the capability before we can begin to figure out how to work with them and leverage that system." *Is NASA ruling-out partial support for development, even though such support could help ensure the availability of a system that could complete the expanded Survey at a considerably lower estimated cost than the options provided in NASA's report to Congress?*

A5. Maximizing use of the proposed LSST is probably part of the most cost-effective way for NASA to meet the 90 percent goal, though not on the timeline specified in the *NASA Authorization Act of 2005* (P.L. 109–155). LSST (or a generic equivalent) is expected to be reprioritized by the National Academies in its upcoming astronomy and astrophysics decadal survey process, and this report will play a significant role in future prospects for LSST within the Foundation's broader set of priorities. NASA will continue to monitor its further development in order to insert at the appropriate time capabilities and commitments for its use in the NEO survey effort.

Q6. NASA Ames recently hosted a workshop on the potential of low-cost spacecraft to characterize NEOs. What, if any, plans does NASA have to pursue such missions?

A6. NASA held a workshop on low-cost missions to NEOs at Ames Research Center on October 20–21, 2007. The workshop agenda blended three major themes: (1) the importance of characterizing small NEOs and the kinds of science measurements that need to be made; (2) how to get to the targets (i.e., target populations, orbital dynamics, direct vs. gravity-assist trajectories, opportunities for secondary payloads and missions of opportunity); and (3) options for low-cost missions (i.e., small spacecraft, instruments, proximity operations, propulsion, landers, and impactors).

A primary conclusion from the workshop is that low-cost missions to NEOs can play a role in exploring and characterizing these objects. Since a major objective is to explore the diversity of the NEO population and characterize their physical properties, launching multiple small missions could be cost-effective if the technology can be sufficiently matured. NASA already plans numerous "mission of opportunity" solicitations for which such proposals could be submitted.

Questions submitted by Representative Tom Feeney

Q1. NASA's Near-Earth Object (NEO) report, delivered this March, provides several options for meeting the goal of achieving 90 percent detection, tracking and characterization of Potentially Hazardous Objects (PHOs), and the report establishes a clear relationship between resources invested and the time needed to achieve 90 percent coverage. In essence, the report shows that for an additional investment of approximately $536 million, we could buy-down a decade of time to complete the survey. In your view, is that additional investment necessary? Does the threat posed by PHOs compel faster completion of the survey?

A1. NASA's analysis shows that not completing the NEO survey down to 140 meters until the 2025–2030 timeframe does not statistically carry a level of risk that requires costly actions.

Q2. What are the most difficult types of NEOs to detect? Is there, for instance, a portion of the sky that won't be covered by ground-based facilities? Are there certain types of orbits that make it difficult to detect and track asteroids and comets?

A2. Small NEOs composed of dark, carbonaceous materials are difficult to detect because they are intrinsically faint. NEOs of any size and composition on very Earth-like orbits can be potentially difficult to detect because they may spend a considerable number of years far from Earth on the other side of the Sun. Such objects may spend many years being effectively unobservable to ground- or Earth-based telescopes because of their apparent faintness or apparent proximity to the Sun.

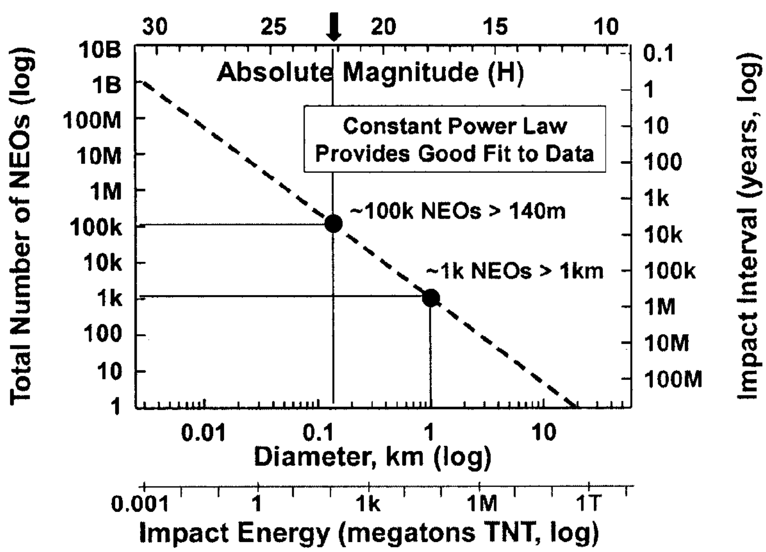
In general, the present bias toward NEO survey programs being located in the northern hemisphere does not significantly affect progress in completing the Spaceguard Survey for kilometer and larger NEOs; objects not detected during a southern-hemisphere-visible close approach will most likely be detected on a subsequent northern-hemisphere close pass. The present baseline survey plan for the Large Synoptic Survey Telescope (LSST) as developed by the project's proponents, which will, if funded, be based in the southern hemisphere and be a significant contributor to a follow-on survey for 140m and larger NEOs, conversely leaves some time gap in northern hemisphere NEO detection capabilities. The LSST project proponents are, however, actively exploring options for modifications to their baseline observing plan to include a portion of the northern ecliptic (the central plane of the solar system—where most NEOs spend most of their time) in order to increase their detection rate of NEOs.

In any case, all surveys able to find 90 percent of potentially hazardous objects reduce the actuarial risk by the same amount, even if some small percentage of the objects is more difficult to detect by a specific system.

Q3. Once the LSST and Pan-STARRS telescopes are operating, and surveys for PHOs that are 140 meters or larger has commenced, what is the business and public safety case for expanding the search to detect and track smaller PHOs—or instance, down to a size of 50 meters? What are the cost and schedule implications?

A3. An object of about 50 meters and average density would not be expected to survive all the way through the Earth's atmosphere and strike the surface, but this depends on the object's composition and structure. It could be expected to cause an explosion a few kilometers above the Earth's surface and may therefore cause some blast damage at ground level.

The number of objects and frequency of impact increases as threshold size decreases, roughly based on the following figure, which is also Figure 2 in the report on NEO's NASA submitted to Congress in March 2007.



Therefore, it is estimated that, while there may be about 20,000 Potentially Hazardous Object (PHO)s 140 meters and larger, there are estimated to be about 100,000 PHOs 50 meters and larger and impacts by these smaller objects will therefore be more frequent.

Simulations suggest that a next generation search for potentially hazardous objects (PHOs) down to 140 meters that includes only Pan-STARRS (assumed 2010 start) and LSST (assumed 2014 start) would discover roughly 42 percent of the PHOs larger than 50 meters by the end of 2020 and 59 percent by the end of 2029. Using a one-meter infrared telescope in a Venus-like orbit (assumed 2014 operations start) in addition to the ground-based Pan-STARRS and LSST surveys, the discovered population of 50 meters and larger sized objects would be complete to the level of 78 percent at the end of 2020 and 92 percent complete by the end of 2029. This assumed timeline would require that these systems operate for over a decade, and therefore might require multiple advanced spacecraft to be built (depending on design life), and would also require an even more capable operational data management infrastructure.

Although no estimated costs for such a program are available, it is likely that such a search would require significantly more resources than necessary for the Congressional goal of 90 percent of 140 meters objects outlined in the *NASA Authorization Act of 2005* (P.L. 109–155). The completion of the Congressional goal alone would retire 99 percent of the actuarial risk from PHOs of all sizes. Once significant progress has been made toward the Congressional goal, more consideration may be given to finding and tracking all potentially hazardous objects.

Q4. During the hearing several witnesses mentioned the Air Force's funding of the Pan-STARRS telescope facility in Hawaii as a possible new ground observatory that would be very adept at detecting NEOs. What is the status of Pan-STARRS and the likelihood that all four telescopes will be built? Would the Air Force be willing to make available a portion of the telescope's time to NEO surveys if less than four telescopes are built?

A4. NASA understands that the Pan-STARRS Project Office acts as the Air Force's agent for discussion of capabilities related to NEO detection and survey, so all discussions have been directly with that project office at the University of Hawaii. Pan-STARRS currently is in check-out of its first prototype telescope at the Air Force facility on Haleakala, Maui. NASA cannot speculate on the future funding that will be made available by the Air Force to this project. However, the Pan-STARRS Project Office has already begun discussions with our NEO Program on how the single prototype telescope could be used to complete our currently ongoing one kilometer NEO survey, so it is likely they will work with the survey effort at whatever level of capability they are able to achieve.

Q5. How adaptable are current and proposed space-based infrared satellites to the role of NEO detection, tracking, and characterization? For instance, can Spitzer be used, even if its cryogenic coolant is depleted? And what about WISE (Wide-field Infrared Survey Explorer), due to be launched in 2009?

A5. The majority of existing astronomical telescopes are designed with limited fields of view so they can focus on a specific object of interest. The fewer number of telescopes designed for survey work has relatively large fields of view (FOV) so that they can cover more sky more quickly. For instance, the Spitzer telescope's largest FOV is only five arc minutes by five arc minutes, or less than 10 percent of the area size that would be useful for a survey effort, usually considered to be at least one by one degree FOV. In "back of the envelope" terms, this means it would take Spitzer more than ten times longer to conduct the survey effort than a telescope designed for it, even if it were dedicated to the effort full-time. This of course is not possible.

Of greater potential is the Wide-field Infrared Survey Explorer (WISE) since, as its name implies, it has a wide FOV instrument. Currently being developed for a late 2009 launch for a six month astrophysics mission to map the infrared sky, the WISE instrument is also capable of detecting many asteroids, of which a portion will be NEOs. NASA is evaluating what it will take to make its operations useful to the NEO survey effort. However, the limitations of WISE relative to what it takes to do the NEO survey will limit the results NASA can get from it. Those limitations are its static pointing capability, because it only points along the plane of its orbit so a NEO must pass through that plane at some time to be detected by WISE, and its limited lifetime of only six months—although NASA is exploring what it would take to double that lifetime. If a spacecraft with the capability of WISE could operate for 10 years, it could go a long way towards completing the survey effort, but in only six months it may detect only about 400 previously unknown NEOs.

The NASA study looked at all known spacecraft, including those operated and planned by the Air Force, and although several of these projects provided potential technology that could be used in a NEO survey spacecraft, no others had the right combination of capability and operational application that would be useful to the effort.

Q6. The NEO Survey Analysis indicates that a space-based observatory has certain advantages over ground-based telescopes. How seriously is NASA giving consideration to building and launching a space-based observatory?

A6. The space-based alternatives have both benefits and risks when compared with ground-based assets. However, both types of systems can meet the Congressional goal of surveying 90 percent of 140 meters objects outlined in the *NASA Authorization Act of 2005* (P.L. 109–155). If a system is built, the benefits and risks would be weighed against cost differences to make a selection. NASA does not have plans for building either a ground or space-based asset for NEO detection within its budgeted program. However, there are a few programmed space flight opportunities for competitive selection to which a capability might be proposed by the external community.

Q7. One deflection solution, suggested by NASA, is to detonate a nuclear device in the vicinity of a PHO. What are the advantages and disadvantages of using this approach? What circumstances would argue against using a nuclear device in lieu of alternative approaches?

A7. The report on NEOs NASA submitted to the Congress in March 2007 did not recommend any one specific deflection solution—different scenarios might require completely different combinations of systems and solutions. However, the alternatives analysis for this report found:

- Deflection systems using nuclear explosives carry the highest deflection capability per kg of payload launched of the alternatives studied, therefore significantly reducing launch costs and increasing launch opportunities.
- Deflection systems using nuclear explosives were evaluated to be applicable to the widest range of threats (size, composition, shape, spin rate, etc.), although other alternatives may have advantages in certain scenarios.
- Nuclear explosives were evaluated to be among the most reliable and repeatable of the deflection techniques evaluated, with the highest level of technology readiness relative to alternatives.
- Impulsive methods, including nuclear explosives and kinetic impactors, provide their deflection instantaneously. This improves performance in "quick response" scenarios and permits multiple successive attempts that are likely to be necessary to achieve desired levels of deflection campaign reliability.
- Deflection systems using nuclear explosives are likely to be among the lowest cost due to significantly lower launch costs, lower payload development costs, and lower operations costs than slow push methods.
- Deflection systems using nuclear explosives carry unique operations and launch safety risks, all of which must be evaluated in the event a credible threat to the Earth is actually detected.
- Possible deflection scenarios cover a wide range of threat characteristics including size, mass, composition, spin rate, shape, cohesion, and number of gravitationally bound objects. As the NASA study indicated, the alternatives studied provide a "tool kit" of options to a decision-maker when an actual threat becomes apparent.

Nuclear deflection is possibly the most effective option when cost, schedule, technology readiness, operational issues, and the need for characterization are considered, but it does have unique political, policy, and safety considerations. A series of one or more standoff nuclear devices may be the only option as the mass of the threat grows, but there are some instances (e.g., when the risk of fragmentation is high) where they may not be the primary selection.

To achieve the level of reliability likely to be required to mitigate a potential threat, it is likely that multiple deflection techniques would need to be pursued as part of a deflection campaign such that no technology or system is a single point of failure. The use of nuclear explosives is evaluated to be very effective for many threat scenarios, and it is one of many options in the tool kit of defection alternatives.

Questions submitted by Representative Dana Rohrabacher

Q1. The need for a comprehensive potentially hazardous Near-Earth Objects (NEO) program seems to require expertise of several agencies. How do you suggest coordination be handled?

A1. At present, no department or agency of the United States is assigned the responsibility for a NEO contingency notification plan or the responsibility to mitigate threats posed by potentially hazardous near Earth asteroids and comets. As with other major natural disasters, a coordinated approach involving multiple federal agencies would clearly be required. NASA has not developed a position on how responsibilities should be assigned among U.S. departments and agencies.

Q2. Describe some of the proposed mitigation techniques and their trade offs.

A2. The report on NEOs NASA submitted to the Congress in March 2007 examined a number of techniques for deflecting a Potentially Hazardous Objects (PHO) that have been categorized as either "impulsive" or "slow push." The tables below provide an overview of the impulsive methods and the slow push techniques, where the velocity change results from the continuous application of a small force, considered in the report. Each of these concepts is developed further in the report.

Table 1. Impulsive Deflection Alternatives Considered

Impulsive Technique	**Description**
Conventional Explosive (surface)	Detonate on impact
Conventional Explosive (subsurface)	Drive explosive device into PHO, detonate
Nuclear Explosive (standoff)	Detonate on flyby via proximity fuse
Nuclear Explosive (surface)	Impact, detonate via contact fuse
Nuclear Explosive (delayed)	Land on surface, detonate at optimal time
Nuclear Explosive (subsurface)	Drive explosive device into PHO, detonate
Kinetic Impact	High velocity impact

Table 2. Slow Push Deflection Alternatives Considered

Slow Push Technique	**Description**
Focused Solar	Use large mirror to focus solar energy on a spot, heat surface, "boil off" material
Pulsed Laser	Rendezvous, position spacecraft near PHO,
	focus laser on surface, material "boiled off" surface provides small force
Mass Driver	Rendezvous, land, attach, mine material, eject material from PHO at high velocity
Gravity Tractor	Rendezvous with PHO, fly in close proximity for extended period, gravitational attraction provides small force
Asteroid Tug	Rendezvous with PHO, attach to PHO, push
Enhanced Yarkovsky Effect	Change albedo of a rotating PHO; radiation from sun-heated material will provide small force as body rotates

In the impulsive category, the use of a nuclear device was found to be the most effective means to deflect a PHO. Because of the large amount of energy delivered, nuclear devices would require the least amount of detailed information about the threatening object, reducing the need for detailed characterization. While detonation of a nuclear device on or below the surface of a threatening object was found to be 10–100 times more efficient than detonating a nuclear device above the surface, the standoff detonation would be less likely to fragment the target. A nuclear standoff mission could be designed knowing only the orbit and approximate mass of the threat, and missions could be carried out incrementally to reach the required amount of deflection. Additional information about the object's mass and physical properties would perhaps increase the effectiveness, but likely would not be required to accomplish the goal.

Non-nuclear kinetic impact alternatives are the most effective non-nuclear option, transferring 10–100 times less momentum than nuclear options for a fixed launch mass. Impact velocities, varying from 10–50 km/s, produced a factor-of-three variation in deflection performance. In addition, kinetic impacts are also sensitive to the porosity, elasticity, and composition of the target and may require large performance margins if these characteristics are not well determined.

Slow push techniques analyzed in this study included a gravity tractor, which could alter the course of an object using the gravitational attraction of a massive spacecraft flying in close proximity, and a space tug, which could attach itself to a PHO and move it using high-efficiency propulsion systems. An attached space tug has generally 10–100 times more performance than the gravity tractor, but it requires more detailed characterization data and more robust guidance and control and surface attachment technologies. This technique could be effective in instances where small increments of velocity (less than one mm/s) could be applied to relatively small objects (less than 200 meters in diameter) over many decades. In general, the slow push systems were found to be at a very low technology readiness level (with the exception of the gravity tractor, which was medium) and would require significant development efforts.

Q3. What is your assessment of the need for a nuclear deflection capability?

A3. There is no need for any deflection capability at this time. No impact threat has yet been identified. If a timely detection capability is fielded, there will most likely be significant warning time in which to develop other parts of the system such as sufficiently capable characterization and deflection spacecraft.

Q4. What are the weakest links in the "system" considering the overall goal to protect Earth from asteroid impacts?

A4. Finding any potential threats so that their orbits can be determined is the weakest link by far. Unless we find threats, we will be unable to react. If we do find threats in a timely manner, there will very likely be significant warning time in which to develop other parts of the system such as sufficient characterization and deflection spacecraft.

Q5. Dr. Donald Yeomans stated that the highest priority regarding NEOs is to "find them early, find them early, find them early." *Yet NASA refused to recommend a program to find them (140 meters and larger) early as directed by law. Why? How does NASA justify this refusal?*

A5. NASA recommended an approach commensurate with the resources the Agency has been appropriated to accomplish its task.

Q6. What is your estimate on the number of undiscovered asteroids in the 140 meter and above range? Describe the potential damage that an asteroid in the 140 meter range could cause striking an ocean within, say, 500 miles from a U.S. coast.

A6. The latest estimate of the total number of near-Earth asteroids (NEAs) larger than 140 meters in diameter is at least 20,000, but could be higher. However, the mean time between impacts of an object 140 meters in size anywhere on the Earth's surface is estimated as about 5,000 years; larger objects would be even less frequent. Objects striking the ocean within about 500 miles of a U.S. coast would be very infrequent, considerably longer than 100,000 years between events.

The impact of a 140-meter-size object, striking at a typical impact speed of about 20 km/s, would deliver and explosive energy equivalent of some 170 megatons. Estimates of the tsunami effects from asteroid impact vary from researcher to researcher, but recent analyses, based on studies of waves generated by underwater explosions, indicate that the risk of impact tsunami from asteroid impacts in this size range has previously been overstated. Assuming precisely where an ocean impact might occur and then extrapolating potential damage from a related tsunami event lends to analysis of a "worst on worst" scenario that couples one highly improbable event to another and biases any resulting assessment. However, the recent studies have indicated the deepwater tsunami wave height at a point 1000 km (~600 miles) from the impact of a 140-meter diameter stony asteroid might be on the order of only a few meters, but this deepwater wave height can increase dramatically when the waves reach the shoreline because the waves slow in shallow water and concentrate the wave energy. Based on recent assessments of tsunami risks for various locations, estimates are that the typical run-up factor (the ratio of the vertical height above sea level of the tsunami at its furthest point inland to its deepwater wave height) for impact tsunamis is only two to three, but this can vary considerably, depending on local topography and the direction of travel of the wave. All this suggests that one might expect a run up tsunami wave height of up to 10 meters or so from an ocean impact of a 140-meter diameter stony asteroid. This is roughly comparable to the measured run-ups from the tsunami that accompanied the Sumatra earthquake of December 26, 2004.

Q7. Asteroids are more easily detected in the infrared spectrum. An asset such as the Wide-field Infrared Survey Explorer (WISE) satellite has an effective capability for searching for NEO's infrared output. Is WISE being tasked for this role? What other infrared detection devices can or will be used to detect NEOs?

A7. WISE is not currently tasked for this role, but NASA is beginning to investigate what might be done with the WISE spacecraft that could be useful to the NEO survey effort. However, because of the limited duration of the WISE mission, its usefulness to the survey effort will be limited.

NASA continues to look at other infrared capabilities in development or planning, but no other possibilities have yet been identified.

ANSWERS TO POST-HEARING QUESTIONS

Responses by Scott Pace, Associate Administrator, Program Analysis and Evaluation, National Aeronautics and Space Administration (NASA)

Questions submitted by Chairman Mark Udall

Q1. Dr. Green's testimony notes that "The science community may propose a Near Earth Object (NEO) survey mission under the competitively-selected Discovery program." *While some space science missions may offer the potential to contribute to NEO detection, in addition to their scientific investigations, a NEO survey mission is not a science mission if its purpose is primarily to detect NEOs. Does NASA have any plans to consider developing a dedicated Discovery-class space-based NEO survey mission to respond to the directive in the* NASA Authorization Act of 2005? *If so, how would NASA carry out such a development-what organization within NASA would have responsibility for it?*

A1. A great deal of science can be learned about the history and evolution of the Solar System by inventory of all the pieces of mass that exist in it, including those as small as a few 100 meter sized objects, and understanding how they evolved to their current positions. Exciting theories about the repositioning of the outer planets have recently come to light based on studies of the dynamics of the small body population.

Although a small body survey mission has not yet be selected in the Discovery program, there have been a few missions proposed to accomplish this type of work. There are no plans to "dedicate" a Discovery mission to an NEO survey effort, but NASA solicitations will remain open to these types of proposals. If the selection process determines that such a mission is the best option, considering many technical feasibility factors in addition to the science, it will also be managed under the highly successful structure that has been instituted by NASA's Science Mission Directorate in the Planetary Science Division's Discovery Program.

Q2. NASA is planning to replace the existing Deep Space Network (DSN) antennas at Goldstone with an upgraded system. Will NASA maintain the current planetary radar capability at Goldstone as part of the upgrade? When, in concrete terms, will NASA know the specifics of plans for the DSN upgrade and planetary radar capability at Goldstone?

A2. NASA is in the process of evaluating the driving requirements for capabilities provided by the DSN. These requirements, which include planetary radar capability at Goldstone, are being worked jointly among three Mission Directorates—Space Operations, Exploration Systems, and Science. This collaboration will drive the decision on the needed capabilities and will formulate the options for maintaining or upgrading the DSN assets. NASA expects to complete these plans by May 2008.

Q3. NASA is providing funding to the Air Force's Pan-STARRS project.

Q3a. When did NASA start funding the project and how much funding is being provided on an annual basis? Is the funding provided through a grant, contract, or other type of agreement? How much funding does NASA plan to provide in total? Is the funding being provided to the Air Force or the University of Hawaii?

A3a. The NASA NEO Program started limited funding to the Pan-STARRS project in 2007 with a partial award to a proposal submitted to the program by the University of Hawaii, who manages the Pan-STARRS development for the Air Force. This partial award was a one-year grant to the University of Hawaii of $450,000. Any future funding will depend on the success of pending and future proposals Pan-STARRS submits to competitive opportunities of the NEO Program that NASA announces through its annual Research Opportunities in Space and Earth Sciences.

Q3b. What, specifically, is the funding being used for and what will be provided to NASA in return?

A3b. The funding is largely being used to adapt existing "moving object detection" software from a current Spaceguard project for use by the Pan-STARRS data processing system. This allows the option for NASA to make use of Pan-STARRS for NEO detection in the future.

Q3c. Who made the decision to fund Pan-STARRS—and did NASA approach the Air Force or did the Air Force approach NASA?

A3c. The decision to fund a part of the proposal submitted by the University of Hawaii to the NEO Program was made through NASA's Research and Analysis peer review process. The final selecting official was Dr. James Green, Planetary Science Division Director.

Q3d. Has NASA discussed with the Air Force or University of Hawaii any changes to the observing times and sequences of Pan-STARRS to optimize the telescope for an expanded NEO search? If so, what is the status of those discussions?

A3d. As Pan-STARRS nears operational capability, there have been preliminary discussions with the project office about what observing techniques and cadences could be used to best optimize the Pan-STARRS operations to achieve all its requirements, to include NEO detection. NASA has not had any direct discussions with the Air Force, as the Agency understands that the Pan-STARRS Project Office acts as its agent for these matters.

Q4. Dr. Green's testimony described NASA's NEO contingency notification plan, which lays out the procedures for notification up through the NASA Administrator if a NEO is detected with a significant probability of impacting Earth.

Q4a. Does a notification or warning system exist beyond NASA for informing the public and federal and State disaster and emergency response agencies? If not, what should be done?

A4a. At present, no department or agency of the United States is assigned the responsibility for a contingency notification plan regarding threats posed by potentially hazardous near Earth asteroids and comets. As with other major natural disasters, a coordinated approach involving multiple federal agencies would clearly be required. NASA has not developed a position on how responsibilities should be assigned among U.S. departments and agencies.

Q4b. How will policy and legal issues involved in addressing NEOs—e.g., when and how to warn the public and whether to use nuclear explosives to deflect an asteroid—be handled on national and international levels? What steps have NASA and other federal agencies taken to date to address such issues?

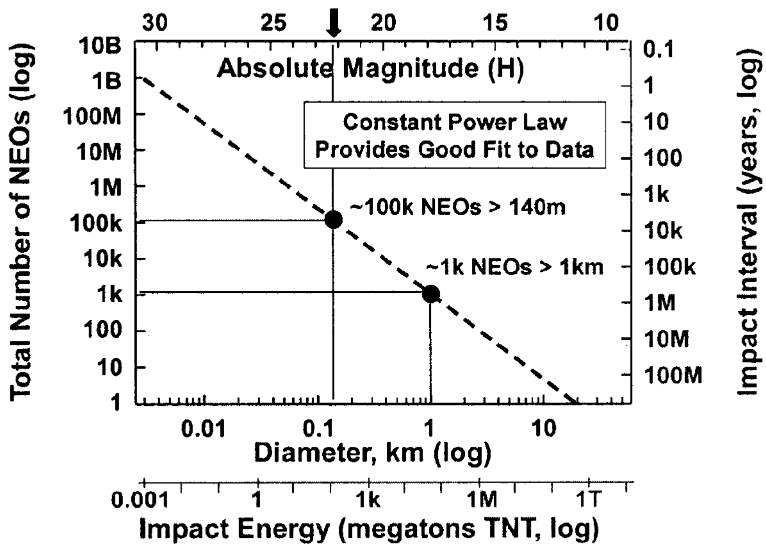
A4b. At present, no department or agency of the United States is assigned the responsibility to mitigate threats posed by potentially hazardous near Earth asteroids and comets. As with other major natural disasters, a coordinated approach involving multiple federal agencies would clearly be required. NASA has not developed a position on both the policy and legal issues addressing NEOs or how responsibilities should be assigned among U.S. departments and agencies. NASA would defer to the Department of State to assess the best approaches to international cooperation on this issue.

Questions submitted by Representative Tom Feeney

Q1. Once the LSST and Pan-STARRS telescopes are operating, and surveys for potentially hazardous objects (PHOs) that are 140 meters or larger has commenced, what is the business and public safety case for expanding the search to detect and track smaller PHOs—for instance, down to a size of 50 meters? What are the cost and schedule implications?

A1. An object of about 50 meters and average density would not be expected to survive all the way through the Earth's atmosphere and strike the surface, but this depends on the object's composition and structure. It could be expected to cause an explosion a few kilometers above the Earth's surface and may therefore cause some blast damage at ground level.

The number of objects and frequency of impact increases as threshold size decreases, roughly based on the following figure, which is also Figure 2 in the report on NEO's NASA submitted to Congress in March 2007.



Therefore, it is estimated that, while there may be about 20,000 PHOs 140 meters and larger, there are estimated to be about 100,000 PHOs 50 meters and larger and impacts by these smaller objects will therefore be more frequent.

Simulations suggest that a next generation search for potentially hazardous objects (PHOs) down to 140 meters that includes only Pan-STARRS (assumed 2010 start) and LSST (assumed 2014 start) would discover roughly 42 percent of the PHOs larger than 50 meters by the end of 2020 and 59 percent by the end of 2029. Using a one-meter infrared telescope in a Venus-like orbit (assumed 2014 operations start) in addition to the ground-based Pan-STARRS and LSST surveys, the discovered population of 50 meters and larger sized objects would be complete to the level of 78 percent at the end of 2020 and 92 percent complete by the end of 2029. This assumed timeline would require that these systems operate for over a decade, and therefore might require multiple advanced spacecraft to be built (depending on design life), and would also require an even more capable operational data management infrastructure.

Although no estimated costs for such a program are available, it is likely that such a search would require significantly more resources than necessary for the Congressional goal of 90 percent of 140 meters objects outlined in the *NASA Authorization Act of 2005* (P.L. 109–155). The completion of the Congressional goal alone would retire 99 percent of the actuarial risk from PHOs of all sizes. Once significant progress has been made toward the Congressional goal, more consideration may be given to finding and tracking all potentially hazardous objects.

Q2. How adaptable are current and proposed space-based infrared satellites to the role of NEO detection, tracking, and characterization? For instance, can Spitzer be used, even if its cryogenic coolant is depleted? And what about WISE (Wide-Field Infrared Survey Explorer), due to be launched in 2009?

A2. The majority of existing astronomical telescopes are designed with limited fields of view so they can focus on a specific object of interest. The fewer number of telescopes designed for survey work has relatively large fields of view (FOV) so that they can cover more sky more quickly. For instance, the Spitzer telescope's largest FOV is only five arc minutes by five arc minutes, or less than 10 percent of the area size that would be useful for a survey effort, usually considered to be at least one by one degree FOV. In "back of the envelope" terms, this means it would take Spitzer more than ten times longer to conduct the survey effort than a telescope designed for it, **even if it were dedicated to the effort full-time.** This of course is not possible.

Of greater potential is the Wide-field Infrared Survey Explorer (WISE) since, as its name implies, it has a wide FOV instrument. Currently being developed for a late 2009 launch for a six month astrophysics mission to map the infrared sky, the WISE instrument is also capable of detecting many asteroids, of which a portion will be NEOs. NASA is evaluating what it will take to make its operations useful to the NEO survey effort. However, the limitations of WISE relative to what it takes to do the NEO survey will limit the results NASA can get from it. Those limitations are its static pointing capability, because it only points along the plane of its orbit so a NEO must pass through that plane at some time to be detected by WISE, and its limited lifetime of only six months—although NASA is exploring what it would take to double that lifetime. If a spacecraft with the capability of WISE could operate for 10 years, it could go a long way towards completing the survey effort, but in only six months it may detect only about 400 previously unknown NEOs.

The NASA study looked at all known spacecraft, including those operated and planned by the Air Force, and although several of these projects provided potential technology that could be used in a NEO survey spacecraft, no others had the right combination of capability and operational application that would be useful to the effort.

Q3. The NEO Survey Analysis indicates that a space-based observatory has certain advantages over ground-based telescopes. How seriously is NASA giving consideration to building and launching a space-based observatory?

A3. The space-based alternatives have both benefits and risks when compared with ground-based assets. However, both types of systems can meet the Congressional goal of surveying 90 percent of 140 meters objects outlined in the *NASA Authorization Act of 2005* (P.L. 109–155). If a system is built, the benefits and risks would be weighed against cost differences to make a selection. NASA does not have plans for building either a ground or space-based asset for NEO detection within its budgeted program. However, there are a few programmed space flight opportunities for competitive selection to which a capability might be proposed by the external community.

Q4. One deflection solution, suggested by NASA, is to detonate a nuclear device in the vicinity of a PHO. What are the advantages and disadvantages of using this approach? What circumstances would argue against using a nuclear device in lieu of alternative approaches?

A4. The report on NEOs NASA submitted to the Congress in March 2007 did not recommend any one specific deflection solution—different scenarios might require completely different combinations of systems and solutions. However, the alternatives analysis for this report found:

- Deflection systems using nuclear explosives carry the highest deflection capability per kg of payload launched of the alternatives studied, therefore significantly reducing launch costs and increasing launch opportunities.
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- Deflection systems using nuclear explosives are likely to be among the lowest cost due to significantly lower launch costs, lower payload development costs, and lower operations costs than slow push methods.
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Questions submitted by Representative Dana Rohrabacher

Q1. The need for a comprehensive potentially hazardous Near-Earth Objects (NEO) program seems to require expertise of several agencies. How do you suggest coordination be handled?

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Q2. Describe some of the proposed mitigation techniques and their trade offs.

A2. The report on NEOs NASA submitted to the Congress in March 2007 examined a number of techniques for deflecting a PHO that have been categorized as either "impulsive" or "slow push." The tables below provide an overview of the impulsive methods and the slow push techniques, where the velocity change results from the continuous application of a small force, considered in the report. Each of these concepts is developed further in the report.

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Table 2. Slow Push Deflection Alternatives Considered

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In the impulsive category, the use of a nuclear device was found to be the most effective means to deflect a PHO. Because of the large amount of energy delivered, nuclear devices would require the least amount of detailed information about the threatening object, reducing the need for detailed characterization. While detonation of a nuclear device on or below the surface of a threatening object was found to be 10–100 times more efficient than detonating a nuclear device above the surface, the standoff detonation would be less likely to fragment the target. A nuclear standoff mission could be designed knowing only the orbit and approximate mass of the threat, and missions could be carried out incrementally to reach the required amount of deflection. Additional information about the object's mass and physical properties would perhaps increase the effectiveness, but likely would not be required to accomplish the goal.

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Q3. What is your assessment of the need for a nuclear deflection capability?

A3. There is no need for any deflection capability at this time. No impact threat has yet been identified. If a timely detection capability is fielded, there will most likely be significant warning time in which to develop other parts of the system such as sufficiently capable characterization and deflection spacecraft.

Q4. What are the weakest links in the "system" considering the overall goal to protect Earth from asteroid impacts?

A4. Finding any potential threats so that their orbits can be determined is the weakest link by far. Unless we find threats, we will be unable to react. If we do find threats in a timely manner, there will very likely be significant warning time in which to develop other parts of the system such as sufficient characterization and deflection spacecraft

Q5. Dr. Donald Yeomans stated that the highest priority regarding NEOs is to "find them early, find them early, find them early." Yet NASA refused to recommend a program to find them (140 meters and larger) early as directed by law. Why? How does NASA justify this refusal?

A5. NASA recommended an approach commensurate with the resources the Agency has been appropriated to accomplish its tasks.

ANSWERS TO POST-HEARING QUESTIONS

Responses by Donald K. Yeomans, Manager, Near-Earth Object Program Office, Jet Propulsion Laboratory

Questions submitted by Chairman Mark Udall

Q1. Planetary radar facilities have been cited as critical for providing more precise orbital determinations of potentially hazardous NEOs. However, the two radar facilities currently being used to obtain data on NEOs [Arecibo and Goldstone] may not be available in the future. What are the implications should existing planetary radar facilities become unavailable?

A1. While the two mentioned planetary radars cannot participate in the near-Earth object (NEO) discovery process, they do provide very accurate range and velocity information that is not available with the traditional optical positional data used to discover these objects. Together with optical observations, the use of radar data within the NEO orbit determination process immediately refines the object's orbit and allows the NEO's future motion to be accurately determined so that future close Earth approach distances can be ascertained far earlier than would be the case without the radar data. After several years of optical data taken at multiple returns of the NEO to the Earth's neighborhood, a NEO orbit computed based solely upon the optical data can also accurately predict the object's future motion. However, it often takes many years before the necessary optical data are in hand and for the more numerous smaller NEOs, the first discovery opportunity is often the best opportunity to gather the necessary data prior to a potentially threatening pass near the Earth. In short, radar data are most critical for quickly identifying the most threatening objects and should one be found on an Earth threatening trajectory, the use of radar data could make the difference between having the time to mitigate the threat or not.

Q2. Could you please explain how the Arecibo and Goldstone planetary radar facilities work together? How, if at all, would the loss of one of the facilities affect the orbital determination of a potentially hazardous object? Would there be a potential effect on the accuracy, the time required for determining a trajectory, the number of objects to be tracked, or some combination of these factors?

A2. As noted in the response to Question 1, the use of radar data allows for a rapid identification of a potentially hazardous object (PHO) and a potentially Earth threatening future encounter. Although the two planetary radars cannot "see" every PHO at every return to the Earth's neighborhood, the loss of one of the planetary radars would substantially decrease the number of PHOs having the radar data necessary to quickly secure their orbits. Hence, without these radar observations, it would take several years more of the optical data to secure their orbits to a point where an Earth threatening encounter could be ruled out (or in). With the use of radar data in the PHO orbit determination process, there would be far more time to deal with the PHO if it turned out to be on an Earth threatening trajectory. The Arecibo and Goldstone radar facilities are very complementary in that the 70 meter sized Goldstone antenna is movable and can track objects within its range from horizon to horizon (8–10 hours). The 305 meter Arecibo antenna has nearly three times the reach, or range, of the Goldstone antenna but can only track objects for about two hours within 20 degrees of its overhead (zenith) position. Often a PHO is first tracked by Arecibo and then by Goldstone (or vice versa) so the use of both instruments is particularly valuable in terms of providing the extended observations necessary to characterize the PHO's size, shape, density, spin state and whether or not it has a moon. Knowledge of these latter characteristics will be invaluable for science and for selecting an appropriate mitigation technology—should that become necessary.

Q3. The asteroid Apophis has been identified as an object that has a small chance of impacting Earth in 2036. What role will Arecibo and/or Goldstone play in improving our understanding of Apophis and refining predictions of a potential impact?

A3. Potentially hazardous asteroid Apophis will make a very close approach to Earth on April 13, 2029 coming as near as 4.6 Earth radii from the Earth's surface (i.e., lower than communication satellites in geosynchronous orbits about Earth). With the aid of radar data taken in 2005 and 2006, the orbit of Apophis has been accurately determined and an Earth collision in 2029 ruled out. However, in the unlikely event that Apophis passes within a 600 meter sized "keyhole" in space during the 2029 close Earth passage, Apophis will return seven years later and strike the Earth (April 13, 2036). To further refine the existing orbit for Apophis and rule out a passage through this tiny keyhole, we will need to understand and model some very subtle perturbative effects due to the pressure of sunlight and the radiation of heat from the surface of Apophis. In order to do this, it will be important to determine the size, shape and spin state of Apophis. Arecibo radar observations made in early 2013 would allow these physical observations to be made. Together with optical data, radar observations in 2013 would reduce the 2029 orbit uncertainties by more than 90 percent. Thus, it is very likely that the passage of Apophis through the 2029 keyhole (and impact in 2036) can be ruled out.

Q4. How do the capabilities of Pan-STARRS compare to that of LSST? Are they complementary facilities for an expanded NEO Survey, or could one facility meet the goal of detecting NEOs as small as 140 meters in size in a timely fashion?

A4. Both Pan-STARRS and LSST have the capability to be far more efficient in finding NEOs than any of the currently operating surveys. The efficiency with which a search telescope can detect NEOs is proportional to the size of the telescope's aperture area multiplied by the telescope's field of view. The four telescope array of the planned Pan-STARRS has four 1.8 meter telescopes each with a field of view of seven square degrees. LSST has a single 8.4 meter telescope (effective aperture = 6.7 meters) with a 9.6 square degree field so LSST would be about five times more efficient in terms of NEO discoveries. However, Pan-STARRS will be located on Hawaii in the northern hemisphere while LSST will be located in the southern hemisphere so these telescopes will be viewing different regions of the sky and will have different weather patterns. Thus they will be very complementary search systems and their observing schedules, search regions and data reduction techniques could be coordinated to ensure a more efficient and robust search strategy. With a start in 2014, the LSST, optimized for NEO searches (as described in Dr. Tyson's testimony), could reach the goal of discovering 90 percent of the potentially hazardous asteroids 140 meters and larger by 2026. In addition, with the Pan-STARRS four telescope array also operational by 2010, the goal could be reached almost two years earlier. Furthermore, the placement of Pan-STARRS in the north and LSST in the south would provide for an increase in warning efficiency for those smaller and more numerous objects that are discovered on their final approach to Earth.

Q5. The Discovery Channel Telescope is under construction and expected to become operational in 2010. The telescope design is expected to enable versatility in its use, which could include the detection of near-Earth asteroids. One estimate puts the total cost of building the telescope at $40–50 million. What contribution, if any, would this type of low-cost telescope provide to the expanded NEO Survey? Should this system be considered as part of the next-generation search or as part of a gap-filler until a Survey using LSST and/or Pan-STARRS gets underway?

A5. The Discovery Channel Telescope has an aperture size of 4.2 meters and when used in the (as yet unfunded) prime focus mode, will have a field of view of 2.3 square degrees. For NEO discovery, it will then be about two times less efficient than Pan-STARRS and 11 times less efficient that LSST. However, the Discovery Channel Telescope will be far superior to any currently used NEO search telescopes and could by itself discover more than 50 percent of the PHAs larger than 140 meters within ten years time. It will be located in Arizona so that it will be in a different region of the world (with different weather patterns) from both Pan-STARRS and LSST. The Discovery Channel Telescope should indeed be considered part of the next generation search.

Q6. What are the data management requirements to support the expanded Survey and what should the priorities be in addressing those requirements? How big a job is it likely to be?

Q6a. Dr. Green's testimony indicates that NASA has started to evaluate the needs of the Minor Planet Center to accommodate the increase in detection that will result in an expanded survey. Should NASA consider other entities for handling data management under the expanded search? Should the data management task be competed?

A6a. Currently the Minor Planet Center (MPC) is receiving, processing and archiving up to 75,000 observations each day and as the next generation of search gets underway, that amount could increase 100-fold. Steps are already underway to establish the interfaces necessary for the MPC to interact with the next generation surveys and manage the enormous increase in data they will provide. In a change from the current survey data processing procedures, the next generation surveys (e.g., Pan-STARRS, LSST) will do much of their own data processing, including the identification of their nightly observations with existing asteroids, the computation of preliminary orbits for newly discovered objects and the archiving of these data. This moving object pipeline system (MOPS) is well along in its development and both Pan-STARRS and LSST will take advantage of it. Hence, while the increased work load on the MPC will be significant, much of the work will be carried out by the surveys themselves. Steps are being taken to ensure that the transition to the next generation search is smooth and that the data processing is nearly completely autonomous so only a modest increase in staffing at the MPC will be required. In the NASA call for Near-Earth Object Observations peer-reviewed proposals in early 2008, there will be an opportunity for other institutions to compete for the role that the MPC in Cambridge Massachusetts is currently fulfilling.

Q7. How much time would be required to prepare a mitigation approach if a hazardous object were discovered to be on a collision course with Earth? How much time would likely be available?

A7. Once the current NEO survey goal has been reached, some 90 percent of the one kilometer and larger sized NEOs will have been discovered. Once the next generation search is complete, all of the one kilometer-sized NEOs will have been discovered along with 90 percent of those potentially hazardous objects larger than 140 meters. At that point, 99 percent of the statistical or actuarial risk from NEOs will have been retired since it will then be possible to track their motions decades into the future and determine if any among them represent a threat to Earth. This is the key issue for getting on with the next generation search—we must find them early enough to allow the time to mitigate if a true Earth threatening object is discovered. After the next generation of search is complete, 90 percent of the 140 meter sized objects will have well understood future motions and should one of them have a significant non-zero Earth impact probability, there would be typically decades to further refine the orbit using optical and radar data and in the vast majority of cases, these additional data will collapse the orbital uncertainties to such an extent that troublesome future Earth encounters can be ruled out. If, in the unlikely event that an Earth impact cannot be ruled out, there should be the necessary number of years to place a spacecraft in orbit about the asteroid, track it and hence accurately monitor the asteroid's motion to determine if the threat remains real. In addition, this rendezvous spacecraft would then be available to monitor the asteroid's motion subsequent to a deflection attempt (e.g., by an impacting spacecraft) to verify that the attempt had been successful in avoiding the potential Earth impact at the predicted time. This monitor spacecraft could also verify that the deflection attempt did not push the asteroid into a tiny nearby keyhole in space that would bring it back to a subsequent Earth impact. This latter possibility, while very unlikely, could then be mitigated using the small gravitational "pull" of the close neighboring spacecraft being used as a gravity tractor.

The development and flight of a rendezvous spacecraft along with the mitigation approach would likely take 10–20 years depending upon the impactor's orbit, the available launch vehicle, the launch opportunities and the mitigation technique itself. The next generation of search is designed to provide many decades of advance warning time for the vast majority of Earth threatening asteroids.

Q8. Dr. Green's testimony described NASA's NEO contingency notification plan, which lays out the procedures for notification up through the NASA Administrator if a NEO is detected with a significant probability of impacting Earth. Does a notification or warning system exist beyond NASA for informing the public and federal and State disaster and emergency response agencies? If not, what should be done?

A8. To my knowledge, there currently exists no notification or warning system beyond NASA for informing the public and federal/State disaster and emergency response agencies. However, the next generation of search for potentially hazardous objects (PHOs) will dramatically increase both the number of known PHOs in the population and the number of warnings where the risk of a PHO Earth impact cannot be immediately ruled out. During the next generation of PHO search, these warnings could increase by up to a factor of 40 over what we currently experience. I would recommend that the lines of communication be opened between NASA's NEO program and the U.S. disaster response agencies to begin the long-term planning for these warnings and for the rare circumstance where one of these PHO warnings turns into a real threat.

Questions for the Record Submitted by Representative Tom Feeney

Q1. NASA's NEO report, delivered this March, provides several options for meeting the goal of achieving 90 percent detection, tracking and characterization of Potentially Hazardous Objects, and the report establishes a clear relationship between resources invested and the time needed to achieve 90 percent coverage. In essence, the report shows that for an additional investment of approximately $536 million, we could buy-down a decade of time to complete the survey. In your view, is that additional investment necessary? Does the threat posed by PHOs compel faster completion of the survey?

A1. While the mean time between impacts for 140 meter sized potentially hazardous objects (PHOs) is approximately 5,000 years, the next impact is equally likely to occur tomorrow morning or in 5,000 years. The mean time between impacts of the far more numerous 50 meter sized PHOs is about 700 years and hence the impact probability for one of these impacts in this century is about 13 percent. NASA currently invests approximately $4 million dollars per year in its NEO Observations program and if the current NEO surveys continue at the current level of activity, it would take more than a century to reach the goal of finding 90 percent of the PHOs larger than 140 meters. To reach this goal by the end of the 2020, as requested in the *NASA Authorization Act of 2005,* the survey could be done with the aid of a dedicated LSST class 8.4 meter telescope (2015 start time) or done using a space-based infrared telescope of 0.5 or 1.0 meters (2012–2014 start). If the 2020 goal line is relaxed a few years, the 90 percent completion goal could be achieved in 2026 with the LSST used in a shared mode with only 15 percent of the time being devoted exclusively to PHO searches. As outlined in the testimony of Dr. Tyson, this option would require about $125 million dollars for the entire effort through 2026.

The threat posed by PHOs is real and the impact of a 140 meter sized PHO would strike the Earth's surface with the energy equivalent of about 100 mega tons of TNT explosives—roughly 7,700 times more energetic than the Hiroshima nuclear device. Nevertheless, it is my personal opinion that, given the infrequency of impacts by relatively large PHOs upon the Earth, there is no compelling reason to insist upon a survey completion by 2020; a relaxation of the completion date by 5–10 years would be acceptable.

Q2. What are the most difficult types of NEOs to detect? Is there, for instance, a portion of the sky that won't be covered by ground-based facilities? Are there certain types of orbits that make it difficult to detect and track asteroids and comets?

A2. With the exception of a single search telescope located in Siding Spring Australia, all current NASA supported NEO search telescopes are located in the northern hemisphere. However, the orbits of NEOs will, over time, bring them into view from the northern hemisphere so that for discovery purposes, the paucity of search telescopes in the south is not a particular problem. However, for warning of objects that are on a final Earth threatening trajectory, northern and southern hemisphere observation capabilities are required. The most difficult NEOs to detect include those objects that 1.) spend most of their time interior to the Earth's orbit (i.e., they are rarely visible in a dark sky) or 2.) they do not often return to the Earth's neighborhood. This latter scenario can arise because they have relatively long orbital periods about the sun or their orbital periods are similar to that of the Earth so they can spend long periods of time before approaching the Earth or becoming visible in the night sky.

Q3. Once the LSST and Pan-STARRS telescopes are operating, and surveys for PHOs that are 140 meters or larger has commenced, what is the business and public safety case for expanding the search to detect and track smaller PHOs—for instance, down to a size of 50 meters? What are the cost and schedule implications?

A3. Fifty meters is roughly the lower size limit where a rocky Earth impacting object could be expected to cause ground damage from an air blast. That is, an object of this size would not generally punch through the Earth's atmosphere and strike the Earth but it would be expected to cause an explosion a few kilometers above the Earth's surface and hence cause ground damage. For example, nearly 100 years ago in June 1908, a 50 meter sized object is thought to have created a 5–10 megaton (of TNT) explosive event in the Tunguska region of Siberia causing ground damage over a region of 2,000 square kilometers.

As one moves down to smaller and smaller PHOs, they become more and more numerous so while there may be more than 10,000 PHOs larger than 140 meters, there is likely to be seven times that number of PHOs larger than 50 meters. The current ongoing survey goal to discover and track 90 percent of the one kilometer and larger sized objects has discovered about five percent of the smaller objects down to 140 meters in size. Similarly, simulations suggest that the next generation search for PHOs down to 140 meters that includes only Pan-STARRS (2010 start) and LSST (2014 start) will discover roughly 42 percent of the potentially hazardous objects (PHOs) larger than 50 meters by the end of 2020 and 59 percent by the end of 2029. If one were to include in the next generation search a one meter infrared telescope in a Venus-like orbit (2014 start) in addition to the ground-based Pan-STARRS and LSST surveys, the discovered population of 50 meter and larger sized objects would be complete to the level of 78 percent at the end of 2020 and 92 percent complete by the end of 2029. However, this latter result would depend upon a rather long 15 year lifetime for the infrared space telescope and would entail significant data down-link issues.

I am not aware of a study to determine survey costs for discovering and tracking 90 percent of the 50 meter sized PHOs but it would likely require far more resources than have been considered to date. It is true that the likelihood of Earth being struck with a 50 meter sized PHO is about seven times that for a PHO of 140 meters. However, at some point there is a crossing between the diminishing hazard from smaller and smaller objects and the increasing costs required to find them. It should be noted that the completion of the goal to discover and track 90 percent of the PHOs larger than 140 meters would retire 99 percent of the actuarial risk from PHOs of all sizes so this is the appropriate goal for the next generation of search. A future study of this issue would have to determine whether or not a comprehensive survey to discover 90 percent of the smaller PHOs down to 50 meters in the near future would be cost effective.

Q4. During the hearing several witnesses mentioned the Air Force's funding of the Pan-STARRS telescope facility in Hawaii as a possible new ground observatory that would be very adept at detecting NEOs. What is the status of Pan-STARRS and the likelihood that all four telescopes will be built? Would the Air Force be willing to make available a portion of the telescope's time to NEO surveys if less than four telescopes are built?

A4. The Pan-STARRS project is a University of Hawaii Institute for Astronomy effort that has been sponsored through United States Air Force grants beginning in FY 2002. The project has been proceeding well in developing the world's largest digital cameras, high precision wide field optics, and software systems to process and archive an unprecedented stream of world class astronomical research data. The ownership and operations of the Pan-STARRS systems is under the authority of the University of Hawaii.

The ultimate goal is to construct four co-located 1.8 meter aperture telescopes (PS4) that will function as a single unit each clear night to search the entire accessible sky twice each lunar month (about 28 days). It seems likely that the PS4 four telescope system will be built within a few years, but the precise schedule will depend upon the availability and timing of the necessary funding as well as completing the construction permitting process that includes a federal environmental impact statement (EIS). As noted in the EIS Preparation Notice published in the *Federal Register* in January 2007, the preferred site is at the Mauna Kea summit on the Big Island of Hawaii, and the alternate site is the Haleakala summit on the island of Maui.

Prior to construction of the four telescope array, a prototype single 1.8 meter telescope (PS1) has been built and sited at the Haleakala summit. The state-of-the-art 1400 megapixel (1.4 billion pixel) CCD camera has been built, tested and mated to the telescope, and the telescope itself achieved "first light" on Aug. 22, 2006. Development is nearly complete of the image processing pipeline (IPP) and the Moving Object Processing System (MOPS) that is designed to identify moving objects within our Solar System (mostly asteroids), and preliminary testing is well underway. An international consortium has committed $10M to fund a 3.5 year PS1 science mission that should begin in mid-2008. Once operational, the primary objective of PS1 is to discover near-Earth objects and it should be more than 20 times more efficient at finding them than any currently operational NEO search effort. This will be true even though the telescope will be conducting a suite of other scientific observations including studies of outer solar system objects, planets around other stars, supernova, galaxy clusters, and gravitational lensing. The supernova and gravitational lensing studies will significantly clarify our current understanding of the dark energy and dark matter issues at the forefront of modern cosmology.

At this time, the best estimate for beginning PS4 construction is late 2009 or early 2010. This is primarily due to the timescale for completing the EIS and obtaining the necessary construction approvals. If sufficient funding continues to be available, the likelihood is high to successfully complete the full system. Commissioning of the first one or two PS4 telescopes should begin in 2011 with the completed four telescope suite becoming fully operational in 2013.

Q5. One deflection solution, suggested by NASA, is to detonate a nuclear device in the vicinity of a PHO. What are the advantages and disadvantages of using this approach? What circumstances would argue against using a nuclear device in lieu of alternative approaches?

A5. There are two categories of mitigation responses for Earth threatening PHOs: a relatively quick flight time impulsive push (perhaps by an impacting spacecraft or a nuclear device) or a longer flight time rendezvous mission followed by either an impulsive or slow push technique (e.g., gravity tractor). If there is sufficient time, the longer flight time rendezvous is preferred because a resident spacecraft can provide both a verification that the asteroid is actually on an Earth threatening trajectory or not and it can verify that a deflection maneuver was successful. A nuclear device could be used in a stand-off mode where the explosion is above the asteroid's surface so that the resultant neutron radiation then ablates the asteroid's front side and introduces a thrust in the direction opposite to the vaporizing material. A far more efficient, but less controlled, technique could be achieved by placing the nuclear device upon, or below, the asteroid's surface. A nuclear response may be required for a large (larger than a few hundred meters) PHO that is found to be on an Earth-threatening trajectory and for which there is not sufficient time to use an alternate technique. This is a very unlikely scenario since the larger objects that might require a nuclear response are also the easiest to discover so a large Earth threatening object will likely be discovered many decades in advance of the potential impact event thus allowing the use of an alternate technology that lacks the problems of the nuclear option—problems that include launch safety, public concern and the possible necessity to modify existing treaties. The advantages of using a nuclear device are that one or more devices could deliver to an Earth threatening asteroid far more energy per kilogram of delivered (launch) mass than any alternative mitigation technique and the technology is mature. The disadvantages include the surface interaction of such a powerful impulsive device with a PHO of unknown structure, which would introduce an uncertainty in the deflection response and possibly a partial breakup of the asteroid itself. The latter scenario might introduce a shotgun-like effect upon the Earth unless the breakup and subsequent dispersal could be initiated soon enough prior to a potential collision that the vast majority of the small fragments would miss the Earth altogether. In short, a nuclear device option should be maintained as a viable mitigation technology but utilized only in the relatively rare situations when a more controlled deflection technique is not adequate or possible.

Questions submitted by Representative Dana Rohrabacher

Q1. The need for a comprehensive potentially hazardous NEO program seems to require expertise of several agencies. How do you suggest coordination be handled?

A1. NASA has been properly given the responsibility to discover, track and catalog near-Earth objects (NEOs) and to determine if any of these objects pose a future threat to Earth. For these efforts, a number of governmental and academic agencies have provided advice and expertise along with survey search and computing facilities. My suggestion would be to maintain NASA's lead role in these activities. In the event a potentially hazardous object (PHO) is found to be on an Earth threatening trajectory, a mitigation technology effort may be required. Such an effort would require that a spacecraft be built, launched, tracked and navigated to rendezvous with the PHO to monitor its motion and conduct a mitigation procedure if that were warranted. Within the U.S., only NASA has that type of experience so it would seem to me that NASA should be given the U.S. lead in mitigation technology planning as well. NASA should, of course, solicit suggestions and advice from other relevant agencies. In particular, should a nuclear deflection mitigation attempt become necessary, other U.S. agencies (e.g., DOD, DOE) would need to be intimately involved in the mitigation attempt.

The threat of a PHO impact is an international problem and should have an internationally agreed upon solution. Such a threat could generate far more problems than just the technologies required for mitigation—including effective communication with the public and disaster preparedness. To my knowledge, there has been very little discussion within the international community to address the totality of the PHO threat issues. There is an ongoing activity within the Association of Space Explorers to address some of these issues and they plan to introduce a draft NEO deflection protocol to the Scientific and Technical Subcommittee of the U.N. Committee on the Peaceful Uses of Outer Space (COPUOS) during their 2009 session. One possible way forward would be the assignment of responsibility to a particular U.S. government agency to begin interagency discussions to define the NEO mitigation responsibilities of specific government agencies and to establish a recommended strategy for selecting a mitigation technology option. These U.S. discussions and recommendations would then need to be coordinated and integrated with those arising from the activities of the UN/COPUOS Scientific and Technical Subcommittee in 2009.

Q2. Describe some of the proposed mitigation techniques and their trade offs.

Q3. What is your assessment of the need for a nuclear deflection capability?

A2,3. Some of the following discussion has been mentioned in response to Representative Feeney's question 5. For completeness, some points are repeated below.

Viable mitigation techniques for deflecting Earth threatening asteroids can be grouped into two categories. The first category of mitigation techniques includes "slow push" technologies that are designed to change the asteroid's orbital velocity over relatively long periods of time. The second category includes impulsive events that are designed to change the asteroid's orbital velocity using the energy of an explosive device or the energy imparted to the asteroid as a result of a high velocity impacting spacecraft. Either category of mitigation technology would benefit from a rendezvous spacecraft that would be placed in orbit around, or hover near, the hazardous asteroid. Radiometric tracking of this "monitor spacecraft" could be used to dramatically improve the orbit of the asteroid and hence determine whether or not it was actually a threat to Earth. Should a deflection maneuver prove necessary, this monitor spacecraft could continue to track the asteroid during and after the deflection attempt to verify that the deflection was successfully carried out and the asteroid would indeed miss the Earth at the predicted impact epoch. Finally, in the very unlikely scenario that the deflection maneuver prevented an Earth impact at a certain future epoch number 1 but pushed it toward a tiny keyhole in space that would allow it to strike Earth at a subsequent impact epoch number 2, the monitor spacecraft could be used as a gravity tug to move the asteroid the few hundred meters necessary to prevent the asteroid from entering the impact plane keyhole. In short, if there is sufficient time, a monitor spacecraft should be maintained in the immediate neighborhood of the Earth threatening asteroid.

Within the first category of slow push techniques, there are only a few viable methods that could be used including the "tugboat" approach where the spacecraft attaches to the asteroid and uses its thrusters to slowly tow it and the so-called gravity tractor where a massive spacecraft uses its thrusters and the gravitational attraction between the spacecraft and asteroid to gently pull the asteroid and alter its orbital velocity and position in space. The tugboat approach presents significant engineering challenges in that it must first secure the asteroid in its grip, and then tow it using its thrusters, being careful to thrust only when the asteroid's rotation brings it back to the same position in space. The gravity tractor approach, with its tiny pull capability, needs to be very close to a rotating irregular asteroid so it has challenges in safely maintaining the necessary close proximity to the asteroid. Some attention has been given to other slow push techniques including solar concentrators or pulsed lasers that could focus intense radiation on the asteroid, ablate or vaporize the near side material and thus introduce a small thrust in the opposite direction from the material that is streaming off the asteroid's side nearest the solar concentrator or laser device. Both of these techniques would provide significant engineering challenges and each system would have vaporizing material driven back toward the devices themselves—thus attenuating the intensity of the focused radiation and perhaps contaminating the system's optics.

Within the second category of impulsive deflection techniques, the high velocity spacecraft impact and the explosive device impulse techniques (including nuclear devices) are mature technologies. A high velocity impact of a spacecraft with comet Tempel 1 was successfully carried out by NASA in July 2005 so the autonomous navigation technologies for such a deflection technique have already been demonstrated. However, a high velocity impact of a spacecraft with a target asteroid will produce only a modest change in the asteroid's velocity and is only a useful technology if the asteroid is smaller than a few hundred meters in diameter or there are many years available between the deflection attempt and the predicted Earth impact.

One or more nuclear devices could be used in a stand-off mode where the explosion is above the asteroid's surface so that the resultant neutron radiation then ablates the asteroid's front side and introduces a thrust in the opposite direction to the vaporizing material. A far more efficient, but less controlled, technique could be achieved by placing the nuclear device upon, or below, the asteroid's surface. This nuclear response may be required for a large (larger than a few hundred meters) PHO that is found to be on an Earth threatening trajectory and for which there is not sufficient time to use an alternative technique. The advantages of using a nuclear device are that one or more devices could deliver to an Earth threatening asteroid far more energy per kilogram of delivered (launch) mass than any alternative mitigation technique and the technology is mature. The disadvantages include the interaction of such a powerful impulsive device with the surface of a PHO of unknown structure, which would introduce an uncertainty in the deflection response and possibly a partial breakup of the asteroid itself. The latter scenario might introduce a shotgun-like effect upon the Earth unless the breakup and subsequent dispersal could be initiated soon enough prior to a potential collision that the vast majority of the small fragments would miss the Earth altogether. In short, a nuclear device option should be maintained as a viable mitigation technology but utilized only in the relatively rare situations when a more controlled deflection technique is not adequate or possible.

ANSWERS TO POST-HEARING QUESTIONS

Responses by Donald B. Campbell, Professor of Astronomy, Cornell University; Former Director, Arecibo Observatory

Questions submitted by Chairman Mark Udall

Q1. The asteroid Apophis has been identified as an object that has a small chance of impacting Earth in 2036. What role will Arecibo play in improving our understanding of Apophis and refining predictions of a potential impact?

A1. During the close approach of Apophis to the Earth in 2013 at a distance of about nine million miles, it is my understanding that radar observations with Arecibo and Goldstone combined with optical measurements will significantly reduce the probability of a potential impact during its passage by the Earth in 2036. Arecibo observations in 2013 will provide some information about Apophis's size but its large distance will preclude the high resolution characterization measurements that would provide detailed information about its shape and size.

Q2. Your testimony notes that "No study has been done of the precise role that the Arecibo radar and how many hours of NEO observations will be needed when the new, high sensitivity searches commence. . .. This needs to be done." *What, specifically, would such a study entail, what entity or entities would be capable of conducting it, and how much time do you believe such a study would require?*

A2. Such a study would entail determining the number and distribution of the hours of use of the radar system on the Arecibo telescope that would be needed for follow-up astrometric and characterization observations of newly discovered NEOs once the Pan-STARRS and LSST NEO searches are underway. Such a study would be best carried out by the National Astronomy and Ionosphere Center, which operates the Arecibo Observatory for the NSF, with input from the scientists involved with NEO radar observations and orbit determination at Arecibo and the Jet Propulsion Laboratories. The first Pan-STARRS system is expected to come online in the next year leading to a significant increase in the NEO detection rate. Direct experience with this system will provide the best guide as to the needed increase in the hours of operation of the Arecibo radar. Based on this, the study should be completed by early 2009.

Q3. What is the estimated cost of decommissioning the entire Arecibo observatory and what is the estimated time that would be required to disassemble the facility?

A3. There is no current reliable estimate for the cost of decommissioning the entire Arecibo Observatory. The National Science Foundation has contracted for a study of the decommissioning costs. My understanding is that the contractor will deliver their report to the NSF in February, 2008.

Questions from Representative Tom Feeney

Q1. NASA's NEO report, delivered this March, provides several options for meeting the goal of achieving 90 percent detection, tracking and characterization of Potentially Hazardous Objects, and the report establishes a clear relationship between the resources invested and the time needed to achieve 90 percent coverage. In essence, the report shows that for an additional investment of $536 million, we could buy down a decade of time to complete the survey. In your view, is that additional investment necessary? Does the threat posed by PHOs compel faster completion of the survey?

A1. Given the relatively low probability in any given year of an impact by a NEO, in my view significant expenditures to complete the survey in a shorter time period are not justified. If significant cost savings can be achieved by extending the deadline a small number of years beyond 2020 then this should be seriously considered. Dr. Tyson's testimony indicated that by devoting 15 percent of the observing time on the LSST to NEO searches the 90 percent requirement could be achieved in about 12 years. Assuming that the LSST begins operations in 2014, this would mean a completion of the survey by 2026. This date does not include contributions from other searches such as Pan-STARRS. Providing partial support for the construction and operating costs of the LSST for a NEO survey would appear to be a cost effective method for completing the survey.

Q2. What are the most difficult NEOs to detect? Is there, for instance, a portion of the sky that won't be covered by ground-based facilities? Are there certain types of orbits that make it difficult to detect and track asteroids and comets?

A2. NEOs whose orbits are primarily interior (i.e., closer to the Sun) to Earth's orbit are more difficult to detect from Earth than those NEOs that spend most of their time outside the Earth's orbit because they need to be observed shortly after sunset or shortly before sunrise.

Q3. Once the LSST and Pan-STARRS telescopes are operating, and surveys for PHOs that are 140 meters or larger has commenced, what is the business and public safety case for expanding the search to detect and track smaller PHOs—for instance, down to size 50 meters? What are the costs and schedule implications?

A3. As discussed during the Hearing, the difficulties of finding NEOs increases as their size gets smaller. The 140 meter size limit for 90 percent completion seems a sensible and achievable goal for now in terms of the potentially available resources and costs. As pointed out by Mr. Schweickart, this search, if it is carried out, should also find close to 50 percent of objects down to 50m in size. As the search progresses, the issues related to a "complete" survey of smaller NEOs can be realistically addressed and decisions made.

Q4. You state that Cornell was required by NSF to seek other funding commitments to fill the void left by NSF's reduction. What has been Cornell's experience finding new funding? Are you optimistic that other sources will be found?

A4. Cornell representatives are in ongoing discussions with governmental and educational bodies in Puerto Rico and they are moderately optimistic that funding for programs that enhance the role of the Arecibo Observatory in education and public outreach can be obtained through, or in collaboration with, Island institutions. However, these programs would not, and should not, be a substitute for the observatory's basic research mission. It appears very unlikely that year-on-year funding can be obtained from sources within Puerto Rico or elsewhere to partially support the operation of the observatory as a federally owned and funded scientific research institution except possibly, in the case of the observatory's planetary radar program, from NASA.

Q5. One deflection solution, suggested by NASA, is to detonate a nuclear device in the vicinity of a PHO. What are the advantages and disadvantages of this approach? What circumstances would argue against using a nuclear device in lieu of alternative approaches?

A5. I have not spent adequate time studying this issue to make an informed response to the question.

Questions submitted by Representative Dana Rohrabacher

Q1. With regard to NASA's Spaceguard *program, what changes, if any, do you recommend to make the program more effective? In your view, is further legislation required from Congress to implement needed changes?*

A1. I am not directly involved with NASA's current *Spaceguard* program aimed at discovering 90 percent of NEOs with sizes larger than one km. This program was a search program and appears to be largely achieving its objectives. It is now important to move to the next stage currently under discussion, the discovery of 90 percent of NEOs larger than 140m, determination of which ones are truly potentially hazardous via orbit determination and the investigation of possible mitigation schemes based on characterization studies.

Q2. How important do you consider characterization in the overall NEO issue priorities?

A2. Characterization has two objectives: 1) The understanding of the range of properties exhibited by NEOs to inform the design of mitigation strategies; 2) The characterization of specific objects that pose a definite threat to Earth so that the appropriate mitigation strategy can be implemented. The first of these is ongoing and the coming more sensitive searches will potentially provide a larger range of asteroid characteristics to be included in mitigation studies. These studies need to be pursued. For the second case, clearly the identification of PHOs via searches coupled with precise orbit determination to identify any objects that truly do threaten Earth comes first with characterization an input to mitigation planning.

Q3. What capabilities are required for a comprehensive deflection campaign?

A3. As discussed by Mr. Schweickart and others, the technology needed for a comprehensive deflection campaign largely already exists. What is missing is a program with clear responsibility for its implementation vested in one organization.

Q4. What is your estimate of the number of undiscovered asteroids in the 140 meter and above range? Describe the potential damage that an asteroid in the 140 meter range can cause striking an ocean within, say, 500 miles of a U.S. coast?

A4. The March 2007 NEO Report to Congress gives the estimated number of NEOs greater than 140m in size as approximately 100,000. The impact energy for a 140m NEO would be about 100 megatons of TNT equivalent. Published studies have shown that the release of this much energy as a result of an impact into the ocean would certainly have the potential for a very serious consequences to the local and, perhaps, distant seaboards.

Q5. Asteroids are more easily detected in the infrared spectrum. An asset such as the WISE satellite has an effective capability for searching for NEO's infrared output. Is WISE being tasked for this role? What other infrared detection devices can or will be used to detect NEOs?

A5. I am not involved with the WISE satellite program. This question would be better answered by NASA.

Q6. Could you describe some of the losses that might occur to U.S. research in radio and radar astronomy, and atmospheric sciences if the facility were to close as threatened by one of the supporting NSF directorates? How is the telescope unique? What unique research opportunities does Arecibo offer the U.S. and global scientific community? What new research is scheduled and proposed for Arecibo?

A6. Arecibo is the world's largest single dish radio telescope with sensitivity in its frequency band that is four to five times higher than any other single dish radio telescope. It is also unique in that it is equipped with two very high powered transmitters used for radar studies of solar system bodies including NEOs and for studies of the Earth's ionosphere. Its great sensitivity has allowed Arecibo to play a critical role in the study of pulsars with one notable example being the discovery of the binary pulsar PSR 1913+16 for which timing measurements, also using Arecibo, gave the first strong evidence for the existence of gravitational waves. Russell Hulse and Joseph Taylor received the Noble prize in 1993 for this work. Arecibo's sensitivity will continue to make it a major contributor via pulsar observations to study of gravitational waves, tests of General Relativity, the properties of nuclear matter in neutron stars, the electron density distribution and magnetic fields in our galaxy and, potentially, black holes via the hoped for discovery of a black hole—neutron star (i.e., pulsar) binary system.

Because of it sensitivity, Arecibo is the only radio telescope than can study gas (i.e., neutral hydrogen in distant galaxies) over a cosmologically significant volume allowing it to study how gas and dark matter are distributed and evolve through cosmic time. This is one of the major current research programs at the Arecibo Observatory with participants from a significant number of universities and research institutions in the U.S. and abroad.

Arecibo's ionospheric research program is supported by the NSF Division of Atmospheric Sciences. Arecibo is the most sensitive component of a chain of incoherent scatter ionospheric radars supported by the NSF stretching from the polar regions to the magnetic equator. The results from coordinated observations by all the participants in the chain provides input into ionospheric modeling programs the results of which impact the study of Space Weather and are potentially important for climate change studies. Arecibo's location allowing it to study the ionosphere at mid-magnetic latitudes makes it a unique contributor to this effort.

Arecibo is one of only two high powered radar systems with the capabilities for studying solar system bodies and it is the most sensitive by a factor of about 20. It makes major contributions to the orbit determination and characterization for NEOs including comets, to studies of the surfaces and internal structure of the Moon and terrestrial planets, and to the study of planetary satellites.

The closing of the world's largest radio telescope means that its great sensitivity will not be available for the ongoing research work described above or for other continuing research efforts. Perhaps just as importantly, it also means that Arecibo will not be available to pursue new research opportunities that may arise in the future that can be best exploited by utilizing a telescope with Arecibo's sensitivity. The discovery of pulsars is a classic example, it was almost as if the designers of the Arecibo telescope had pulsar research in mind before pulsars were discovered.

Q7. Please describe some of the resources that Arecibo provides for discovery and research programs and examples of results.

A7. As described above, Arecibo's huge collecting area makes it the most sensitive single dish telescope in the world. Its two high powered transmitters give it unique capabilities for radar studies of solar system bodies and the Earth's ionosphere. The Observatory is also equipped with an array of optical instruments that are used for studies of the lower part of the ionosphere.

Among Arecibo's many accomplishments are: 1) the discovery of a significant number of known pulsars including the binary pulsar that led to our best indication that gravitational radiation exists and the first milli-second period pulsar, a class of very fast rotating pulsars that are the most precise pulsar "clocks" needed, for example, in the proposed pulsar gravitational wave "observatory"; 2) The discovery of the first planets around another star, in this case a neutron star; 3) The mapping of the structure of the local universe from redshift (recessional velocity) measurements based on observations of neutral hydrogen in galaxies; 4) The discovery that Mercury rotates 1.5 times for each orbital "year" about the Sun and, in conjunction with the Goldstone radar and the NSF Green Bank Telescope, that Mercury has at least a partially molten core; 5) The first mapping of the surface of Venus at high enough resolution to study its surface features; 6) Confirmation of the existence of binary NEOs; 6) The confirmation of the Yarkovsky leading to a revolution in our ideas on how small asteroids move from the main asteroid belt between Mars and Jupiter into the inner solar system to become NEOs; 7) Detailed studies of the electron density distribution, temperature, winds and composition of the Earth's ionosphere.

ANSWERS TO POST-HEARING QUESTIONS

Responses by J. Anthony Tyson, Professor of Physics, University of California, Davis; Director, Large Synoptic Survey Telescope Project

Questions submitted by Chairman Mark Udall

Q1. Your testimony notes that by making adjustments to the LSST observations, the expanded NEO survey could be completed within 12 years and that "the current cost estimate for LSST in 2006 dollars is $389M for construction and $37M per year for operations. For a 12-year long survey, the 15 percent of the total cost is $125M." *What is the breakdown of the $125M estimate for the NEO-related activities, and is it inclusive of the 12-year operations? How confident are you of that cost estimate, and why?*

A1. The LSST construction and operations budget are based on proven estimating practices of dividing the entire project into over 1,000 individual work tasks and obtaining documented cost estimates on each task either from commercial vendor estimates or engineering estimates. The total cost estimate also contains a 30 percent contingency to absorb unexpected technical problems and/or higher costs than estimated today. The costing process and the estimates have been peer reviewed and endorsed by an NSF panel of external experts. The $125M figure was calculated from the extra effort in an LSST survey of the sky required to reach the Congressional goal of 90 percent completeness for Potentially Hazardous Asteroids (PHA) of 140 meter diameter and larger. This extra effort was quantified through multiple simulations of LSST operations. We are confident that this is an accurate estimate of the level of effort required. This extra effort devoted to the PHA discovery program amounts to $120M during operations, plus $5M for development of advanced orbit linking and operations pipeline software. The $120M is inclusive of the added PHA portion of operations during the full 12-year survey.

Q1a. Your testimony also mentions that "To keep LSST on schedule, about $5M should be spent on optimized NEO orbit software pipeline development in the last phase of R&D and the construction phase. . .." *Is this funding included in the $125M overall cost required to modify LSST for the NEO survey?*

A1a. Yes.

Q1b. When would the required software development for the NEO survey need to begin in order to start the Survey in 2014, assuming LSST commences operations at that time?

A1b. 2009.

Q1c. What approvals and funding are required before LSST can be developed and how confident are you that LSST will be ready for operations in 2014–2015, as noted in your testimony?

A1c. The LSST project has been funded for R&D by the NSF. The construction proposal to the NSF was reviewed in September 2007 and the project had been recommended to move on to the next milestone review in the fall of 2008. At this time we are on track for NSF construction start in FY 2011. Long lead sub-component fabrication has begun (such as the $21M primary mirror), with private funding.

Q2. You testified that "with LSST, one sees each one of these asteroids 100 to 200 times, even more. So, it is possible to derive a pretty good orbit for those, and distinguish them from the background." *What is the level of accuracy in NEO orbits that you estimate would be possible with LSST? What implications, if any, would this have for further orbital determination from planetary radar facilities.*

A2. In very general terms, the orbits from a single apparition set of observations will be good enough for the NEO to be predicted and located again any time it comes within range for the next several decades, and the path can be predicted well enough to rule out any future impact with the Earth for many decades to come, for the vast majority (over 99 percent) of detected objects. However, there will be, as there are now (e.g., the asteroid Apophis) cases where the optical position data will be unable to rule out a future impact, and radar facilities will be key assets for providing the observations needed to rule out (or in, if we should be unlucky) future impacts for a small number of cases. It can be expected that radar will continue to be needed for a similar number of key observations in the future as it has been in the past. Radar however cannot be used to survey the sky and discover PHAs.

Questions submitted by Representative Tom Feeney

Q1. NASA's NEO report, delivered this March, provides several options for meeting the goal of achieving 90 percent detection, tracking and characterization of Potentially Hazardous Objects, and the report establishes a clear relationship between resources invested and the time needed to achieve 90 percent coverage. In essence, the report shows that for an additional investment of approximately $536 million, we could buy-down a decade of time to complete the survey. In your view, is that additional investment necessary? Does the threat posed by PHOs compel faster completion of the survey?

A1. One can hasten the survey to some degree with greater expenditure on other complementary systems. However, there is a natural limit to the minimum time that a survey can be completed to, say 90 percent, which results from the fact that the asteroids move in orbits with orbital periods of several years and often spend years at a time simply out of the range of visibility from the Earth, or in some cases, even from space. Thus, it is not possible with any detection system, no matter how capable, to see all PHAs instantly, or even in a very short time. The fundamental "time constant" for surveying is the timescale of the orbit periods, that is, a few years. This amounts to the "exponential time constant" of a survey, and to reach 90 percent takes a factor of two or three times the time constant, or about a decade. Speeding things up from a decade requires near-Herculean effort, for example putting a rather large telescope in a "Venus-like" orbit, and even that reduces the time by only a few years. On the other hand, time is our friend if we consider going a little more slowly. Thus, backing off to a capable ground-based survey can reach the goal set by Congress in only a few years longer than the 15 years (from 2005) originally mandated by the Congress. It is more important not to back off in the completeness level than in the time to achieve it. I share the opinion of many in the NEA community that it is key to get started now on a capable survey, but that it is not worth the investment in a space facility to shorten the survey by a few years.

Q2. What are the most difficult types of NEOs to detect? Is there, for instance, a portion of the sky that won't be covered by ground-based facilities? Are there certain types of orbits that make it difficult to detect and track asteroids and comets?

A2. Some NEOs are more difficult to detect than others, although "blind spots" in the sky not covered by the surveys is not the cause of that difference. Any asteroid in an orbit that can hit the Earth will spend some time in the visible part of the sky, so it is only a matter of time before it passes into a visible region. The goal of the survey is to find PHAs decades before an impact, not on final approach only days before an impact. In the latter case, yes, an impactor can arrive from the direction of the sun and not be seen until it hits. But in the former case, during a close (but not impacting) pass by the Earth, if it comes from the direction of the sun it will become visible after closest approach as it moves away, and vice versa if it comes from outside moving in. Thus, in either case, it will be seen by the survey and duly cataloged for any future approaches or impact paths. The difficulty of finding PHAs is therefore mostly a matter of how often an asteroid passes within range of the survey. One class that is difficult are objects in very long orbits, similar to comets, that only come in close to the Earth every decade or so. We simply have to wait until they come around. Another group are resonant objects that have orbit periods that are close to multiples (including 1.0) of the Earth's orbit period. Imagine an asteroid with a period very near 5.0 years, which comes close to the Earth's orbit when the Earth is on the other side of the sun. Every five years it is behind the sun, so we can't see it. At other times it is far from the sun (and also the Earth), so even when it is in the view range of the survey it is very faint. Yet another group are asteroids with very nearly 1.0 year orbit period. A number of these have been discovered which appear to "loop" the Earth in eccentric or inclined orbits. These objects drift away from the Earth's vicinity after several annual loops, not to return again for decades or longer, after they lose or gain one full circuit of the sun relative to the Earth. There are undoubtedly other such objects currently parked on the opposite side of the Earth's orbit that will slowly drift into near-Earth space, and could be an impact hazard, but we cannot find them from the Earth until after they move out from behind the sun. Nevertheless, an Earth-based survey would find them years before any possible impact. One can find them sooner with a space-based survey in a different heliocentric orbit (say near Venus), but is it worth it? It is improbable that there is even one object as large as one km in diameter, and maybe only a few larger than 140m, in such orbits, so the value of taking the extra effort to find them is questionable.

Finally, comets are intrinsically difficult to track, due to the non-gravitational forces of the gasses being emitted. Thus, it would be impossible to predict an impact with certainty very long in advance even if we found a rare comet on a potentially collision course. And of course the long-period comets come around less than once in a lifetime, so new ones never seen before keep coming. Finding and cataloging comets far in advance of an impact is thus not possible with today's technology or any foreseeable technology.

Q3. Once the LSST and Pan-STARRS telescopes are operating, and surveys for PHOs that are 140 meters or larger has commenced, what is the business and public safety case for expanding the search to detect and track smaller PHOs—for instance, down to a size of 50 meters? What are the cost and schedule implications?

A3. In my response to question 1 above, one can see that there is a clear diminishing return in value for cost of ever larger surveys of ever smaller PHAs. See also the NASA report on the feasibility of extending the search for near-Earth objects to smaller limiting diameters: *http://neo.jpl.nasa.gov/neo/report.html* The first generation "Spaceguard" survey has reduced the impact risk from about 1,000 casualties per year to about 100 per year, at a cost of a few tens of millions of dollars. This is certainly quite good value returned. The next generation survey, to 140 meter diameter, should reduce risk by another 90 casualties per year, at a cost of some hundreds of millions of dollars. The cost/benefit ratio of such a survey appears to be in a justifiable range that is worthy of policy consideration. A further step, say to 50 meter diameter, would seem on the face of it to be beyond the range of what could be justified on a cost/benefit basis. In terms of cost and schedule, we do not possess the technology at present to catalog 50 meter objects at large enough distances to find a large fraction of them in, say, ten years at reasonable cost. However, the same systems that find 90 percent of objects larger than 140 meters in ten years will find 90 percent of objects to 50 meters diameter over a longer time, of order of a human lifetime. So by about 2100, we will eventually find nearly every PHA that can make it through the atmosphere. That is sooner than the odds of the next one hitting the Earth, so the level of patrolling of the skies contemplated by LSST will very likely find the next impacting object before it finds us.

Q4. One deflection solution, suggested by NASA, is to detonate a nuclear device in the vicinity of a PHO. What are the advantages and disadvantages of using this approach? What circumstances would argue against using a nuclear device in lieu of alternative approaches?

A4. Many of the implications of this question are matters of policy rather than science. However, there are technical aspects. My comments are based on the 2006 NASA NEO workshop in Vail. A major disadvantage of nuclear approaches is that we do not know how efficient a nuclear standoff explosion might be, or if it would disrupt the body into fragments still largely traveling on the same path, or if it would push it aside, as proposed. Thus, one cannot know in advance whether a standoff explosion would be effective, or even if shown to be effective in a test case, whether it would be equally effective on another asteroid—the one actually coming our way. The same uncertainty accompanies the "kinetic impactor" method of deflection, but it is vastly more politically acceptable to conduct impact experiments, such as the "Deep Impact" comet mission, than it would be to conduct nuclear tests in space. Furthermore, the most likely scenario we may be faced with is the case of an object that may, but with less than 100 percent certainty, be on a collision course, but we will not know for sure until after the optimum time to take action. In such a case, it would be politically difficult, as well as strategically dangerous, to take action with nuclear explosions when such action might not be needed at all, and even if so could produce unpredictable results. Much more prudent would be an approach that is more controllable and can be monitored for effect, such as the proposed combination of a rendezvous vehicle that can monitor the effect of a kinetic impactor and serve as a "gravity tractor" as needed for fine-tuning the deflection. In any case, one should weigh the benefit of developing deflection plans in advance of a discovered need.

Questions submitted by Representative Dana Rohrabacher

Q1. With regard to NASA's Spaceguard program, what changes, if any, do you recommend to make the program more effective? In your view, is further legislation required from Congress to implement needed changes?

A1. The Pan-STARRS and LSST surveys are planned to use somewhat different search patterns, and object identification algorithms, than those used by the current surveys. Whether it would be cost-effective to implement changes of this nature in the current surveys is questionable when they will become obsolete in terms of depth of survey very soon anyway. It would certainly be short-sighted to shut down the current surveys in anticipation of the next generation before those surveys come on line at some decent level, but NASA, and the Congress, should be prepared to make the transition to the next generation as soon as it is possible to do so. To retire the risk from Potentially Hazardous Asteroids, Congress could do two things: (1) assure that a ground-based survey capable of achieving 90 percent completeness for PHAs of larger than 140 meters gets started as soon as possible and, (2) assure availability of the Arecibo radar (since that will continue to be an occasionally essential asset into the next generation of surveys.)

Q2. How important do you consider characterization in the overall NEO issue priorities?

A2. Physical observations, to measure sizes, shapes, spins, densities, mineralogy, and so forth of discovered asteroids is of very high scientific interest, but is of secondary importance as far as the impact hazard issue is concerned. The statistical characterization method has serious limitations when a robust characterization of that particular asteroid with our name on it is required. Characterizing a statistically meaningful subset of discovered objects is necessary in order to understand the population (for example, to even know what fraction of objects larger than a given size have been discovered), but this can be done from observations of a small fraction of the discovered population that happens to be most easily observable, thus it is not necessary to have a large commitment of telescopes as large or even larger than the survey instruments, as has sometimes been claimed. This is not to say that no commitment is needed, but it can be satisfied with existing facilities currently engaged in asteroid observations.

Q3. What capabilities are required for a comprehensive deflection campaign?

A3. This is outside the purview of the LSST project. While R&D is needed, my personal opinion is that deployment of deflection hardware should wait until a demonstrated need is discovered.

Q4. What is your estimate on the number of undiscovered asteroids in the 140 meter and above range? Describe the potential damage that an asteroid in the 140 meter range could cause striking an ocean within, say, 500 miles from a U.S. coast.

A4. It is estimated that there are about 20,000 NEAs larger than 140 meter in diameter, and presently, there are somewhat over 3,500 known, leaving about 17,000 undiscovered. In terms of Potentially Hazardous Asteroids, there are approximately 4,000 total estimated, and about 600 known. A 140 meter diameter asteroid striking the ocean 500 miles (800 km) from shore might produce a tsunami wave a meter or two in height as it approaches the shore. The "run up" amplification depends a great deal on the off-shore depth profile, but might be a factor of two or three, to a height of five meters or so. Such a wave might run inland a km or so, depending on the flatness of the land on shore. The effects of such an impact tsunami could be comparable to a major hurricane, and the chance that the impact would be at a particularly vulnerable location rather than somewhere else is comparable to that for a hurricane.

Q5. Asteroids are more easily detected in the infrared spectrum. An asset such as the WISE satellite has an effective capability for searching for NEO's infrared output. Is WISE being tasked for this role? What other infrared detection devices can or will be used to detect NEOs?

A5. Infrared technology is not yet mature enough to be competitive with optical (reflected sunlight) surveying. From the ground, the highly emissive and absorbing atmosphere reduces thermal IR sensitivity to less than that of optical, regardless of detector technology. From space, IR has a modest theoretical advantage, less than one might suppose because the resolution of a given aperture telescope in the thermal IR is about twenty times less than at visible wavelengths, and the background level of sky brightness and confusing sources, after allowing for the reduced resolution, is substantial. There are some technological problems: detector arrays are not yet as large as those for optical wavelengths, to operate efficiently they need to be cooled to the limit (or beyond) of passive cooling systems, and with many images each with billions of pixels there would be on-board computation challenges.

While WISE will survey the entire sky and, indeed, detect many asteroids, there are a number of reasons that it will not be capable of making a substantial contribution to the PHA survey. First, the WISE survey strategy does not have a cadence that is tuned to discovering and cataloging moving objects. Moreover, with only a six-month mission, many PHAs will be out of range and completely unobservable during the brief period of mission operations. Finally, its modest instrument (0.4 meter aperture, 0.8 degree field of view) is not well-suited for this purpose. However, WISE will make great strides in the realm of asteroid characterization. The four separate IR band passes will allow the characterization of a large number of asteroids, some of which may not be actually discovered until later. This information, combined with optical catalogs, such as the Sloan Digital Sky Survey, will enable subsequent PHA surveys such as LSST to make good statistical inferences about the makeup and size of new discoveries. WISE will detect a lot of asteroids, but is not capable of replacing even present optical survey systems, let alone systems like Pan-STARRS or LSST, even if re-tasked solely to the NEA survey. The advance of IR technology should be monitored for its potential to contribute to NEA surveys, but at present it does not appear to be mature enough to contemplate changing from ground-based optical surveys to space-based IR surveys.

ANSWERS TO POST-HEARING QUESTIONS

Responses by Russell "Rusty" L. Schweickart, Chairman and Founder, B612 Foundation

Questions submitted by Chairman Mark Udall

Q1. How well understood are the potential approaches to deflecting asteroids? What is the confidence level in the technologies that would be required? What information is needed to assess the various approaches, and how will decisions be made on which mitigation strategy to take?

A1. The basic elements of an asteroid deflection are quite well understood. One must alter the orbit of the asteroid to 1) miss a direct Earth impact, and 2) avoid passing through any of the hundreds of return keyholes as the asteroid passes by the Earth. The technologies which have the required capability for the first of these objectives are kinetic impact (KI) and nuclear stand-off explosion. KI is essentially running into the asteroid in a specific direction with a specific velocity, similar to what was done in 2005 by the Deep Impact spacecraft running into comet Tempel 1. A stand-off nuclear explosion in space has never been done but on a theoretical basis should work. Both techniques can be characterized as strong but imprecise. Therefore essentially all asteroids which might threaten impact can be deflected from a primary impact (98–99 percent can be deflected using KI). However such a deflection has no possibility of insuring that the asteroid will not pass through any of hundreds of return keyholes resulting in a certain impact within several years. Therefore a precision deflection capability using the gravitational tractor (GT) concept (or other if any become available) is needed to immediately follow-up the imprecise primary deflection to insure that no keyhole passage is permitted.

There need to be detailed analytic assessments and simulations performed on all three techniques. The KI and GT techniques should ultimately be flight tested on a real (but non-threatening) asteroid to fully validate a deflection campaign. I do not recommend demonstrating the nuclear explosion concept, although simulations could, and should be run.

An actual deflection decision is virtually independent of the technology. A deflection campaign would require two coordinated missions, first a transponder/gravity tractor (t/GT) mission to precisely pin down the asteroid orbit and confirm a pending impact. If confirmed the t/GT would observe the subsequent KI impact from a safe distance, then pull in close to the asteroid to 1) confirm a successful primary deflection, and 2) determine whether or not the asteroid is headed for a return keyhole. In the unlikely case that the asteroid is headed for a keyhole the t/GT would then be employed to make a small but precise modification in the asteroid's new orbit to assure the asteroid misses the keyhole. This sequence is the only way, using existing technology, to guarantee a successful deflection. In the extremely improbable event (probability of occurrence once per 100,000+ years) that the asteroid at issue is too large for a KI deflection, a nuclear stand-off explosion would be needed as a substitute. The precision component (t/GT) would still be essential to the success of the deflection campaign.

The decision to deflect, per se, would of necessity be an international decision due to the inherent shifting of risk from one geographic region to another during any deflection. The Association of Space Explorers (ASE) is working on the deflection decision process in cooperation with the United Nations. While the action will of necessity be the responsibility of one or more space-faring nations, the decision process will involve many nations since the uncertainty in the impact point and the shifting of risk during any deflection will involve nations across the planet.

Q2. How mature are the non-nuclear versus the nuclear technologies for deflecting an asteroid?

Q2a. What should the priorities be in further developing those technologies?

A2a. The non-nuclear (KI) technology is a flight proven technique having been used (albeit for different purposes) during the Deep Impact mission of July 4, 2005. The primary difference is that comet Tempel-1 (the target of the Deep Impact spacecraft) was significantly larger than those asteroids likely to require deflection. Furthermore there is an unknown (likely small) possibility of fragmentation of the asteroid. Finally the "momentum multiplier," the degree to which the ejection of debris from the kinetic impact multiplies the effectiveness of the impact, is highly variable and uncertain. The last two factors can, and should, be validated by an actual demonstration mission.

The nuclear stand-off explosion is entirely theoretical. While terrestrial weapons effects analysis is a highly developed and sophisticated field of knowledge the use of nuclear explosions in space is not well understood and cannot, without modification of existing treaties, be tested. Proponents of the use of nuclear explosions generally feel very confident in their computer models, but atmospheric and vacuum explosions are very different from one another. Additionally the concerns mentioned above re KI also apply to the nuclear option, i.e., the possibility of fragmentation and the uncertainty of the "multiplier" effect. The primary difference in eliminating these uncertainties is that there is no impediment to testing KI in a demonstration mission whereas demonstrating a nuclear stand-off in an actual mission would be a major international political challenge, not to mention arguably a treaty violation.

The gravity tractor (GT) is not in a "versus" situation, being a necessary component of any deflection campaign, nuclear or non-nuclear. In terms of technology maturity the primary challenge for the GT is engineering the control and guidance software for the "towing" maneuver. Engineering simulations of the GT are about to get underway and testing should be done in an actual flight demonstration. A slightly modified Don Quixote mission (a NEO deflection mission considered by the European Space Agency) could simultaneously demonstrate both the KI and t/GT concepts.

Priority should clearly be given to developing and testing the KI and t/GT concepts since they are the most likely to be called on for deflection. Only one to two percent of potential deflection challenges would require a nuclear option and that percentage will drop essentially to zero as the revised search program is executed over the next 15–20 years.

Q3. What do you see as the most important next step in advancing our understanding of deflection approaches?

A3. Testing and demonstrating both the kinetic impact (KI) and gravity tractor (t/GT) concepts. As mentioned above a slight modification of ESA's Don Quixote mission could fully validate both components of a deflection campaign in a single program for a total cost of between $500M and $1B dollars. In a cooperative program with ESA, NASA's share of this would be comparable to the cost of an average low-cost scientific mission.

Q4. What do you think would be the most appropriate next steps in addressing the governance issues discussed at the hearing?

A4. Step 1 would be to assign responsibility to NASA for 1) analyzing and developing NEO impact warning concepts, and 2) for developing and testing NEO deflection technology.

Search is important, without question. However someone now needs to be working through the complex issues of what we do when we discover a NEO which "has our address" on it. . . or, more likely *appears* to have our address on it. With the exception of flight testing the deflection concepts, these actions require very little money; the task is primarily to conceptually work through the complex issues involved.

Step 2 would be to address the larger question of overall responsibility for handling this devastating but preventable natural hazard. This issue is particularly challenging in that unprecedented levels of destruction are at issue and in the process of eliminating the risk of an impact for everyone certain nations will of necessity have to accept a temporary increase in risk to their populations. Such a collective international decision will require considerable diplomatic efforts involving not only cost sharing, but also liability, indemnification, oversight and other sensitive considerations. While the technical aspects of warning and deflection will inform many of these considerations the primary challenge embedded here is national and international policy.

In addressing this it would seem that no single Congressional committee has appropriate jurisdiction. Therefore at the outset the Congress and the Administration would benefit from the issue being considered in depth by an appropriate highly-regarded professional organization, such as the National Academies.

Questions submitted by Representative Tom Feeney

Q1. NASA's NEO Report, delivered this March, provides several options for meeting the goal of achieving 90 percent detection, tracking and characterization of Potentially Hazardous Objects, and the report establishes a clear relationship between resources invested and the time needed to achieve 90 percent coverage. In essence the report shows that for an additional investment of approximately $536 million, we could buy-down a decade of time to complete the survey. In *your view, is that additional investment necessary? Does the threat posed by PHOs compel faster completion of the survey?*

A1. This is an excellent public policy question, not a technical one. I believe that the following are considerations which should be taken into account in addressing the issue.

1. A growing segment of the general public is aware of the NEO threat. A smaller, but also growing segment of the public is aware that we have the technology today to not only warn us of a pending impact but also to prevent a devastating impact. Over the next decade, under any circumstances, there will be a number of what will be reported in the press as "close calls." There will also likely be several, perhaps even hundreds, of NEOs that will appear to be threatening and will be reported (and misreported) by the public media. The issue, and its "solution," will become widely known to the public.
2. A widely stated fact is that "If we know about them, we can do something about it. The ones we need to worry about are the ones we don't know about." The public will come to know that the survey could be accelerated by 10 years at the cost of foregoing a single scientific satellite, or less (see comment below). Alternatively adding $500M to the NASA budget over 5–7 years would suffice.
3. 2008 is the 100th anniversary of the "Tunguska Event." There will be a great deal of publicity about this and many legitimate and not so legitimate presentations and discussions.
4. Every hurricane, earthquake and tsunami which creates great damage in the next decade will be another poster child for the possibility of a NEO impact, especially if one occurs in temporal proximity to a NEO "near miss."
5. From an "objective" perspective the NASA/JPL staff could compute the probability of an impact of various sizes occurring in the absence of the faster survey and compute the cost-effectiveness of the additional $536M of "insurance." (In rough terms, using Apophis as an example, the cost of an impact is approximately $400B. If the probability of an Apophis impact (and its unfound cohorts) not being found is one in 1000 then the actuarial value of finding it in time to prevent the impact is $400M. Such an actuarial analysis could be performed).

Note: Dr. J. Anthony Tyson, Director of the LSST, testified at the hearing that if NASA were to fund 15 percent of the LSST costs it would effectively have at its disposal, for $125M, a dedicated LSST and be able to meet the Congressional 140 meter goal within 12 years from LSST by 2026.

Q2. What are the most difficult types of NEOs to detect? Is there, for instance, a portion of the sky that won't be covered by ground-based facilities? Are there certain types of orbits that make it difficult to detect and track asteroids and comets?

A2. There are two factors which are critical; size and type of orbit. Small NEOs can only be seen when they are very close to the Earth compared with larger NEOs. There are also many more small NEOs than large ones (e.g., 1,000 NEOs larger than one km in diameter vs. 40,000 NEOs larger than 140 meters diameter, and 800,000 at 40 meters and larger.) and therefore the vast majority of unfound NEOs are at the smallest end of the spectrum of those which can do damage on the Earth's surface.

The second factor is the orbit size. Those NEOs whose orbits are smaller than the Earth's, i.e., whose orbits lie primarily inside the Earth's orbit, spend most of their time with a "look angle" too close to the Sun and its glare to be seen by optical telescopes. They are typically seen for a month or two for several years in succession, followed by many years when they cannot be seen at all. These NEOs are classified as Atens. When an Aten is also small the two issues compound such that a 40–140 meter diameter object may be seen only once or twice in a decade. Obtaining an accurate orbit is therefore quite difficult for these objects.

As pointed out in the NASA report, a space-based telescope placed in a Venus-like orbit would be able to look outward (i.e., away from the Sun) and both discover and track these Atens which are challenging to observe from the Earth's surface.

Comets (long period comets) orbit the Sun in very large orbits which extend beyond the orbit of Jupiter. They are only detected when they approach the Sun within the orbit of Jupiter and begin to out-gas due to gradual heating. From detection to the time they cross the Earth's orbit is typically only several months. This is inadequate time to mount a deflection and they are generally not considered objects from which we can protect ourselves. Happily they are also one percent of the asteroid problem and are therefore (currently) disregarded.

Q3. Once the LSST and Pan-STARRS telescopes are operating, and surveys for PHOs that are 140 meters or larger has commenced, what is the business and public safety case for expanding the search to detect and track smaller PHOs—for instance, down to a size of 50 meters? What are the cost and schedule implications?

A3. As regards "the business case" (the potential for "mining" asteroids) essentially the only issue is the cost to get to the asteroid. This depends entirely on the specific orbit, with those in Earth-like orbits being the least costly to target. Even a 40 meter diameter asteroid weighs in at 100,000 metric tons; a great deal of potentially useful resource for development. Therefore since there are many more small asteroids than large the most promising targets for resource utilization will be found among this population.

Public safety is at issue any time an asteroid impacting the Earth can cause significant damage at the surface. The Earth's atmosphere protects us from NEOs smaller than 30–40 meters. Those in the vicinity of 40–100 meters may not reach the surface but will explode with such energy in the lower atmosphere that they create devastation at the surface even without reaching it per se. At sizes larger than 100–150 meters they reach the surface of the Earth substantially intact causing even greater damage and potentially tsunamis if they impact the ocean.

It is clearly a policy judgment but I (representing the Association of Space Explorers) consider a Tunguska-like impact to be approximately the threshold size at which public demand would mandate a deflection effort (this assumes that the NEO is known in advance and projected to impact). Had the Tunguska asteroid (approximately 45 meters in diameter, exploding with five megatons of energy or 333 Hiroshima bombs) exploded over a city instead of the middle of a Siberian forest it would likely have killed everyone in the city. It therefore seems prudent, from a public safety consideration, to ultimately extend the search down to this (or some equivalent) threshold limit.

What needs to be recognized is that *in the process* of reaching the goal of 90 percent of the population of NEOs 140 meters and larger we will also discover approximately 40–50 percent of the NEOs 50 meters and larger. Without any further investment in larger telescopes an additional two decades (i.e., 2040) of search (which will be done in any case in order to monitor the larger NEOs) will ultimately extend this figure to near 90 percent. If one chooses to reach the 90 percent discovery level for 50 meter objects earlier (say by 2030) then either larger ground based telescopes or a modest (~1 meter) space telescope in Venus-like orbit would have to be employed. The life cycle cost of this would approximate $1B according to NASA's estimation in their NEO Report to Congress.

Q4. One deflection solution, suggested by NASA, is to detonate a nuclear device in the vicinity of a PHO. What are the advantages and disadvantages of using this approach? What circumstances would argue against using a nuclear device in lieu of alternative approaches?

A4. The only advantage of using a nuclear device over a kinetic impactor (KI) is in those rare instances where the total impulse required to deflect the NEO at issue is greater than can be provided by the KI. Assuming adequate warning (i.e., 15–20 years) this threshold is reached at approximately a 400 meter diameter NEO. An object of this size is statistically encountered only once every 100,000 years. At the current time we have discovered about 40 percent of NEOs this size and the probability that any of these will impact Earth in the next 100 years is zero. By completion of the new survey (140 meters) we will have discovered about 95 percent of the 400 meter NEOs. Assuming that none of them is about to strike the Earth (very highly likely) it is only the remaining five percent still unknown which would pose a threat necessitating the use of a nuclear device for deflection. The probability of one of these residual five percent striking Earth is once per 2,000,000 years.

The other, also very unlikely circumstance in which a nuclear device would be required is if, in the next few decades we discover a NEO of almost any size which is predicted to impact within 5–10 years from discovery. Since the probability of the smallest objects of concern (therefore the most populous and most likely to impact) is once in 1,000 years, the probability of encountering one of these in the next 10 years is one in 10,000. This small number is further reduced by the fact that at the completion of the 140 meter survey we will have discovered only (say) 50 percent of the 50 meter objects and therefore there would be only a 50 percent chance that we would have discovered such an impactor before it hit.

The bottom line is that non-nuclear means are able to handle 98–99 percent of the current population of dangerous asteroids (those above the threshold mentioned above) and this will grow to well over 99.9 percent within the next two decades as we discover most of the remaining NEOs which would require nuclear means.

But why not (NASA asks) use nuclear if it will work? Because the entire issue of NEO deflection is ultimately a collective (i.e., international) decision and the world has clearly and unequivocally stated in treaties and elsewhere that it wants to keep nuclear weapons out of space. Can the U.S. act unilaterally? Of course. Is this wise? Absolutely not. Where non-nuclear means are adequate to do the job there is no objective reason for considering nuclear explosives.

From the technical perspective the use of a nuclear device will also be highly unpredictable. The potential for fragmenting the NEO will be extremely difficult to rule out given the very unlikely case that an actual flight demonstration on an asteroid will be available. Furthermore the total impulse imparted to the NEO will be highly uncertain (as will be that of the kinetic impactor) and unlike the kinetic impactor which is easily tested, this uncertainty will remain. In any circumstance both the kinetic impactor and the nuclear stand-off explosion (or any other impulsive deflection technique) will not provide the precise orbit change needed to insure that the NEO will not pass through a return keyhole after the primary deflection maneuver. Therefore a deflection campaign must of necessity include the weak but precise deflection capability of a gravity tractor (GT) or other precision deflection technique to "trim" or slightly adjust the primary deflection in the event that it is headed for a keyhole post-primary deflection.

In summary; those circumstances requiring the strength of a nuclear deflection are extremely improbable (and will become much less probable over time) and, given international treaties and world opinion against nuclear explosives in space the sufficiency of non-nuclear means will be the option of choice.

Questions submitted by Representative Dana Rohrabacher

Q1. With regard to NASA's Spaceguard program, what changes, if any, do you recommend to make the program more effective? In your view, is further legislation required from Congress to implement needed changes?

A1. Reading the question in the narrow sense, i.e., the *Spaceguard Survey* per se, I would emphasize recommendation #1 in my written testimony that the Congress, whether through Authorization or Appropriations, should require that NASA comply with the law and both recommend and initiate a search program (and supporting budget) to meet the 140 meter goal. Whether it takes 15 years or 17 years is far less important than that a specific program be committed to and initiated.

Reading the question in its broader sense, i.e., the *Spaceguard Survey* as the overall initiative to protect the Earth from asteroid impacts, I would call on the Congress to expand NASA's current limited activities to include 1) developing a recommended NEO impact warning concept, and 2) developing and testing NEO deflection technology. (These are contained as recommendations #3 & 4 in my written testimony.) Not only is it important that we move ahead regarding the issue of "what do we do when we find one with our address on it?" but by systematically thinking through the issues involved in warning and mitigation, the search program per se will begin to focus on the most critical information needed rather than simply meeting a somewhat abstract numerical quota.

One further observation here; under any circumstance the discovery rate of NEOs will dramatically increase in the immediate future due to the introduction of Pan-STARRS and LSST into the search process. There is no doubt whatever that given the considerable expansion in the number of NEOs discovered we will find many that will *appear* to threaten impact with Earth. If, by way of illustration, the current discovery rate of NEOs that appears to threaten impact is one per year, then even without any further commitment by NASA, that rate of discovery of *apparently* threatening NEOs will rise to 30 or more per year over the next 5–7 years. This will, without question, get the attention of the press and the public. Therefore it is critical that specific action beyond the *search program* be underway to assure the public that their safety is being responsibly attended to.

Q2. How important do you consider characterization in the overall NEO issue priorities?

A2. Let me emphasize immediately that I am in the minority in what I am about to say, even among my fellow NEO community peers. I believe that my minority position is justified, having arguably thought through the deflection issues more thoroughly than most of my compatriots.

I believe that characterization of NEOs, in the classic sense of learning the specific technical characteristics of asteroids per se (thermal, structural, mineralogical, and other descriptive characteristics) is not a priority in regard to protecting Earth from impacts. With respect to classical scientific values it is very important; but protection of the Earth from impacts is a public safety issue, not a scientific one.

The basis for this low priority is that the inherent performance of the kinetic impact deflection concept (and nuclear explosion as well) is highly uncertain and variable. The momentum imparted to a NEO by crashing into it is determined more by the energy and the variable nature of the impact geometry than by any knowledge that can be gained through classical characterization efforts. Each NEO is unique and likely non-homogeneous. The effect of an impact will vary depending on the slope of the surface on which it happens to impact as well as on the specific local structural characteristics. The rotation of the NEO, whether it is hit a glancing blow, and whether there happens to be buried ice or other volatiles at the specific impact site are also both unknowable and likely highly variable.

Therefore the technical parameter beta (the "momentum multiplier") has a wide range, usually approximated today as ranging from two to 10 or more. This large uncertainty, even assuming heroic characterization efforts, will never be reduced to a reliably predictable single value. Therefore a kinetic impact or nuclear explosion *will always* produce a range of predicted deflection results, e.g., 3–20 Earth radii, or 2–15 Earth radii. It is this intrinsically uncertain nature of the impulsive deflection techniques which risks deflecting the NEO such that it will miss the Earth (good) but risk passing through a return keyhole (bad). For this reason it will always be necessary to have an observer spacecraft, with a *transponder and precision deflection capability* (e.g., gravity tractor), standing by in real time to both confirm the success of the primary deflection *and* execute a precise adjustment to the deflection to avoid a future keyhole passage and subsequent impact.

Given that the primary deflection will *always* have a degree of uncertainty sufficient to risk passage through any of hundreds of return keyholes, a precision orbit adjustment capability will *always* be required. This statement will remain true regardless of any amount of money spent on NEO characterization, given the many variables of a kinetic impact or nuclear explosion having nothing to do with NEO characteristics. So why spend the money when the inherent uncertainties can (and must) be handled by the precision trim capability?

Conversely, if one is (and we should be) interested in the potential for utilization of asteroidal resources at some future time, then characterization of NEOs is very important indeed. This is, however, classical science in its proper role and not public safety.

Q3. What capabilities are required for a comprehensive campaign?

A3. A comprehensive deflection campaign (for a "direct" NEO impact threat) will consist of the following 5 steps;

1) The launch and rendezvous of a transponder equipped spacecraft (t/GT) with the NEO,
2) The determination (confirmation) of a pending impact based on the dramatically improved orbit determination,
3) The launch and impact of a kinetic impactor (KI),
4) The determination of the precise post-impact NEO orbit, and
5) A precise orbit adjustment (trim) maneuver if the NEO is determined to be headed toward a return keyhole (t/GT).

Given that the primary deflection may place the NEO on a path toward a return keyhole, a precision deflection capability will always be necessary. Therefore since a gravity tractor (or other future precision deflection technology becomes available) will also have a transponder aboard the spacecraft for steps 1, 4, and 5 would logically be a single transponder/gravity tractor (t/GT) combination.

If the threatening asteroid is being deflected not from a direct impact but rather from a keyhole (with subsequent impact), then only steps 1, 2, and 5 need be employed. An example of this situation is the current Apophis case where, if in 2013 it is determined that the NEO is indeed headed for the 7/6 keyhole in its 2029 close approach to Earth, a t/GT mission alone can be utilized to affect the deflection (i.e., steps 1, 2 and 5 above.)

Q4. The need for a comprehensive potentially hazardous NEO program seems to require expertise of several agencies. How do you suggest coordination be handled?

A4. The primary technical expertise required for a comprehensive NEO impact mitigation capability lies within NASA per se. The exception to this is the remote possibility of encountering a NEO threat which exceeds the capability of the kinetic impactor for primary deflection. If it is deemed prudent to prepare for this unlikely eventuality then NASA will need to coordinate with DOE regarding nuclear stand-off deflection capabilities and requirements. This coordination can be done in much the same manner as currently done when NASA utilizes nuclear materials (e.g., RTGs) or as was done in the recently canceled Prometheus program which utilized a nuclear reactor.

Q5. Describe some of the proposed mitigation techniques and their trade offs.

A5. There are three techniques available with no new technological developments required prior to use. In all three cases there is significant engineering required. (Many neutral observers would challenge these statements for the nuclear stand-off option, however I will not challenge the advocates here.) These three divide into two types; the impulsive (virtually instantaneous action) techniques of kinetic impact (KI) and nuclear stand-off explosion, characterized by significant total impulse capability but with a highly unpredictable outcome, and the "slow push" technique (using NASA's term) of the gravity tractor, characterized by a modest total impulse capability but high precision and full controllability. Either of the impulsive techniques would necessarily be used in concert with the latter to insure a fully successful deflection.

The nuclear option has the disadvantages of both political opposition, especially international, and technological uncertainties which can never (in all likelihood) be tested prior to potential use. The guidance and timing constraints to achieve a planned result in addition to the possible fragmentation of the NEO are all significant challenges which will persist until actual use is attempted. A further leap of faith is taking at their word the nuclear effects experts who claim that the behavior of a NEO exposed to a pulse of neutrons will behave as the computer models predict. On the positive side the total impulse available for altering the orbit of a NEO is potentially greater than any other option.

The kinetic impact (KI) and gravity tractor (GT) technologies use available and proven technology, albeit in both cases engineering software needs to be developed and tested. Both techniques can, and should, be fully tested and demonstrated. This should be done in the near future to provide both official and public confidence prior to the time that a threatening NEO is discovered. The KI concept could also cause NEO fragmentation, but in this case it can be tested early and inform operational design to provide confidence in actual use. The GT concept is completely benign since it makes no contact with the NEO and can easily be tested and its performance validated in the immediate future.

There have been other deflection concepts proposed but all, in one way or another, require advanced technology development, the resolution of key unknown factors, or pose less cost effective solutions than those currently available. All such techniques should be further investigated and analyzed to support decisions on future technology development and testing. None, however, should be considered to be currently ready for deployment as are the three recommended above.

Q6. What is your assessment of the need for a nuclear capability?

A6. There is a very limited, near-term value in having a nuclear capability conceptually available for NEO deflection. The need is very limited, however, and a determination of the high cost and complexity of further development of this technique must be judiciously weighed against the very low probability of it being needed viz. non-nuclear techniques.

Based on current analysis it appears that the KI technique can provide the total impulse to deflect any NEO up to approximately 400 meters in diameter given 15–20 years of warning. Given that the statistical frequency of a 400 meter NEO impacting Earth is about once per 100,000 years the probability of needing to use nuclear deflection is approximately .05 percent over the next 50 years. (I use 50 years on the assumption that by that time more capable non-nuclear technologies will be developed.) Further reducing this probability is the fact that we have already discovered about 40 percent of the 400 meter NEOs and none has any possibility of impacting Earth in the next 100 years. The likelihood therefore drops to .03 percent based on the remaining 60 percent of yet to be discovered 400 meter NEOs. However based on similar reasoning, by the completion of the new 140 meter search program in ~15 years the completion rate for 400 meter NEOs will approximate 95 percent of the population reducing further the probability of needing to use nuclear technology to about .004 percent. Finally, for warning times exceeding 20 years or so any significant development costs can await such warning and still be ready for deployment if needed.

The missing element in the above paragraph is the similarly very low probability that within the next 15 years a 400 meter or larger NEO will be discovered with an impact date within 20 years, i.e., an "immediate" impact. In this instance only the extant nuclear technology would be available for use. The probability of this situation arising can be approximated based on the statistical impact rate of 400 meter NEOs at once per 100,000 years. This is based on all of the 400 meter NEOs being unknown. If we assume that it will take approximately 20 years to discover "all" of the 400 meter NEOs then the probability a 400 meter NEO impacting within the next 20 years is one in 2,000 or .05 percent. However since we have already discovered 40 percent of the 400 meter NEOs and will reach about 95 percent within the next 15 years, this probability is .03 percent now and will diminish to .004 percent within 15–20 years.

The public policy question is then, what expense is justified in investing specifically in preparing nuclear technology for use in deflecting NEOs over the next 20 years with the probability of use being about one in 10,000? Beyond that timeframe adequate warning time will permit this investment if and when needed.

My personal opinion is that this investment is not justified, other than perhaps some minor analytic studies.

Q7. Why, in your written testimony, do you state that the most important question you have been asked by the Committee is "What governance structures need to be established to address potential NEO threats?"

A7. From my work on this issue over the past six years it has become evident to me that the most challenging aspect of protecting the Earth from NEO impacts will be the decision-making process. Without elaboration, "we can know something is coming at us, and we can have something to do about it, but unless we can make the decision to take action, we will still end up like the dinosaurs." Clearly this is an overly dramatic statement since the likelihood of being struck by a small NEO which might devastate a city-sized area is 1000s of times more likely than an extinction event. Nevertheless it clearly makes the point that warning and deflection are simple compared with the world making a coordinated decision to mount a NEO deflection campaign.

The key to understanding this claim lies in the use of the word "world." Without going into too much technical detail the need for a coordinated international decision arises from a combination of the orbital mechanics of NEO impact and the need for those nations at risk, and those nations placed at risk by the deflection itself, being involved in the decision. Such up front questions as who pays?, will there be indemnification for the deflecting entity?, will a deflection be mounted at all or should we "take the hit" are all examples of the need for international coordination.

What has not yet been generally recognized, even within the "NEO community" is that in many (if not most) instances we will not be able to wait until after it is certain that a NEO will impact before launching a deflection campaign. The slow development of precise knowledge of the NEO's orbit over time, combined with the episodic nature of the collection of this knowledge assures that in many cases the quality of our knowledge at the latest possible time a deflection can be launched will require that we launch on probabilities of impact less than one. In certain instances where the threat is a NEO headed for a return keyhole prior to impact this launch decision may have to be made with the probability of impact being as low as one in 100 or even less.

These observations translate on the ground into challenging international sociopolitical issues. When the probability of Earth impact is less than one, all we know is that there is a risk corridor extending completely across the Earth's surface, anywhere within which the NEO could hit, if it is indeed headed for impact. This generally narrow corridor (usually only 10s of kilometers wide) will cross many national boundaries thereby limiting which countries are at risk of an impact. However which specific country is destined for impact if a deflection is not completed is unknown, and will generally remain so until a transponder is brought into position at the NEO by the t/GT spacecraft, the first element of a deflection campaign. Therefore a decision to deflect will be of great interest to many but not all countries (the risk corridor may cross as few as two to or as many as 10 or more countries). Will only these few countries called on to decide on a deflection and bear the cost? Or is the world community as a whole to debate the justification for sharing the cost? Will all, or a few, or none provide indemnification for the designated deflection entity? And by whom is the deflection to be performed and how will that nation, or consortium be chosen? Etc., etc. This is only a small sampling of the many difficult decisions that must be made in order to initiate a NEO deflection. Can such a decision be made unilaterally? Of course. However the implied liability and international furor should such an act be executed will likely inhibit such action. Even if, e.g., the U.S. is threatened by such an impact and a unilateral action would seem justified, the consequence of such action would be to place other nations temporarily at risk in the process of deflecting the impact away from the planet.

Clearly from this brief discussion it can be seen that the deflection (or mitigation) decision process will involve very difficult international political negotiations and trade-offs. The U.S. will have to be represented and indeed may well play a dominant role in such determinations. However the nature of the issues, while informed by technical realities, is primarily socio-political and it is doubtful that this responsibility would logically fall to NASA. Other logical candidates, in my personal order of priority would be Department of State, Department of Homeland Security, and Department of Defense.

How this assignment of responsibility is to be determined is the public policy challenge to which I referred in my written testimony. Notwithstanding the challenging nature of the issues I believe the process of deciding this issue should start immediately given the protracted debate which will soon be initiated within the United Nations. This issue is currently on the UN Committee on Peaceful Uses of Outer Space (COPUOS) agenda for 2009 and the Association of Space Explorers is leading an international effort to draft a proposed UN Program for Asteroid Threat Mitigation which will be presented in the 2009 COPUOS session. The U.S. needs to be prepared to not only participate but lead in these discussions.

Q8. You've made a number of recommendations regarding actions that should be taken by NASA and/or the Congress. Could you please estimate the cost of implementing these recommendations?

A8. B612 Foundation has no credible capability to make such cost estimates. Nevertheless, with this being said I will address the question as best I can based on many years of working in the industry and on analogous program experience. I will refer, without elaboration, to the recommendations in my written testimony in addressing the question.

Recommendation 1. ". . .the Congress should again direct NASA in the clearest language possible to comply with the law and recommend a search program and supporting budget."

The cost of complying with this recommendation is specifically addressed in the NASA report to Congress. In addition, however, I strongly advise consideration of the oral and written testimony presented at the hearing by Dr. J. Anthony Tyson, Director of the LSST Project. Dr. Tyson pointed out that NASA could, in fact, and contrary to the NASA estimated cost in its report, obtain effectively a dedicated LSST for 15 percent of the life cycle cost of the telescope by contributing a total of $125M to the LSST Project.

Recommendation 2. ". . .NASA should produce a supplement to its Report to Congress based on new knowledge which has come to light since it began its analysis."

Given the baseline work already accomplished in the preparation and delivery of the NASA NEO Report to Congress and the relatively few but critical issues missed by NASA, it would seem that this supplement to the Report could be accomplished at 15–25 percent of the cost of the initial report. This is, however, purely a guess.

Recommendation 3. "NASA should assign someone in its NEO Program to the specific task of thinking through, analyzing and understanding the NEO deflection challenge."

The cost of implementing this recommendation is simply the cost of one or possibly two additional FTEs at JPL.

Recommendation 4. "NASA should validate a basic NEO deflection capability through the execution of a demonstration mission."

As described in my testimony a slight modification to ESA's proposed Don Quixote program could validate the fundamental elements of a full deflection campaign. Were NASA to undertake this full program on its own the program would involve the design, launch and execution of two relatively simple space missions in concert. The cost should therefore approximate the cost of two typical scientific missions or $600–800M.

If, as should certainly be seriously considered, NASA were to cost share a cooperative program based on ESA's Don Quixote program with the Europeans, its cost share should drop to below $400M.

Recommendation 5. ". . .that the Congress expressly assign to NASA the technical development elements of protecting the Earth from NEO impacts as a public safety responsibility."

This recommendation's costs are largely covered by the combination of recommendations 3 & 4 above. The primary issue here is not any specific action but rather a clear and unequivocal assignment of responsibility. The development and/or testing of any new technology, in addition to that in recommendation 4, would be handled and cost justified on a case by case basis in future NASA budgets based on justified need.

Recommendation 6. ". . .that the Congress study the issue of overall governmental responsibility for protection of the Earth from NEO impacts, perhaps with the assistance of specialized policy entities, and ultimately hold public hearings to engage a wide perspective on the issue."

The cost of this recommendation would be the cost of a directed policy study (e.g., contracted to the National Academies by NASA) for perhaps $1–2M plus the cost of Congressional hearings on the issue.

Q9. Can you give an example or two of why NASA needs to think about deflection and not just about search and discovery?

A9. I interpret this question to mean not "why NASA?" but rather "why does deflection and not just search and discovery need to be thought about now?"

The answer is that within the next 15 years, assuming that the Congressional 140 meter goal is responsibly addressed, we will be adding hundreds of thousands of NEOs to the existing database. Of this total approximately 150,000 of the NEOs discovered would, if they threaten an Earth impact, be equivalent to the Tunguska impact or larger and therefore be candidates for deflection. The remaining hundreds of thousands would be small enough that the atmosphere would prevent serious damage.

Working by similarity to the existing NEO database, of these 150,000 NEOs there will likely be 4500 or more (~3.2 percent of the total database) with a non-zero (i.e., some actual) probability of Earth impact within the next 100 years. Of these 4500, if one or two percent are of comparable or greater concern than Apophis and 2004 VD17 in the current database (both mentioned in the NASA Report) then there will be on the order of 45–90 NEOs of what might be called elevated concern by 2022. Of these NEOs it is highly likely that several, if not many, will have potential impact dates which will challenge our readiness to respond, i.e., by 2022 we will have dozens, and perhaps as many as 100 NEOs in our database which appear to be threatening, and many of them will have uncomfortably short response times.

Knowing this to be the situation (and the numbers are clearly only approximate) from both statistics and similarity to our actual experience to date, it would be irresponsible to wait until the completion of the survey program and only then begin to develop a response plan. Were we to do that it would be immediately clear that our response capability would be delayed by perhaps 10 years or more. The consequence of such a delay would be that for 10s of potential impact threats, which we could have responded to if we had directed NASA to "think about deflection and not just search and discovery" could not be prevented but only mitigated through evacuation, etc.

Is it likely that any of these NEOs of elevated concern would actually impact? By definition, elevated concern means that they would have an unusually high probability of impact. If this elevated impact probability averaged one in 1,000 than in the example above the probability of any of them being an actual impact would be ~4.5–9 percent. This, as in most things NEO, is a public policy/public safety call. But given the relatively low cost of being prepared I believe that the public would be justifiably outraged if they were asked to accept a five percent chance of an impact for 10 years which could have been prevented by thinking ahead and allocating less than one half of one percent of the NASA budget to being prepared.

Appendix 2:

Additional Material for the Record

NASA REBUTTAL TO REMARKS MADE BY MR. SCHWEICKART DURING THE NOVEMBER 8, 2007, HEARING REGARDING NEAR EARTH OBJECTS

The report on Near-Earth Objects NASA submitted to the Congress in March 2007 explicitly addressed a keyhole scenario on page 22, scenario A1. Figure 4 in this report shows that in any case where a small momentum change is required to deflect a threat, such as with a keyhole, the number of deflection options increases. The NASA report does not agree with the characterization that "primary" and then "potentially secondary" deflections are required. Instead it finds that, more generally, a series of missions will most likely always be planned to ensure that a particular threat does not impact the Earth with acceptable certainty. The study team also found that the options analyzed in the study would be a toolkit from which a deflection campaign could be designed, depending on the specifics of the threat scenario. The NASA report does not characterize post-deflection keyholes as a "minefield." The report found that the likelihood of diverting a threatening object by a well-designed deflection mission into a keyhole to be very unlikely, and that even in this unlikely occurrence, a follow-on mission would by design be ready to complete the deflection. The report also does not indicate that this secondary deflection, if necessary, would necessarily be best performed by a slow push method.

STATEMENT OF THE PLANETARY SOCIETY
IN SUPPORT OF PLANETARY RADAR
AT THE ARECIBO OBSERVATORY

PROTECTING THE EARTH

Less than a century ago, a near-Earth object (NEO) slammed into Siberia, devastating 1,000 square miles. If it had struck just a few hours earlier or later in a populated area, it could have killed several hundred thousand people. NEOs pose a real and dangerous threat to Earth.

In the past few years, we have been discovering, tracking, and characterizing the comets and asteroids that travel through our neighborhood of space. We have learned much—about near-misses, the probability of collisions, the diversity of asteroid and comet physical properties, and the effects of impacts in the past. We have even learned that one asteroid, named Apophis, will pass closer to Earth in 22 years than our geosynchronous communications satellites, and its trajectory has a small probability of taking it on a collision course with Earth seven years after that.

Radar tracking is the only way to precisely know the probability of impact, and the Arecibo telescope is the most powerful instrument for the job, 20 times more sensitive for NEO radar tracking than any other instrument in the world. Unfortunately, Arecibo is slated to be closed by the National Science Foundation in a misguided attempt to free up funding for new projects that do not yet exist.

Arecibo is the largest radio-telescope in the world. It has been, and continues to be, an enormously productive scientific facility, covering a broad range of science studies. While its contributions to radio astronomy, ionospheric and atmospheric observations have proven valuable for the past several decades, it is its planetary radar capabilities that remain unique. Because of Arecibo's powerful one-million watt transmitter, and the large 1,000-foot aperture, the telescope is uniquely able to characterize potentially hazardous NEOs and determine the danger they pose. Radar signals from this facility are the only ones that can be regularly used for reaching and tracking NEOs that may be coming close to Earth.

The cost of operating Arecibo is just a few million dollars per year. Isn't the safety of Earth worth that?

In addition to tracking NEOs, Arecibo has returned other recent important results from planetary radar, including the best physical characterization of any potentially hazardous asteroid as large as a kilometer, ultra precise determinations of Mercury's spin state that reveal that planet to have a molten core, and the identification of several binary asteroids in the near-Earth population.

Arecibo is caught in a bureaucratic argument. The Arecibo Observatory is a National Science Foundation (NSF) operation, but they consider the subject of NEOs and planetary radar to be in NASA's bailiwick. NASA supports ground-based astronomy, and supported the Arecibo radar for many years, but the agency now objects to picking up the funding of what is currently an NSF program.

The House Science and Technology Committee has been the leading government advocate for understanding the nature and possible threat from objects (NEOs) that might impact the Earth. In the past, the Committee has had to direct NASA to provide increased support to this area. The Planetary Society has no position on whether this should be a NSF program or a NASA program; but, we strongly feel that it should be an American program with congressional support. We urge you to provide such support to keep the Arecibo planetary radar operating.

The Planetary Society recently conducted a privately funded, international competition to design a mission to tag the asteroid Apophis, in case its Earth approach is close enough to require higher accuracy tracking. The competition attracted thirty-seven proposals and has generated much public interest.

The cost of a tagging mission to Apophis would be at least $100 million—and the only way to know if such a mission is necessary is to refine the current estimate of Apophis' orbit with the powerful radar tracking of a telescope like Arecibo. Avoiding one unnecessary tagging mission would more than pay back any investment of funds to keep Arecibo open. And if some object out there really is on a collision course with Earth and we don't have the means to track it properly, the price we would pay would be astronomical.

Thank you for your consideration.

IEEE★USA
Building Careers & Shaping Public Policy

IEEE

08 November 2007

The Honorable Dana Rohrabacher
Committee on Science and Technology
U.S. House of Representatives
2300 Rayburn House Office Building
Washington, DC 20515

Dear Representative Rohrabacher:

The IEEE USA is opposed to the proposed funding reductions for the Arecibo radio and radar telescope, which may lead to its shutdown. In addition to the site's proven valuable radio astronomy mission, the facility provides a unique radar capability for high precision tracking and characterization of Near Earth Objects (NEOs).

The National Science Foundation (NSF) received a report from the Division of Astronomical Sciences Senior Review Committee of the Division of Astronomy in October 2006. This report recommended the shut down of the Arecibo radio observatory in Puerto Rico. However, the report largely ignored the radar observatory functionality of the Arecibo site.

The National Aeronautics and Space Administration (NASA) released a mandated Near Earth Object Survey and Deflection Analysis of Alternatives report to Congress in March of 2007. This report recommends backing off from the Near Earth Object (NEO) goals contained in the NASA Authorization Act of 2005 due to funding and asset limitations.

The remote sensing capabilities of radar technology provide advantages in a mix of NEO assets not available through passive observations alone. The NASA report states that radar is not used as an initial NEO detection device. However, radar does have the capability to quickly determine a NEOs position, direction, distance, velocity, and can help characterize its composition. The NASA report places a decadal time frame to arrive at these parameters optically for NEOs. The report also characterizes current ground based space radar capacity as oversubscribed. The radar functionality of Arecibo becomes critically important in the short warning scenario of a previously unknown potentially hazardous object, which may threaten the earth, and poses a high severity of consequences if an impact with the earth occurs. The Arecibo observatory provides a unique asset in the radar observation of NEOs which is not duplicated on earth or with space borne platforms. The role played by Arecibo in the resolution of the asteroid Apophis and establishing that it will not collide with earth in 2029 is an example of its usefulness.

With advances in radio frequency components, signal processing technology, and computational capabilities, the radio astronomy mission of Arecibo has been, and should continue to be enhanced over the years providing radio astronomers with an exploration tool for the cost of maintaining the site.

The IEEE USA recommends that Congress request the continued operation of the Arecibo facility by NSF and NASA, which includes the radio astronomy and the NEO radar mission, as well as providing the necessary funding of the Arecibo site to the Agencies.

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Sincerely,

John W. Meredith

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JM/WW:mcs