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Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies

Final Report

Committee to Review Near-Earth Object Surveys and Hazard Mitigation Strategies
Space Studies Board
Aeronautics and Space Engineering Board
Division on Engineering and Physical Sciences
NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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Dedication

We dedicate this report to our beloved friend and colleague, Steven J. Ostro (1946-2008), who devoted his professional life to the radar study of asteroids and other small bodies in the solar system. His deep understanding, unflagging concentration, and devotion to developing the potential of his junior colleagues led to many significant discoveries on the characteristics, dynamics, and unusual shapes of near-Earth objects

Preface

The Consolidated Appropriations Act, 2008,[1] required NASA to ask the National Research Council (NRC) to conduct a study of near-Earth object (NEO) surveys and hazard mitigation strategies. Near-Earth objects orbit the Sun and approach or cross Earth's orbit. In a June 2, 2008, letter, James L. Green, director, Planetary Science Division, NASA, and Craig Foltz, acting director, Astronomical Sciences Division, National Science Foundation (NSF), wrote to Lennard Fisk, then chair of the Space Studies Board, requesting that the Space Studies Board, in cooperation with the Aeronautics and Space Engineering Board conduct a two-part study to address issues in the detection of potentially hazardous NEOs and approaches to mitigating identified hazards (See Appendix B). The ad hoc Committee to Review Near-Earth Object Surveys and Hazard Mitigation Strategies consists of a steering committee, a panel on survey/detection, and a panel on mitigation.

The statement of task requires the committee to include an assessment of the costs of various alternatives, using independent cost estimating. Options that blend the use of different facilities (ground- and space-based) or involve international cooperation were considered. Each study phase resulted in a report to be delivered on the schedule provided below. Key questions addressed during each phase of the study are the following:

Task 1: NEO Surveys

What is the optimal approach to completing the NEO census called for in the George E. Brown, Jr. Near-Earth Object Survey section of the 2005 NASA Authorization Act[2] to detect, track,[3] catalogue, and characterize the physical characteristics of at least 90 percent of potentially hazardous NEOs larger than 140 meters in diameter by the end of year 2020? Specific issues to be considered include, but are not limited to, the following:

- What observational, data-reduction, and data-analysis resources are necessary to achieve the Congressional mandate of detecting, tracking, and cataloguing the NEO population of interest?
- What physical characteristics of individual objects above and beyond the determination of accurate orbits should be obtained during the survey to support mitigation efforts?
- What role could be played by the National Science Foundation's Arecibo Observatory in characterizing these objects?
- What are possible roles of other ground- and space-based facilities in addressing survey goals, e.g., potential contributions of the Large Synoptic Survey Telescope (LSST) and the Panoramic Survey Telescope and Rapid Response System (Pan STARRS)?

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[1] Consolidated Appropriations Act, 2008 (H.R. 2764; P.L. 110-161), Division B—Commerce, Justice, Science, and Related Agencies Appropriations Act, 2008. December 26, 2007.

[2] National Aeronautics and Space Administration Authorization Act of 2005 (P.L. 109-155), S. 1281, January 4, 2005, Section 321, George E. Brown, Jr. Near-Earth Object Survey Act.

[3] The committee notes that the statement of task includes the term "detect," which includes spotting asteroids that have previously been discovered. The committee therefore uses the more appropriate term "discover" to refer to the locating of previously unknown objects.

Task 2: NEO Hazard Mitigation

What is the optimal approach to developing a deflection[4] capability, including options with a significant international component? Issues to be considered include, but are not limited to, the following:

- What mitigation strategy should be followed if a potentially hazardous NEO is identified?
- What are the relative merits and costs of various deflection scenarios that have been proposed?

NASA and NSF requested an initial report for the first task no later than September 30, 2009. The committee delivered its interim report, containing only findings, but no recommendations, in early August.

Congress has charged the committee to recommend ways to discover and (partially) characterize 90 percent of NEOs exceeding 140 meters in diameter by the year 2020 (smaller objects are not discarded, once found). However, during its first meeting, the committee was explicitly asked by congressional staff to consider whether or not the congressionally established discovery goals should be modified.

[4] The committee interprets "deflection" to mean "orbit change."

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee of the National Research Council (NRC). The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

James B. Armor, Jr., The Armor Group, LLC,
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Ronald Turner, ANSER, and
Bong Wie, Iowa State University.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Louis J Lanzerotti, New Jersey Institute of Technology. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Summary

The United States spends about four million dollars annually searching for near-Earth objects (NEOs).[1] The goal is to detect those that may collide with Earth. This funding helps to operate several observatories that scan the sky searching for NEOs, but is insufficient to detect the majority of NEOs that may present a tangible threat to humanity. A smaller amount of funding (significantly less than $1 million per year) supports study of ways to protect Earth from such a potential collision ("mitigation").

Congress established two mandates for NASA's search for NEOs. The first, in 1998 and now referred to as the Spaceguard Survey, called for the agency to discover 90 percent of NEOs with a diameter of 1 kilometer or greater within 10 years. An object of this limiting size is considered by many experts to be the minimum that could produce global devastation if it struck Earth. NASA is close to achieving this goal, and should achieve it within a few years. However, as the recent (2009) discovery of an approximately 2- to 3-kilometer-diameter NEO demonstrates, there are still large objects to be detected.

The second mandate, established in 2005, known as the George E. Brown, Jr. Near-Earth Object Survey Act, called for NASA to detect 90 percent of NEOs with diameters of 140 meters or greater by 2020. As the committee noted in its August 2009 interim report:

Finding: Congress has mandated that NASA discover 90 percent of all near-Earth objects 140 meters in diameter or greater by 2020. The administration has not requested and Congress has not appropriated new funds to meet this objective. Only limited facilities are currently involved in this survey/discovery effort, funded by NASA's existing budget.

Finding: The current near-Earth object surveys cannot meet the goals of the 2005 George E. Brown, Jr. Near-Earth Object Survey Act directing NASA to discover 90 percent of all near-Earth objects 140 meters in diameter or greater by 2020.

The Survey and Detection of NEOs

The charge from Congress to the committee was stated as two tasks. The first asked for the optimal approach to completing the George E. Brown, Jr. Near-Earth Object Survey. The second asked for the optimal approach to developing a capability to avert a NEO-Earth collision, and for options that included a significant international component.

The committee concluded that there was no way to define "optimal" in a universally acceptable manner: there are too many variables involved that can be both chosen and weighted in too many plausible ways. Recognizing this fact, the committee first took a broad look at all aspects of the hazards to Earth posed by NEOs and then decided on responses to the charge. The body of this report contains

[1] NEO denotes "Near Earth Object," which has a precise technical meaning, but can be usefully thought of as an asteroid or comet whose orbit approaches Earth's orbit to within about one-third the average distance of Earth from Sun. These objects are considered to be the only ones potentially capable of striking Earth, at least for the next century, save for comets that can enter the inner solar system from the outer system through the "slingshot" gravitational action of Jupiter.

extensive discussions of these many aspects. This summary concentrates on responses to the charge and at the end provides a few comments on some of the other main conclusions drawn from the report.

Regarding the first task of the charge, the committee concluded that it was infeasible to complete the NEO census mandated in 2005 on the required time scale (2020), in part because for the past 5 years the administration requested no funds, and the Congress appropriated none, for this purpose. The committee concluded that there are two primary options for completing the survey:

Finding: The selected approach to completing the George E. Brown, Jr. Near-Earth Object Survey will depend on nonscientific factors:

> **If completion of the survey as close to the original 2020 deadline as possible is considered most important, a space mission conducted in concert with observations using a suitable ground-based telescope and selected by peer-reviewed competition is the best approach. This combination could complete the survey well before 2030, perhaps as early as 2022 if funding were appropriated quickly.**
>
> **If cost conservation is deemed most important, the use of a large ground-based telescope is the best approach. Under this option, the survey could not be completed by the original 2020 deadline, but could be completed before 2030. To achieve the intended cost-effectiveness, the funding to construct the telescope must come largely on the basis of non-NEO programs.**

Multiple factors will drive the decision on how to approach completion of this survey. These include, but are not limited to, the perceived urgency for completing the survey as close to the original 2020 deadline as possible, the availability of funds to complete the survey, and the acceptability of the risk associated with the construction and operation of various ground- and space-based options.

Of the ground-based options mentioned in the statement of task and the additional ones submitted to the committee in its public request for suggestions, the most capable appears to be the Large Synoptic Survey Telescope (LSST). The LSST is to be constructed in Chile and has several science missions, as well as the capability of observing NEOs. Although the primary mirror for the LSST has been cast and is being polished, the telescope has not been fully funded and is pending prioritization in the astronomy and astrophysics decadal survey currently underway.

Unless unexpected technical problems interfere, a space-based option should provide the fastest means to complete the survey. However, unlike ground-based telescopes, space options carry a modest launch risk and a more limited lifetime: ground-based telescopes have far longer useful lifetimes and could be employed for continued NEO surveys and for new science projects. (Ground-based telescopes generally have an annual operating cost that is approximately 10 percent of their design and construction costs.)

The committee notes that objects smaller than 140 meters in diameter are also capable of causing significant damage to Earth. The most well-known case from recent history is the 1908 impact of an object at Tunguska in the Siberian wilderness that devastated more than 2,000 square kilometers of forest. Previous estimates of the size of this object were on the order of approximately 70 meters in diameter. Recent research indicates that the object could have been substantially smaller (30 to 50 meters in diameter), with much of the damage it caused due to shock waves from the explosion of the object in Earth's atmosphere. The committee strongly stresses that this new conclusion is preliminary and must be independently validated. Since smaller objects are more numerous than larger ones, however, this new result, if correct, implies an increase in the frequency of such events to approximately once per 3 centuries.

All told the committee was struck by the many uncertainties that suffuse the NEO subject. One other related example: do airbursts from impactors in this size range over an ocean cause tsunamis that can severely damage a coastline? This uncertainty and others have led the committee to a recommendation:

Recommendation: Because recent studies of meteor airbursts have suggested that near-Earth objects as small as 30 to 50 meters in diameter could be highly destructive, surveys should attempt to detect as many 30- to 50-meter objects as possible. This search for smaller-diameter objects should not be allowed to interfere with the survey for objects 140-meters in diameter or greater.

In all cases, the data-reduction and data-analysis needs mentioned in the charge would be covered by the projects themselves and by continuation of the current funding of the Minor Planet Center, as discussed in the report.

Characterization and the Arecibo and Goldstone Observatories

Obtaining the orbits and the physical properties of NEOs is known as characterization and is primarily needed to inform planning for any active defense of Earth. Such defense would be carried out through a suitable attack on any cosmic object predicted with near certainty to otherwise collide with Earth and cause significant damage. The apparently huge variation in the physical properties of NEOs seems to render infeasible development of a comprehensive inventory via in situ investigations by suitably instrumented spacecraft: the costs would be truly astronomical. A spacecraft reconnaissance mission might make good sense to conduct on an object that, without our intervention, would hit Earth with near certainty. Such a mission would be feasible provided that there were sufficient warning time for the results to suitably inform the development of an attack mission to cause the object to miss colliding with Earth.

On the other hand, the committee concluded that vigorous, ground-based characterization at modest cost is important for the NEO task. Modest funding could support optical observations of already-known and newly discovered asteroids and comets to obtain some types of information on this broad range of objects, such as their reflectivity as a function of color, to help infer their surface properties and mineralogy, and their rotation properties. In addition, the complementary radar systems at Arecibo and Goldstone are powerful facilities for characterization within their reach in the solar system, a maximum of about one-tenth of the Earth-Sun distance. Arecibo, which has a maximum sensitivity about 20-fold higher than Goldstone's, but does not have nearly so good sky coverage as Goldstone, can for example, model the three-dimensional shapes of (generally very odd-shaped) asteroids, and estimate their surface characteristics, as well as determine whether the asteroid has a (smaller) satellite or satellites around it, all important to know for planning active defense. Radar can also accurately determine orbits of NEOs, from a few relatively closely spaced (in time) observations, which has the advantage of being able to quickly calm public fears (or possibly, in some cases, show that they are warranted).

Finding: The Arecibo and Goldstone radar systems play a unique role in the characterization of NEOs, providing unmatched accuracy in orbit determination, and insight into size, shape, surface structure, and other properties for objects within their latitude coverage and detection range.

Recommendation: Immediate action is required to ensure the continued operation of the Arecibo Observatory at a level sufficient to maintain and staff the radar facility. Additionally, NASA and NSF should support a vigorous program of radar observations of NEOs at Arecibo and NASA should support such a program at Goldstone for orbit determination and characterization of physical properties.

For both Arecibo and Goldstone continued funding is far from assured, not only for the radar systems, but for the entire facilities. The incremental annual funding required to maintain and operate the radar systems even at their present relatively low levels of operation, is about $1 million at each facility (see Chapter 4). The annual funding for Arecibo is approximately $12 million. Goldstone is part of the Deep Space Network and its overall funding includes additional equipment for space communications.

Mitigation

Mitigation refers to all means of defending Earth and its inhabitants from effects of an impending impact by a NEO. Four main types of defense are discussed in this report. The choice of which one(s) to use depends primarily on the warning time available and on the mass and speed of the impactor. The types of mitigation are:

1. *Civil defense.* This option may be the only one feasible for warning times shorter than perhaps a year or two. Depending on the state of readiness to apply an active defense, civil defense may be the only choice for even longer times.
2. *"Slow push" or "slow pull" methods.* For these options the orbit of the target object would be changed so that it avoided collision with Earth. The most effective way to change the orbit, given a constraint on the energy that would be available, is to change the velocity of the object, either in or opposite to the direction in which it is moving (direct deflection—moving the object "sideways"—is *much* less efficient). These options take considerable time to be effective, of the order of decades, and even then would be useful only for objects whose diameters are no larger than 100 meters or so.
3. *Kinetic impactors.* In these scenarios the target's orbit would be changed by sending one or more spacecraft with very massive payload(s) to impact directly on the target at high speed in its direction, or opposite to its direction, of motion. The effectiveness of this option depends not only on the mass of the target, but on any net enhancement due to material being thrown out of the target, in the direction opposite to that of the payload upon impact.
4. *Nuclear explosions.* For non-technical reasons, this would likely be a last resort, but it is also the most powerful technique and could take several different forms, as discussed in the report. The nuclear option would be usable for objects up to a few kilometers in diameter.

For larger NEOs (more than a few kilometers in diameter), which would be on the scale that would inflict serious global damage and, perhaps, mass extinctions, there is at present no feasible defense. Luckily such events are exceedingly rare, the last known being about 65 million years ago.

Of these options, only kinetic impact has been demonstrated (via the very successful Deep Impact spacecraft that collided with comet Tempel-1 in July 2006). The other options have not advanced past the conceptual stage. Even Deep Impact was on a scale far lower than would be required for Earth defense for an NEO on the order of 100 meters in diameter, and impacted on a relatively large—and therefore easier to hit—object.

Although the committee was charged with determining the "optimal approach to developing a deflection capability," it concluded that work in this area is relatively new and immature. The committee therefore concluded that the "optimal approach" starts with a research program.

Further Research

The committee was struck by the significant unknowns in many aspects of NEO hazards that could yield to Earth-based research and was led to:

Recommendation: The United States should initiate a peer-reviewed, targeted research program in the area of impact hazard and mitigation of NEOs. Because this is a policy driven, applied

program, it should not be in competition with basic scientific research programs or funded from them. This research program should encompass three principal task areas: surveys, characterization, and mitigation. The scope should include analysis, simulation, and laboratory experiments. This research program does not include mitigation space experiments or tests which are treated elsewhere in this report.

National and International Cooperation

Responding effectively to hazards posed by NEOs requires the joint efforts of diverse institutions and individuals. Thus organization plays a key role. Because NEOs are a global threat, efforts to deal with them could involve international cooperation from the outset. (However, this is one area where one nation, acting alone, could address such a global threat.) The report discusses possible means to organize, both nationally and internationally, responses to those hazards. Arrangements at present are largely *ad hoc* and informal here and abroad, and involve both government and private entities.

The committee discussed ways to organize the national community to deal with the hazards of NEOs and also recommends an approach to international cooperation.

Recommendation: The United States should take the lead in organizing and empowering a suitable international entity to participate in developing a detailed plan for dealing with the NEO hazard.

One major concern with such an organization, especially in the disaster-preparation area, is the maintenance of attention and morale given the expected exceptionally long intervals between harmful events. Countering the tendency to complacency will be a continuing challenge. This problem would be mitigated if, for example, the civil defense aspects were combined in the National Response Framework with those for other natural hazards.

Recent NEO-Related Events

The U.S. Department of Defense, which operates sensors in Earth orbit capable of detecting the high-altitude explosion of small NEOs, has in the past shared this information with the NEO science community. The committee concluded that this data-sharing was important for understanding issues such as the population size of small NEOs and the hazard that smaller NEOs pose. This sharing is also important to validate airburst simulations, characterize the physical properties of small NEOs (such as their strength), and to assist in the recovery of meteorites.

Recommendation: Data from NEO airburst events observed by the U.S. Department of Defense satellites should be made available to the scientific community to allow it to improve understanding of the NEO hazards to Earth.

In 2008, Congress passed a NASA appropriations act that called for the Office of Science and Technology Policy to determine by October 2010 which agency should be responsible for conducting the NEO survey and detection and mitigation program. Several agencies are possible candidates for such a role.

During its deliberations the committee learned of several efforts outside the United States to develop spacecraft to search for categories of NEOs. In particular, Canada's NEOSSat and Germany's AsteroidFinder are interesting and capable small scale missions that will detect a small percentage of specific types of NEOs, those primarily inside Earth's orbit. These spacecraft will not accomplish the goals of the George E. Brown, Jr. Near-Earth Object Survey Act. However, they highlight the fact that other countries are beginning to seriously consider the NEO issue. Such efforts also represent an opportunity for future international cooperation and coordination in the search for potentially hazardous NEOs. In addition, the committee was impressed with the European Space Agency's early development of the Don Quijote spacecraft mission that would consist of an observing spacecraft and a kinetic impactor. This mission, though not funded, would have value for testing a mitigation technique and could still be an opportunity for international cooperation in this area.

Finally, the committee points out a current estimate of the long-term average annual human fatality rate from impactors: slightly under 100. At first blush, one is inclined to dismiss this rate as trivial in the general scheme of things. However, one must also consider the extreme damage that could be inflicted by a single impact; this presents the classic problem of the conflict between extremely important and extremely rare. The committee considers work on this problem as insurance, with the premiums devoted wholly towards preventing the tragedy. The question then is: What is a reasonable expenditure on annual premiums? The committee offered a few possibilities for what could possibly be accomplished at three different levels of funding (see Chapter 8); it is, however, the political leadership of the country that determines the amount to be spent on scanning the skies for potential hazards and preparing our defenses.

1

Introduction

Our planet inhabits a hazardous environment. Earth is continually bombarded by cosmic objects. Luckily for us, most are very small and cause no harm to life. Some, however, are large and cause considerable harm. Evidence of these collisions, large and small, is abundant, from the dense defacement of Mercury and the Moon to the craters festooning the surfaces of even small asteroids. Although impacts of cosmic objects on Earth have occurred since its very formation, humanity has been at best dimly aware of these events until very recently. Only two centuries ago it was widely doubted that objects orbiting the Sun could or would collide with Earth.

In general, we cannot predict precise times and locations of future impacts, but can make statistical statements about the probability of an impact. Objects larger than about 30 meters in diameter probably strike Earth only about once every few centuries, and objects greater than about 300 meters in diameter only once per hundred millennia. Even objects only 30 meters in diameter can cause immense damage. The cosmic intruder that exploded over Siberia in 1908 may have only been a few tens of meters in size; yet this explosion severely damaged a forest of more than 2,000 square kilometers. Had an airburst of such magnitude occurred over New York City, hundreds of thousands of deaths might have resulted.

Assessing risk is difficult primarily due to lack of sufficient data. Our best current estimates are given in Chapter 2, where the risk is presented with its dependence on impactor size and associated average impact frequency, along with damage estimates in terms of lives and property. Figure 1.1 illustrates the estimated frequency of NEO[1] impacts on Earth for a range of NEO sizes. For impactor diameters exceeding about 2 to 3 kilometers, world-wide damage is possible, thus affecting all of humanity and our entire living space (the minimum size at which impactors can cause global devastation is still uncertain). While exceedingly rare, the consequences of such a collision are enormous, almost incalculable. This presents the classic "zero times infinity" problem: nearly zero probability of occurrence, but nearly infinite devastation per occurrence.

Humanity has the capacity to detect and perhaps to counter an impending natural disaster. This capacity, and interest in exercising it, has developed and sharply increased in the space age, most likely sparked by the discovery in the late 1980s of the approximately 200-kilometer-diameter Chicxulub crater formed by an impact 65 million years ago in the Yucatan peninsula. The asteroid or comet that caused this crater is estimated to have been about 10 kilometers in diameter; its impact wrought global devastation, likely snuffing out species in huge numbers including dinosaurs. Later, in the 1990s, the collision of comet Shoemaker-Levy 9 with Jupiter emphasized that impacts are currently possible.

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[1] NEO denotes "Near Earth Object," which has a precise technical meaning, but can be usefully thought of as an asteroid or comet whose orbit approaches Earth's orbit to within about one-third the average distance of Earth from Sun. These objects are considered to be the only ones potentially capable of striking Earth, at least for the next century, save for comets that can enter the inner solar system from the outer system through the "slingshot" gravitational action of Jupiter.

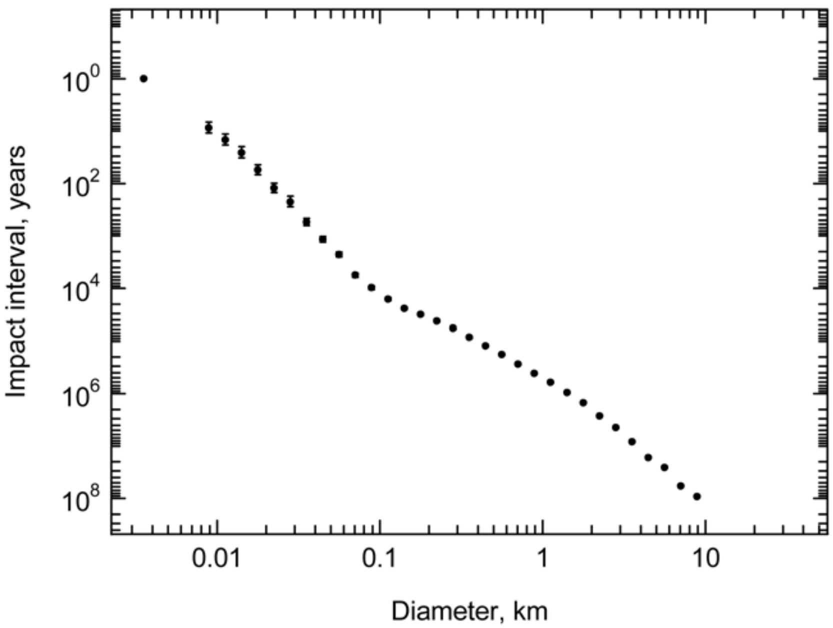

FIGURE 1.1 Current estimates of the average interval in years between collisions with Earth of near Earth objects of various sizes, from ca 3 meters to 9 kilometers in diameter. The uncertainty varies from point to point, but in each case is of the order of a factor of 2, there is also a strong correlation of the values from point to point. SOURCE: Courtesy of Alan W. Harris, Space Science Institute.

To assess the current hazards, surveys were undertaken in the 1970s and greatly augmented in the 1990s to discover and track all objects that pass near Earth's orbit—defined as near-Earth objects, or NEOs—to determine the likelihood that one or more would collide with Earth. These surveys, involving relatively small telescopes whose primary mirrors ranged in diameter from 0.6 to 1.2 meters were seeking objects with diameters greater than 1 km; also detected were many smaller objects that approached Earth closely enough to be seen.[2]

Congress requested that the National Research Council (NRC) undertake a study, sponsored by NASA, to address two tasks:

Task 1: NEO Surveys

What is the optimal approach to completing the NEO census called for in the George E. Brown, Jr. Near-Earth Object Survey section of the 2005 NASA Authorization Act[3] to detect, track,[4] catalogue, and characterize the physical characteristics of at least 90 percent of potentially hazardous NEOs larger than 140 meters in diameter by the end of year 2020? Specific issues to be considered include, but are not limited to, the following:

- What observational, data-reduction, and data-analysis resources are necessary to achieve the Congressional mandate of detecting, tracking, and cataloguing the NEO population of interest?
- What physical characteristics of individual objects above and beyond the determination of accurate orbits should be obtained during the survey to support mitigation efforts?

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[2] Brightness is the key determinant of detectability; the apparent brightness of an object as seen from Earth varies with the inverse square of its distance from Earth (e.g., twice as close implies four times as bright).

[3] National Aeronautics and Space Administration Authorization Act of 2005 (P.L. 109-155), S. 1281, January 4, 2005, Section 321, George E. Brown, Jr. Near-Earth Object Survey Act.

[4] The committee notes that the statement of task includes the term "detect," which includes spotting asteroids that have previously been discovered. The committee therefore uses the more appropriate term "discover" to refer to the locating of previously unknown objects.

- What role could be played by the National Science Foundation's Arecibo Observatory in characterizing these objects?
- What are possible roles of other ground- and space-based facilities in addressing survey goals, e.g., potential contributions of the Large Synoptic Survey Telescope (LSST) and the Panoramic Survey Telescope and Rapid Response System (Pan STARRS)?

Task 2: NEO Hazard Mitigation

What is the optimal approach to developing a deflection[5] capability, including options with a significant international component? Issues to be considered include, but are not limited to, the following:

- What mitigation strategy should be followed if a potentially hazardous NEO is identified?
- What are the relative merits and costs of various deflection scenarios that have been proposed?

In response to this assignment from Congress, the National Research Council created a steering committee and two panels (one for each task) to undertake a study to address these issues.

Although the possibility of a large NEO impact with Earth is remote, conducting surveys of NEOS and studying means to mitigate collisions with them can best be viewed as a form of insurance. It seems prudent to expend some resources to prepare to counter this collision threat. Most homeowners, for example, carry fire insurance, although none expects her or his house to burn down any time soon. The distinction between insurance for the collision hazard and other "natural" hazards, such as earthquakes and hurricanes, is that we now have the possibility to detect and prevent most serious collisions. In the case of earthquakes, for example, despite efforts, primarily in China, Japan, and the United States, we cannot yet reliably predict either the epoch or the severity of an earthquake. We do nonetheless fund the analog of an insurance policy through studies of this hazard and through the design and construction of earthquake-resistant structures, and in development of plans for response and recovery. The goal is to reduce both the number of fatalities and the damage to property from earthquakes. According to available figures from the NRC report *Improved Seismic Monitoring—Improved Decision-Making: Assessing the Value of Reduced Uncertainty*,[6] the United States alone now spends well in excess of $100 million annually on this suite of efforts. The annual United States death rate from earthquakes, averaged over the past two centuries for which data are available, is approximately 20 per year, with 75 percent of that figure attributed to the 1906 San Francisco earthquake, mostly from related fires. For Japan, both the expenditure and the fatality figures are far larger. China and other parts of Asia have also suffered massive casualties from earthquakes. The September 2009 earthquakes that caused loss of life in Indonesia, Samoa and American Samoa highlight this ongoing threat to human life.

Given the low risk over a period of, say, a decade (see Chapter 2), how much should the United States invest in this insurance? This question requires a political, not a scientific, answer. Yet the question bears upon the committee's charge. The committee was asked to recommend the optimum approach for each of the tasks, with the definition of "optimum" left to the committee. A unique characteristic of the NEO research premiums, which distinguishes them from the usual types of insurance, is that the entire premiums would be directed towards the prevention of the catastrophe.

In no case, however, is it wise to consider application of techniques more than a few decades into the future. The technologies available at that time would likely be both more efficient and more effective, rendering present approaches obsolete. This is not to suggest waiting for those future technologies, leaving Earth unaware and threats to Earth unmitigated in the meantime.

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[5] The committee interprets "deflection" to mean "orbit change."

[6] National Research Council, *Improved Seismic Monitoring—Improved Decision-Making: Assessing the Value of Reduced Uncertainty,* The National Academies Press, Washington, D.C., 2006.

The remainder of this report is devoted to description of the various aspects of the hazard that we have considered, to our findings and recommendations in response to our charge, and to our prioritization of them in the context of our somewhat arbitrarily chosen alternative budget levels. In particular, Chapter 2 is directed towards clarifying, as well as now feasible, the risks associated with asteroid and comet hazards, and the uncertainties in our knowledge of those risks. These studies include both small and large potential impactors, their various possible orbits, the effects of airburst and ocean impacts, and the key issue of warning time.

Chapter 3 contains our committee's analysis of the survey/detection questions, including presently mandated goals, their possible modifications, and the possible means—ground- and/or space-based methods—of achieving them.

Chapter 4 addresses characterization, the gathering of information on the properties of asteroids and comets that form the pool of potential impactors. The emphasis is on asteroids and on properties that would importantly affect any attempts at an active defense of Earth against an impending impact. The various properties of relevance are listed and their importance explained. Methods are described for characterization, ranging from laboratory studies of meteorites, through detailed observations of airbursts, to ground- and space-based remote and in-situ observations of samples from the pool. This chapter also devotes especial attention to the role of radar observations, consistent with our charge, and to the complementary nature of the various means for characterization. A vital issue is the wide variation in the key properties from one object to another.

Chapter 5, addresses mitigation, examining the available techniques and the situations for which each is applicable. The goal is to avoid a collision through changing the orbit of (or destroying) an impactor headed for Earth. The committee also examined the state of (un)readiness of each technique, and discussed developments and tests needed to establish confidence that the counter measures would work when called upon. As to deployment of any counter measure, a main guide is the ancient maxim: "First, do no harm." Obedience to this admonition is not so trivial as it might appear. With the years-long warning times likely needed to successfully complete a mitigation mission, the corresponding accuracy of prediction of the impact might well be poor. In particular, the error ellipse that describes the uncertainty in the prediction of impact might well not approach the near certainty desired, indicating the need for caution.

The committee's work uncovered many facets of the overall problem that needed attention to sensibly plan and execute options that were considered. The committee therefore recommends a research program, discussed in Chapter 6, to address these issues. Included among these topics are airbursts from impactors in the decameter-size range, with various compositions and structures, as well as the current distribution in the sky of objects that could impact Earth over, say, the next century or so. This proposed research program should include peer evaluation of proposals.

The collision hazard posed by cosmic objects is, as noted, global. It therefore seems sensible to deal with this hazard in its international context. Also needed is national leadership and responsibility. In Chapter 7 we discuss such leadership, noting that the Office of Science and Technology Policy has been tasked with addressing this issue. In this chapter, we emphasize international aspects—organization, coordinated activities and responsibilities, and means for settling disputes that might arise in the planning stages and especially from a failed mitigation effort.

The committee was asked to produce independent cost estimates of typical solutions that it considered for survey completion and mitigation. To this end, the NRC hired Science Applications International Corporation to use parametric models and other statistical techniques to produce estimates of these options. However, the committee notes that many of these options are technically immature and cost estimates at this early stage of development are notoriously unreliable. At best, these cost estimates provide only crude approximations of final costs of pursuing any of these options, so <u>the committee did not use these cost estimates in reaching its conclusions.</u> The cost estimates are included in Appendix A.

Throughout this report, the committee has sought to eliminate jargon and acronyms whenever possible, and has added a Glossary as Appendix E to provide additional clarity. However, the committee did not totally avoid specialized vocabulary.

2

Risk Analysis

Impacts are one of the most fundamental processes shaping planetary surfaces throughout the solar system. Images of many solar system objects are dominated by craters formed throughout the last 4.5 billion years. Smaller airless bodies in particular retain a significant history of collisions. Earth's moon has been used to determine variation in the rate of impacts since the earliest days of the solar system. Imagery, coupled with dating of lunar materials, has allowed us to demonstrate that the rate of impacts has gradually diminished since these early times.

While the frequency of impacts due to bodies of all sizes is considerably less than during the first 700 million years of solar system history, as the planetary orbits have stabilized and a significant proportion of the smaller objects has been accreted, the most significant risk remains from collisions with bodies on oval-shaped orbits (such as comets) and objects with orbits near that of Earth.

The average amount of material accreted daily to Earth is estimated to be in the range of 50 to 150 tons of very small objects (Love and Brownlee, 1993). This material is mostly dust, although there are abundant small objects that burn up quickly in the atmosphere and are evidenced by meteor trails. More rarely, larger objects impact Earth. It is now widely believed that the impact of an ~10-kilometer-diameter object formed the Chicxulub crater near the Yucatan peninsula about 65 million years ago, very likely resulting in the extinction of the dinosaurs. Its mass is similar to the total amount of dust and other small objects accreted to Earth during the time since that impact.

Substantial atmospheres around planetary bodies act as significant filters to incoming objects. Smaller objects, particularly those that are lower in density and more fragile, vaporize in the upper reaches of the atmosphere, while more intact larger bodies may survive to impact the surface. Thus, small craters are much less common on bodies with dense atmospheres, such as Earth, Venus and Titan, than they are on Mercury and the Moon, with Mars somewhere in between. Of course there are still substantial numbers of large impact craters even on Venus with its dense carbon dioxide atmosphere; the lack of weathering and erosion, coupled with low rates of volcanic and tectonic activity over the last 0.5 billion years, has allowed the retention there of a significant number of craters, most largely unaltered since emplacement. By contrast, the movement of water on Earth and the action of plate tectonics have both resulted in loss of much of the cratering record. There are more than 170 established impact craters on Earth, including the ~1.2-km Meteor Crater in Arizona (Figure 2.1). The largest known terrestrial crater is the 300-kilometer-diameter Vredefort Crater in South Africa, dated at around 2 billion years old.

Over the last several decades, research has clearly demonstrated that major impact events have occurred throughout Earth's history, often with catastrophic consequences. The Chicxulub impact apparently caused a mass extinction of species, possibly resulting from a global firestorm due to debris from the impact raining down across the planet. It may also have caused dramatic cooling for a year or more and global climatic effects that may have lasted a long time (e.g., O'Keefe and Ahrens, 1989). While many species became extinct at this time (including perhaps 30 percent of marine animal genera), many survived and ultimately thrived in the post-dinosaur world. It may be that impacts throughout the history of this planet have strongly helped shape the development and evolution of life-forms.

FIGURE 2.1 Meteor Crater (also known as Barringer Crater) in Arizona, with the Great Pyramids of Giza and the Sphinx inserted for size comparison. This crater is one of the most familiar impact features on the planet. This crater is about 1,200 meters in diameter and 170 meters deep; the interior of the crater contains about 220 meters of rubble overlying bedrock. The crater was formed about 50,000 years ago through the impact of a ~40-meter iron-nickel meteorite moving at ~13 km/s. SOURCE: Crater image courtesy of U.S. Geological Survey, composite created by Tim Warchocki.

Several recent events and new analyses have highlighted the impact threat to Earth:

1. As Comet Shoemaker-Levy 9 came close to Jupiter in 1992, tidal forces caused it to separate into many smaller fragments that then may have regrouped via self-gravity into at least 21 distinct pieces (e.g., Asphaug and Benz, 1994). These pieces impacted Jupiter in July 1994, creating a sequence of visible impacts into the gaseous Jovian atmosphere. The resultant scars in Jupiter's atmosphere could be readily seen through Earth-based telescopes for several months. In July 2009, a second object, though much smaller than Shoemaker-Levy 9, impacted Jupiter, also causing a visible dark scar in the Jovian atmosphere. Such clear evidence of major collisions in the contemporary solar system does raise concern about the risk to humanity.
2. In December 2004, astronomers determined that there was a non-negligible probability that near-Earth asteroid Apophis (see Chapter 4 for more details) would strike Earth in 2029. As Apophis is a near-300-meter-diameter object, a collision anywhere on Earth would have serious regional consequences and possibly produce transient global climate effects. Subsequent observations of Apophis ruled out an impact in 2029, and also determined that it is quite unlikely that this object could strike during its next close approach to Earth in 2036. However, there likely remain many Apophis-sized NEOs that have yet to be detected. Also we became aware of the threat from Apophis only in 2004, raising concerns about whether we would be able to mitigate the threat of such an object, should Earth collision be determined to have a high probability of occurrence in the relatively near future.
3. In June 1908, a powerful explosion blew down trees over an area spanning at least 2,000 square kilometers of forest near the Podkamennaya Tunguska River in Central Siberia. As no crater was located, scientists initially argued against an asteroid or comet origin. However, subsequent analysis and more recent modeling (see, e.g., Chyba et al., 1992; Boslough and Crawford, 1997; 2008) have indicated that modest-sized (the Tunguska object may have been only 30 to 50 meters in diameter) objects moving at high supersonic speeds through the atmosphere can disintegrate spontaneously, creating an airburst that causes substantial damage without cratering. Such airbursts are potentially more destructive than are ground impacts of similarly sized objects.
4. A stony meteorite 1- to 2- meters in diameter traveling at high supersonic speeds, created an impact crater in Peru in September 2007. According to current models with standard assumptions, such a

small object should not have impacted the surface at such a high velocity. This case demonstrates that specific instances can vary widely from the norm and is a reminder that small NEOs can also be dangerous.

5. On October 6, 2008, asteroid 2008 TC_3 was observed by the Catalina Sky Survey (Chapter 3) on an Earth-collision course. Although the object was deemed too small to pose much of a threat, Spaceguard and the Minor Planet Center (Chapter 3) acted rapidly to coordinate an observation campaign over the following 19 hours with both professionals and amateurs to observe the object and determine its trajectory. The 2- to 5-meter-diameter object entered the atmosphere on October 7, 2008, and the consequent fireball was observed over northern Sudan (Figure 2.2) (Jenniskens et al., 2009). Subsequent ground searches in the Nubian desert in Sudan located 3.9 kg (in 280 fragments) of material from the meteorite.

FIGURE 2.2 The long-lasting airburst trail over Sudan after the impact of 2008 TC_3 on October 7, 2008. SOURCE: Courtesy of M. Elhassan, M. H. Shaddad, and P. Jenniskens.

These recent events, as well as our current understanding of impact processes and the population of small bodies across the solar system, but especially in the near-Earth environment, raise significant concerns about the current state of knowledge of potentially hazardous objects, and our ability to respond to the threats that they might pose to humanity.

INVENTORY OF NEOS AND POTENTIALLY HAZARDOUS NEOS

Introduction

Our ability to detect NEOs is dependent on how bright each object appears in the sky, which depends primarily on its distance from Earth, its size, its albedo (how well light reflects from its surface), and its location relative to the Sun. NEOs that appear very close to the Sun when viewed from Earth make observation difficult or even impossible. The brightness of each NEO also changes as it moves through its orbit, coming closer and further from Earth. As a result, it is very difficult to detect all NEOs in the entire population, particularly smaller (fainter) asteroids. Figure 2.3 shows the distribution (on September 21, 2009) of known asteroids in the inner solar system. The green dots represent asteroids that do not currently approach Earth. The yellow dots are Earth-approaching asteroids, ones having orbits that come close to Earth but do not cross Earth's orbit. The red boxes mark the locations of asteroids that cross Earth's orbit although they may not necessarily closely approach Earth. (Note that these objects are not all in the same orbital plane, and so it is more accurate to envision some of the objects above the page and some below it. The image is also very misleading; on this scale the asteroids would be invisible. The vast majority of the solar system is empty space, but there are nonetheless many objects present.) Of course, while we have located many NEOs, there are many that have yet to be discovered, some of which may represent a significant threat of impact on Earth. Using estimates of the distribution and orbits of these undiscovered NEOs, we can statistically address the hazard posed by NEOs, particularly those that are large enough to cause significant damage should they impact Earth.

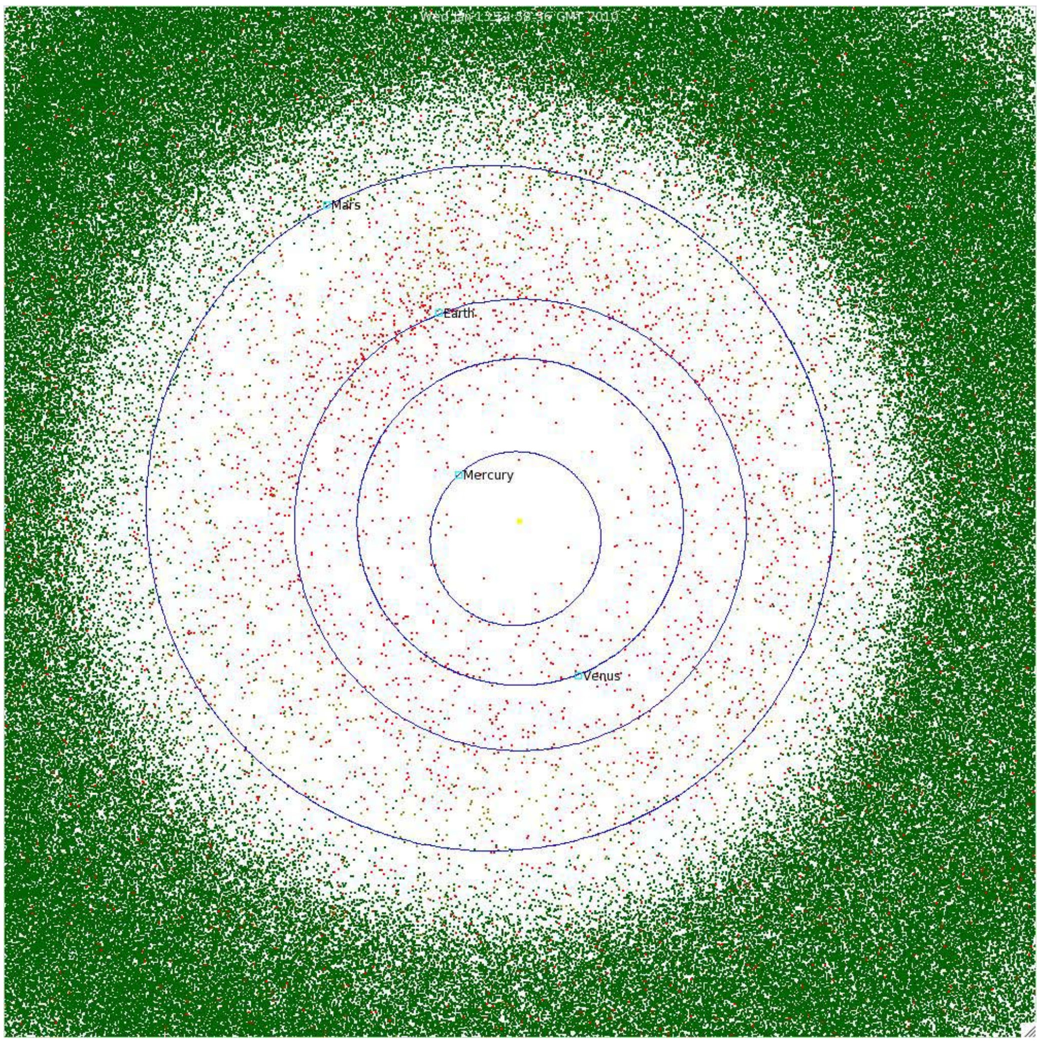

FIGURE 2.3 Distribution of currently known asteroids (in January 2010). Contrary to the impression given by this illustration, the space encompassed by this figure is predominantly empty. SOURCE: Courtesy of Scott Manley, Armagh Observatory.

To determine what fraction of the entire NEO population we have detected, we need to compute the total expected number of objects from knowledge of the properties of known NEOs and how objects are expected to get brighter and fainter as they move through their orbits. Using computer models we can determine the fraction of all NEOs of different sizes that will be detected for a particular survey strategy. As surveys approach completion and our knowledge of the NEO population increases, refinements are possible to the computer simulations that allow greater confidence in the predicted numbers of NEOs in each size range. Current estimates (Harris 2009) indicate that there should be a total of about 940 NEOs larger than 1-kilometer in diameter. Based on this estimate and current NEO detections, we conclude that nearly 85 percent of all 1-km or larger objects in the near-Earth environment have been detected. We have also shown that none of these objects presents a threat of impact on Earth within the next century. This calculation includes near-Earth asteroids but does not include long-period comets (orbital periods in excess of 200 years), which are believed to present less than of order 1 percent of the total NEO impact threat (Stokes et al., 2003). Although impacts of objects smaller than 1-km do less damage than larger ones, it is this smaller class of objects that, due to their far greater numbers, presents the most frequent threat to humanity.

Estimates of the "risk" that exists in the portion of the NEO population that has yet to be discovered requires the following components:

1. The orbital distribution of undiscovered asteroids and comets capable of producing damage to human life or property. This information is used to compute the collision probabilities and impact velocities of the possible impactors on Earth.
2. The mass distribution of potential Earth impactors. Given the uncertainties about the properties of comets and asteroids, previous works have concentrated on the distribution of brightness of these objects at a standard distance from both Earth and Sun. This distribution is then converted into an "uncalibrated" size distribution by making assumptions based on present (incomplete) understanding of the average properties of these objects. Thus we can estimate equivalent diameters, *D,* from measurements of brightness, *H*, where the term "diameter" used here and in the subsequent text refers to the equivalent diameter of a sphere of the same volume.
3. The amount of "damage" produced by impactors when they strike different locations on Earth. Damage is usually calculated from components of the impact. One component is the impact energy distribution, which is computed from points 1 and 2, above. A second component is to assign a set worth to things of value on Earth (e.g., human life, infrastructure/property) in a manner similar to that used by insurance actuarial assessors. As property damage or loss of life will vary significantly with geographical point of impact, realistic assessments of "damage" must allow for the stochastic nature of impacts and usually involve the use of "Monte Carlo" computer simulations.

The previous reports by Stokes et al. (2003) and NASA PA&E (2006) reviewed available data on NEOs and made extensive calculations of the potential hazard to mankind due to various populations of NEOs. In the next sections, we briefly review the computations in Stokes et al (2003) and NASA PA&E (2006). Both of these documents were fairly extensive in their descriptions and are still close to state of the art. Thus we only update the calculations based on more recent scientific analysis, point out uncertainties and sensitivities of the results to assumptions, and comment where new work is needed.

The Distribution of NEO Orbits

The basis for the distribution of NEO orbits in both Stokes et al. (2003) and NASA PA&E (2006) comes from the work of Bottke et al. (2002). The method is fairly detailed but, in brief, they used dynamical modeling to determine the primary source regions of NEOs (e.g., portions of the main asteroid belt, and the trans-Neptunian region that acts as a source of "Jupiter family" comets) and to create probability distributions of the destinations of the NEOs (e.g., into the Sun, interactions with planets, return to the asteroid belt). The probability distributions were then compared to models of observations of known NEOs detected by surveys (e.g., Spacewatch and LINEAR; see Chapter 3).[1] These surveys found that most kilometer-sized NEOs come from the inner and central parts of the asteroid belt. Only a small percentage (<20) comes from the outer main belt or are comets delivered from the trans-Neptunian region. Based on this distribution of orbits, they find about 20 percent of the NEOs have orbits that pass within 0.05 AU of Earth. NEOs in this class are called "potentially hazardous NEOs". Stokes et al. (2003) and NASA PA&E (2006) used potentially hazardous NEOs to determine survey strategies.

The Bottke et al. (2002) model has held up fairly well over the last several years as we have neared 85 percent completion of the survey for objects greater than 1 km in diameter. Some limitations of this model exist for dimmer (or smaller) NEOs. For example, the NEO data used to calibrate the Bottke et al. (2002) NEO model were mainly kilometer-sized objects; few sub-kilometer sized objects were known when the model was developed. If the population of kilometer-sized objects has the same distribution of orbits as the sub-kilometer-sized objects, the Bottke et al. (2002) model should work for the latter group. There are indications, however, that this equivalence may not hold. In particular:

- Studies of fireballs (i.e., objects burning in Earth's atmosphere) indicate that these sub-meter-to meter-sized objects mainly come from the central part of the asteroid belt (Morbidelli and Gladman, 1998), whereas studies of large NEOs indicate that the primary source of these objects is the inner part. It remains unclear whether these differences in source regions have meaningful consequences for the probabilities of collision with Earth and for the impact velocities for NEOs with diameters between 100 meters and 1 kilometer.
- The population of smaller NEOs is more likely to be more affected than larger objects by collisions or non-gravitational force effects (Rubincam, 2000; Bottke et al., 2006; Walsh et al., 2008). The effects of such mechanisms could modify or even disrupt certain NEOs and thereby modify the overall orbit and size distributions of the population.

Additional survey and numerical work will be needed to settle these questions. In addition, although the population models based on Bottke et al. (2002) have predicted rather well the discoveries to date, their model may need to be re-calibrated as the survey is extended to smaller objects. Furthermore, as we pass 90 percent survey completion, we are approaching the tails of the distribution of orbits where the model is far less robust.

The Size Distribution of NEOs and Potentially Hazardous NEOs

Most NEOs with diameters under half a kilometer remain undiscovered, although many of the larger objects in this size range have been identified in past surveys. Although the size distribution of these objects can be estimated by modeling NEO survey data (e.g., NEO discoveries plus accidental rediscoveries), our incomplete knowledge of these objects limits our ability to assess the nature of this impact hazard. To this end, Stokes et al. (2003) and NASA PA&E (2006) decided it was reasonable to attempt a conservative, upper-limit-type estimate of the NEO population over all sizes. They concluded that the cumulative number, N, of NEOs with diameters greater than D could be described by:

$$N = 942D^{-2.354},$$

where D is in units of kilometers. The exact number of NEOs greater than 1-kilometer in diameter is uncertain, but reasonable estimates as noted above, suggest it is somewhere around 940, in agreement with the above formula. Another calibration point for this function comes from detections of small objects (1- to 20-meter-diameter) entering our atmosphere (e.g., Brown et al., 2002; Silber et al., 2009; also,

[1] Spacewatch was one of the first NEO discovery systems, established in 1981 and run by the University of Arizona. The LINEAR program at MIT Lincoln Laboratory is funded by the United States Air Force and NASA and was the most successful NEO search program from 1997 until 2004.

Chapter 4). The number of potentially hazardous NEOs has been estimated to be 21 percent of the above function (Stokes et al. 2003; see also Bottke et al., 2002).

More recent estimates of the distribution of sizes under 1 km come from Harris (2009), who "debiased" the existing database of NEO discoveries and accidental rediscoveries using the methods described in NASA PA&E (2006). His work indicates that somewhere between the calibration points described above, the NEO size distribution deviates from the above formula by factors of a few, suggesting that the curve is steeper for very small NEOs and shallower for intermediate sizes between 100 meters and 1 kilometer (Figure 2.4). The apparent "dip" in the NEO size distribution is consistent with earlier estimates made by Rabinowitz et al. (2000) using a more limited set of data produced by the Spacewatch survey. This dip is also broadly consistent with small, fresh crater populations found on both the Moon and Mars (e.g., Baldwin, 1985; Ivanov et al., 2002).

We do not know the specific orbits of undiscovered NEOs, but we can use what we know about their population and size distribution to perform a probabilistic "risk assessment" for this fraction. We assume that the undiscovered objects follow the above model distribution for NEO orbits and sizes. We can pick an object randomly from this distribution of orbits and calculate the annual probability of its impact on Earth. When an object is found and its orbit becomes known, it is removed from the pool of random objects. This newly discovered object may or, much more likely, may not have a trajectory with appreciable probability of impacting Earth. If it were on a potential impact trajectory, we would follow it closely to decide on countermeasures, as discussed in Chapter 5. If it were non-hazardous, then our total assessed statistical risk from the remaining undiscovered objects would be decreased to a lower value that we refer to as the "residual risk."

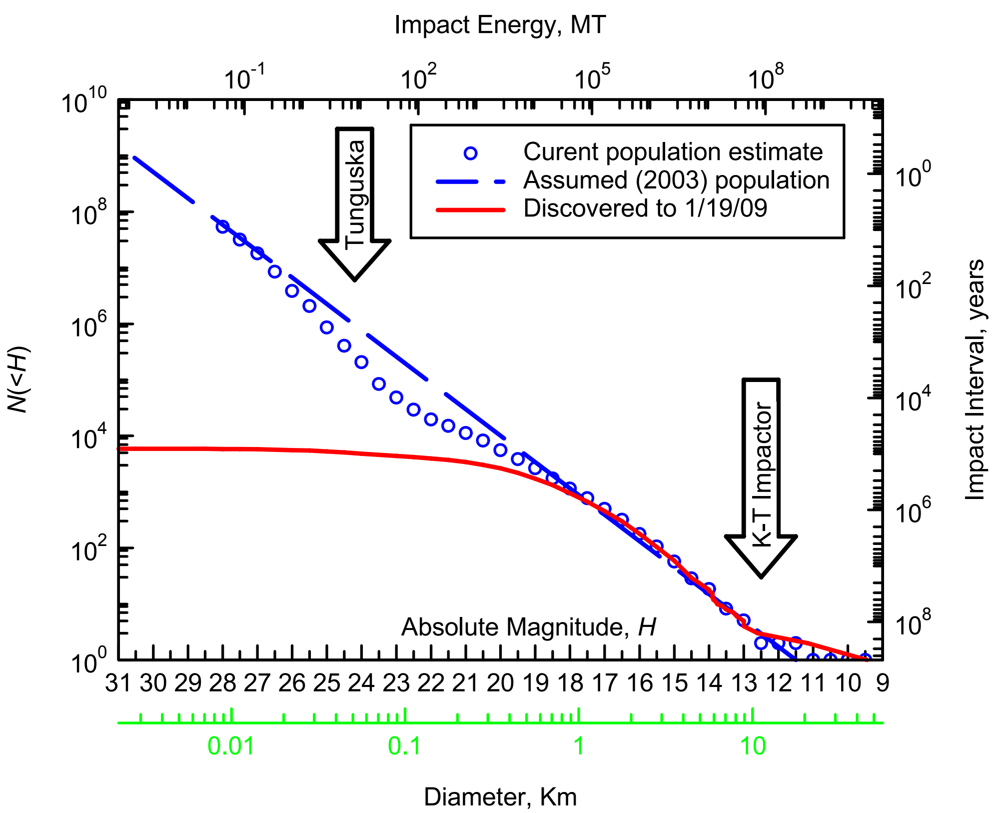

FIGURE 2.4 Numbers, N, of objects brighter than absolute magnitude *H* (see Appendix E) as a function of *H*. Ancillary scales give the average impact interval (right), impact energy in megatons of TNT for an assumed velocity of 20 km/s (top), and NEO diameter determined from the absolute magnitude using an average value for the NEO albedo. Variance in impactor velocity and albedo will result in uncertainties in the calculation of impact energy and NEO diameter. Note: "K-T" refers to the boundary between geological eras set 65 million years ago. SOURCE: Courtesy of Alan W. Harris, Space Science Institute.

We elaborate below on the process of statistical risk reduction. Risk *assessments* reflect our lack of perfect knowledge. Disregarding non-gravitational forces for sake of discussion, we can think of all NEOs as being on deterministic trajectories, so that the probability of an impact of a given size NEO over a prescribed time period is either one or zero. Surveys and tracking only affect our *assessment* of the risk in the same sense as looking both ways before you cross the street. Observation does not affect the distribution of either cars or NEOs, but is indispensable for determining what actions should be taken to remain safe in both situations.

Having determined the sizes and distribution of orbits for NEOs, we want to understand the risk to human life and property that is presented by various sizes of NEOs. Although the impact of a large NEO (diameter greater than 1 km) anywhere on Earth would have major consequences in terms of loss of life and damage to property, the frequency of such impacts is very low (Figure 2.4, Table 2.1) and thanks to Spaceguard we have already detected nearly 85 percent of such objects. None of those detected objects has a significant chance of impacting Earth in the next century.

TABLE 2.1 Approximate Average Impact Interval and Impact Energy for NEOs

Type of Event	Characteristic Diameter of Impacting Object	Approximate Impact Energy (MT)	Approximate Average Impact Interval (years)
Airburst	25 m	1	200
Local scale	50 m	10	2000
Regional scale	140 m	300	30,000
Continent scale	300 m	2,000	100,000
Below global catastrophe threshold	600 m	20,000	200,000
Possible global catastrophe	1 km	100,000	700,000
Above global catastrophe threshold	5 km	10, 000,000	30 million
Mass extinction	10 km	100,000,000	100 million

NOTE: This table provides only very approximate long-term average data for impact energy (also known as kinetic yield) and impact interval. The correlation of impact diameter with scale of damage and impact energy is based on assumptions delineated in Stokes et al. (2003). Warning: There may be significant variability is the scale of damage and impact energy depending on the velocity and physical/chemical characteristics of the impacting NEO. MT stands for megatons, which refers to the chemical energy release of a million tons of TNT.
SOURCE: NASA PA&E (2006), updated by Harris (2009).

Damage Produced by the Impact of NEOs

To evaluate the risk posed by NEOs, we must estimate the distribution in time of impact energy on Earth. This distribution can be computed from three components. The first component is the collision probability of potentially hazardous NEOs with Earth, which is a function of the distribution of orbits. Stokes et al. (2003) estimated that the average collision rate with Earth per single NEO is 1.6×10^{-9} yr^{-1} and per single potentially hazardous NEO is 8.4×10^{-9} yr^{-1}. The second component is the impact velocity distribution of potentially hazardous NEOs with Earth, which again is a function of the distribution of orbits. Stokes et al. (2003) used an impact velocity for potentially hazardous NEOs striking Earth of 20 km/s in their computations. The third component is the mass distribution of potentially hazardous NEOs striking Earth. This component is obtained by calculating the masses of the objects on the assumption that they have densities of 2.5 g cm-3. Table 2.1 is based on such information to provide an approximate indication of the average impact interval and impact energy for objects of various sizes.

Even were these data accurate, the determination of impact hazard would remain challenging for the following reasons:

- The direct and indirect effects produced when an asteroid or comet strikes the land or ocean are only poorly understood at present;
- The population of our planet is not uniformly distributed. For example, there is a higher population density near coastlines, where people may be susceptible to impact-driven tsunamis (whose damage potential is very uncertain);
- Until the population of small NEOs is understood, we can only characterize impact effects of undiscovered objects statistically. As noted above, most impact simulations indicate the likelihood that human life will be significantly affected by impacts over short timescales (i.e., under 1,000 years) is low. However, as we have not yet detected and characterized all NEOs, it is possible (but very unlikely) that an NEO will "beat the odds" and devastate a city or a coastline in the near future;
- While actuarial studies provide an assessment of property values, and may be used to place a value on a human life, it is very challenging to measure, for example, the value of religious, historical, ecological, cultural, and political sites, as well as of entire societal entities (such as ethnic groups, cities, and nations). These values may vary greatly across communities, regions, and nations;
- Beyond very crude estimates, we do not know the size threshold for impacts that would lead to a global catastrophe and kill a significant fraction of Earth's population due to firestorms or climate change and the associated collapse of ecosystems, agriculture, and infrastructure. There may not even be a well-defined threshold, because global effects probably depend critically on impact location and surface material properties (e.g., land, sea, ice sheet), season, and so on.

As Stokes et al. (2003) provide an in-depth discussion of these issues, there is no need to reproduce it in detail here.

Land Impacts That Are Incapable of Producing Global Effects

Land impacts correspond to damage produced by asteroids or comets that either strike the ground or explode low enough in the atmosphere to produce damage on the ground. Stokes et al. (2003) based their damage assessments on the modeling work of Hills and Goda (1993). According to their estimates, hard, stone objects between 40 and 150 meters in diameter explode upon entry into Earth's atmosphere and generate airbursts capable of producing surface damage. In this manner, they are similar to the Tunguska airburst.

Larger, more energetic impacts naturally produce destruction over a wider area. As the size of the damage zone increases, more cells within the gridded map in the Monte Carlo code are affected, though damage decreases as a function of distance from the impact site. To account for a range of outcomes, error estimates were included that accounted for minimum, nominal, and maximum numbers of fatalities per event.

The results from the Stokes et al. (2003) Monte Carlo analysis indicate that 75 percent of all impacts do not produce any fatalities because they impact the oceans or uninhabited land areas. The most common impact events that produce highly lethal results are the smallest ones (<200 m). Though their blasts are smaller in scope, their larger numbers give them more chances to affect a highly populated region.

Our understanding of the immediate damage produced by land impacts capable of producing craters is reasonably mature because their effects are constrained by nuclear weapon tests as well as craters on planetary surfaces. For airbursts, however, a lot of work is needed to improve our understanding of their consequences. For example, many groups have studied the 1908 Tunguska blast. Using insights from nuclear blast data as well as seismograms and barograph records of the Tunguska event, scientists estimated that the height of the explosion was about 10 km and that the energy yield was 10 to 20 MT (Chyba et al., 1993). According to the new estimate of size distribution made by Harris (2009), the average interval between such events on Earth would be on the order of one every 2,000 years.

Work by Boslough and Crawford (1997; 2008), however, indicates that a much lower yield could produce the same effects. They found that asteroid airbursts do not act like point explosions in the sky (e.g., like a nuclear bomb explosion) but instead are more analogous to explosions along the line of descent. In an airburst, kinetic energy (see Appendix E) is deposited along the entry path, with significant downward momentum transferred to the ground. Accordingly, they suggest that smaller explosions with net yields of 3 to 5 MT may be sufficient to produce Tunguska-like impact events. If true, the average interval between Tunguska-like events using the Harris (2009) size distribution (see Figure 2.4) would be on the order of a few hundred years. These results would increase the calculated hazard from smaller objects, perhaps as small as 30 meters or so. Further research is needed to better characterize this threat.

Tsunamis Produced by Ocean Impacts

Ocean impacts from asteroids or comets affect their immediate surroundings but also have the potential to launch tsunamis that inundate coastlines and affect populated areas. Because tsunamis can potentially affect a wide area and because people like to live along coastlines, impact-driven tsunamis may present a disproportionate contribution to the total hazard from small NEOs.

In the Stokes et al. (2003) model, impact-driven tsunamis were simulated using the results of Chesley and Ward (2003) (see also Chesley and Ward, 2006; Ward and Asphaug, 2000). Ocean runup and damage to infrastructure along coastlines were computed as functions of impactor size and distance to the coastline. The population residing along different coastlines was taken from the work of Small et al. (2000). Given the many uncertainties in the model (e.g., precise shape of the coastline, depth of the sea floor adjacent to the coastline, harbor obstructions, distance of people and property from the coastline, and so on), Stokes et al. (2003) assigned large lower and upper bounds to the assignment of damage within each geographic cell in the Monte Carlo analysis.

There is considerable uncertainty about the nature and damage produced by impact-driven tsunamis, in large part because (1) we cannot easily do direct experiments, (2) impact-driven tsunamis present a difficult non-linear modeling problem; computer simulations need extremely high resolution and fidelity to treat important factors such as breaking waves, and runup along a specific coastline, (3) the precise nature of the coast and sea floor near population centers strongly affects the results (e.g., consider the Pacific coast versus the shallow Gulf coast), and (4) loss of life may be avoided by early warnings of an incoming tsunami.

The classic work in this field is from Van Dorn et al. (1968), who used nuclear detonation data to show that the waves produced by a large blast would likely break upon the continental shelf. Their motivation for this study was to show that tsunamis produced by nuclear blasts make poor tactical weapons if the goal is to knock out enemy submarines lying along the coast of the United States. The idea that large waves break at considerable distances off-shore is now referred to as the “van Dorn” effect (e.g., Korycansky and Lynett, 2007). Using the original Van Dorn report as a guide, Melosh (2003) argued that impact-driven tsunamis would have similar wavelengths and thus would also break along continental shelves. He predicted the damage from these events would be minimal. Korycansky and Lynett (2005) numerically confirmed the existence of the Van Dorn effect, but Korycansky and Lynett (2007) pointed out that some ocean runup is still expected from waves that break. They suggested their work should be incorporated into next-generation Chesley and Ward (2006)-type models to better determine damage from these events. (Note that the Van Dorn effect could only apply where there are continental shelves. Small amounts of bottom friction may nullify the effect—it remains hypothetical.)

At present, our assessment of the impact hazard is limited by our understanding of impact-driven tsunamis. The uncertainties of NEO impact tsunamis therefore recommends three research areas: (1) the coupling of impact energy into ocean wave energy, both through water impacts and through airbursts, (2) the propagation of impact-induced waves across oceans, and (3) the effect on the world's coastlines.

Impacts Capable of Producing Global Effects

The motivation for the original Spaceguard Survey was to find all of the larger than 1-kilometer in diameter NEOs capable of striking Earth. According to Toon et al. (1997), 2- to 3-kilometer-diameter asteroid impacts may be capable of causing global damage due to the firestorm generated by infall of impact debris or indirectly by affecting the climate and producing a so-called "asteroid winter." Given the uncertainties in these calculations, Stokes et al. (2003), like other groups before them, decided to be conservative, and assumed that all objects with diameters greater than 1.5 kilometers rather than 2 to 3 km would cause a global catastrophe.

Nonetheless, the true hazard represented by multi-kilometer impactors is only modestly understood at present. Other than Toon et al. (1997) and a few other groups, little modeling has been done on the worldwide environmental effects produced by such impactors other than the one associated with the now-famous impact of a ~10 km object 65 million years ago that apparently resulted in the extinction of the dinosaurs. More work in this area is clearly needed.

Long Period Comet Impacts

Stokes et al. (2003) provide considerable description of the threat represented by long period comets, and there is no need to repeat their arguments here. In brief, they find that the comet hazard constitutes only a tiny fraction (of order <1 percent) of the total risk to life on Earth by impacting NEOs (prior to the Spaceguard Survey) and that producing a complete catalog of hazardous long-period comets is far beyond the abilities of any proposed survey. For these reasons, they suggested that limited resources would be better utilized in finding and cataloging Earth-threatening near-Earth asteroids and short period comets. With the completion of the Spaceguard survey (detection of 90 percent of NEOs >1 kilometer in diameter), long-period comets will no longer be a negligible fraction of the remaining statistical risk, and with the completion of the George E. Brown, Jr. Near-Earth Object Survey (90 percent of NEOs > 140 meters in diameter), long period comets may dominate the remaining unknown impact threat. Furthermore, these comets present a difficult challenge as they are large objects and we will have only a short warning time (months to a very few years maximum) before impact. Thus mitigation options are very limited, as noted in Chapter 5.

Assessing the Hazard

From their Monte Carlo analyses described above, Stokes et al. (2003) estimated the hazard from all potential impactors in terms of fatalities per year. However, since 2003, new information has been presented that affects the shape of the hazard curve (Figure 2.5). For example:

- The NEO and potentially hazardous NEO size distributions may not follow the simple law as shown by the dashed line in Figure 2.4 but instead may have a dip, as illustrated by the open circles. If so, the frequency of impacts of objects with diameters in the 50 to 500 meter range might decrease by a factor of 2 to 3 below the Stokes et al. (2003) estimates;
- The number of fatalities from impact-driven tsunamis in the Stokes et al. (2003) analysis was treated inconsistently, with different numbers of fatalities used in separate parts of the calculation;

• The ground damage produced by airbursts from Tunguska-like events may have been underestimated. Increasing the area of damage in the Monte Carlo analysis by such events from impactors in the size range of about 50 to 150 meters and lowering the size threshold for surface damage, increases the risk from such objects.

These revised factors, illustrated in Figure 2.5, yield the fatalities per impact event versus size of impactor (Harris, 2009). There is a tail on the fatalities curve at small diameters, which reflects the increase in statistical risk associated with airburst events, and revision downward in the deaths associated with tsunamis resulting from ocean impacts. However, this latter revision may not be warranted. Above the conservatively assumed global catastrophe threshold of 1.5 km, the number of fatalities ramps up from 10 percent of the world's population, to the entire population above 10 km. Clearly, there are many assumptions in developing such models that result in difficult-to-determine uncertainties in the calculated fatalities. Nonetheless, this Figure 2.5 provides a useful illustration of the significant increase in potential destruction and death with impactor size.

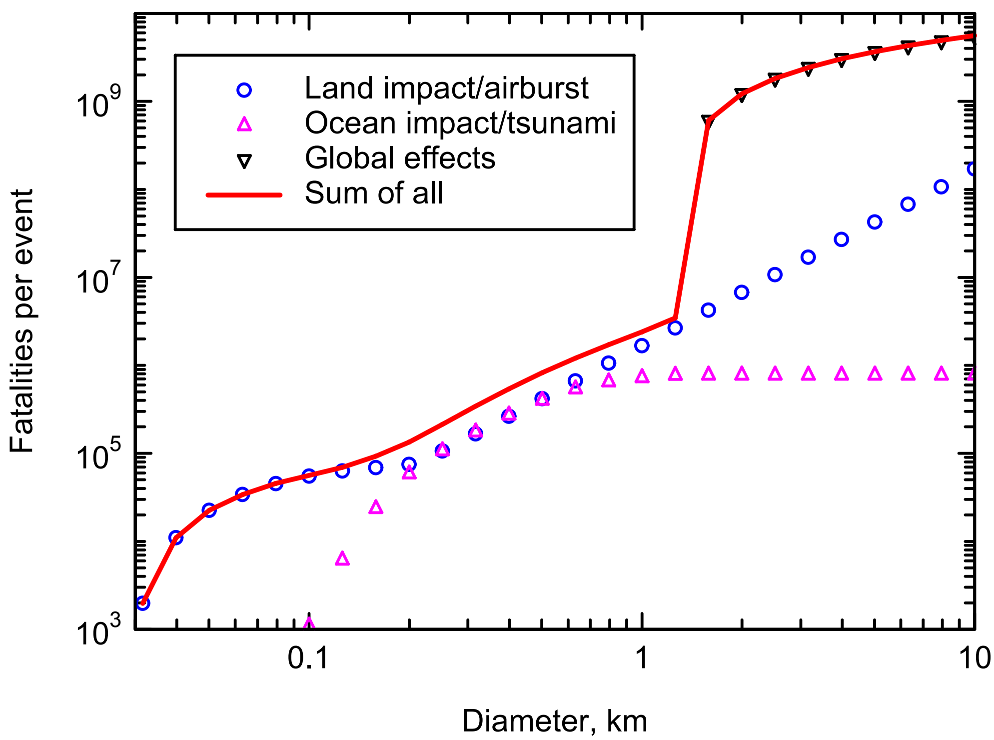

FIGURE 2.5 Model of fatalities per event for impacts of various size NEOs. The solid curve represents the total fatalities associated with both ocean and land impacts, including those with global effects. The sharp increase in the solid (red) curve reflects the assumption of a large increase in fatalities for an impact that crosses the global-effect threshold. SOURCE: Courtesy of Alan W. Harris, Space Science Institute.

To assess the effectiveness in reduction of statistical risk from the various survey activities, consider the predicted average annual fatalities derived by multiplying the expected deaths per event by the frequency of events of a certain size. This risk is "actuarial" and is an average of many thousands of years with few fatalities and a single low-probability, high-fatality impact year. Nevertheless, it is an objective method that can be used for order-of-magnitude comparisons with other risks that take place on radically different time scales. Figure 2.6 shows such a figure from Harris (2009) for the NEO population before the Spaceguard Survey. The plot shows fatalities per year and clearly indicates that most of the threat comes from the larger objects that exceed the global catastrophe threshold, even though the probability of an impact by these objects is very low relative to that for smaller objects. The two sets of histograms are based on (1) the potentially hazardous NEO population of Stokes et al. (2003) and their assumed hazard due to airburst and tsunamis, and (2) the recalculation based on the revised population curves shown in Figure 2.4 and reassessed impact hazard for airburst and tsunamis from Harris (2009), as illustrated in Figure 2.5, which, as noted earlier, may not be warranted.

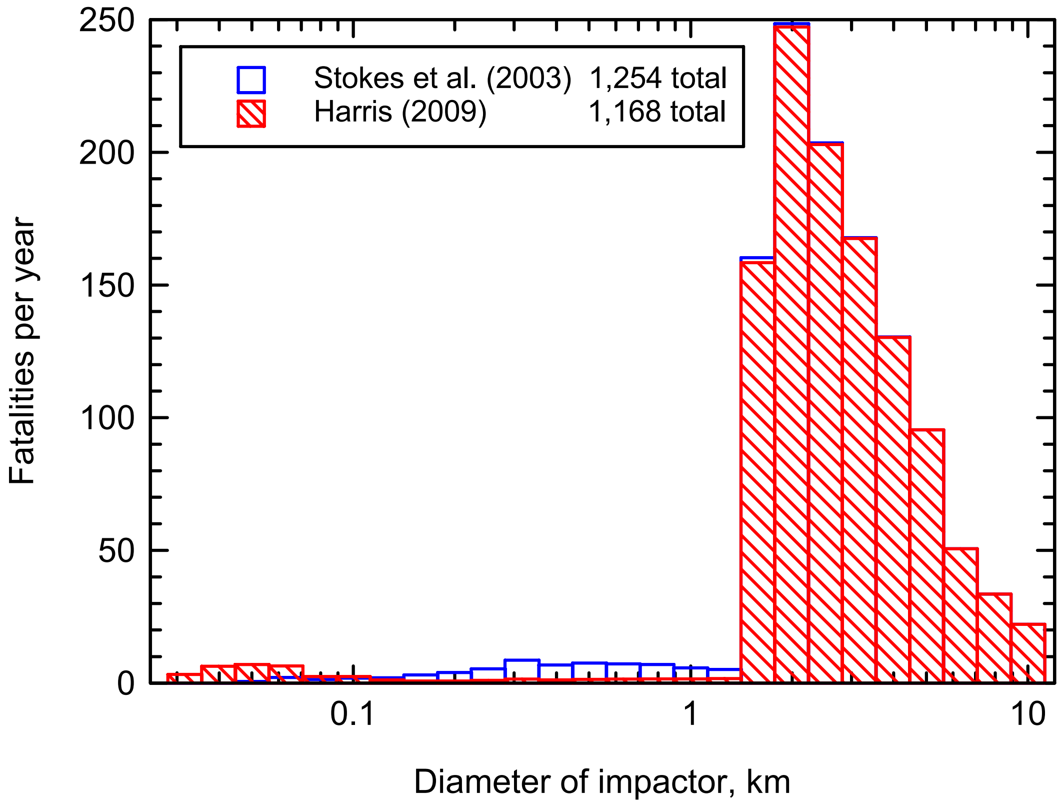

FIGURE 2.6 Estimated average fatalities per year for impacts by asteroids of various sizes calculated for the circumstances prior to the Spaceguard Survey. One curve references the data used in the Stokes et al. (2003) study. The new revised data includes corrections resulting from understanding of the threat due to tsunamis and airbursts, and recent revisions to the size distribution of NEOs (see Figure 2.4). SOURCE: Courtesy of Alan W. Harris, Space Science Institute.

Assuming that 85 percent of the NEOs with diameters larger than 1 kilometer have been discovered, which is close to the present state of affairs, Harris (2009) calculated the hazard statistics shown in Figure 2.7. Here the reassessed risk presented by the remaining 15 percent of the NEOs with diameters greater than 1 kilometer is comparable to that from all smaller objects. Figure 2.7 predicts that, in an actuarial sense, there is a long-term statistical average of about 91 fatalities worldwide per year due to impacts. Because the assessed statistical hazard from mid-range objects has dropped, the overall hazard has decreased as well. The drop from >1000 to 91 expected fatalities per year clearly demonstrates the results of the Spaceguard Survey to date, which has "retired" the statistical risk from most objects above the assumed global catastrophe threshold. Using the Stokes et al. (2003) data, the data for asteroids smaller than 1 kilometer is "humped," with a peak near 300 to 400 meters. This hump is significantly reduced when more realistic assessments are made of the effects of impact-driven tsunamis.

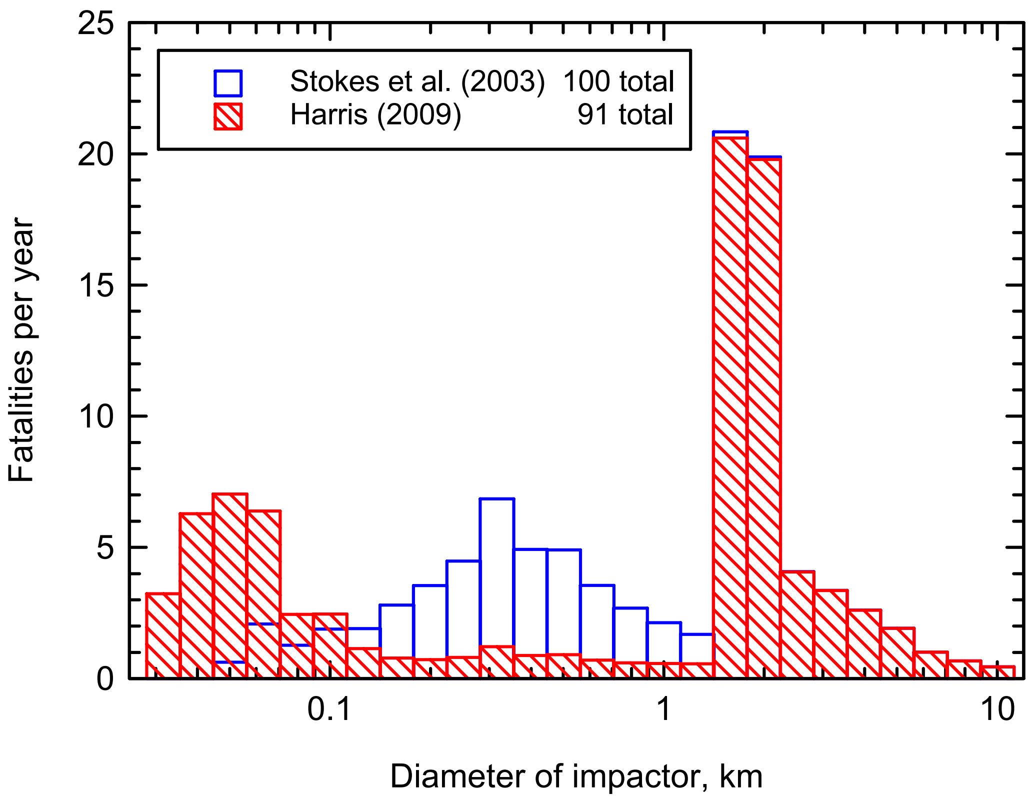

FIGURE 2.7 Estimated average fatalities per year for impacts by asteroids of various sizes calculated for the circumstances after 85 percent completion of the Spaceguard Survey. One curve references the data used in the Stokes et al. (2003) study. The new revised data includes corrections resulting from improved understanding of the threat due to tsunamis and airbursts, and recent revisions to the size distribution of NEOs (Figure 2.4). SOURCE: Courtesy of Alan W. Harris, Space Science Institute.

The residual hazard was used to establish the Stokes et al. (2003) goal that a future survey should try to identify 90 percent of the NEOs with diameters of 140 meters or greater. This limiting value, according to a potentially hazardous NEO survey simulation, could remove a significant proportion of the remaining statistical hazard that still exists after the conclusion of the Spaceguard Survey. Completion of this survey does not change the probability of Earth impact for any undetected NEO. However, if none of the objects detected in the survey is on a collision course with Earth, the total statistical risk of impact is decreased due to reduction in the total number of unknown potentially hazardous NEOs. Nonetheless, this survey may detect one or more NEOs on a collision course with Earth. (Carrying out a survey, per se, does not remove whatever risk there is; we just learn more about that risk.) In carrying out this survey, a substantial fraction of NEOs with diameters 50 meters and above will also be discovered and catalogued. Although not specifically designed for the purpose, such surveys may also detect as many as half of the NEO "imminent impactors" larger than 10 meters in the hours to months prior to impact with Earth. Discovery of such objects shortly before impact provides an opportunity to save lives by evacuation rather than by our changing of their orbits.

Based on these results, one could argue that a change is needed in the minimum size of the object to be included in the search, say, from 140 meters down to 50 meters. Nevertheless, the committee concluded that work on detecting these smaller objects, should not be at the expense of detecting objects 140-meters and greater in diameter (see recommendation in Chapter 3). Additional information could change the relative statistical hazard associated with the various size ranges of NEOs as we obtain:

- Orbital distributions and collision probabilities for sub-kilometer-sized impactors;
- Estimates of the effects of Tunguska-like and larger impacts, including tsunami damage;
- Maps that more realistically account for human population distribution and growth.

As was clearly stated in the Stokes et al. (2003) and NASA PA&E (2006) studies, completion of the survey as currently conceived will result in a significant amount of the residual statistical risk residing with the long-period comet population.

Warning Time for Mitigation

A key issue in the hazard from NEOs is that the length of time needed to execute a mitigation strategy involving orbit change is likely to require acting before our knowledge of the trajectory is sufficiently accurate to know with high confidence that an impact would occur without mitigation. It is possible, therefore, that action to mitigate could be deferred until it is too late if plans are not already in place to act when the probability of impact reaches some level that is well below unity. As addressed in Chapter 5, the time required to mitigate optimally (other than only via civil defense) is in the range of years to decades, but this long period may require acting before we know with certainty that an NEO will impact.

Chodas and Chesley (2009) have simulated the discovery of objects that would impact within the 50 years starting at the beginning of the next generation of surveys (see Chapter 3), using estimates of the (decreasing) orbital uncertainty as observations are accumulated. While there are many assumptions in this approach, the most important is whether or not the surveys and the follow-up programs to determine the orbits will be funded and will operate as assumed. Chodas and Chesley (2009) assume that an NEO is declared "truly hazardous" and worthy of mitigation preparations when the probability of hitting Earth reaches 0.5 (any other assumption regarding the decision point is also easily simulated). In this simulation, about 90 percent of impacting NEOs larger than about 140 meters in diameter are discovered in a 10-year survey. The temporal distribution of discoveries in this simulation showed that several percent of the 140-meter sized objects that impact do so before discovery, but the total number of impactors per century is not large, so that a few percent represent an exceptionally unlikely event. Most of the impactors in this size range are discovered to be truly hazardous within several years of discovery, typically at the next time that the object is in a location in which it is viewable, thus providing warning times of a decade to several decades. By contrast, more than 10 percent of the objects larger than 50 meters that would impact within 50 years do impact before discovery and there are many more of these than of the larger objects. Such smaller objects would generally be found to be truly hazardous within weeks to months before impact. Objects in the size range 10 to 50 meters make up the majority of all potentially hazardous NEOs larger than 10 meters. While the damage that could be caused by one of these smaller objects is smaller than for a larger object, those smaller ones that are detected are likely to be found at most hours to months prior to their final plunge, with civil defense being the only plausible mitigation strategy.

Currently, by far the most probable scenario is that of a small impactor, likely to cause at most only local destruction. However, the assessed probability of any particular scenario is changing with time as the next generation surveys discover most of the larger objects and our understanding of impact processes, such as airbursts and tsunami generation, improves. Thus, planning for mitigation must continue to evolve over time. Furthermore, when working with the statistics of small samples, and particularly when less-likely scenarios have outcomes that are so much more catastrophic than the most likely scenario, one should not assume that the next event will be the most likely one.

TABLE 2.2 Expected fatalities per year, worldwide, from a variety of causes

Cause	Expected Deaths Per Year
Shark attacks	3-7
Asteroids	91
Firearms accidents	2,500
Earthquakes	36,000
Malaria	1,000,000
Traffic accidents	1,200,000
Air pollution	2,000,000
HIV/AIDS	2,100,000
Tobacco	5,000,000

NOTE: The entries in this table are of various types. For example, the fatality rates given for shark attacks, firearms, earthquakes, traffic accidents, and HIV/AIDS entries, are extrapolations, based on past reported individual deaths due to these causes, estimates of the completeness of these reports, and the assumption that future such deaths will continue at the same average rates (or straightforward extrapolations from them). The asteroid impact entry has been treated in this chapter and is based on models for impact and tsunami effects, an assumption of ecological collapse above some global catastrophe threshold, and a statistical calculation of risk based on the known NEO size distribution, with the temporal rate expected to vary enormously from the rate given, i.e., to be zero most years, sizable in a relatively few years, and enormous in only extremely few years over a time span of a billion years. The malaria and tobacco fatalities entries are inferences based on plausible assignments of causes of deaths; such assignments are, individually, far less reliable than, e.g., in the case of shark attack fatalities. Mitigation Panel member Mark Boslough wanted an additional entry in this table for fatalities due to climate change. The steering committee disagreed with including this entry because it did not think a reliable estimate is available, among other reasons. Dr. Boslough has written a minority opinion as Appendix D.

SOURCE: Data for this table were derived from a variety of sources, including the World Health Organization:
Air pollution: http://www.who.int/mediacentre/factsheets/fs313/en/index.html and http://whqlibdoc.who.int/hq/2006/WHO_SDE_PHE_OEH_06.02_eng.pdf.
Asteroids: Harris (2009) and Figure 2.7;
Earthquakes: Worldwide, 1970-2009, from USGS, cited in http://earthquake.usgs.gov/earthquakes/eqarchives/year/;
HIV/AIDS: http://data.unaids.org/pub/EPISlides/2007/2007_epiupdate_en.pdf;
Malaria: http://apps.who.int/malaria/wmr2008/malaria2008.pdf;
Shark attack: International Shark Attack File, http://www.flmnh.ufl.edu/fish/sharks/ statistics/statsw.htm.
Tobacco: http://www.emro.who.int/TFI/PDF/TobaccoHealthToll.pdf; and
Traffic accidents: http://whqlibdoc.who.int/publications/2004/9241562609.pdf.

Societal Elements of NEO Risks

Unlike most other known natural hazards to humanity, such as earthquakes, volcanic eruptions, tsunamis, hurricanes, and tornadoes, NEO impacts present a very large spread of disaster scales ranging from small property damage to global extinction events. Larger impacts may result in global climatic changes that can result in famine and disease, infrastructure failure and, potentially, societal breakdown. Smaller impacts could be misinterpreted and thereby conceivably even trigger wars. While there are numerous small incidents that present little risk to people and property, major impact events occur very infrequently. Impacts represent the extreme example of “low-probability, high-consequence” events. Although the probability of such a major impact within the next century may be small, a statistical risk of such an impact remains. Because of the nature of the impact threat, the expected fatality rate from impacts is an "actuarial" estimate based on calculations with attempted conservative assumptions. All the other estimates are based on attribution of causes of actual fatalities from ongoing threats that may change in the future.

In contrast to other known natural hazards, there has been no significant loss of human life to impacts in historical times, due to the low frequency of major impacts and the higher probability of impact in unpopulated (notably the oceans) than populated regions. Unlike the other hazards in Table 2.2, the hazard statistics for NEOs are dominated by single events with potentially high fatalities separated by long time intervals. Should scientists identify a large life-threatening object on a collision course with Earth, tremendous public resources to mitigate the risk would almost certainly be brought to bear. However, options for effective mitigation become much more limited when threatening objects are identified with only months to years, rather than decades or centuries, before impact. Thus, one of the greatest elements of risk associated with NEOs is the public expectation that governments will protect them against any threat from NEOs, coupled with an unwillingness so far of governments and agencies to expend public funds in a concerted effort to identify, catalogue and characterize as many potentially dangerous NEOs as possible as long before a damaging impact event as feasible.

Given these issues, there are a number of concerns that can be addressed by an NEO detection, characterization and mitigation program:

1. The statistical risk to human life and property associated with impacts of NEOs is real, but falls outside the everyday experience of most of humanity. This risk must therefore be communicated effectively to the community at large in the context of other natural disasters, particularly those that the local community is likely to encounter. Scientists must carefully assess and explain the hazard so that appropriate public policy measures, commensurate with the level of risk, can be put into action.
2. There must be an assessment of the statistical risk from NEOs that is reasonable and acceptable to the general public. The George E. Brown, Jr. Near-Earth Object Survey Act 2005 mandate of discovery of 90 percent of objects 140 meters in diameter or greater was based on many assumptions about impact hazards. However, periodic reassessment of the impact threat needs to be performed as the knowledge base on NEO populations, their physical characteristics, and impact-associated processes increases.
3. It is important to assess the length of time that the public is prepared to wait for scientific surveys to reach target goals of detection and characterization, and for mitigation technologies to reach desired maturity. Whereas surveys will never be 100 percent complete, given the diversity of the objects, their origins, and their orbits, it is important to make surveys as close to 100% as feasible to assure the public that all reasonable precautions are being taken.
4. An assessment is needed of the levels of expenditure that the public is prepared to accept in order to reach such goals for detection, and similarly for characterization, and mitigation. Although the costs are almost vanishingly small relative to other elements of the federal budget (other than advanced mitigation strategies), public support for such activities may be absent lacking demonstration of a clear and present threat.

Undoubtedly issues 2, 3, and 4 are strongly interrelated as higher mandated percentage detections of increasingly smaller objects over shorter time periods would drastically increase cost. Equally, a comprehensive near-term mitigation strategy to address the full spectrum of possible NEO threats would be more expensive than a phased program of technology development. In the following chapters, various scales of NEO detection, characterization and mitigation programs are presented that seek to identify a greater percentage of potentially threatening objects, and to expeditiously develop the knowledge and capability to mitigate the risk associated with them. In addition, a program of research activities is presented to provide better constraints of the threat presented by various classes of NEOs impacting in diverse environments.

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3

Survey and Detection of Near-Earth Objects

Congress has established two mandates addressing NEO detection for NASA. The first mandate, now known as the Spaceguard Survey, directed the agency to detect 90 percent of near-Earth objects 1 kilometer in diameter or greater by 2008. By 2009, the agency was close to meeting that goal. Although the estimate of this population is continually revised, as astronomers gather additional data about all NEOs (and asteroids and comets in general), these revisions are expected to remain. The 2009 discovery of asteroid 2009 HC_{82}, a 2- to 3-kilometer-diameter NEO in a retrograde ("backwards") orbit, is, however, a reminder that some NEOs 1 kilometer or greater in diameter remain undetected.

The second mandate, the George E. Brown, Jr. Near-Earth Object Survey section of the 2005 NASA Authorization Act, directed that NASA detect 90 percent of near-Earth objects 140 meters in diameter or greater by 2020. However, what the surveys actually focus on is not all NEOs, but the potentially hazardous NEOs. It is possible for an NEO to come close to Earth, but to never intersect Earth's orbit and therefore not be potentially hazardous. The surveys are primarily interested in the potentially hazardous NEOs, and that is the population that is the focus of this chapter. Significant new equipment (i.e., ground-based and/or space-based telescopes) will be required to achieve the latter mandate. Neither the White House budgeted nor Congress approved new funding for NASA to achieve this goal, and little progress on reaching it has been made during the past 5 years.

The criteria for the assessment of the success of an NEO detection mandate rely heavily on estimates that could be in error, such as the size of the NEO population and the average reflectivity properties of an object's surface. For many years, the average albedo (fraction of visible light reflected from the object's surface) of the NEOs was taken to be 0.11. More recent studies (Stuart and Binzel, 2004) determined that the average albedo was more than 25 percent higher, or 0.14; with significant variation in albedo present among the NEOs. The variation among albedos within the NEO population also contributes to the uncertainties in estimates of the expected hazardous NEO population. This difference implies that, on average, NEOs have diameters at least 10 percent smaller than previously thought, changing our understanding of the distribution of the NEO population by size.

Ground-based telescopes have difficulty observing NEOs coming from near the Sun's direction because their close proximity to the Sun—as viewed from Earth—causes sunlight scattered by Earth's atmosphere to be a problem and also poses risks to the telescopes when they point toward these directions. Objects remaining in those directions have orbits largely interior to Earth's; our understanding of their number is as yet very uncertain. In addition, there are objects that remain too far from Earth to be detected almost all of the time. The latter include Earth-approaching comets (comets with orbits that approach the Sun at distances less than 1.3 AU and have periods less than 200 years), of which 151 are currently known. These represent a class of objects probably doomed to be perpetually only partly known, as they are not likely to be detected in advance of a close Earth encounter. These objects could dominate the impact threat to humanity, after the completion of exhaustive searches for NEOs.

Thus, assessing the completeness of the NEO surveys is subject to uncertainties: Some groups of NEOs are particularly difficult to detect. Asteroids and comets are continually lost from the NEO population because they impact the Sun or a planet, or because they are ejected from the solar system. New objects are introduced into the NEO population from more distant reservoirs over hundreds of thousands to millions of years. The undiscovered NEOs could include large objects like 2009 HC_{82} as well as objects that will be discovered only months or less before Earth impact ("imminent impactors"). Hence, even though 85 percent of NEOs larger than 1 km might already have been discovered, and eventually more than 90 percent of NEOs larger than 140 meters will be discovered, NEO surveys should nevertheless continue, because objects not yet discovered pose a statistical risk: We must be constantly vigilant.

Finding: Despite progress toward or completion of any survey of near-Earth objects, it is impossible to identify all of these objects because objects can change their orbits for example due to collisions.

Recommendation: Once a near-Earth object survey has reached its mandated goal, the search for NEOs should not stop. Searching should continue to identify as many of the remaining objects and objects newly injected into the NEO population as possible, especially imminent impactors.

THE SPACEGUARD EFFORT

Recognizing that impacts from near-Earth objects represent a hazard to humanity, the United States, European Union, Japan and other countries cooperatively organized to identify, track and study NEOs in an effort termed "Spaceguard." From this organization, a non-profit group named the Spaceguard Foundation was created to coordinate NEO detection and studies, currently located at the ESA Centre for Earth Observation (ESRIN) in Frascati, Italy. The United States input to this collective effort comprises three aspects: telescopic search efforts to find NEOs, the Minor Planet Center (MPC) at the Harvard-Smithsonian Center for Astrophysics, and the NASA NEO Program Office at the Jet Propulsion Laboratory. Existing, retired, and proposed telescopic systems for the U.S. NEO searches are detailed below. Other telescopic survey, detection and characterization efforts are conducted worldwide, and work synergistically with U.S. telescopic searches (e.g., Asiago-DLR Asteroid Survey, jointly operated by University of Padua and the German space agency DLR; Campo Imperatore Near-Earth Object Survey at Rome Observatory; the Bisei Spaceguard Center of the Japanese Spaceguard Association). To date, the U. S. search effort has been the major contributor to the number of known NEOs. The functions of the two U.S. data and information gathering offices, the Minor Planet Center (MPC) and the NEO Program Office, are complementary. A European data and information gathering office, the Near-Earth Objects Dynamic Site (NEODyS) is maintained at the University of Pisa in Italy, with a mirror site at the University of Valladolid in Spain. These three services are described here.

Minor Planet Center (MPC)

The Minor Planet Center (MPC) serves as the clearinghouse for positional information from observers of minor planets (including all asteroids) from all observatories across the world. The MPC is charged with processing and publishing every single positional measurement made, worldwide, of asteroids, comets, and outer satellites of the Jovian planets. Its efforts are sanctioned by the International Astronomical Union (IAU), the international professional society for astronomers. The IAU provides guidance but currently only minor financial support for the MPC. Current MPC efforts are supported mostly by NASA's Near-Earth Object program, with a much smaller contribution from the Smithsonian Institution.

As of December 2008, the MPC had a data base of 59,000,000 observations of more than 435,000 small bodies, with a second data base of more than 10,000,000 observations of objects having no or incomplete orbital information. The MPC receives daily observations of small bodies. The MPC first identifies new observations with known objects, or determines that the object is new. All orbits of identified objects are updated and improved daily. Most, but not all, MPC processing is now automated.

Observations of near-Earth objects are made available to the public in less than 24 hours; comet observations can require up to a week to process and are largely not automated (Spahr, 2008).

All incoming observations from NEO surveys are checked routinely for potential NEOs. This process is now automated: any new discovery is assigned a probability code of being an NEO based on its orbit. New possible NEOs are posted on the web NEO Confirmation Page (NEOCP) in order to facilitate follow-up observations within minutes of posting. The NEOCP updating is 95 percent automatic; data and calculated orbits are publicly available.

Recent upgrades to computer equipment allow the MPC to calculate tens of thousands of orbit improvements per day. Access has also been established to a 1000+ node supercluster run by the Smithsonian Institution, and the MPC is purchasing nodes for this computer. The MPC is currently able to handle the large volumes of data expected in the near future from NEO discovery programs using larger telescopes.

Near-Earth Object Program Office

The Near-Earth Object Program office operates at the Jet Propulsion Laboratory for NASA, and is charged with coordinating the NEO observations program for NASA. This office is fully funded by NASA and maintains Web-accessible information about NEOs, including their close approaches to Earth as well as NEO discovery statistics.

The NEO Program Office also maintains the automated Sentry software, a collision monitoring system that continually scans the most current asteroid orbit data for objects that could hit Earth in the next 100 years. When a potential impactor is detected, its future orbit is calculated along with its uncertainty, and the results are published in the Sentry Risk Table on the NEO Program Office website.

Near-Earth Objects Dynamic Site (NEODyS)

The Near-Earth Objects Dynamic Site maintains web-accessible information about near-Earth objects including orbits, an information data base sorted by individual near-Earth object, and risk assessment of possible impact. The NEODyS is maintained at the University of Pisa, Italy, with a mirror image site at the University of Valladolid, Spain, to ensure that information is always accessible to users.

PAST NEO DISCOVERY EFFORTS

The survey and discovery effort for NEOs has advanced through several phases. Significant initial progress in the effort to identify the NEO population benefited greatly from the seminal efforts at many different telescope systems. The size of NEOs that can be detected is, however, related to the sizes of telescopes and their optics, cameras, and detection software, as well as to the observing strategy of the teams performing the search. In recent years, some previous NEO survey programs have ended or are being phased out of operation because surveys more capable of finding smaller-diameter NEOs have become operational, and the emphasis on detection has shifted to increasingly smaller diameter objects. These previous surveys, the Lowell Observatory Near-Earth-Object Search (LONEOS) and the Near-Earth Asteroid Tracking (NEAT) program, are described below.

Lowell Observatory Near-Earth-Object Search (LONEOS)

The Lowell Observatory Near-Earth-Object Search, operated by the Lowell Observatory, had the capability to scan the entire sky accessible from Flagstaff, Arizona, every month. The 0.6-meter diameter telescope could record objects about 100,000 times (12.5 magnitudes; see Appendix E) fainter than can be seen with the naked eye. The project, funded by NASA, began in 1993 and concluded at the end of February 2008. LONEOS discovered 288 NEOs.

Near-Earth Asteroid Tracking (NEAT)

The Near-Earth Asteroid Tracking program began in 1995 and was initially a collaborative effort between NASA, the Jet Propulsion Laboratory, and the U.S. Air Force. This program originally converted a Ground-based Electro-Optical Deep Space Survey (GEODSS) 1-meter diameter telescope on Haleakala, Maui, Hawaii, to the world's first fully automated asteroid-search telescope. Operations on the GEODSS telescope ended in 1999. In 2000, the NEAT program completed both the conversion of the Maui Space Surveillance System 1.2-meter diameter telescope on Haleakala, and the conversion of the 1.2-meter diameter Oschin telescope at Mt. Palomar, California, to become fully automated and to search for NEOs. NEAT ceased operations in 2007 after detecting over ~20,000 objects, ~430 of which were NEOs.

PRESENT NEO DISCOVERY EFFORTS

In 2005, five NEO detection programs were operational: Catalina Sky Survey (CSS); the Lincoln Near-Earth Asteroid Research (LINEAR) program; and Spacewatch, as well as LONEOS and NEAT. Today, only CSS, LINEAR and Spacewatch remain operational. These three NEO detection programs primarily address the congressional charge to detect 90 percent of NEOs down to 1-kilometer diameter.

Catalina Sky Survey

Of the three search programs currently in operation, the Catalina Sky Survey (CSS) currently discovers NEOs at the highest rate. CSS is a system of three telescopes, located at the Mt. Lemmon Observatory in Arizona, the Mt. Bigelow Observatory also in Arizona, and the Siding Spring Observatory in Australia (all funded by NASA). The Mt. Lemmon Observatory is the largest and most productive of these telescopes, having a 1.5 meter diameter mirror and 1.2 square degree field of view, enabling it to detect asteroids as faint as $V = 22$ (i.e., 22^{nd} visual magnitude; see Appendix E). The Siding Spring facility has a 0.5-meter-diameter telescope for discovery. The Catalina Observatory houses the original CSS telescope, which has a 0.7-meter diameter mirror. These telescopes work together to carry out sustained, highly productive searches for NEOs. Because two of these observatories are operating on the opposite side of Earth from the third, same night follow-up on a newly discovered object can usually be accomplished, facilitating the rapid determination of its orbit and thus an evaluation of the hazard posed by the object. Indeed, this follow-up technique allowed the CSS to both discover the asteroid 2008 TC_3, and determine that it would impact the Sudan within 19 hours. The CSS utilizes a human operator in analyzing observations, who can spot faint moving objects that current versions of automated software may miss. The CSS has discovered more than 2,100 NEOs.

LINEAR

The LINEAR program at MIT Lincoln Laboratory is funded by the United States Air Force and NASA and was the most successful NEO search program from 1997 until 2004. The goal of LINEAR is to demonstrate the application of technology originally developed for the surveillance of Earth orbiting satellites to discovering and cataloguing of NEOs. LINEAR consists of a pair of GEODSS telescopes at

Lincoln Laboratory's Experimental Test Site at the White Sands Missile Range in Socorro, New Mexico. These two 1-meter-diameter telescopes were eventually joined by a third telescope used for confirmation of NEO orbits, and were able to detect asteroids as faint as V=20. LINEAR has discovered 2,210 NEOs. LINEAR accounted for more than 50 percent of all near Earth object discoveries from 1998 to 2004. In 2005, the rate of discoveries by the Catalina Sky Survey increased substantially and overtook LINEAR.

Spacewatch

Spacewatch was one of the first NEO discovery systems, established in 1981 and run by the University of Arizona. Routine detections of asteroids and comets started in 1984 with a 0.9-meter diameter telescope on Kitt Peak, Arizona, and a relatively small CCD (see Appendix E) imaging array. Upgrades in 1989 enlarged the field of view and resulted in Spacewatch's first detection of an NEO. Automated software to identify and discover NEOs was implemented in 1990; this was the first time automated, real-time software was used for detection of moving cosmic objects and proved the efficiency of such software. In 2001, a second telescope 1.8 meters in diameter was added to the program. The smaller Spacewatch telescope typically detects NEOs brighter than V=21 over its field of view of 2.9 square degrees, while the larger telescope can potentially detect NEOs as faint as V=23 over a field of view of 0.7 square degrees. The larger telescope is primarily used for recoveries of previously discovered, fainter NEOs, to confirm their orbits, while the smaller telescope was used primarily for NEO discovery surveys. Spacewatch has discovered more than 700 NEOs. The Spacewatch program is anticipating transitioning from conducting discovery observations to a recovery/characterization role as more powerful surveys come online.

CURRENT SPACE-BASED DETECTION EFFORTS

No nation has had or currently operates a space-based observatory dedicated to the discovery and/or characterization of NEOs. Space-based observatories are, however, planned for launch that will help to discover and/or characterize NEOs, especially due to the sensitivity of the observatories' telescopes to infrared light, as explained below.

Asteroids in orbits that bring them close to Earth are especially menacing if they are dark and have evaded detection by ground-based surveys in visible light. Also, since the assumed albedo might not be representative of a dark object, the calculated diameter could also be misrepresented as smaller than the object's true diameter. But dark objects are especially detectable in infrared light. The bias against lower-albedo (darker) asteroids is reduced through the use of infrared observations in space: At the temperatures and albedos that dominate the solar system inside Mars' orbit, the diameters computed from infrared signals are more accurate than those derived from visible-light reflections from asteroids and comets. Thus, the detections of potentially hazardous NEOs by an infrared telescope (one sensitive to infrared light) will result in a more accurate size-frequency distribution for these objects. Additionally, the background from other astronomical sources is ~100 times lower at infrared wavelengths of 10 microns (a micron is one millionth of a meter) than at visible wavelengths, since most stars emit far less infrared light than visible light. This difference reduces the chance for interference from other strong astronomical sources. Combined with visible-light data, the albedos of NEOs detected in the infrared can also be derived. This derivation of albedos offers insight into composition and surface properties. The United States' NEOWISE mission (see below) will leverage this infrared advantage.

Canada and Germany are both building spacecraft (see below) that could contribute to the discovery of NEOs, especially those whose orbits are partially or fully inside Earth's. These NEOs are less able to be observed by ground-based telescopes because they are so close to the Sun, as seen from Earth. Spacecraft searching for NEOs from orbits where they can be positioned to observe objects, while the spacecraft is not pointed toward the Sun, have an advantage for observing NEOs with orbits largely inside Earth's orbit. Neither mission, however, will detect fainter or smaller objects than ground-based telescopes.

Wide-field Infrared Survey Explorer for Near-Earth Objects (NEOWISE)

The Wide-field Infrared Survey Explorer (WISE) is a NASA spacecraft mission launched in December 2009. WISE will produce a high sensitivity imaging survey of the entire sky in four infrared wavelength bands centered at 3.3, 4.7, 12, and 23 microns. It will deliver a catalog of sources and a calibrated, position-registered image atlas. Using a cooled 0.4-meter-diameter aperture telescope and always looking 90 degrees from the Sun, WISE will conduct an all-sky survey for 6 months. Imaging is obtained simultaneously in the four bands, and every location on the sky will be imaged at least 8 times.

NASA has funded an enhancement to the baseline WISE mission, called NEOWISE, to facilitate solar system science. NEOWISE is expected to discover hundreds of new NEOs with sizes as small as ~100 meters in diameter. The advantage of this infrared-detected sample is that it is inherently less biased against discovery of low albedo objects than optical surveys, and, combined with ground-based visible observations of the same NEOs, can be used to determine asteroid diameters with errors of only a few percent.

Canada's Near-Earth Object Surveillance Satellite (NEOSSat)

The Near-Earth Object Surveillance Satellite (NEOSSat) is currently being constructed in Canada as a joint venture between the Canadian Space Agency (CSA) and Defense Research and Development Canada, an agency of the Canadian Department of National Defense. NEOSSat is based upon a previous satellite, MOST, launched in 2003, which remains operational long after completion of its initial mission. Set to launch in mid 2010, NEOSSat is scheduled to operate continuously for at least one year and should operate considerably longer.

NEOSSat will conduct two simultaneous projects during its operational lifetime: High-Earth Orbit Surveillance System (HEOSS), which will monitor and track human-made satellites and orbital debris; and Near-Earth Space Surveillance (NESS), which will discover and track NEOs. NEOSSat will be the first satellite to be built on Canada's Multi-Mission Microsatellite Bus, and will be roughly the size of a large suitcase with a mass of approximately 75 kg. It will have a 15-centimeter-diameter mirror. This microsatellite will operate in a "Sun-synchronous" orbit at an altitude of ~700 kilometers.

NEOSSat will be the first dedicated space platform designed to obtain observations on both human-made and natural objects in near-Earth space. The NESS project will focus primarily on discovering NEOs interior to Earth's orbit. NEOSSat will expand overall knowledge of potentially hazardous asteroids, monitor NEOs for cometary activity, perform follow-up tracking of newly discovered NEOs, and explore the synergies between ground-based and space-based facilities involved in NEO detection.

Germany's AsteroidFinder

The German Aerospace Agency (DLR) has selected AsteroidFinder as the first payload to be launched under its new national compact satellite program. Currently, the spacecraft is planned to launch sometime in 2012 with a one-year baseline mission duration with the possibility of an extension; it is funded through the development stage. It will be equipped with a 30-centimeter-diameter telescope mirror. The satellite will operate in low-Earth orbit. Its primary goals are to estimate the population of NEOs interior to Earth's orbit, their size distribution, and their orbital properties. AsteroidFinder will thus aid in the assessment of the impact hazard due to NEOs.

ADDRESSING THE 140-METER REQUIREMENT: FUTURE GROUND- AND SPACE-BASED NEO DISCOVERY EFFORTS

The NASA Authorization Act of 2005 ordered 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 Earth. It shall be the goal of the Survey program to achieve 90 percent completion of its near-Earth object catalogue (based on statistically predicted populations of near-Earth objects) within 15 years after the date of enactment of this Act."

The 140-meter diameter requirement was based on the modeling presented in the 2003 NASA Science Definition Team (SDT) near-Earth object study. An impacting object with a 140-meter or greater diameter, which could cause major regional destruction on Earth, occurs on average every ~30,000 years.

To detect 90 percent of all potentially hazardous NEOs larger than 140 meters in diameter, a telescope must be able to reach a limiting magnitude of V = 24. With the magnitude limitations discussed above, CSS, LINEAR, and Spacewatch are incapable of meeting the goal of discovering 90 percent of all potentially hazardous NEOs larger than 140 meters in diameter or greater by 2020 or any later date.

FUTURE TELESCOPE SYSTEMS FOR NEO SURVEYS

The pursuit of NEOs as small as 140 meters in diameter requires that more advanced telescope systems be constructed and used to detect these objects. Required, for ground-based telescopes for example, are larger diameter telescope mirrors to increase light gathering power to observe smaller (therefore fainter at a given location) objects; imaging instruments with larger fields of view on the sky to maximize sky coverage for the surveys; more advanced observing strategies for optimizing NEO detection in the areas of the sky that are searched; faster operating detectors; and large data storage options. Because of the rate of motion on the sky of asteroids, exposures are limited to about 30 seconds. So a telescope needs to be able to gather sufficient light from dim objects in that short time to achieve the goal--a smaller telescope using longer exposures to reach that magnitude just will not do. Multiple smaller telescopes imaging the same field to make up the aperture will work, but smaller telescopes imaging fields non-simultaneously will not. There is cost, schedule, and technical performance risk involved with construction of any big diameter mirror or large detector, although the risk for such ground-based telescopes is less than that for spaceborne telescopes.

The new systems described below are examples of ones that could contribute significantly to the detection of NEOs that could impact Earth in the future, and thus support efforts required to meet the mandated goal.

Large Synoptic Survey Telescope (LSST)

The Large Synoptic Survey Telescope (LSST) is a survey project under development, sponsored by a large consortium, centered around a telescope with an 8.4-meter diameter mirror having a 9.6 square degree field of view. This survey would scan the entire sky accessible from its planned location on El Pachon, a developed site in Chile. The survey plan is to scan the visible sky twice per night every 3 to 4 days in five visible and near-infrared wavelength bands. The LSST can reach a limiting magnitude of V = ~25.1 for detecting NEOs. The major science goals for LSST include cataloging and characterizing all classes of moving objects in the solar system, and hence identifying NEOs. By building a telescope with a wide field of view to cover the sky quickly, coupled with a big mirror to detect faint objects, the LSST expects to use the same images to fulfill most of its science goals Each area of sky observed in one night will include two back-to-back 15-second image exposures, combined to become one 30-second exposure.

The output of the survey will include very large multi-color, multi-epoch catalogs of asteroids and comets, with precisely calibrated sky location and brightness. Simulations of LSST operations (c.f., Ivezic, 2009) show typical NEOs will have hundreds of observations spaced across the lifespan of the survey (10 years under 'normal' operations), and often more than 50 observations across 6 months, allowing for better characterization of the NEOs. The Moving Object Processing System (MOPS) developed for PanSTARRS1 (see below) is also under further development by the LSST team, for use in detecting and determining orbits for all moving objects. All data produced by LSST will be publicly available. Within 60 seconds of acquisition of an image at the telescope, real-time data processing will identify moving sources (e.g., NEOs) and forward the data to the MOPS system. Images will then be transmitted to the National Center for Supercomputing Applications at the University of Illinois, Champaign-Urbana, Illinois, for permanent storage, and to multiple Data Access Centers, which are designed for public queries of the LSST data and include additional data processing software.

According to the LSST project, LSST will be capable of detecting 90 percent of all potentially hazardous NEOs larger than 140 meters in about 17 years under normal (non-NEO optimized or dedicated) operations (c.f., Chesley, 2008). The LSST project's simulations using the LSST operations simulator and an NEO model supplied by PanSTARRS in MOPS (based on the Bottke et al. (2002) NEO distribution) show that by optimizing operations for NEO detection (a shared LSST), the required time could be reduced to about 12 years to detect 90 percent of all potentially hazardous NEOs larger than 140 meters (Chesley, 2008). These optimizations result in similar performance gains as for an entirely dedicated LSST, as simulated by S. Chesley for this report. They include exposing for longer time intervals in the area of the sky within +/- 10 degrees of the plane of Earth's orbit to observe fainter objects and detect NEOs at larger distances; limiting observations to only those three wavelength bands in which NEOs have the strongest signals; adding observations targeted to locations at 60- to- 90-degree angles away from the Sun, and within 10 degrees of the plane of and inside Earth's orbit, thus maximizing the surface of the NEO illuminated by the Sun.

Design and development for LSST has been ongoing for more than 4 years, but construction funding is still pending. A total budget for construction and 12 years of operations of approximately $800 million is estimated by the project to be necessary for the basic LSST telescope (Ivezic, 2009). Several project management milestones have been passed, including an NSF Critical Design Review. The mirror is being ground and polished (see Figure 3.1), and first science operations are hoped for in 2016.

Optimizing the system for NEO detections requires approximately 15 percent additional cost to compensate for extended observations specific to NEO detection but not useful to meet other goals. The LSST project estimates that $125 million of additional funding is required for this optimization (Chesley, 2008).

Even if dedicated to the NEO issue and completed in 2015, LSST alone could not meet the 2020 deadline for detecting 90 percent of all potentially hazardous NEOs larger than 140 meters in diameter. However, simulations show that the LSST could reach this goal before 2030, as indicated above. (Note: not all NEOs will come in view in the southern sky, although most will eventually. The LSST observational strategy focuses on "sweet spots" for NEOs, where most objects will intersect at some point in their orbits.)

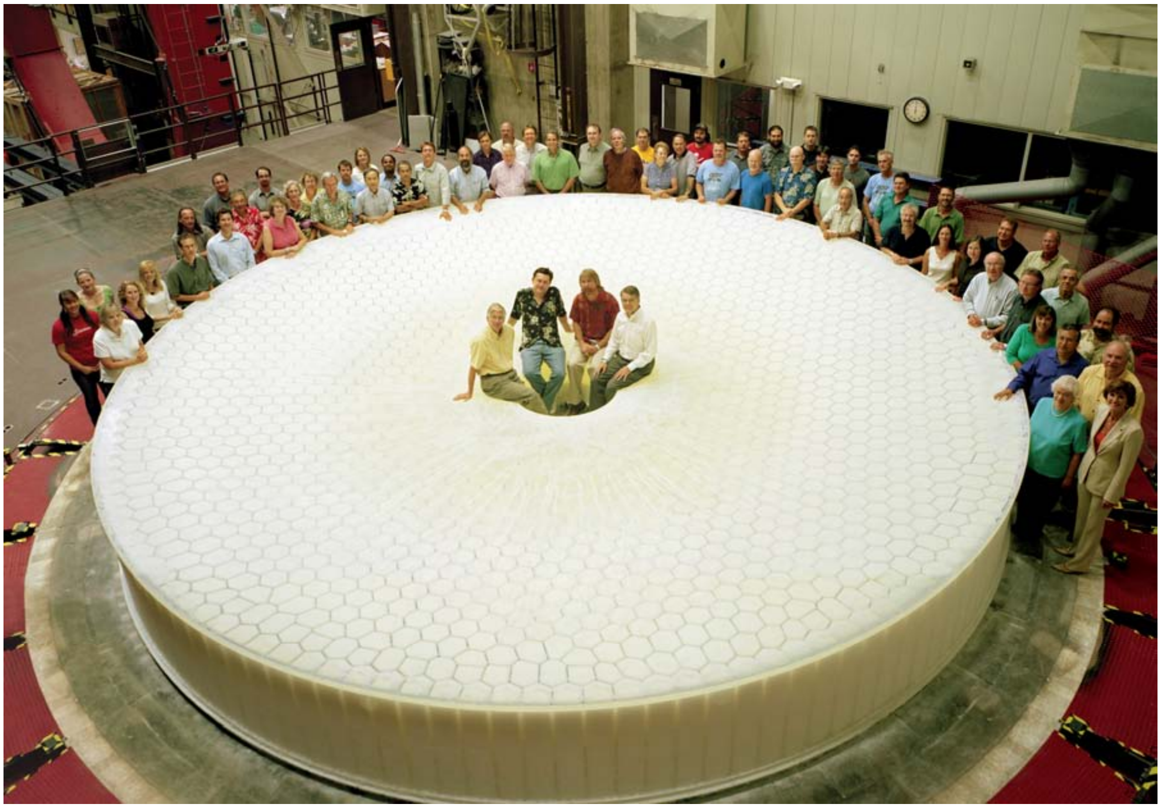

FIGURE 3.1 The Large Synoptic Survey Telescope 8.4-meter-diameter mirror after being successfully cast at the University of Arizona Mirror Laboratory. SOURCE: Courtesy of Howard Lester/LSST Corporation.

Panoramic Survey Telescope and Rapid Response System 4 (Pan-STARRS4 or PS4)

Pan-STARRS 4 (PS4) is the planned development of the Pan-STARRS survey project. The U.S. Air Force funded Pan-STARRS 1 (PS1), the prototype 1.8-meter-diameter mirror telescope with its 7-square degree field of view and 1.4-billion-pixel camera PS1 has been constructed and partially tested, but has not yet started science operations. (See Figure 3.2.) The PS1's major advance is its very large field of view camera and its sophisticated software for detecting moving objects, the Moving Object Processing System (MOPS).

The PS4 would take the completed PS1 and add three more (not yet built) identical or nearly identical telescopes, for a total of four 1.8-meter-diameter telescopes. All four telescopes pointing at the same area of sky and observing the same wavelength bands at the same time, could then achieve limiting magnitude in its most sensitive band of 23.5, i.e., approximately twice as sensitive as PS1. Major goals for PS4 include identifying and cataloging potentially hazardous NEOs, with follow-up to be done on other telescopes. The observing plan for PS4 is unavailable; however, if PS4 operates under the same observing schedule as PS1, exposures will range from 30 seconds to 60 seconds, covering a large portion of the visible sky twice per night every 5 to 10 nights in five wavelength bands. Observations would concentrate on the same areas of the sky as the LSST observations (see above). Large numbers of observations of individual NEOs would potentially yield rates of rotation and optical surface properties for a substantial fraction of the NEOs. The Moving Object Processing System (MOPS) developed for PS1 will be further developed for PS4 (as well as for LSST), to allow for the greater computational burden required by the ability to detect fainter objects.

PS4 would produce a catalog of NEOs precisely calibrated in location and brightness. The NEO discoveries will be released to the public through the Minor Planet Center.

The PS1 prototype telescope is completed but is being re-examined due to a problem with achieving its expected performance. A second telescope is currently in the initial phases of construction. For PS4, three telescopes similar to the prototype must be completed, as well as the housing structure for all four telescopes. PS2, i.e., PS1 and the second telescope, will be located on Haleakala in Maui. The planned site for PS4 is Mauna Kea, Hawaii; PS2 will be moved to Mauna Kea. Additional clusters of telescopes could be added at other locations.

The PS1 telescope was funded through the U.S. Air Force. Most of the original funding for PS4 has been spent building PS1. Funding for completion of PS4 has not been identified.

PanSTARRS4, even if completed and used on an "optimistic" schedule, could not alone meet the 2020 deadline, or any date, for detecting 90 percent of all potentially hazardous NEOs larger than 140 meters in diameter.

FIGURE 3.2 The Pan-STARRS1 telescope on Haleakala, Maui, Hawaii. SOURCE: Courtesy of Brett Simison, Institute for Astronomy, University of Hawaii.

Catalina Sky Survey Binocular Telescopes (CSS+)

The Catalina Sky Survey (CSS) University of Arizona's team of astronomers proposes a series of three binocular telescopes fully dedicated to discovering NEOs. (Catalina Sky Survey Team, 2009) The proposal is based upon using six existing 1.8-meter-diameter primary telescope mirrors, an existing observing site and other equipment, commercially available off-the-shelf hardware and software components, and established detection methodologies. Two developed observatory sites are currently being considered for the location of the telescopes: San Pedro Martir, Mexico, and Mt. Hopkins, Arizona. The six 1.8-meter diameter mirrors composing the original Multiple Mirror Telescope's primary mirrors would be used. (See Figure 3.3.) Two mirrors would be placed in tandem to create one binocular telescope, having an equivalent mirror diameter of 2.4 meters. The individual binocular telescope can detect objects to a limiting near-infrared magnitude of R = 22.6. Each binocular telescope could survey independently; images obtained simultaneously from any combination of these telescopes could be added together. Three binocular telescopes operated together would produce an equivalent mirror diameter of 4.2 meters, and could detect objects to a limiting diameter of R = 23.2 (Beshore, 2009). A commercially available 100-million-pixel camera would be used in each telescope. The images acquired in one binocular telescope would cover 4 square degrees of the sky.

The CSS+ would have capability unique among the proposed NEO survey telescopes to acquire spectra of the sunlight reflected from a target NEO across the broad wavelength range of 0.4 to 2.4 microns. Small mirrors would be installed in the instrument attached to a binocular telescope that could switch between the instrument's imaging mode to a pair of low-resolution spectrographs. The wavelength range would cover many absorption features caused by the presence of materials on the object's surface, allowing the system to discern part of the surface composition of the object.

On-site processing of data would take place initially; including the detection of moving objects, and calculation of their precise sky locations and brightnesses. The currently proposed coverage strategy includes obtaining 3 to 4 exposures of the same area of sky with binocular telescopes surveying independently in locations 45-to90 degree angles away from the Sun, and a four-exposure search of locations 60-to-90 degrees away from the Sun. Follow-up observations would be conducted on the same night. For observations covering locations ≥ 20 degree latitudes from the plane of Earth's orbit, two binocular telescopes would conduct independent four-exposure searches with follow-up to be provided by a third telescope using two or three exposures. Three binocular telescopes would survey independently in Earth's plane with observations repeated on the next night, allowing new discoveries to be made by correlation between observations on more than one night. Follow-up observations would be made on subsequent nights. Consistent with the existing Catalina Sky Survey technique, human eye examination of images would also be conducted. This technique has allowed the CSS to identify additional interesting objects. The detection of 2008 TC_3 was partially due to human eye identification. The system would aim to discover and characterize NEOs in a fashion complementary to that of the LSST and PS4 systems. As a dedicated facility, it would also retain the choice to vary or adjust the survey strategy as needed during operations.

The CSS+ is currently not funded. The six 1.8-meter-diameter mirrors and mirror cells are currently in storage at Mt. Hopkins, Arizona, and both the sites at Mt. Hopkins and San Pedro Martir have power and support buildings in place. Assuming that site negotiations are completed and arrangements for the use of the mirrors is established before start, the project team estimates that the time required to complete one binocular combination is 28 months, with full operation of three telescope combinations in 40 months (Beshore, 2009).

The resulting observations from this development have not yet been simulated by the NEO program office. CSS+ could not alone detect 90 percent of all potentially hazardous NEOs larger than 140 meters in diameter, as its limiting magnitude is not sufficient to reach the faintest NEOs.

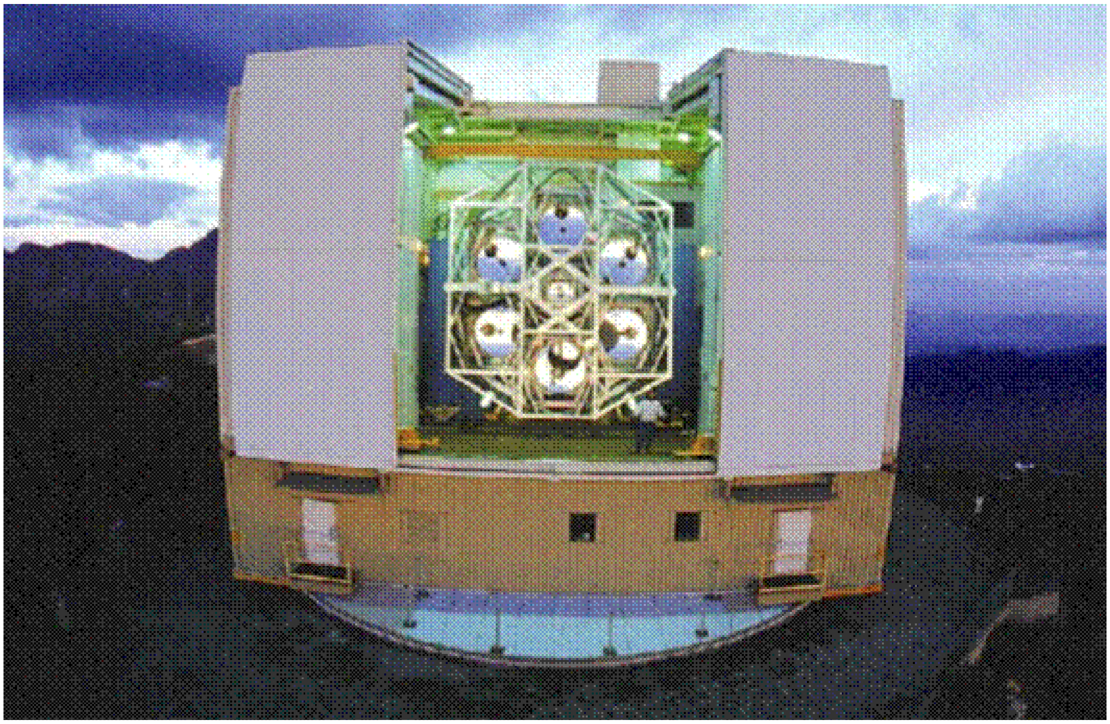

FIGURE 3.3 The six 1.8-meter-diameter mirrors that until 1999 composed the primary mirrors in the (old) Multiple Mirror Telescope. These mirrors now in storage are proposed for use in the CSS+ (see text). SOURCE: Courtesy of the MMT Observatory.

FIGURE 3.4 The Discovery Channel Telescope under construction. SOURCE: Courtesy of Lowell Observatory.

Discovery Channel Telescope

The 4.2-meter-diameter mirror Discovery Channel Telescope (DCT) is a collaborative effort between Lowell Observatory and Discovery Communications. The telescope is being constructed on a cinder cone at Happy Jack, Arizona, southeast of Flagstaff. (See Figure 3.4.) It is designed overall to contribute to multiple astronomical search projects, including searches for NEOs.

Its camera is planned to have a 2.3-degree field of view. The nominal search method is designed to obtain four exposures per night on a specific area of sky. These exposures would be repeated on two additional nights per month, providing follow-up observations. NEO search observations would be conducted over a wide wavelength range. For detecting NEOs in one night, the limiting VR magnitude (a combination of V (visible) and R (near infrared) magnitudes) is 23.8. Data from the focal plane would be delivered to control and reduction computers housed in the telescope building. This initial storage of the data will be handled by DCT.

For the NEO search, data processing would be based on the methodology used by LONEOS. Data reduction will encompass two techniques. A traditional source detection technique would be used and data for all NEOs identified would be immediately reported to the Minor Planet Center. A "frame-subtraction" technique based on existing Lowell Observatory routines will also be used. All NEOs discovered with the frame-subtraction technique would be made public immediately. All frames will be archived at Lowell Observatory.

Construction of the housing structure and the telescope mount was completed in fall 2009. The primary mirror was constructed by Corning and will be coated by the Department of Optical Sciences, University of Arizona. First light (not requiring the camera) is expected in early 2011. Project estimates of the time required to build the camera are ~4 years. Schedule risk, construction risks, and technical risks are low for the overall project.

The telescope construction has been entirely privately funded through the Discovery Channel and private donors; however, the ~$14.5 million for the camera is not yet funded.

DCT is an outgrowth of the LONEOS NEO detection system (see above) run by the same astronomers at Lowell Observatory. It is expected that DCT can contribute significantly to the NEO search, but DCT could not alone meet the 2020 deadline for detecting 90 percent of all potentially hazardous NEOs larger than 140 meters in diameter, as its limiting magnitude is not sufficient to reach the faintest NEOs. The DCT could, however, be a valuable follow up asset for NEOs detected at other locations.

Space-Based Detection Techniques

The 2003 NASA SDT study concluded that an infrared space telescope is a powerful and efficient means of obtaining valuable and unique detection and characterization data on NEOs. The thermal infrared, which denotes wavelengths of light from about 5 to 10 microns, is the most efficient color regime for an NEO search. An orbiting infrared telescope that detects these wavelengths and has a mirror between 0.50 and 1 meter in diameter is sufficient to satisfy the goal of detecting 90 percent of potentially hazardous NEOs 140 meters in diameter or greater. Plus, locating an NEO-finding observatory internal to Earth's orbit is preferable for identifying NEOs that are inside Earth's orbit.

Specific advantages to space-based observations include:

- A space-based telescope can search for NEOs whose orbits are largely inside Earth's orbit. These objects are difficult to find using a ground-based telescope as observations risk interference from the Sun when pointing to the areas of the sky being searched.
- Thermal-infrared observations are immune to the bias affecting the detection of low-albedo objects in visible or near infrared light, by observing the thermal signal from the full image of the NEO, providing more accurate albedo measurements (see discussion above).

- Space-based searches can be conducted above Earth's atmosphere, eliminating the need to calibrate the effects introduced by the atmosphere on the light from an NEO.
- Observations can be made 24 hrs/day.

Two concepts for space-based infrared telescopes are discussed here, as illustrations of means to satisfy the congressional mandate to identify 90 percent of all potentially hazardous NEOs larger than 140 meters in diameter.

0.5-Meter Infrared Space Telescope

There is a Discovery-class mission proposal from the Jet Propulsion Laboratory, estimated by JPL to cost slightly under $500 million, designed to complete the George E. Brown, Jr. Near-Earth Object Survey (Mainzer, 2009). This is a proposal for a 0.5-meter diameter infrared telescope that would be placed inside Earth's orbit, on the Earth-Sun line at the so-called Earth-Sun L1 Lagrange point (see Appendix E), to survey for NEOs. It would survey nearly continuously in the regions where NEOS are predicted to be orbiting the Sun (Chesley and Spahr, 2004). In its 5-year baseline mission, the telescope could discover ~75 percent of all NEOs larger than 140 meters in diameter; after 10 years, 90 percent completeness would be achieved (Chesley and Spahr, 2004). In combination with a suitable ground-based telescope or telescopes, these times to completion could be accelerated (see Figures 3.7 and 3.8 for examples where the spacecraft is modeled as the 0.5-meter IR ("infrared") telescope at the L1 Lagrange point). Sixteen-million-pixel detectors covering a single infrared wavelength band spanning 6 to 10 microns would be used. The proposal draws its heritage from the very successful Spitzer Space Telescope and from WISE (Mainzer, 2009).

NEO SURVEY Spacecraft

The NEO Survey is a spacecraft mission proposal from Ball Aerospace and Technologies Corp, estimated by Ball to cost ~$600 million, designed to complete the George E. Brown, Jr. Near-Earth Object Survey (Reitsema, 2009). NEO Survey would have a 0.5-meter-diameter infrared telescope in a Venus-trailing orbit. The NEO Survey design allows observations over slightly more than the entire anti-Sun hemisphere. It should complete its mission of detecting more than 90 percent of all potentially hazardous NEOs larger than 140 meters in slightly under 8 years. With the addition of a suitable ground-based telescope system (see Figures 3.7 and 3.8, where NEO Survey is modeled as the 0.5-meter IR telescope at Venus orbit, Chesley and Spahr, 2004), NEO Survey could complete this mission in under 5 years of operations. NEO Survey draws its heritage from Spitzer Space Telescope and Kepler (Reitsema, 2009).

Figure 3.5 shows the basic concept of operations for NEO Survey, and illustrates the greatly expanded search region available from a Venus-like orbit compared to any Earth-based option. The depicted orbits are to scale, and the red ellipse is the nominal Venus-like orbit having an orbit radius of 0.7 AU with an orbital period of ~206 days. The Venus-like orbit distinguishes the NEO Survey operations concept because it is the spacecraft's *orbit in general* that is important, not the spacecraft's location along the orbit. The results are not sensitive to the orbit's final details as long as the final orbit falls within a distance from the Sun of between 0.8 AU and 0.6 AU.

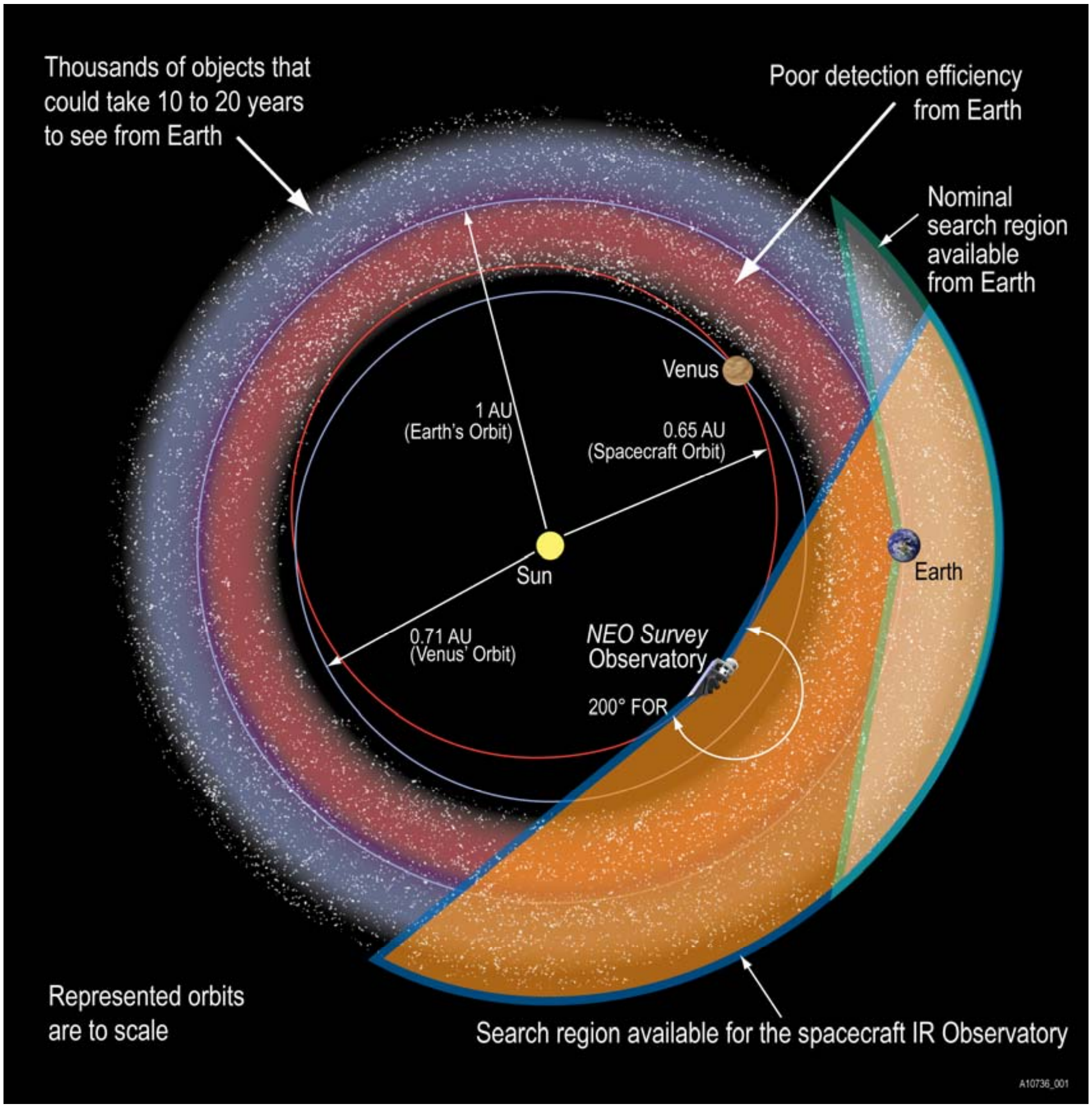

FIGURE 3.5 The region of the sky observed by NEO Survey (see text). SOURCE: Courtesy of Ball Aerospace and Technologies Corporation and NASA.

SURVEY/DETECTION SCHEDULES

Despite the congressional call in 2005 for a start to this mandated survey, no funds have yet been allocated for it.

Table 3.1 below summarizes the relative merits of a number of different possible survey techniques. Their performance and efficiency can be parameterized via a number of different criteria, including number of NEOs discovered, how fast the 90 percent goal is reached, estimated development time, additional characterization information recovered, and general programmatic and technical risks.

The first column describes the various projects, including the current Spaceguard systems (Catalina Sky Survey and LINEAR) as well as planned or proposed projects in both visible and infrared wavelengths. Only those projects that either currently exist or have a "reasonable" probability of existing were included. Facilities that could only negligibly contribute to the survey goal (e.g., the Hubble Space Telescope or the James Webb Space Telescope) have not been assessed here.

TABLE 3.1 Comparison of Various Options for Achieving the Survey Goals

Project	Years to 90% for 140 meter[a]	% of 140-meter NEOs[b]	Estimated Development Time (years)	Characterization Science[c]	Programmatic Risk	Technical Risk
DCT	N/A	50%	? (camera only)	V, R	Not fully funded; primary purpose not NEO discovery	Technology development
PS1	N/A	5-10% for 3.5 yrs	1	gri	Fully funded	Technology development
PS4	N/A	~75%	5	gri, lightcurve	Not fully funded; primary purpose not NEO discovery	Technology development
LSST	17 12	81% 90% (shared)	7	ugriZY, lightcurve	Not fully funded; primary purpose not NEO discovery	Technology development
CSS	N/A	8%	N/A, already exists	V	None (completed)	None
LINEAR	N/A	8%	N/A, already exists	V, R	None (completed)	None
0.5 m IR @ L1/L2	11	88%	5	6-10 µm, IR lightcurve	Not funded; primary purpose is NEO discovery and study	2% launch loss[d]
2m vis @ L1/L2	16	83%	6	V, R Vis lightcurve	Not funded; primary purpose is NEO discovery and study	2% launch loss[d]
0.5 m IR @ Venus	7.5	95%	5	6-10 µm, IR lightcurve	Not funded; primary purpose is NEO discovery and study	2% launch loss[d]
2m vis @ Venus	7	94%	5	V, R vis lightcurve	Not funded; primary purpose is NEO discovery and study	2% launch loss[d]
0.5 m IR @Venus – 2 bandpass	7.5	~95%	5	3-5.5, 6-10 µm, IR lightcurve	Not funded; primary purpose is NEO discovery and study	2% launch loss[d]
Combined systems: 0.5 m IR @Venus + PS1	5.5	97%	5[e]	gri, 6-10 µm lightcurves in visible and IR	Requires ground and space facilities to be funded and operated	2% launch loss[d]
Combined systems: 0.5 M IR @ Venus + LSST	3-4	98%	7[f]	ugriZY, 6-10 µm lightcurves in visible and IR	Requires ground and space facilities to be funded and operated	2% launch loss[d]

NOTE: DCT = Discovery Channel Telescope; CSS = Catalina Sky Survey; IR = infrared; LINEAR = Lincoln Near Earth Asteroid Research; LSST = Large Synoptic Survey Telescope; N/A = not applicable; PS1 = PanSTARRS1; PS4 = PanSTARRS4.

[a] "N/A" if >20 yrs total.

[b] For fixed start date, and fixed operations interval = 10 years.

[c] The notations u, g, r, I, Z, and Y refer to the various filter types that would be used on these telescopes. Optical colors, albedos, color temp (1 versus 2 band system infrared); composition versus taxonomy versus albedo; trying to get bulk density; lightcurve studies.

[d] Typical failure rate for Delta or Atlas)

[e] Dominated by IR telescope development time

[f] Dominated by LSST development time

The second column contains the number of years required for the various projects to reach 90 percent completeness for potentially hazardous objects larger than 140 meters in diameter. This time interval represents time doing the survey; development time is excluded. Programs that take in excess of two decades to reach 90 percent completeness are denoted by N/A in this column, as any program taking longer than two decades is deemed by the committee to be an unworkable solution. The third column describes the percentage completeness for NEOs larger than 140 meters in diameter at 10 years after start of the projects' survey operations. The fourth column gives the projects' own estimates of the development time; i.e., the time from the start of the preliminary design phase to the beginning of survey operations. For projects already under development, the time given is the estimated time remaining (from the date of this report) before survey operations could begin. The fifth column describes any ancillary characterizations enabled by the particular survey program, such as those discussed in Chapter 4 (g, r, i, Z, and Y refer to specially designated bands of wavelengths of light; µm denotes "micron"). The sixth column describes programmatic risks, if any. This column also encapsulates the risk that projects whose primary purpose is not the search for NEOs might not, in fact, carry out the NEO survey over the lifetime of the project. The seventh column captures any technical risks unique to a particular project, such as the risks associated with a launch vehicle. The descriptions given in this column are based on each project's current predicted survey style. The numbers in several of the columns have intrinsic uncertainties since (1) many projects are in their planning stages and have not settled on an observing mode, and (2) there are still substantial uncertainties in the estimated number of NEOs larger than a given size.

Figures 3.6, 3.7, 3.8, 3.9, and 3.10 show the relative times to completion for various types of combined space-based and ground-based systems for limiting diameters of 140, 50, and 30 meters. (The importance of the 50 meter and 30 meter objects is discussed later in this chapter.) These plots should be viewed as sliding scales, with the *survey portion only* beginning at the year 0 (i.e., programmatic and construction lead time is not included). These plots are based on the modeling and assumptions by Chesley included in the 2006 NASA Near-Earth Object Survey and Deflection—Analysis of Alternatives study (NASA PA&E, 2006). The completeness percentages are considered by Chesley to be accurate to ±2 percent for results near 90 percent completeness. The plots are made with an assumption of a average albedo for NEOs of 0.11. Thus, they represent a lower limit to the number of objects detected in those size ranges. They therefore could be used with more confidence for the relative differences of detection systems for a given condition.

Finding: The mandated survey to locate 90 percent of near-Earth objects 140-meters in diameter or greater has not yet been funded by the federal government. Because the survey requires several years to budget and build new equipment, and then to conduct the search, completion by 2020 is not realistic.

Figure 3.8 compares the ability of the proposed largest ground-based telescope and ground and space-based telescope combinations to complete the survey of NEOs. Including the developmental lead time required, a dedicated or shared LSST telescope is the only ground-based system currently proposed that could complete the survey of 90 percent of the potentially hazardous 140-meter objects within 20 years of the start of observations. In contrast, the survey can be completed within 20 years including the estimated 5-yr development period by infrared space-based options and visible space-based options in Venus type orbit (Figure 3.7). Combinations of space-based infrared and ground-based telescopes can accelerate the completion of the survey (Figure 3.8).

Extending the search to smaller diameter objects (Figure 3.9) demonstrates that the ground-based LSST cannot reach a detection of 90 percent of the 50-meter and 30-meter populations within 30 years of beginning operations. Combining LSST with a 0.5-meter space-based infrared telescope (Figure 3.10) allows a detection of 90 percent of the potentially hazardous NEOs down to 50-meter-diameter, but is still not adequate to detect 90 percent of those down to 30-meter-diameter in 30 years' operation. Detecting 90 percent of the smallest NEOs that might cause significant damage upon impact is thus a very difficult task.

For different size regimes, some overarching conclusions can be drawn:

- *90 percent completeness for detection of potentially hazardous NEOs 140-meter in diameter or larger*—In theory, this goal could be achieved by 2020. Experience suggests, however, that the congressional goal cannot be met by 2020. Most options could complete this survey within 20 years, including those involving only ground-based telescopes.
- *90 percent completeness for detection of potentially hazardous NEOs 50-meter in diameter or larger*—All space-based or combination of space-based and ground-based options could complete this survey, although not all in 20 years. No currently planned ground-based only option is able to complete this survey.
- *90 percent completeness for detection of potentially hazardous NEOs 30-meter in diameter or larger*—No combination of telescope systems discussed above can complete this survey within 20 years, although significant progress could be made.

Combined ground- and space-based surveys have a number of advantages. Such surveys discover more NEOs of all sizes, including a substantial number smaller than 140 meters in diameter. These combined surveys also provide more characterization data about the entire NEO population. With both infrared and visible data for most targets, it will be possible to obtain accurate diameter estimates for all objects, as well as measurements of their albedos and their surface and thermal properties. These high value characterization data could help to guide mitigation campaign studies. Additionally, a dual survey provides much information on the population of objects smaller than 140 meters in diameter.

Finding: The selected approach to completing the George E. Brown, Jr. Near-Earth Object Survey will depend on nonscientific factors:

- **If completion of the survey as close to the original 2020 deadline as possible is considered most important, a space mission conducted in concert with observations using a suitable ground-based telescope and selected by peer-reviewed competition is the best approach. This combination could complete the survey well before 2030, perhaps as early as 2022 if funding were appropriated quickly.**
- **If cost conservation is deemed most important, the use of a large ground-based telescope is the best approach. Under this option, the survey could not be completed by the original 2020 deadline, but could be completed before 2030. To achieve the intended cost-effectiveness, the funding to construct the telescope must come largely on the basis of non-NEO programs.**

As noted above, neither Congress nor the White House has requested adequate funding to conduct the survey to identify ≥ 90 percent of the potentially hazardous NEOs by the year 2020. Multiple factors will drive the decision on how to approach this survey in the future. These include, but are not limited to, the perceived urgency for completing the 140-meter survey as close to the original 2020 deadline as feasible, and the availability of funds to complete the survey successfully. The combination of a space-based detection mission with a large ground-based telescope will complete the survey in the shortest time, i.e., closest to the original 2020 deadline. A space-based mission alone will complete the survey only 2 to 4 years later than a survey conducted with both a space-based telescope and a large ground-based telescope. The cost of optimizing the LSST for NEO detection observations was estimated in 2007 to be an increment of ~$125 million to the cost of the basic telescope system (Ivezic, 2009), becoming the most cost-effective means to complete the survey. (Note that the annual operating cost of a ground-based telescope is approximately 10 percent of the development and construction costs.) The completion date would be extended. The decision to extend this date requires acceptance of the change in risk over that time.

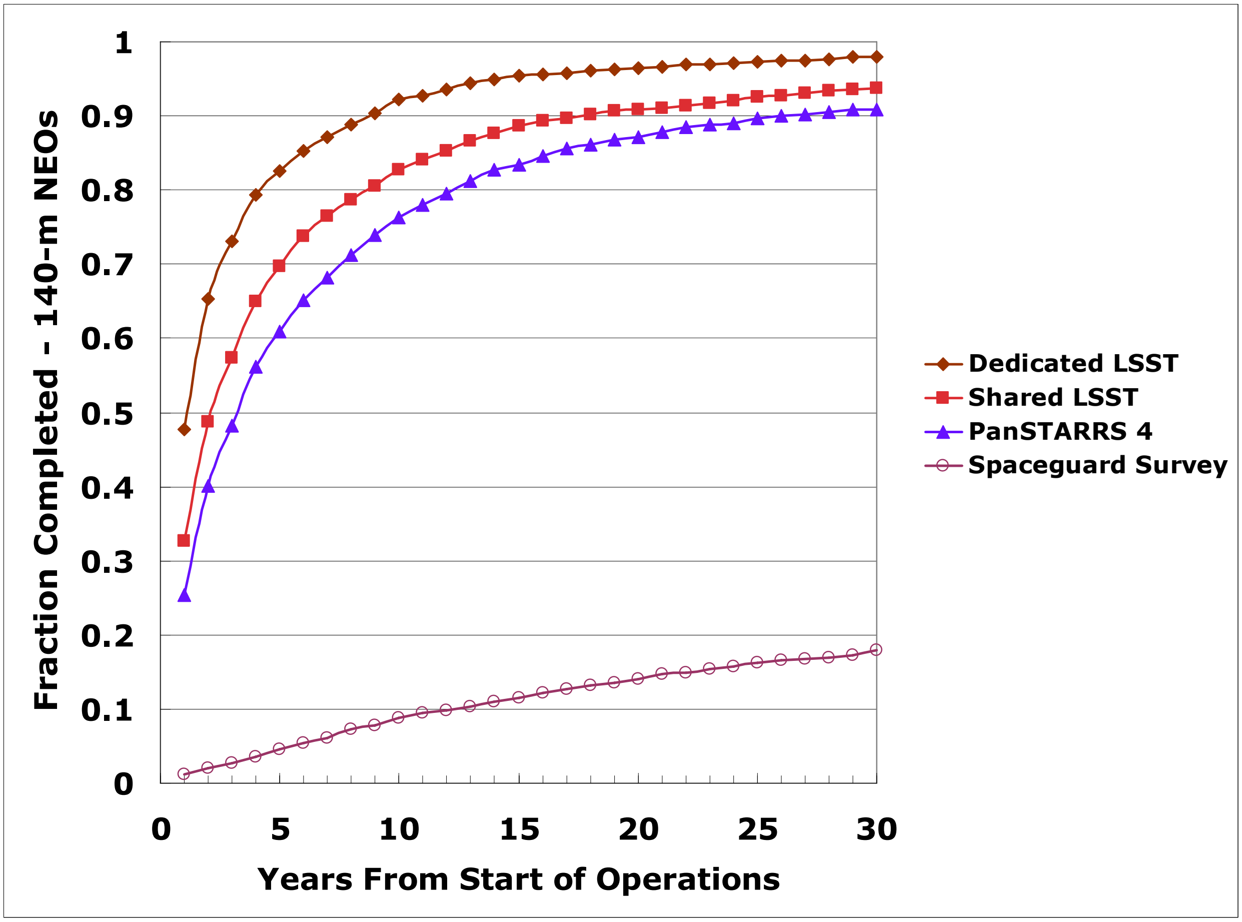

FIGURE 3.6 Years to 90 percent completion for detection of potentially hazardous NEOs 140 meters in diameter or larger with different ground-based telescopes. SOURCE: Courtesy of NASA Program Analysis and Evaluation.

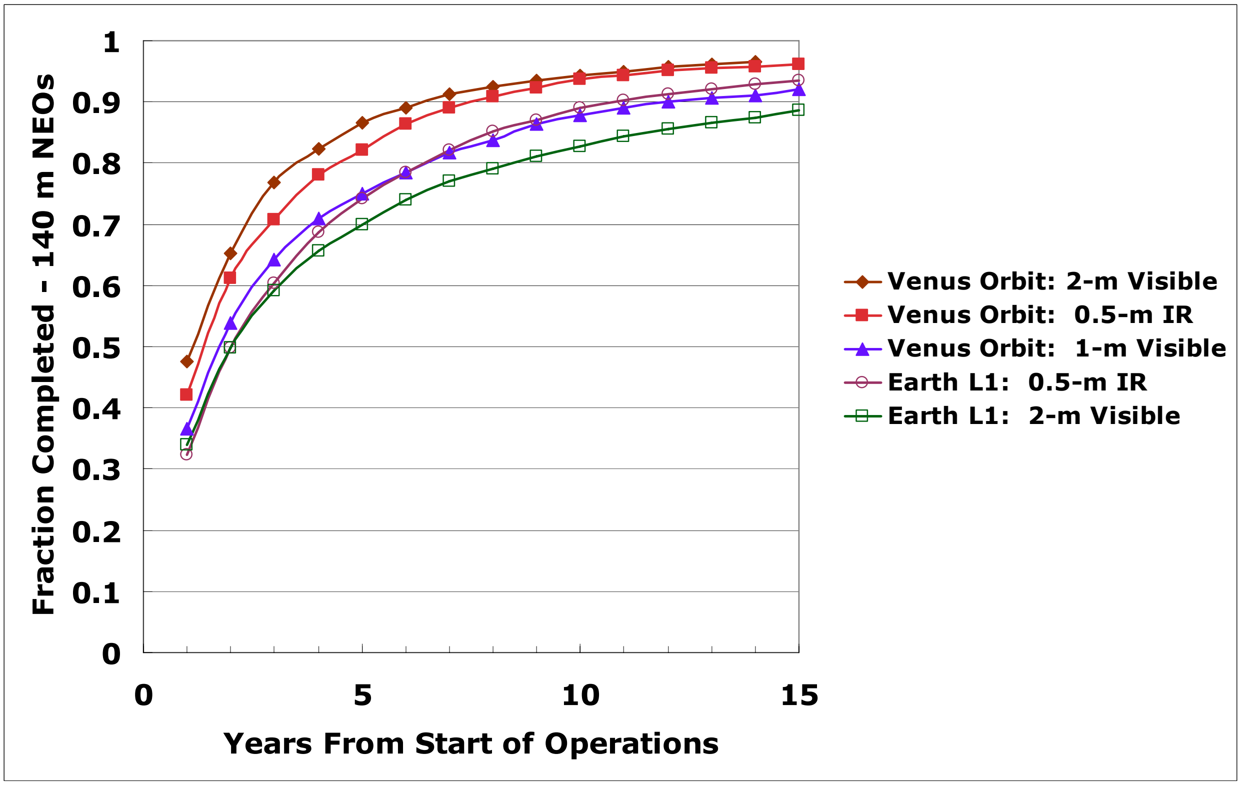

FIGURE 3.7 Years to 90 percent completion for detection of potentially hazardous 140-meter NEOs with different space-based telescopes. SOURCE: Courtesy of NASA Program Analysis and Evaluation.

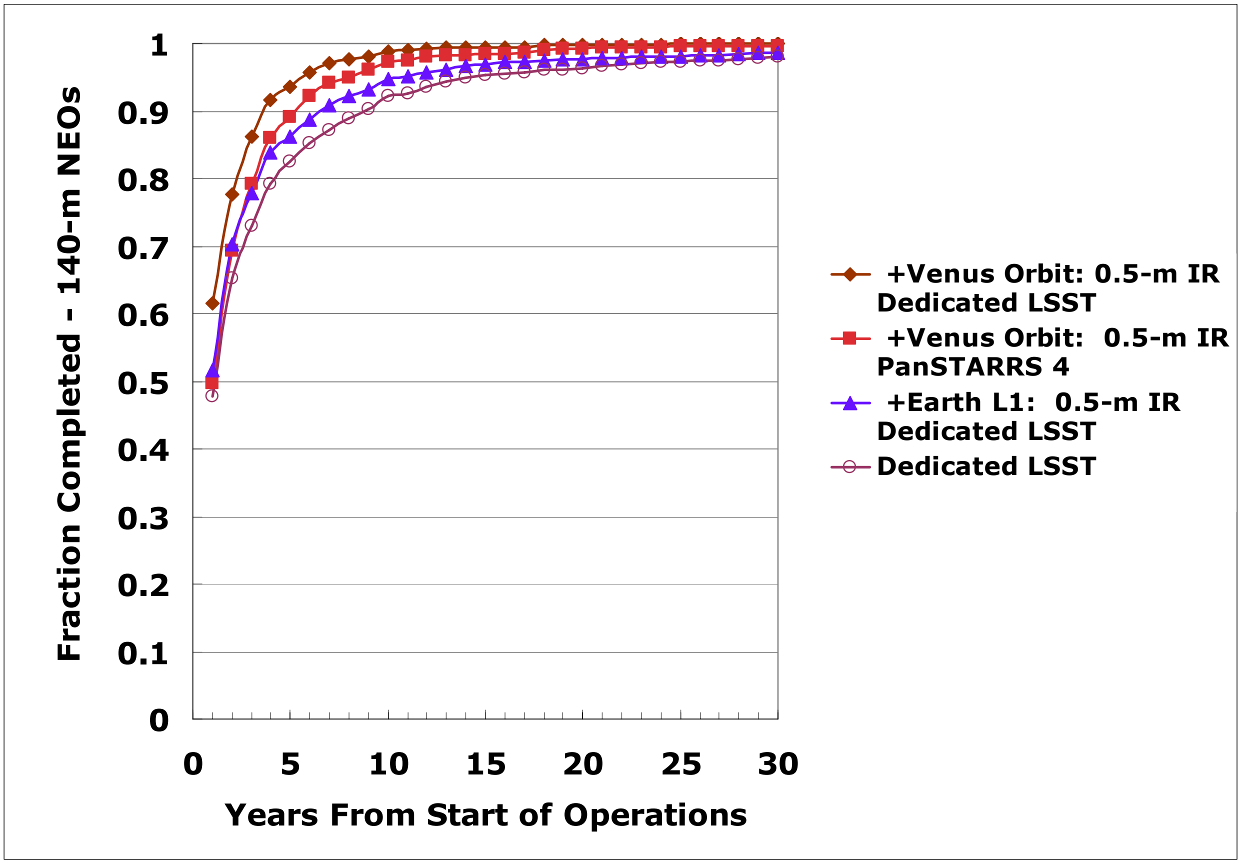

FIGURE 3.8 Years to 90 percent completion of mandated survey for detection of potentially hazardous 140-meter NEOs for combinations of space-based 0.5-meter infrared telescopes and ground-based telescopes. SOURCE: Courtesy of NASA Program Analysis and Evaluation.

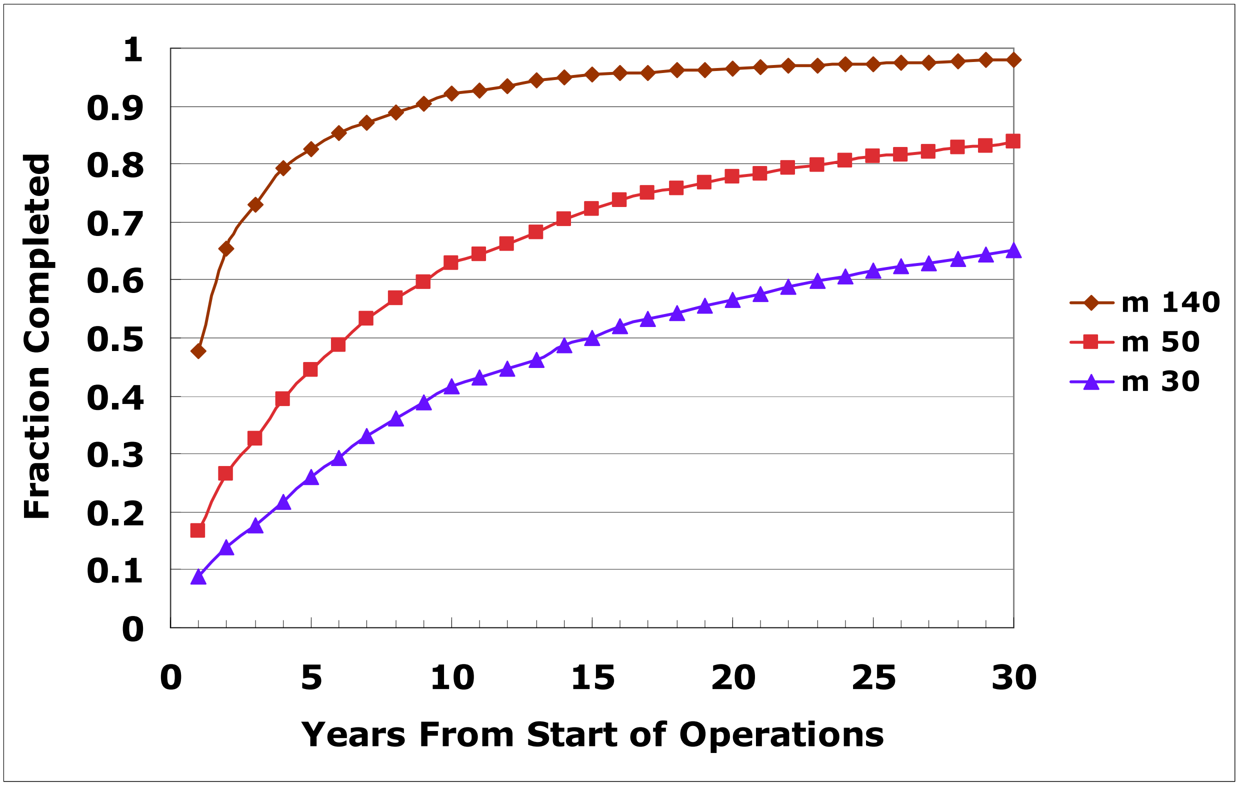

FIGURE 3.9 Years to completion for a dedicated LSST telescope for NEOs with diameters greater than or equal to 30 m, 50 m, and 140 m. The dedicated LSST achieves 90 percent completion for the potentially hazardous 140-meter-or-greater diameter survey within 10 years of start of operations. SOURCE: Courtesy of NASA Program Analysis and Evaluation.

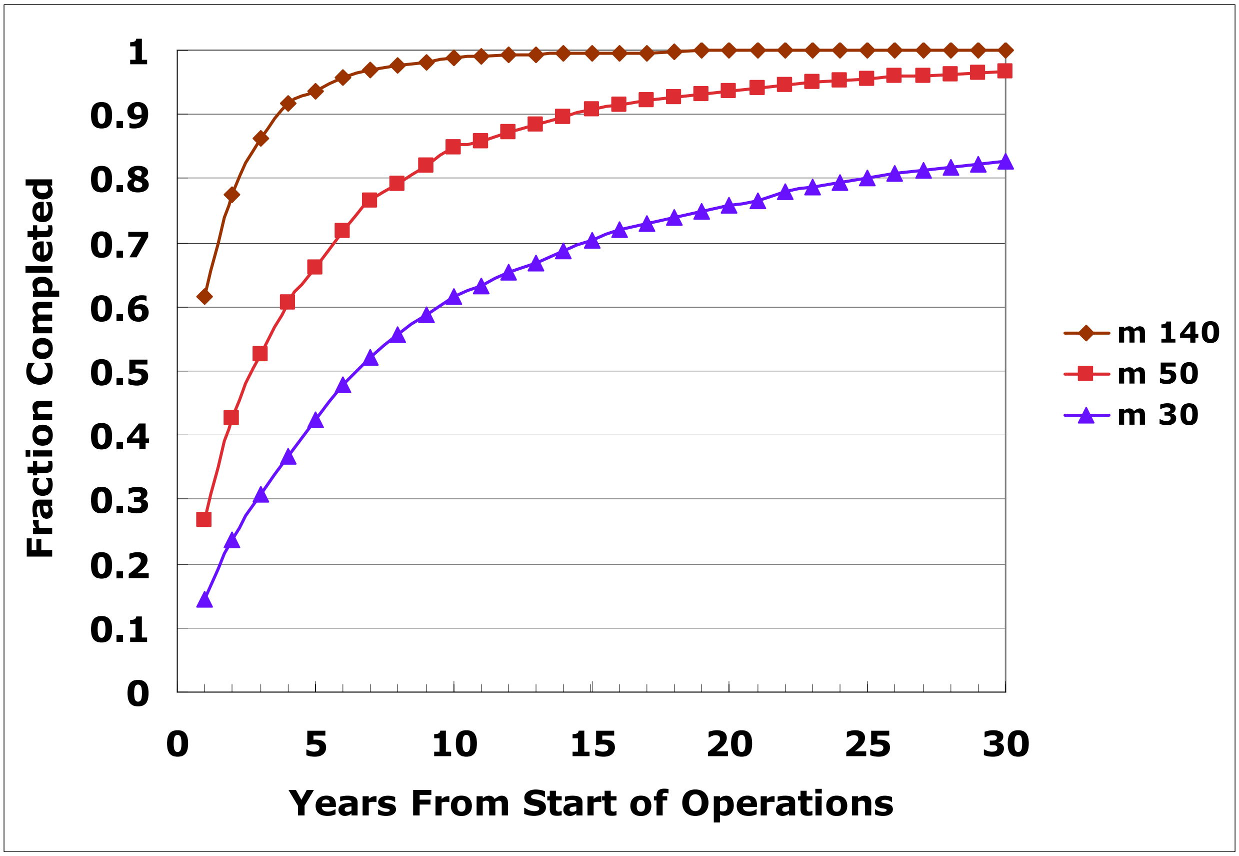

FIGURE 3.10 Years to completion for a 0.5-meter infrared telescope in a Venus-like orbit plus a dedicated LSST telescope for NEOs with diameters greater than or equal to 30 m, 50 m, and 140 m. Note that 90-percent completion is never achieved within 30 years for NEOs with diameters down to 30-meter-diameter. SOURCE: Courtesy of NASA Program Analysis and Evaluation.

Low-Altitude Airburst NEOs: Advance Warning

Increasing concern with the possibility of smaller NEOs resulting in low-altitude airbursts has led the committee to raise the question of identification of hazardous NEOs having smaller diameters than 140 m. The ability to detect objects having diameters of greater than 50 meters and greater than 30 meters was therefore also compared among these telescope systems.

Finding: It is highly probable that the next destructive NEO event will be an airburst from a <50-meter object, not a crater-forming impact.

Recommendation: Because recent studies of meteor airbursts have suggested that near-Earth objects as small as 30 to 50 meters in diameter could be highly destructive, surveys should attempt to detect as many 30- to 50-meter objects as possible. This search for smaller-diameter objects should not be allowed to interfere with the survey for objects 140-meters in diameter or greater.

Imminent Impactors: NEOs on Final Approach to an Earth Impact

With the discovery of NEO 2008 TC_3, found within 19 hours of impact into the Sudan desert, the committee discussed the question of increasing capability to detect imminent impactors on their final approach to Earth. Optimizing the detection of imminent impactors requires a different observing strategy than the approaches discussed above designed to discover hazardous NEOs with long lead times before impacts. The existing Catalina Sky Survey (which found 2008 TC_3) is configured such that with a change in observing sequence, it could discover up to 50 percent of the imminent impactors (i.e., bodies smaller than 1-kilometer that could impact in hours or weeks). Likewise, the Discovery Channel Telescope could make a significant contribution toward identifying imminent impactors. Other types of systems designed specifically to detect such objects could be built but were not considered by the committee. The imminent impactors represent the next level of survey and detection efforts, as their discoveries contribute to gains in knowledge of NEO properties and their prompt discovery will allow for civil defense measures to be instituted in a timely manner.

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4

Characterization

The orbit of an NEO determines whether it will, or will not, strike Earth. Sufficiently accurate orbit information additionally determines the place and time of an impact, should one occur. However, the physical outcome of an impact and its effects on people and property depend upon many factors. Mitigation efforts (Chapter 5) are likewise predicated upon many more properties of the NEO than its orbit alone.

The chief factors governing the effects of an NEO impact are the NEO's mass and speed at impact. These properties determine the amount of energy delivered by the strike (this energy is proportional to the NEO's mass multiplied by the square of its speed at impact). Other factors include the angle of the NEO's approach to Earth's surface and the NEO's density, diameter, composition, and internal structure. Different mitigation strategies require knowledge of different NEO properties, as discussed in Chapter 5.

Characterization encompasses the determination of all relevant properties of an NEO beyond its orbit. Some properties of an NEO that can be determined remotely, such as its brightness at several wavelengths, can be related to its diameter and composition. Other NEO properties, such as mass, porosity or strength, may require a visit by a spacecraft and in situ investigation to determine.

This section examines the properties of an NEO that can be determined from ground investigations, using both optical telescopes and radar, as well as the utility of in situ studies by spacecraft. Additional information on both impact effects and properties of small asteroids as a class can be obtained from the study of airbursts that occur when these objects enter Earth's atmosphere.

GROUND-BASED REMOTE CHARACTERIZATION

Ground-based characterization efforts can establish some aspects of the physical nature of individual NEOs and of the NEO population. However, detailed knowledge of the physical properties of the NEO population lags far behind the current rate of NEO discoveries: considerable effort is required to collect information about these bodies not only to obtain a better understanding of the NEO population, but also to understand how the physical and compositional properties vary from one NEO to another. Such information is important for assessing the hazard potential of individual NEOs that may threaten Earth and the viability of proposed mitigation strategies.

A majority of the work supported under NASA's NEO Observations Program to date has focused primarily on detection and orbit determination of NEOs. These are necessary steps in the effort to assess the potential impact threat from such objects: The object's orbit determines whether or not it is a threat to Earth.

The optical brightness of an NEO also provides a very rough estimate of its equivalent diameter, as noted in Chapter 3. For example, the albedo (reflectivity) of the NEO must be known or assumed to estimate its size. The variations in albedo from one NEO to another (Binzel et al., 2002) are such that the average assumed value, leads, in "extreme" cases, to an uncertainty in diameter of about a factor of two. Furthermore, because small asteroids can be irregular in shape, it is possible to get a biased idea about the size of a small asteroid if it is observed on only one or two occasions from atypical vantage points as the asteroid rotates.

Radar investigations are exploring the physical properties of individual NEOs including their sizes, shapes, surface roughness, rotation periods, and rotation pole orientations, as well as whether they have satellites. In addition, time variations of brightness as NEOs spin ("light curves") are being used to identify body shapes, rotation periods, pole orientation, and the presence of satellites.

The change in the amount of light reflected by an NEO as a function of wavelength (color) of the light provides information on the composition of the NEO. Such "spectra" range in precision from measurement of the brightness in a few broad wavelength bands, a technique permitting a classification of NEOs into a small number of groups of similar composition, to studies that acquire brightness information over a large number of narrow wavelength intervals. Such spectra can be compared to suites of laboratory spectra of meteorites and minerals to accurately determine the composition of the surface of an NEO. Which technique can be used is determined by the brightness of the object, the size of the telescope used for observation, and the time devoted to such observations. Classification and detailed spectral studies have begun to yield the types of minerals present in these objects, which thus lend qualitative insights into their physical strengths, internal structures, and bulk densities.

NEOs are more challenging to observe than planets and their moons. NEOs tend to come into telescopic range for only short times (~few days to weeks) and they often appear either low in the sky, along the star-crowded Milky Way, or during times when the Moon creates background light; conditions at discovery are thus not always optimal for detailed characterization efforts. Nevertheless, the best opportunity to characterize a given NEO occurs when it is optically bright during close Earth approaches, often when the NEO is discovered. Because the telescopes used to discover NEOs spend their time searching for them, follow-up observations for characterization must be done by other telescopes that can afford to devote the necessary time to this effort. However, few optical telescope facilities routinely provide observing time for the physical characterization of NEOs. (Radar characterizations of NEOs are discussed below). Even these few efforts are not well coordinated. Therefore many observable NEOs are not characterized in the detail necessary to develop a better understanding of these objects as a population, or to study the individual objects that present the greatest threats to Earth.

Finding: The best opportunities for physical characterization of most NEOs occur during close Earth approaches when these objects are optically bright. Existing programs of ground-based optical observations for characterization of NEOs are few in number, and are not coordinated among different observing teams. Many observable NEOs are not characterized.

ROLE OF RADAR IN NEO CHARACTERIZATION

Radar observations are complementary to optical measurements. The power of radar derives principally from the precision of its measurements: In optimum conditions, radar can determine the distance ("range") to a target many millions of kilometers away with ~10 meter accuracy, and simultaneously measure speed in the direction towards Earth ("radial velocity") to within 1 millimeter per second, while optical techniques locate the object's angular position in the sky to about a few tenths of a second of arc (the angle formed by a penny viewed face on from about 15 kilometers away) under the best conditions. Both radar-derived range and velocity data and optically derived angular positions are used to estimate the orbit, which enables computation of past and future trajectories.

Optical data alone, taken over a span of a few days after an asteroid is discovered, typically yield orbital predictions whose accuracy in distance and radial velocity can be improved by factors of up to several thousand when combined with radar data from the same interval. This rapid improvement provides an early and accurate assessment of future threat, and is one of the most important roles for radar observation of NEOs. Radar observations, when feasible to make (see below), can extend reliable orbit prediction by centuries and, for threatening objects, can distinguish between a potential hit and miss much sooner than is possible with optical observations alone. For objects observed only when discovered, radar has added an average of 300 years to the interval over which accurate orbit prediction is possible (Ostro and Giorgini, 2004). Even for objects observed for many years, radar distance and radial velocity measurements can reduce uncertainties significantly and improve NEO orbits (Ostro and Giorgini, 2004).

A radar telescope is not an instrument that can be used to discover NEOs (because it requires that the orbits be known well enough to "point" the telescope in four dimensions),[1] it is a powerful tool for rapidly improving our knowledge of the orbit of a newly found object, and thus characterizing its potential hazard to Earth. In addition to orbit improvement, the interaction of radar signals with the surface of the NEO yields information about its physical characteristics. For example, radar observations can be used to estimate the roughness of the top several tens of centimeters of a NEO's surface. Radar reflectivity measurements can distinguish between stony and metallic compositions and may be used to estimate the porosity of NEO surfaces.

Understanding asteroid composition is important for developing mitigation techniques. Radar observations have been used not only to estimate asteroid compositions, but also to distinguish smoothly rotating from tumbling asteroids, as well as objects that appear to be monolithic fragments broken off from an originally larger parent. Some targets appear to be weakly bound "rubble piles," while others display either spheroidal, highly elongated or irregular shapes.

Similarly, radar observations yield direct information as to whether the NEO has a satellite and provide data about the size, rotation, and surface scattering properties of each member. In many cases where the echo is strong enough, radar may provide detailed images of an asteroid's shape at both large and small scales (Figures 4.1, 4.2, and 4.3).

When observations of many rotational phases and geometrical aspects can be obtained, radar images can be used to reconstruct an asteroid's size, shape, and spin state with a level of detail otherwise obtainable only by a spacecraft rendezvous. An asteroid's shape provides fundamental information on its origin and geologic history and provides clues to its internal structure and bulk porosity. Three-dimensional (3D) shapes are available for about 25 NEOs from radar data, while several dozen more are potentially obtainable from data already in hand.

Detailed 3D models open the window to other useful scientific investigations, such as estimated surface slopes and regolith distributions, as well as enabling the advance planning of spacecraft missions in close orbit about an NEO. These investigations may enhance spacecraft navigation and targeting on the NEO, and are useful for realistic simulations of impacts and orbit-change scenarios involved in mitigation planning.

The Arecibo Radar Observatory

The Arecibo Observatory, located near Arecibo, Puerto Rico, is part of the National Astronomy and Ionosphere Center (NAIC) operated by Cornell University under contract with the National Science Foundation. Its chief feature is a fixed 305-meter diameter spherical antenna, of which 225 meters is illuminated by radar waves in a way that allows coverage within 20° of directly overhead. Due to its location 18° north of the equator, Arecibo can observe objects between latitudes of −1° and +38°, and about 33 percent of the sky may be observed by allowing Earth's rotation to move the telescope to point towards the desired celestial target. Arecibo can track an individual object for up to 2.9 hours per day. When combined with its 900 kilowatt (kW) of average transmitting power of waves with a length of 13 cm, this system is by far the most sensitive research radar in the world—about 20 times more sensitive than the Goldstone radar described below, but at the cost of significantly reduced sky coverage.

Figures 4.1, 4.2, and 4.3 show examples of the quality of imagery that can be obtained with Arecibo's radar. These images contain thousands of pixels covering the target NEO; their highest

[1] To use a radar telescope to detect an NEO, one must know in what direction to point the telescope as well as the approximate distance and radial velocity of the NEO, all of which make discovery of an NEO with a radar telescope at best impractical.

resolution greatly exceeds that available from any optical telescope on the ground or in near-Earth space and is matched only by "flyby" and exceeded only by rendezvous spacecraft missions. Because of its greater sensitivity, Arecibo provides significantly more frequent opportunities for high-resolution imaging than does Goldstone. Opportunities for radar imaging with a caliber comparable to those shown here occur several times annually. Within its latitude coverage, Arecibo can detect objects at twice the distance as can Goldstone for similarly sized objects and has contributed two-thirds of all radar range and radial velocity measurements on NEOs obtained in the last decade.

Observing time at Arecibo is awarded on a competitive basis from proposals that are normally submitted quarterly. Arecibo is also available for "urgent" target-of-opportunity observations on short notice, and, in a small number of instances, has been used for radar observations of NEOs within 24 hours of their discovery.

The Goldstone Solar System Radar

The Goldstone Solar System Radar, located in the Mojave Desert in southern California, is part of NASA's Deep Space Network (DSN) and is operated by the Jet Propulsion Laboratory under contract with NASA. Comprising a fully steerable 70-meter-diameter antenna that can transmit 500 kW of waves with a length of nearly 4 cm, this radar has a significant capability for observing echoes from NEOs. It can see approximately 80 percent of the total sky over the course of a day (i.e., every part north of −35° latitude). The Goldstone antenna's primary mission is spacecraft communications and is available for astronomy observations only a few percent of its time. Goldstone is the only one of NASA's three 70-meter telescopes (the others are in Spain and Australia) equipped with a high-power transmitter. The long-term future of Goldstone is uncertain; the Deep Space Network is considering decommissioning all its 70-meter telescopes after 2015 and switching to an array of 34-meter-diameter telescopes. Whether a radar capability comparable to the present Goldstone capabilities would continue is unclear.

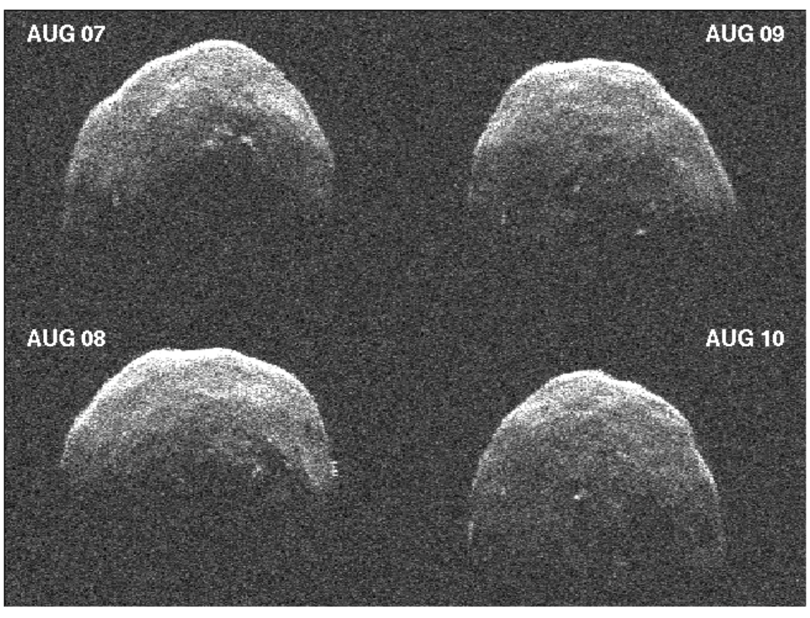

FIGURE 4.1 Arecibo radar images of 2-kilometer-diameter near-Earth asteroid 1992 UY4 from 4 days of data obtained in August 2005. Illumination is from the top; range increases downward and the wavelength of the echoes of the radio waves increases to the left; the Doppler frequency shift due to rotation affects left-right positions of pixels. The resolution of each image is about 7.5 meters in each direction. The images reveal that 1992 UY4 is about 2 km in diameter with a rounded, slightly asymmetric shape, and has numerous topographic features. SOURCE: Courtesy of L.A.M. Benner/NASA/JPL.

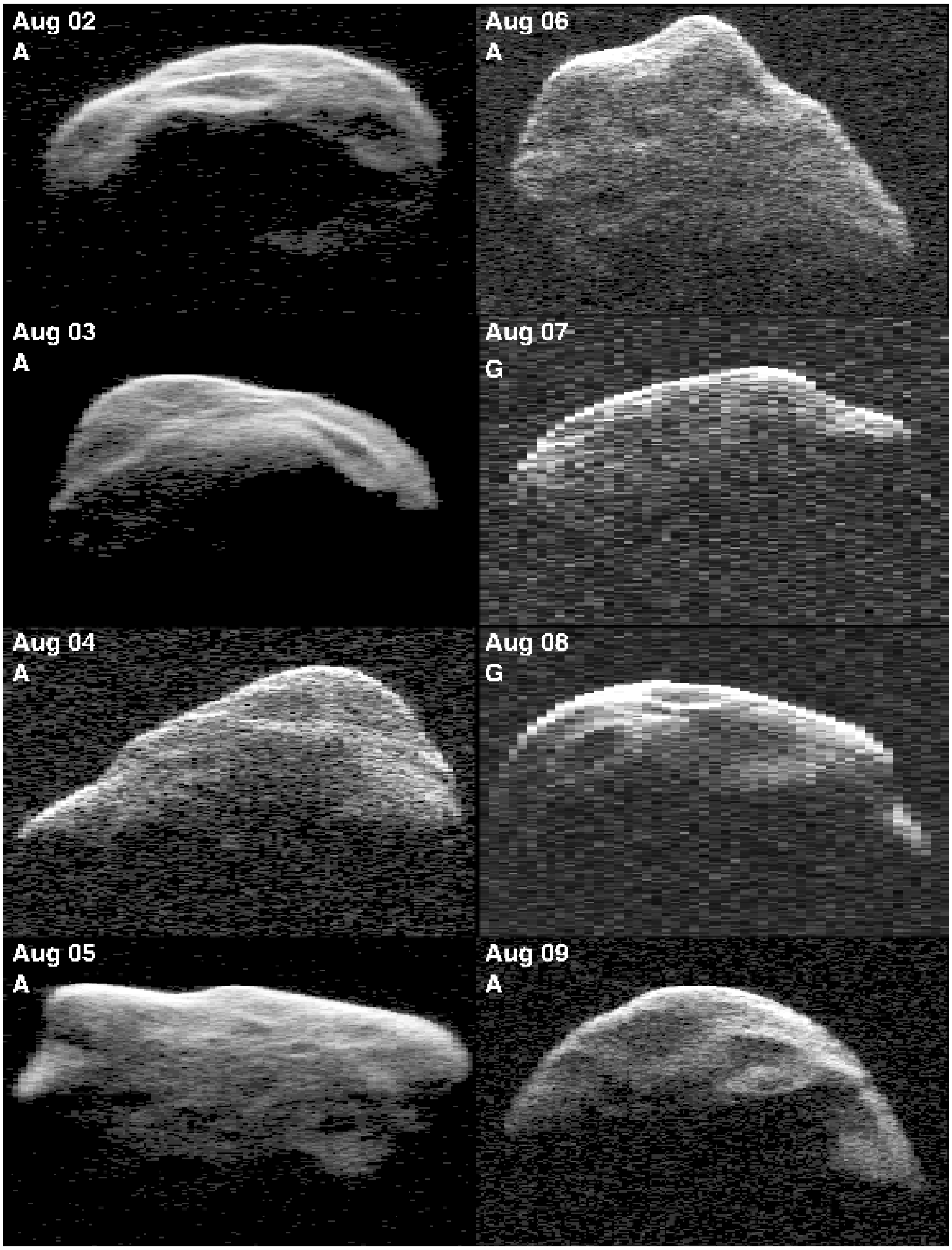

FIGURE 4.2 Arecibo (A) and Goldstone (G) radar images of near-Earth asteroid 1999 JM8. Illumination is from the top; range increases downward and the wavelength of the echoes of the radio waves increases to the left. 1999 JM8 is a very slow rotator with a period of about a week. Each panel corresponds to a sum of images from the referenced 1999 August date. With a diameter of ~7 km, 1999 JM8 is among the largest known near-Earth asteroids. SOURCE: L.A.M. Benner, S.J. Ostro, M.C. Nolan, J.-L. Margot, J.D. Giorgini, R.S. Hudson, R.F. Jurgens, M.A. Slade, E.S. Howell, D.B. Campbell, and D.K. Yeomans, Radar observations of asteroid 1999 JM8, Meteoritics and Planetary Science 37:779-792, 2002. Copyright 2002 by the Meteoritical Society.

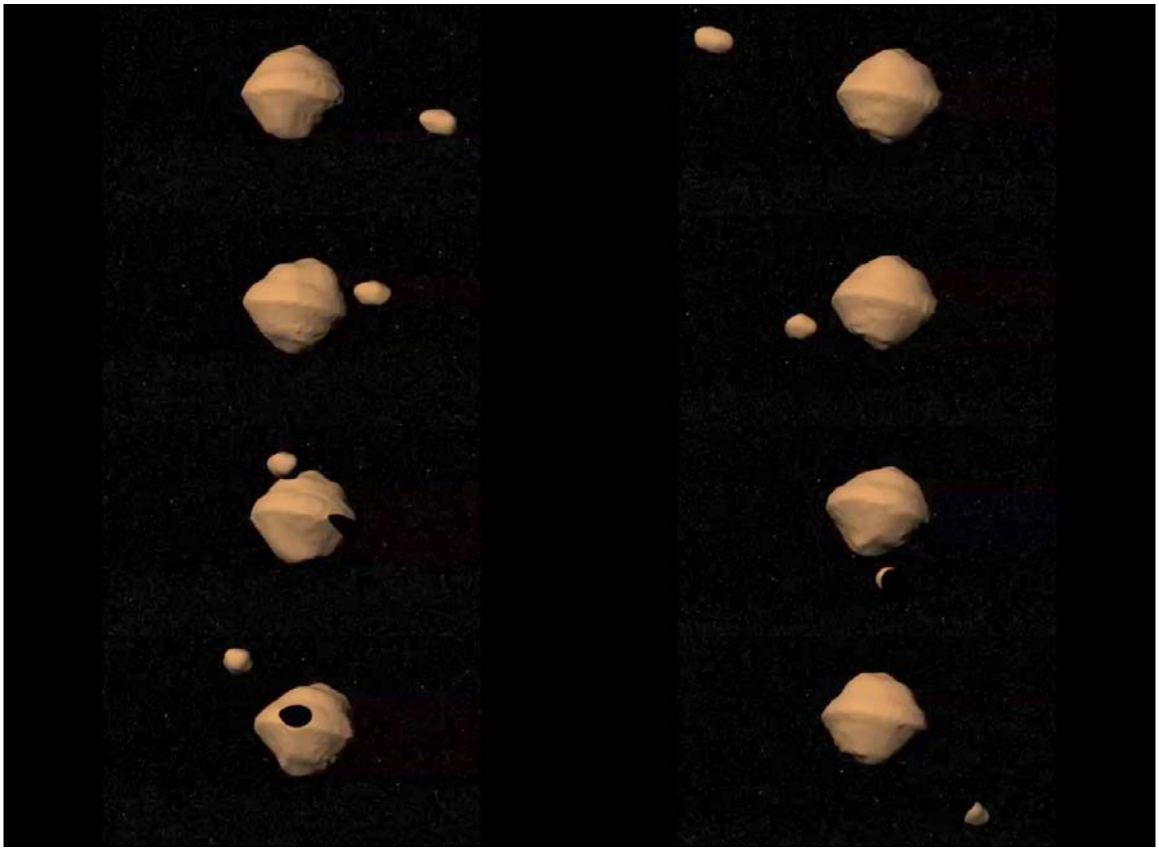

FIGURE 4.3 Renderings of binary near-Earth asteroid 1999 KW4 showing its satellite making one orbit. The figure shows three-dimensional models in shaded relief, reconstructed from a set of radar images obtained at Arecibo and Goldstone in 2001. The models are shown in their proper orientation as viewed from Earth. Radar imaging has shown that ~15 percent of NEOs larger than 200 meters in diameter have one (or sometimes two) satellites. SOURCE: S.J. Ostro et al., Radar reconnaissance of near-Earth asteroids, pp. 143-150 in Near Earth Objects, Our Celestial Neighbors: Opportunity and Risk (A. Milani et al., eds.), Proceedings of the 236th Symposium of the International Astronomical Union, Prague, Czech Republic, August 14-18, 2006, Cambridge University Press, Copyright 2007 International Astronomical Union.

Capabilities of Arecibo and Goldstone

Because it is fully steerable, Goldstone can track objects significantly farther north and south than can Arecibo, and for up to several times longer per day. Limits on Goldstone's coverage are also imposed by the requirement that targets be 20° above the horizon. Opportunities known well in advance are scheduled months or even years ahead. However, the Goldstone radar competes for telescope time with numerous NASA spacecraft missions that have higher priority and often limit the time available for radar observations. The antenna is also available for short-notice target-of-opportunity observations if the flight projects have sufficient scheduling flexibility to accommodate changes, and if radiation clearance can be obtained in time from the numerous military and other government organizations whose airspace surrounds Goldstone. NEO radar observations have been scheduled in as few as 2 days after a request, but recent urgent requests have been at least two weeks in advance. In general, Arecibo has significantly greater flexibility for responding to short-notice target-of-opportunity observing requests than Goldstone.

Radar images obtained at Arecibo and Goldstone can, respectively, now achieve resolutions as fine as 7.5 meters and 19 meters per pixel. Due to its greater sensitivity and finer range resolution, Arecibo provides significantly more high-resolution NEO imaging opportunities than does Goldstone.

A recent JPL internal study found that, despite its restricted pointing capabilities, Arecibo is capable of observing up to two-thirds of newly discovered potentially hazardous nearby NEOs because these nearby objects move so rapidly across the sky that many pass through Arecibo's latitude "window" before they exceed range. The corresponding figure for Goldstone (whose detectable range on a given object is about one-half of Arecibo's) is nearly the same. Arecibo is able to detect 12 percent more of the larger objects (~700 meters in diameter) than Goldstone, but 5 percent fewer of the smaller objects (~70 meters in diameter) due to the smaller Arecibo "window" and shorter times for observation, as noted above.

In practice, most NEOs are observable at both Arecibo and Goldstone, but for the relatively small fraction that remain south of −1° or north of +38°, Goldstone is the only radar capable of observing them. Radar observations at the two telescopes are often scheduled on different days (with those at Goldstone often on dates when targets are too far south or north for Arecibo), which increases coverage of the different surface regions of the NEO, which is very important for 3D shape determination. The capabilities of Arecibo and Goldstone are thus complementary and many observing campaigns have utilized their synergy. Another primary advantage of having two radar facilities is that one can serve as a backup for the other. Mechanical problems, or other demands on the facilities (particularly the need to use Goldstone to communicate with NASA spacecraft), mean that both facilities are rarely available simultaneously.

In the last several years, 20 to 30 NEOs have been observed with radar annually (average = 24), and since the first detection of an asteroid by radar in 1968, 252 near-Earth asteroids and 13 comets have been detected. Table 4.1 lists the number in several size ranges that have been observed:

NEOs have been selected for radar observations primarily on the basis of objects that are expected to yield the greatest scientific return on investment, which often means by providing high-resolution images that are suitable for 3D shape reconstruction. In some instances, such as with Apophis which was observed solely to improve its orbit, observations of targets with weaker radar echoes are scheduled. Many more NEOs are potentially detectable by radar than are scheduled due to limitations in available telescope time, person-power, funding, scheduling conflicts, and equipment problems.

The ability of radar to detect echoes from a cosmic object is a complicated function of the object's distance, diameter, rotation period, and radar reflectivity, and the telescope's size, and transmitter power, as well as the length of the transmitted waves and the sensitivity of the receivers. The most important factor is the distance: the returned signal strength depends on $(1/\text{distance})^4$, so echoes will be 16 times weaker when the distance to a target doubles. Figure 4.4 shows radar echo strengths at Arecibo and Goldstone for a range of distances and sizes.

TABLE 4.1 Sizes of Asteroids Observed Annually by the Arecibo and Goldstone Radar Observatories

Diameter range	Number	Percentage
D > 1 km	92	36.5
0.5 km < D < 1 km	68	27.0
0.2 km < D < 0.5 km	32	12.7
D < 0.2 km	60	23.8

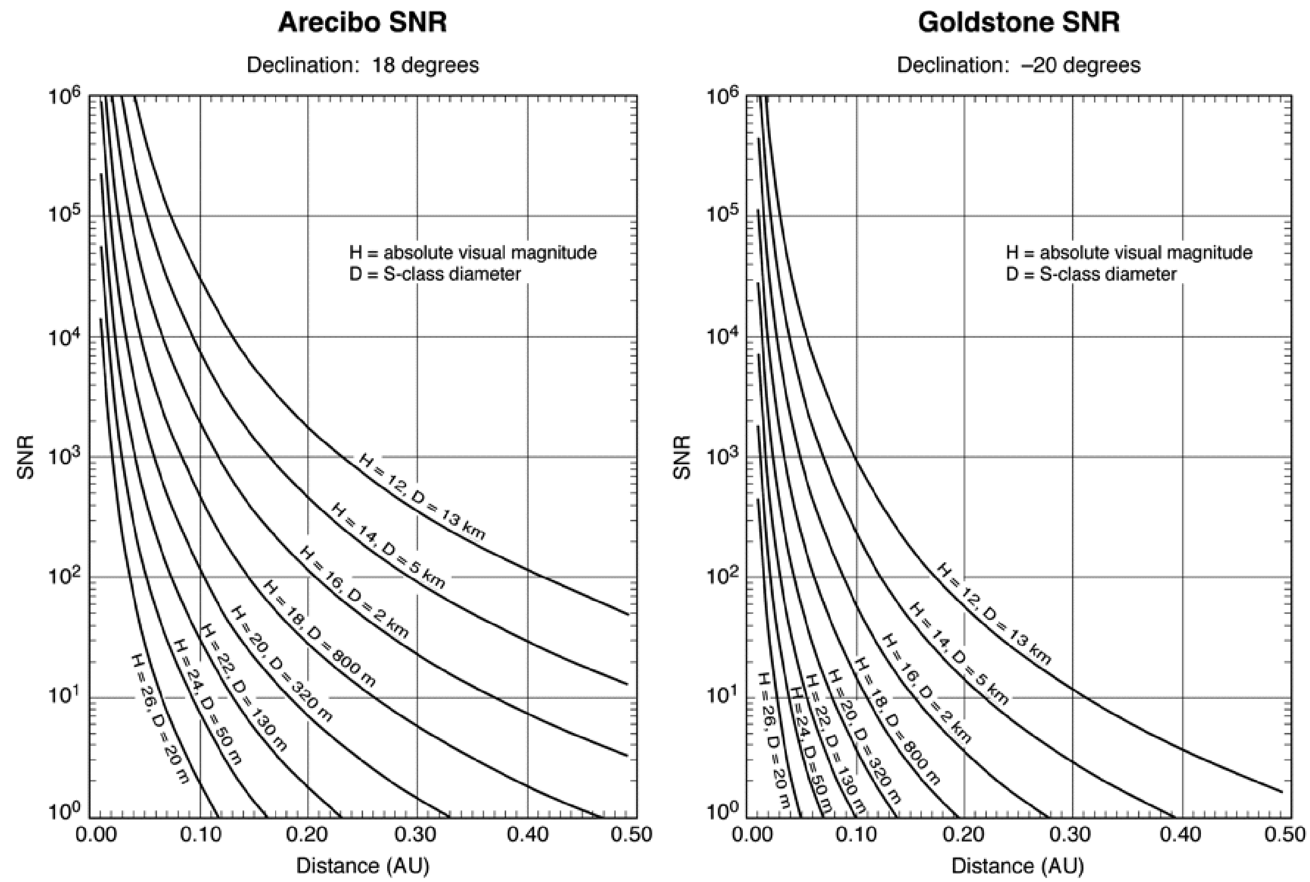

FIGURE 4.4 Signal-to-noise ratios (SNR) for radar echoes received at Arecibo and Goldstone for several combinations of distances and sizes. “S-class diameter” is a category of stony asteroids. SOURCE: Courtesy of Lance A.M. Benner.

How many NEOs could be observed by radar annually? If we adopt a threshold suitable for detection and orbit improvement (e.g., Apophis), but much weaker than is necessary for obtaining high-resolution images, then in a one-year interval starting in May 2008 about 410 NEOs could have been detected by radar if the factors discussed above were not an issue. Of these, 140 NEOs had already been discovered before May 2008 and 270 were found during the ensuing year. During that same interval, about 760 NEOs (other than sungrazing comets) were discovered, so in principle 270/760 = 36 percent of all new NEOs could have been observed by radar. Below is the number of NEOs in different size intervals that were detectable:

During those 12 months, 23 NEOs were observed by radar, so the number that could have been observed was about 18 times larger and substantially more than have been observed by radar in the last 40 years. Thus, Arecibo and Goldstone are grossly underutilized as radar observatories and could make much more substantial contributions than they are currently. Furthermore, when Pan-STARRS 1 begins regular operations, the number of NEOs discovered and thus detectable by radar should increase dramatically.

TABLE 4.2 Number of NEOs in Different Size Intervals That Could Be Detected by the Arecibo and Goldstone Radar Observatories

Diameter	Number Detectable
D > 1 km	46
0.14 km < D < 1 km	110
D < 0.14 km	252
Total	408

Finding: The capabilities of Arecibo and Goldstone are complementary and many observing campaigns have utilized their synergy. One of the primary advantages of having two radar facilities is that one can serve as a backup for the other.

Finding: The number of NEOs observed by radar per year could be increased about fivefold by obtaining sufficient observing time.

Arecibo and Goldstone radar observations of more than 20 NEOs have revealed that surface roughness depends on composition and that very rough surfaces are common. Arecibo and Goldstone radar observations have also revealed that approximately fifteen percent of NEOs larger than 200 meters in diameter have satellites orbiting about them (see Figure 4.3). This information is important for planning mitigation (Chapter 5). The first confirmed NEO “triple system” was discovered at Arecibo. Arecibo has discovered half of all known NEOs with satellites and observed almost all of these systems. Radar, with Arecibo in the lead, has become the most effective tool available for discovering that NEOs have satellites, and for estimating the mutual orbits, masses, sizes, and thus densities of each component.

Arecibo observations of the NEO 1950 DA suggested a small probability of impact with Earth in 2880 and demonstrated that the physical properties of an NEO are intimately coupled with long-term orbit prediction through the accelerations resulting from the absorption of sunlight and asymmetric radiation of heat from the NEO due to its rotation (Giorgini et al., 2002), as well as the direct pressure exerted by sunlight on the NEO. The importance of these effects depends on the NEO mass, thermal properties, size, shape, and rotation period. Arecibo and Goldstone radar observations led to the first detection of such effects for asteroid Golevka and provided an estimate of its density and mass; this is one of only a handful of NEOs for which a mass estimate is available (see Table 4.3).

TABLE 4.3 Numbers of Near Earth Asteroids with Known Physical Properties

Number of NEOs currently known	6,278
Rotation periods	450
Rotation pole directions	25
Detected by radar	246
Shapes estimated from radar data	25
Shapes estimated from optical data	14
Shapes estimated from spacecraft data	2
Masses estimated from spacecraft data	2
Masses estimated from radar data	4
Bulk densities estimated from all sources	10
Size estimated from all sources	108
Near-surface densities estimated from radar	17

The Operational Reliability of Arecibo and Goldstone

Until recently, Arecibo has proven a more dependable radar facility than Goldstone because fewer equipment problems interfered with scheduled observations. That situation has recently changed, largely because of aging on-site primary power turbine generators at Arecibo (commercial power for the operation of extremely high-power transmitters there is not practical). Because of turbine degradation, Arecibo has been unable to guarantee its full nominal power output of 900 kW for several years; by the fall of 2008 the turbine generator had become progressively less reliable, forcing a reduction of power to ~500 to 600 kW, and by the spring of 2009 to only ~60 kW, which caused the cancellation of many NEO radar observations. The government of Puerto Rico has appropriated money for a new, more reliable generating source using diesel engines, but installation of this system is not expected until spring 2010.

Goldstone has also experienced significant equipment problems, most notably with its transmitter, which reduced operations to half power for several months in late 2008, but has recently resumed operating at its nominal power of 430 kW. Keeping the ~45 year-old DSS-14 antenna operating is an increasingly important issue; Goldstone is scheduled to go "offline" for 7 months of maintenance starting in March 2010.

Arecibo and Goldstone Radar Operating Costs

The Arecibo and Goldstone radar systems are currently operational (with the caveats on transmittal power noted above), but neither is funded for dedicated observations of NEOs. The annual cost for Arecibo to carry out up to 300 hours of radar observations plus adequate maintenance is estimated at $2 million (approximately $1 million for the cost of purely radar operation—fuel, salaries, and so on—and $1 million for radar's pro rata share of maintaining the antenna and facility). In 2008 Arecibo devoted about 240 hours to NEO observations. If the radar observations at Arecibo increased, say, to about 500 hours, then the associated operational cost would rise to about $3 million.

Arecibo could carry out radar observations at a significantly higher rate than currently, if additional time and funding were available. At Goldstone the situation is different because its primary mission is spacecraft communication, although if the Deep Space Network decommissions the DSS-14 antenna, considerably more time could be obtained by converting Goldstone to a dedicated radar facility, but at a greatly increased cost since the whole facility would then be charged to the radar budget.

The 2004 Goldstone NEO budget request was $2.4 million, which would have supported a robust observing program. Only $2 million was appropriated, and since then the budget has dropped to about $1 million annually. Since 2002, Goldstone devoted an annual average of about 200 hours to observing NEOs, which constitutes 2.3 percent of all time available on this telescope. During this interval, the number of hours scheduled for NEO radar observations declined by about 50 percent and the fraction of scheduled time that was used for data acquisition declined from about 78 to 63 percent due to increasing difficulty with maintaining different components of the system.

Recent Funding History of the Arecibo Radar

In the 1990s the NSF and NASA funded a $25 million project that increased Arecibo's sensitivity by approximately 20-fold. NASA contributed $11 million to provide new equipment that doubled the transmitter power to 900 kW. This funding followed a history of NASA support for radar observations at Arecibo dating back to the 1970s, and was particularly aimed at improving radar observations of near-Earth asteroids. Following completion of this project in the late 1990s, NASA provided ~$600,000 annually for a few years to support fuel costs, salaries, and maintenance of the Arecibo radar.

Late in 2001 NASA sent a letter to the NAIC that indicated funding for the radar would be eliminated in calendar year 2002. This deadline was subsequently relaxed and the NAIC was instead asked to submit a proposal to NASA for continued funding. In consultation with NSF, NASA began reducing Arecibo's funding in FY 2003 and eliminated it at the end of FY 2005. NAIC has continued to operate the radar using existing funds but at the expense of adequate maintenance of the radar system.

In late 2006, the National Science Foundation convened a senior review that issued a report on observatories funded by NSF. No solar-system scientists served on this panel. The panel recommended annual reductions in funding at Arecibo to a level that would merely permit completion of several (non-radar) astrophysical surveys that still had a few years to run. Unless funding outside the NSF could be secured, this panel recommended that the observatory be closed and decommissioned. According to a March 2009 report by the Congressional Research Service, costs for decommissioning the facility have ranged from $170 to $200 million (Matthews, 2009), more than a decade's total operations of the facility. Because of budgetary commitments for essential maintenance, NAIC was forced to cut Arecibo's operating budget by 24 percent almost immediately following the senior review, but continued to operate the radar within its reduced budget. However, due to continuing budget cuts, NAIC stated that it would soon be necessary to cease operations of the radar altogether, in order to provide sufficient funds for the observatory to complete the recommended astrophysical surveys. Currently NAIC is committing to operate the radar only through FY 2010.

Finding: Radar cannot be used to discover NEOs, but is a powerful tool for rapidly improving our knowledge of the orbit of a newly found object, and thus characterizing its potential hazard to Earth.

Finding: The Arecibo and Goldstone radar systems play a unique role in the characterization of NEOs, providing unmatched accuracy in orbit determination, and insight into size, shape, surface structure, and other properties for objects within their latitude coverage and detection range.

Finding: Congress has directed NASA to ensure that Arecibo is available for radar observations, but has not appropriated funds for this work.

Recommendation: Immediate action is required to ensure the continued operation of the Arecibo Observatory at a level sufficient to maintain and staff the radar facility. Additionally, NASA and NSF should support a vigorous program of radar observations of NEOs at Arecibo and NASA should support such a program at Goldstone for orbit determination and characterization of physical properties.

BOX 4.1
Radar Observations of the Near-Earth Object Apophis

Near-Earth asteroid Apophis, which is approximately 300 meters in diameter, was discovered in March 2004, lost, and then rediscovered in December of that year. It quickly became clear that it would make a very close approach to Earth in 2029, and initial estimates of its orbit showed a significant probability of an impact. Further observations ruled out an impact in 2029.

Apophis was observed at Arecibo as a target-of-opportunity in January 2005, August 2005, and May 2006 solely to reduce uncertainties in its orbit. The radar observations reduced the volume of the statistical uncertainty for the approach in 2029 by more than 90 percent and also revealed a bias in the analysis of the optical observations obtained in March, 2004; the net effect was to shift the predicted 2029 encounter 4.4 Earth radii closer and only 5.6 Earth radii from the surface (Giorgini et al., 2008), a distance comparable to those of many communication satellites During the radar observations, Apophis was between 0.19 to 0.27 AU from Earth (1 AU is the average distance of Earth from the Sun) and a weak radar target.

We thus now know that Apophis cannot impact Earth in 2029, but an impact, although extremely unlikely, has not been ruled out for the approach in 2036. The primary sources of uncertainty are the physical properties of the asteroid and how through interaction with sunlight they propagate into orbit change. Apophis is an unusual case: These properties matter so much because the uncertainties grow enormously due to Apophis' very close approach to Earth in April 2029. Thus, although the 2005 to 2006 radar observations significantly improved the orbit, paradoxically, because the approach is so deep in Earth's gravity well, the uncertainties in subsequent years are greatly magnified. Ignoring these sunlight effects, leads to a probability of impact in 2036 of about 0.000002, but in practice this probability cannot be computed reliably due to uncertainties imposed by Apophis's unknown physical properties as mentioned above.

Optical observations will be obtainable in 2011 and may be sufficient to exclude a 2036 impact. If not, then radar observations at Arecibo or Goldstone when Apophis approaches Earth within 0.14 AU in 2013 should reduce uncertainties in our knowledge of the orbit substantially, with a high probability of completely ruling out an impact in 2036, and a very small probability of indicating a possible impact.

CHARACTERIZATION ISSUES FOR "AIR BURSTS"

Airbursts created by the entry in Earth's atmosphere of NEO's with diameters of up to a few hundred meters pose both a serious threat at the larger end of the size range, and offer a unique opportunity to deduce physical characteristics at the small end of the range. Observations of small airbursts have provided almost the only information existing on the bulk strength, density and composition of small NEOs through their high-speed interaction with Earth's atmosphere. Although kilometer-sized NEO's are not substantially affected by their atmospheric passage, knowledge of their density and probable strength is important for mitigation efforts, making the study of airburst phenomena a prime focus for characterization efforts.

The density of an NEO that enters Earth's atmosphere is most often the main determinant of where its energy is released. Dense and physically strong bodies (e.g., solid bodies) will be more likely to penetrate the atmosphere intact and impact the surface of Earth. Although much of the energy from such impact events goes into crater formation and excavation, producing melt, ejecta, and seismic shaking and/or tsunamis in ocean events, a substantial fraction of its energy (perhaps as large as 2/3 for the event that produced Meteor Crater, Arizona; see Figure 2.1) is nevertheless deposited in the atmosphere. Objects up to a few hundred meters in diameter with low density or physically weak bodies (e.g., highly porous and strengthless rubble piles) are likely to disrupt during atmospheric entry; all of the energy from such events will be deposited directly into the atmosphere, producing shock waves in the air and heat radiation that may cause more widespread damage on the ground than had the atmosphere been absent.

The most notable recorded airburst event occurred in a remote region of Tunguska, Siberia in 1908 and knocked down or defoliated the trees over an area of more than 2,000 km^2. There is a range of estimates for the size of the object that caused this event. Several estimates place the object as approximately one hundred meters in diameter. A recent study, as yet not reproduced, suggests that the event was caused by a small (~30- to 50-meter-diameter) NEO exploding at relatively low altitude (about 10 km up). (Boslough and Crawford, 2008) Since smaller NEOs are thought to be far more numerous than larger ones, there is a reasonable expectation that the next markedly destructive Earth impact event will be an object in the size range of 30 to 50 meters.

Ground-based studies of NEOs using data on both rotation rates and satellites suggest that most NEOs larger than about 150 m are rubble piles, while most smaller ones are monolithic with enough long-term tensile strength to prevent them from flying apart. The larger objects that are weak rubble piles easily disintegrate during atmospheric entry and create airbursts that somewhat resemble high-altitude nuclear explosions. Smaller monoliths may still be dispersed by aerodynamic forces as these monoliths penetrate deeper into the atmosphere and may, or may not, produce craters depending on the strength, density and size of each monolith.

Recent data obtained by spacecraft sensors also indicate that many NEOs may be either composed of gravitationally bound rubble piles or physically weak materials. The investigation by Japan's *Hayabusa* spacecraft of the NEO Itokawa suggests that this asteroid is a prime example of a rubble-pile object with significant porosity. The Hayabusa data show that Itokawa is very porous, roughly the same porosity as sand, and would probably produce a very significant airburst if it impacted Earth.

Information from U.S. Department of Defense's (DOD's) Earth-observing satellites has shown that high-altitude airbursts from relatively small (1- to 5-meter-diameter) objects occur on a regular basis. This key information shows, for the NEOs encountering Earth, how the numbers of these objects depends on their size. To date, none of these airbursts has produced appreciable damage. However, two well-observed airbursts have resulted in meteoritic material being recovered from the ground. The recent impacts of the Tagish Lake meteorite parent body over Canada (January 2000), and asteroid 2008 TC_3 over Sudan (October 2008), lend evidence to support the suggestion that airbursts are relatively common. In addition, these events lend some insights into the material composition of these NEOs. The meteorites recovered from these two airbursts are composed of carbon-rich materials, which suggest that their parent bodies were objects composed of physically weak materials compared to those of other meteorite types (e.g., iron-rich materials). This information, along with the substantial fraction of NEOs with satellites, suggests that many sub-kilometer-sized NEOs are rubble piles or composed of physically weak materials. Therefore, any such NEO found to have an Earth impacting trajectory, would likely deliver its impact energy in the form of an airburst.

Airbursts are also detected by the arrays of microbarobgraph sensors deployed by DOD and the Comprehensive Test Ban Treaty (CTBT) Organization. This international network is called the International Monitoring System and consists of seismic, infrasound, radionuclide and hydroacoustic stations. The data are not publicly available; the scientific community would benefit from unfiltered access to the data produced by these arrays.

One of the least understood aspects of the airburst phenomenon is whether and how these events play a role in the formation of tsunamis. There has been significant debate on the effects of ocean impacts, both by direct impact into, and by airbursts above, the water. Some investigators suspect that an airburst over an ocean may be much more devastating than a similar-sized impact event directly into the water. Modeling of direct oceanic impacts suggests that the impact splash is significant and will be detrimental to those nearby, but that the wavelength of the resultant waves generated is not of sufficient length to cause a tsunami. Other studies, suggest on the contrary that even this type of impact may be enough to generate a tsunami-like phenomenon depending on the terrain that such impact-generated waves may encounter. Still others have found that, based on numerical simulations and data from nuclear oceanic tests, tsunamis are not generated by impact events.

More recent work on airburst events over the ocean suggest that this too is an area of uncertainty. Previous investigations have treated these types of airbursts in a fashion similar to nuclear explosions that deliver their energy from a single point. If this treatment were correct, then the resultant blast waves would not produce a tsunami-type of event. However, a recent study suggests that NEOs entering the upper atmosphere and exploding there act more like a linear series of nearly simultaneous explosions. (Boslough and Crawford, 2008) These blast effects are not as localized as those from the single source models, in which the momentum of the object is carried downwards into the atmosphere and produces a shockwave. If the shockwave were sufficiently strong to depress a wide area of the ocean's surface, the resultant rebound effect of the ocean would create a classic tsunami. Hence the threat from small NEO airbursts over the ocean might present their most significant hazard to humanity given that most of the world's population is concentrated on or near oceanic coastlines.

Finding: U.S. Department of Defense satellites have detected and continue to detect high-altitude airburst events from NEOs entering Earth's atmosphere. Such data are valuable to the NEO community for assessing NEO hazards.

Recommendation: Data from NEO airburst events observed by the U.S. Department of Defense satellites should be made available to the scientific community to allow it to improve understanding of the NEO hazards to Earth.

Finding: Preliminary theoretical studies on low-altitude atmospheric Tunguska-like airbursts from asteroids as small as 30 meters in diameter suggest significant risk exists from these NEOs.

Finding: Current models for generation of tsunamis by impacts into, or airbursts above, the ocean are not yet sufficiently reliable to establish threat levels to coastal communities.

Recommendation: Additional observations and modeling should be performed to establish the risk associated with airbursts and with potential tsunami generation.

IN SITU CHARACTERIZATION RELEVANT FOR MITIGATION

Detailed knowledge of several representative NEOs' physical characteristics would improve understanding of the overall NEO population and help the design and implementation of the mitigation techniques that may be employed should an NEO threaten Earth (but may well not improve knowledge of a specific object on an impact trajectory). Although the physical characteristics of an individual NEO that might strike Earth cannot be accurately predicted in advance, knowledge of the range of possible characteristics will greatly aid in advance planning and might be essential if there is no opportunity to perform detailed characterization studies of the incoming NEO. Dedicated space missions such as *NEAR Shoemaker* and *Hayabusa* have provided detailed information on two vastly dissimilar NEOs. NASA's *NEAR Shoemaker* spacecraft visited one of the largest NEOs, Eros, in February 2000 and the Japan Aerospace Exploration Agency's (JAXA's) *Hayabusa* probe rendezvoused with the sub-kilometer sized asteroid, Itokawa, in September 2005. Both of these robotic missions generated much scientific interest in NEOs and revealed many intriguing surprises and new paradigms for asteroid scientists to consider. It is now apparent from just these two missions, and the suite of ground-based optical and radar observations of NEOs, that NEOs have a much wider range of internal structures, more diverse physical conditions, and more complex surfaces than had previously been realized.

Essential physical properties relevant for mitigation of NEOs are best determined from dedicated spacecraft missions. Although ground-based observations can provide significant information about NEO physical properties (e.g., rotation rates, size estimates, and composition), dedicated spacecraft missions to NEOs providing extended periods for operations and investigation close to NEOs obtain detailed characterizations of their rotational motions, masses, sizes, shapes, surface morphology, internal structure, mineral composition, and collisional history. The data collected from NEO characterization missions would also help to calibrate the ground- and space-based remote sensing data and may permit increased confidence in the remote classification of NEOs and their associated physical characteristics, which could inform future mitigation decisions.

Flyby missions are not well suited for these detailed types of investigations because of the limited time for performing observations during the spacecraft encounter. To attain the required details of an NEO's physical characteristics for hazard mitigation, much more time must be spent near the NEO than is possible in a flyby in order to operate instruments making gamma-ray, x ray and other compositional measurements. Constraints on some surface characteristics and on the object's mass can be obtained, but the uncertainties on the NEO's physical properties obtained from a flyby encounter are far too large to be useful for hazard mitigation purposes. Such missions may be suitable for basic reconnaissance of the NEO population, but overall, the data return relevant to mitigation is low relative to cost.

Continued efforts to obtain characterization data from ground-based studies are desirable, and spacecraft observations of representative NEOs are very important. If those and other constraints do not pose barriers, spacecraft characterization of any NEO for which orbit change is to be attempted is essential, to carry out if possible (see Chapter 5).

Finding: Dedicated flyby spacecraft missions to NEOs provide only limited information relevant for hazard mitigation issues.

Finding: Rendezvous spacecraft missions can provide detailed characterization of NEOs that could aid in the design and development of hazard-mitigation techniques. Such in situ characterization also allows calibration of ground- and space-based remote sensing data and may permit increased confidence in the use of remote classification of NEOs to inform future mitigation decisions.

HUMAN MISSIONS TO NEOS

During its deliberations, the committee was briefed on the possibilities of human missions to near-Earth objects. This subject also received attention during the Human Space Flight Review Committee and was mentioned as part of its "Flexible Path" option in its final report.

In the future NASA's Exploration Systems Mission Directorate may conduct human missions to one or more near-Earth objects. The committee identified no cost-effective role for human spaceflight in addressing the hazards posed by NEOs. However, if human missions to NEOs are conducted in the future, the committee recommends that their scientific aspects be maximized to provide data useful for their characterization.

Recommendation: If NASA conducts human missions to NEOs, these missions should maximize the data obtained for NEO characterization.

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5

Mitigation

Impacts on Earth by NEOs are inevitable and range from harmless fireballs, which are very frequent, through the largest airbursts that do not cause destruction on the ground, which on average occur once in a human lifetime, to globally catastrophic events, which are very unlikely to occur in any given human lifetime but are probably randomly distributed in time. The risks from these NEOs, or more specifically our assessment of the risks in the next century, will be changing as surveys are carried out. Given the inevitability of impacts, and noting that the entire point of surveys is so that we can take appropriate action, how can we mitigate the effects of potential impacting NEOs?

The amount of destruction from an event scales with the energy being brought by the impacting object. Because the range of possible destruction is so huge, no single approach is adequate for dealing with all events. For events of sufficiently low energy, the methods of civil defense in the broadest sense are the most cost effective approach for saving human lives and minimizing property damage. For larger events, changing the path of the hazardous object is the appropriate solution, although the method for changing the path varies depending on the amount of advance notice available and the mass of the hazardous object. For the largest events, from beyond global catastrophe to events that cause mass extinctions, there is no current technology capable of sufficiently changing the orbital path to avoid disaster.

We consider four categories of mitigation:

- Civil defense—such as evacuating the region around a small impact,
- Slow push or pull methods—gradually changing the orbit of an NEO so that it misses Earth,
- Kinetic impact—delivering a large amount of momentum (and energy) instantaneously to an NEO to change its orbit so that it misses Earth, and
- Nuclear detonation—delivering a much larger amount of momentum (and energy) instantaneously to an NEO to change its orbit so that it misses Earth.

For impacting NEOs that are sufficiently small (tens of meters to perhaps 100 meters in diameter) and not very strong (typically not iron meteoroids), the destruction on Earth will be caused by an airburst and its associated blast wave and thermal pulse, as was the case of the event in Tunguska in 1908. Events like this cause destruction over areas up to thousands of square kilometers and evacuation and sheltering are not only plausible but often the most cost-effective approach for saving human lives. These events will also be the most frequent, occurring on average every couple of centuries. They are also the events that are likely to have the least advance warning. For larger events, actively changing the orbit of the hazardous object is likely desirable. The choice among the three methods—slow push/pull, kinetic impact, and nuclear detonation—depends both on the mass of the NEO that has to be moved and on how early the NEO is determined to be hazardous as well as the details of the orbit. The options are laid out in Table 5.1 listing the applicability of each to a given threat. Table 5.2 shows the regimes in which each mitigation method is applicable. Note that the table brings in an additional important aspect of the problem, international coordination, which is discussed in more detail in Chapter 7 of this report. Items in both tables are described below.

TABLE 5.1 Summary of Primary Mitigation Strategies

Mitigation Strategy	Range of Primary Applicability
Civil defense (e.g., warning, shelter, and evacuation)	Smallest and largest threats Any size threat with very short warning time
Slow push (e.g., "gravity tractor" with a rendezvous spacecraft)	A fraction (~10%) of medium size threats Usually requires decades warning time
Kinetic impact (e.g., intercept by a massive spacecraft)	Most medium size threats Requires years to decades warning time
Nuclear detonation (e.g., close proximity nuclear explosion)	Large size threats and short warning medium size threats Requires years to decades warning time

Although all of these methods are conceptually valid, none is now ready to implement on short notice. Civil defense and kinetic impactors are probably the closest to deployable but even these require additional study prior to reliance on them.

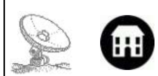
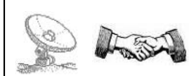
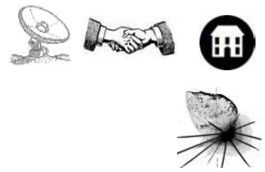
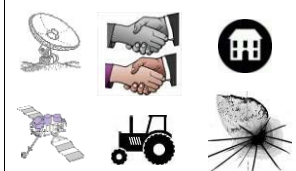
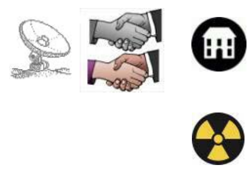
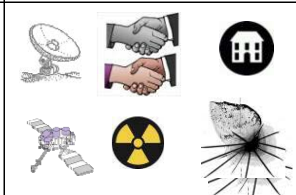
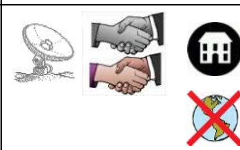
In all cases, the decision to initiate mitigation is a socio-political decision, not a technical decision. This decision is implicit in earlier socio-political decisions about which methods of mitigation to develop and also depends on the level of probability considered to require mitigation. The committee's recommendations regarding the minimum approach to mitigation and more aggressive approaches are discussed later.

The discussion of mitigation is rife with uncertainty. The effect on Earth of a given NEO depends critically on the velocity at which the NEO impacts Earth, a factor that is traditionally ignored in studies of the hazard. The decisions on mitigation must be based on the mass of the NEO, rather than the diameter, because mass is the quantity that most affects the effectiveness of any mitigation and the diameter for a given mass can vary by roughly a factor two. This factor implies a factor of two variation, depending on its density, of the size of an NEO that can be moved far enough to miss Earth. Clearly an earlier warning allows a smaller action to be sufficient but quantifying this is very uncertain. The effectiveness of most, but not all, methods also depends critically on the physical properties of the NEO. Our ability to mitigate depends critically on the details of the intercepting trajectory. There are also significant differences depending on whether we limit ourselves to current technology or include likely future technology such as the next generation of heavy-lift launch vehicles. Thus our discussion of the range of applicability will show overlapping and uncertain ranges.

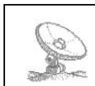
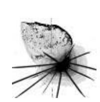
Realistic mitigation is likely to include more than one technique if for no other reason than to provide confidence. In any case of mitigation, civil defense will undoubtedly be a component whether as the primary response or as the ultimate backup.

Finding: No single approach to mitigation is appropriate and adequate to fully prevent the effects of the full range of potential impactors, although civil defense is an appropriate component of mitigation in all cases. With adequate warning, a suite of four types of mitigation is adequate to mitigate the threat from nearly all NEOs except the most energetic ones.

TABLE 5.2. Summary of Implementation of Primary Mitigation Strategies. (Action matrix once high probability of impact by NEO has been established.)

	Warning Time		
Scale of Event	Short (days-few years)	Medium (few years-decade)	Long (multiple decades)
Small (local/national)			
Medium (regional/multinational)			
Large (global/international)			
Largest (global catastrophe/ unable to avoid)			

Legend

	Study and monitor		Civil defense (shelter, evacuation)
	Characterization mission		Slow push orbit change (gravity tractor)
	Bilateral agreements		Kinetic impact
	International agreements/cooperation		Nuclear detonation
			No avoidance capability—global devastation

CIVIL DEFENSE: DISASTER PREPARATION AND RECOVERY

Of the two generic approaches to mitigation of the impact hazard—(1) active orbital change or destruction of the incoming body and (2) passive, traditional natural disaster mitigation based on "all hazards" protocols for evacuation, sheltering, response and recovery, and so on—society will very likely be faced with evacuation and sheltering rather than orbital change or destruction during our lifetimes. The most probable event will be a very late warning of a small (tens of meters in diameter or less) NEO. On the opposite end of the size spectrum, impacts approaching or exceeding the level of "civilization threatening impacts," there are inadequate precedents. For comparable events, one might think of the Black Death, World Wars, or the fictional end-of-the-world stories in "On the Beach" or, more relevantly, "Lucifer's Hammer." Whether human civilization would be fragile or robust in the face of such an event is unclear to us.

Although civil defense is the most likely response, the committee did not possess the expertise needed to fully address the political and economic aspects of even a small asteroid impact. This requires additional study.

There is a spectrum of potential events that might invoke one or more of the social, scientific, and emergency-management approaches to disaster mitigation. Some typical examples, in rough order of increasing severity, include:

- News media reports of a low-probability near- or long-term impact, warranting appropriate response informed by lessons in risk communication. These have happened frequently in the past decade and require no further societal action.
- Prediction of an unusually high likelihood of a major impact at some point in future decades (like the Apophis case in 2004/5). As planning is developed for a rational approach to orbit change, the "risk corridor" for locations where the impact might occur will be known. There could be some immediate economic and political implications (e.g., concerns about property values in potentially threatened locations) despite the fact that further astronomical observations will likely change the probability of impact to zero.
- Prediction of an imminent (hours to days) impact by a very small object (1 to 10 meters in size) on an impact trajectory. This type of warning could become a once-every-few-years event if telescopic searches are optimized for discovering such imminent impactors. Although it is very likely that such an impact will be harmless for people on the ground, prudent people near ground-zero should stay indoors, away from windows, and perhaps not gaze at the atmospheric explosion. Such events might rain down meteorites, or cause an on-ground explosive cratering event as in the case of Carancas (an event in Peru in 2007), and possibly break windows. Practices of risk communication will be important and will need to be planned in advance (see, too, Chapter 7).
- Prediction with a short-term warning (days to weeks) of an impact by a small NEO (10 to 25 meters in diameter). Such an event is likely to occur during this century. Such impacts are near the threshold of causing significant and potentially lethal damage in a modest, few-tens-of-kilometers wide zone near ground-zero, warranting prudent evacuation if on or near land. Here, the approaches would be similar to established procedures for other predictable, localized natural disasters, like a flooding river, or a ready-to-explode volcano. Of course, first-responders will lack knowledge of the characteristics of such devastating events in locations where floods, volcanoes, and so on are not relevant. Thus plans should be made to ensure adequate knowledge transfer from experienced first responders, in the event such a circumstance materializes.
- An unpredicted destructive impact by a modest-sized (10 to 100 meters) NEO. This case is about as likely as the previous one. Such an event could have modest to severe local consequences, but customary response-and-recovery methodologies after natural and man-made disasters will generally be as applicable in this case as in any generic disaster. The kinds of damage from a small impact explosion in the atmosphere, or impact into the ground, are similar to those from other natural disasters, including

building collapse, fires, social confusion, injuries, and death. Of course, the *cause* of the disaster is unusual, and presents the possibility for uninformed, exaggerated responses, such as fears that the impact is a harbinger of more and larger impacts to follow, as exemplified in numerous recent television shows and movies. This fear is very unlikely to be correct, so appropriate risk communication and public involvement of NEO impact experts should be helpful.

- Prediction of a very unlikely but possible impact by a dangerously large (30 to many hundreds of meters diameter) NEO in the next decades. While such predictions will be common in future years, especially after next-generation telescopic surveys become operational, the initial responses should emphasize refining the prediction and possible preparations for NEO deflection missions. The chances of such an impact occurring during the next century are tens of percent. Should the probability of an impact increase to certainty and the regional locale of ground-zero become identified, then preparations should begin to minimize the potential losses to life and property in the event that deflection measures fail or are not implemented. These preparations would involve augmenting provisions for shelter, medical care, food for displaced persons, provision for pets, and so on, including advanced planning for communications, evacuation, and so on.
- Prediction of an imminent (days to a few years) impact by a very dangerously large NEO (100 to many hundreds of meters in diameter). The final procedures will be similar to those described in the previous case, except that the planning for implementation will be less localized. Because the nature of the disaster could be similar in consequences to other large disasters (the worst Earthquakes in history, the Indian Ocean tsunami, World War II), lessons from those historical cases can inform the preparations for, and responses to, the inevitable disaster (since prevention of the impact may not be feasible for either technical and/or political reasons). The cause of such a disaster will have no precedent, and misunderstandings based on badly mistaken popular culture (movies, TV) could have negative repercussions, so reliable risk communication will be especially important.
- Prediction of a possible impact by a potentially civilization-destroying (and species destroying) NEO in the next decades. This potential catastrophe would be unprecedented in human history. Reliance could be placed on efforts to avert the disaster, by orbital change. But, prior to successful change (or after unsuccessful change), if the impact is within a decade of happening, concurrent international efforts could begin to ameliorate the consequences of any impact that might occur, noting that there is likely to be a tendency for the entire social structure to collapse. These efforts will be most effective if they attempt to increase the robustness of all elements of society, ranging from appropriate risk communications and warning, provision for medical care, provision of food/water/shelter, shoring up the global financial/electronic/social/law-enforcement infrastructures, preparing for inevitable response-and-recovery operations.
- Predicted short-term (few years or less) impact by a civilization-or-species destroying NEO. While this apocalyptic possibility is extraordinarily unlikely to happen in our lifetime, traditional approaches to preparing for disaster become irrelevant.

Finding: Civil defense (evacuation, sheltering in place, providing emergency infrastructure) is a cost-effective mitigation measure for saving lives from the smallest NEO impact events and is a necessary part of mitigation for larger events. If an NEO is predicted to impact on a specific, inhabited location, there is likely to be strong pressure for more than the most cost-effective method for saving lives.

SLOW PUSH-PULL METHODS

We now consider the first of three approaches to prevent an impact rather than protecting ourselves from an impact. "Slow push-pull" means the continuous application of a small but steady force to the NEO, thereby causing a small acceleration of the body relative to its nominal orbit. The effect of such small accelerations is most productive if applied along or against the NEO's direction of motion, as this causes a net shift of the NEO along its orbit. This shift can avert an impact by causing the NEO to "show up" at Earth's orbit earlier or later than Earth. A simple rule of thumb formula predicts the drift along the NEO's orbit for a given applied acceleration

$$\Delta s \approx \pm \frac{3}{2} A t_a \left(t_a + 2t_c \right) \qquad \text{(Equation 5.1)}$$

where Δs represents the shift in the NEO's position relative to its nominal orbit, A represents the induced acceleration of the NEO, t_a represents the time during which the acceleration is applied and t_c represents the coast time after application of the acceleration. For estimating the range of NEOs for which a given method is applicable, we will consider orbital changes large enough to move the NEO by 15,000 km, enough to provide a safe miss as long as the orbit is well determined. We will assume that a 10-ton spacecraft is the maximum possible with current launch capability and that a 50-ton spacecraft might be possible with future heavy-lift launch vehicles (see later discussion and Table 5.4).

The proposed slow push techniques can be sorted into a few categories: enhancement of natural effects, application of contact force, and application of gravitational force. Only the last of these techniques, which is likely the easiest from an engineering standpoint, has been studied sufficiently to show that it is feasible. With any slow push technique the efficiency of the approach and possible unintended consequences must be seriously considered. As the accelerations are quite small, overlooked physical phenomena or efficiency losses may substantially change the actual effect.

Enhancement of Natural Effects

In this approach a natural source of momentum is used to accelerate the NEO, most typically the use of photon pressure or solar energy. Changing the NEO's thermal response or reflectivity is one such technique, as this then modifies the natural forces that produce slight deviations from purely gravitational motion for small NEOs. A major drawback of such techniques is the lack of precision and predictability with which they can be applied to the body. Due to this lack, a conservative approach would require overcompensating by a large factor. One simple way to bound the level of acceleration possible using such an approach is to estimate the maximum acceleration that impinging solar radiation pressure can induce on an NEO, realizing that only a fraction of this natural acceleration will be available for modifying the orbit. For an asteroid with a density of 2 g/cm^3, the total solar radiation pressure on a 2-kilometer-diameter asteroid induces an acceleration at 1 AU from the Sun of 2×10^{-15} km/s^2 (multiply the values in km/sec^2 by 6.7×10^{12} to express them in units of 15,000 km/decade^2, where 15,000 is about 2½ Earth-radii, sufficient to provide a safety margin in missing Earth) while a 0.2-kilometer-diameter asteroid has 10 times the acceleration. Because only a fraction of this pressure can be tapped for useful, along-track accelerations, the time it takes to shift the asteroid's location enough to safely miss Earth becomes very long (centuries for an 0.2-kilometer-diameter NEO). The natural acceleration due to thermal effects on the NEO is a small fraction of this upper limit, but so is the likely efficiency in using enhancement.

Enhanced Evaporation of Surface Material

A different, but related, approach is to concentrate solar energy on the surface of the NEO to cause vaporization, creating a jet of mixed vapor and rock debris from the NEO's surface that will then accelerate the body by its reaction to the jet's force. This process operates naturally in comets, and the orbits of very volatile comets change every time they approach the Sun due to their reaction to gas venting from their surfaces. Because the time for heating surface rocks to evaporation can be short (tens of seconds), the NEO's rotation is not an issue: the source of the jet simply tracks over the surface as the NEO rotates beneath the spot where sunlight is focused. No physical ties to the NEO are required and because the acceleration is low, binary NEO systems will not disperse. The main requirement of the evaporation is a large, lightweight solar collector that will concentrate sunlight using an inflatable parabolic mirror and direct it into a series of lenses or mirrors that eventually focus the light on the surface of the NEO. Insofar as the diameter of the solar collector can be scaled to the size of the NEO (the acceleration scales as the inverse of the NEO's mass and the square of the collector diameter), orbits of NEOs up to several kilometers in diameter could, in theory, be sufficiently changed by very large collector systems. However, these systems have not yet been demonstrated. The Sun's energy might also be collected by a large number of smaller parabolic mirrors rather than one large one. In this sense, a solar collector system can be considered modular and scalable. One major unknown of systems of this type is how to prevent evaporated rock material from condensing on and fouling parts of the optical system. This technique could potentially be the most powerful slow-push approach, but its dependence on the properties of the NEO and its controllability (e.g., the enhanced evaporation can change the NEO's rotational state significantly) requires much more study before it can be considered ready for use. A recent study (Kahle et al., 2006) shows that some optical elements, at least in some designs, would not last more than a few minutes due to extreme heating. Thus the technique might be limited to use on NEOs that require very small speed changes, <0.1 mm/s.

Application of Contact Force

In the contact-force approach a mechanical connection to the NEO is assumed, and via this connection a force is applied to the body. An early concept was for a "tugboat" spacecraft to physically push on the NEO, similarly to a tugboat moving a much larger ship by applying a small but consistent force. Also in this vein are "mass drivers" which require a mechanism to be placed on the surface to eject mass from the NEO as propellant. One complicating factor for such approaches is the need to deal with the NEO's rotation; for efficient delivery of force the rotation state of the body must often be altered. These approaches are generally not considered viable given the current lack of mechanical and physical understanding of small body surfaces and sub-surfaces. Once additional information is obtained on these aspects it may be possible to robustly design surface coupling devices and understand the levels of force that can be sustained through them. Until then, the uncertainties in applying these techniques—even were they developed—are too large to allow these techniques to be used with any confidence.

Application of Gravitational Force

Using gravitational force is the only approach that is nearly independent of the physical properties of the NEO, except for its mass (Lu and Love, 2005; Fahnestock and Broschart, 2009; Fahnestock and Scheeres, 2008; Wie, 2008; Yeomans et al., 2008), and it is the slow pull method with the highest technology readiness level. The physics is quite simple—a "gravity tractor" spacecraft positions itself in close proximity to an NEO, which generates an appreciable gravitational attraction between the two bodies. The forces are equal and opposite, but due to the mass disparity the accelerations are quite different. The maximum acceleration that a 10-ton spacecraft could induce on a 1-kilometer-diameter NEO is exceptionally small, on the order of 7×10^{-16} km/s^2 while it is 7×10^{-14} km/s^2 for a 100-meter-diameter NEO of the same density. This force is somewhat larger than the maximum possible acceleration from asymmetry in the NEO's thermal radiation (the Yarkovsky effect). It does indicate that small, natural forces must be understood. The spacecraft thrusts to maintain a fixed location relative to the asteroid, without any of its propellant landing on the NEO's surface, as the gravitational force provides the connection to the NEO. In this way, there is a constant force acting on the NEO in the direction of the spacecraft; the center of mass of the system experiences a net acceleration equal to the acceleration induced on the NEO by the attraction of the spacecraft. Detailed simulations of this approach have been carried out, considering the movement of both single asteroids and binary asteroids—both of which types seem feasible to control. One of the main advantages of the gravity-tractor approach is that there is no need to physically attach the spacecraft to the NEO's surface. Also, the precision of the orbital change can be quite high, as spacecraft can be well instrumented and tracked with high accuracy. Finally, the technology for this approach is well understood and implementable without further scientific studies; thus a technology demonstration of this approach is feasible with current technology. The main caveat is the requirement for the spacecraft propulsion system to operate reliably for perhaps a decade or more.

The attainable accelerations are, however, quite low. We consider displacement by 15,000 km (a bit more than one Earth-diameter) as sufficient margin with a well determined orbit for the NEO. For long warning times (of order four decades), one could spend somewhat less than a decade to design, build, and launch the spacecraft and travel to the NEO, then spend a decade thrusting, followed by somewhat more than two decades of monitoring for NEOs up to about 100 m in diameter. If one launched successor gravity tractors (to overcome fuel and lifetime limitations) one could thrust for the full 30 years and raising the limiting size by a factor 1.5 to 2. Some NEOs, probably fewer than about 10 percent, have trajectories that can pass through small regions of space near Earth, called keyholes, where Earth's gravitational pull changes the NEO's orbit just enough that the NEO hits Earth on a future approach. Changing the orbit of an NEO to miss one of these keyholes can be accomplished for larger objects since the required orbital change is much smaller. Because of the wide range of keyhole sizes (hundreds of meters to hundreds of kilometers in diameter), it is unrealistic to estimate limiting sizes of NEOs in this niche.

Applicability of Slow-Push-Pull Mitigation Techniques

Unless a very long warning time before impact is available, the practical application of slow-push-pull techniques is limited to NEOs that are predicted to pass through a keyhole and to small NEOs near the limit for which civil defense alone might be adequate. As with any attempt to divert an NEO, long warning times typically imply substantial uncertainty in whether the NEO is on a trajectory to impact and may lead to political indecision. On the other hand, slow-push techniques might be ideal for refining the result after a larger orbit change by some other method and they are well suited for preventing an NEO from passing through a keyhole. The well known asteroid Apophis is one of the objects that does pass near a keyhole and might be an appropriate target for a slow push or pull, e.g., with a gravity tractor. However, the probability that Apophis will impact Earth is now so low that mitigation does not appear to be needed at this time.

Finding: Slow-push-pull techniques are the most accurately controllable and are adequate for changing the orbits of small NEOs (tens of meters to roughly 100 m in diameter) with decades of advance warning and for somewhat larger NEOs (hundreds of meters) in those few cases where it would pass through a keyhole that would put the NEO onto an impact trajectory. Of the slow push/pull techniques, the gravity tractor appears to be the most independent of variations in the properties of the NEO and by far the closest to technological readiness.

KINETIC IMPACT METHODS

Kinetic impact mitigation uses one or more very-high-velocity (typically more than about 5 km/s) impacts of a large spacecraft ("impactor") into a hazardous object. These impacts would change the velocity of the hazardous object by some small amount, which would result in a new orbit for the hazardous object that would cause it to miss Earth. The method is relatively simple and effective for

NEOs with diameters up to half a kilometer, and is well within current capabilities given modest hardware and control developments. This method would likely be the method of choice for the mitigation of hazardous objects of that size range when there are years or more of warning time.

In this approach either the spacecraft can "run into" the hazardous object, or the hazardous object can "run into" the spacecraft; only the relative velocity of the impact is relevant. The achievable relative velocity varies significantly with the details of the NEO's orbit but, unlike the variability in other parameters that affect this and other methods, the orbit of any particular NEO will be known with sufficient accuracy that various spacecraft trajectories can be studied with a view to achieving the maximum relative velocity in the best direction at encounter (see also the later discussion of trajectories). The Deep Impact mission demonstrated this principle, although with a smaller impactor on a larger body (6 km diameter). That impact was at 10 km/s and we will adopt that value for estimating effectiveness but we note that for present capabilities the range of relative velocities due to different orbits of the NEOs is likely to be anywhere from a few to a few tens of km/s.

There is one physical parameter that is important—the efficiency of transferring the spacecraft's motion to the motion of the NEO, usually denoted β. If the impactor is simply absorbed by the NEO, the momentum of the impactor is transferred to the NEO, resulting in a change of velocity of the NEO that is the relative velocity of the two divided by the ratio of NEO mass to impactor mass. The effect is enhanced if material is ejected from the NEO, as will usually be the case with β likely to be between 1 and 10. (For material ejected forward, as in a "pathological" case, β could be less than unity.) The value of β is likely to increase with relative velocity, but this effect has not been studied in detail. We note that the value of β is likely to be correlated with density of the NEO, being low (1-2) for very porous NEOs and high (5 or even higher) for hard, rocky NEOs due to the variation with materials mentioned above. The efficiency of changing an NEO's trajectory depends not only on β, but also on the shape of the NEO (which affects the direction of the ejecta) and on the direction of the spacecraft's motion relative to the NEO's motion. As shown later in this chapter, intercept trajectories are often such that the reduction in the effective change to the orbit is not large, but any given case must be analyzed in detail.

The instantaneous change in velocity of an NEO from a kinetic impact is thus given by

$$\Delta v = \beta \frac{mU}{M} \qquad \text{(Equation 5.2)}$$

where m and M are the masses of the impactor and the NEO, U is their relative velocity, and the factor β is greater than or equal to unity (Melosh et al., 1994). This equation can be used to determine the mass m of an impactor required to change the velocity of an NEO by 1 cm/s as a function of an NEO's diameter and the relative velocity, as shown in Figure 5.1. This plot uses the estimates for β (1 to 5) as a function of impact velocity as given by Holsapple (2009). The required mass increases as the time to Earth intercept decreases.

As an extreme example, if the β factor were as much as 10, using a single 10-ton spacecraft impacting at 50 km/s, we could deflect a 700-meter NEO of density 3 g/cm^3 by 1 cm/s. In that case, deflecting even a 1-km body might be possible with 3 impacts. For comparison with slow push/pull methods, an impulsive change of 1 cm/s is comparable to displacing the object by 15,000 km 10 years in the future. But, for a more conservative example consistent with a more porous NEO body, if the β factor is only unity, the mass density is 1.5 g/cm^3 and at a much lower impact velocity of 5 km/s, a 10-ton mass could change the orbit of only a 180-meter-diameter NEO sufficiently to avoid collision in all cases; ten such impacts would be required for a 400-meter-diameter object. Different mission designs may trade spacecraft mass, impact velocity and time from intercept to the time of impact with Earth, were there no mitigation.

To intercept any given NEO will require precise information about its orbit, which will set limits on mission designs. These limits are illustrated in Table 5.3, which shows the body sizes of NEOs whose orbit velocities could be changed by 1 cm/s. The table takes six representative cases by assuming a payload mass of 5 tons (now) or 50 tons (future) with 3 different intercept velocities: 5, 10, and 20 km/s.

These cases are crossed with two types of NEO composition: (1) a somewhat porous body with a density of 1.9 g/cm^3 and (2) a rocky body with a density of 3 g/cm^3.

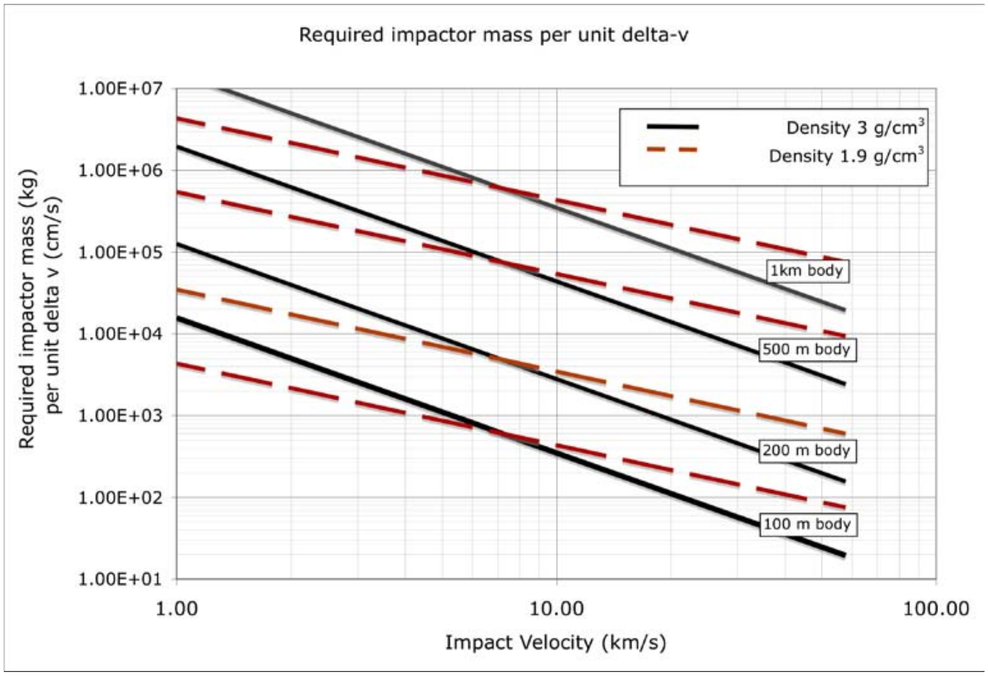


FIGURE 5.1 The estimated mass (kg) required to change the orbit of an NEO per unit required velocity change (cm/s) via a direct impact, as a function of the impact velocity and for different size bodies. For example, a 1 cm/s velocity increment of a 200 m diameter body of density 3 g/cm^3 impacted at 20 km/s requires an impactor mass of 10^3 kg, or one ton. A deflection of 0.1 cm/s would require a 0.1 ton impactor. The reason that the lower density porous body requires less mass at low impact velocity is because it has less mass than a non-porous body of the same diameter. But at the higher impact velocities that porous body does not have the large momentum multiplication that the rocky body has so the non-porous rocky body requires less impact mass.

TABLE 5.3 Sizes of NEOs (diameter in meters) Whose Orbit Velocity Could Be Changed by 1 cm/s with a Single Impact

Intercept Velocity	5 km/s		10 km/s		20 km/s	
Payload	5 tons	50 tons	5 tons	50 tons	5 tons	50 tons
NEO diameter if density = 1.9 g/cm^3	180 m	400 m	220 m	500 m	300 m	600 m
NEO diameter if density = 3.0 g/cm^3	160 m	350 m	240 m	500 m	350 m	750 m

NOTE: 1 cm/s is the order of the required velocity change to displace an NEO along its orbit by 15,000 km in 10 years. These tabular values are based on very limited data about the value of factor β and use the scaling theory of Holsapple (2009) to extrapolate to the larger velocities. The 5-ton payloads are possible now, and the 50-ton-payload cases are based on the planned Ares cargo vehicle. Achievable intercept velocities will depend on the orbital parameters of the NEO and may be limited by targeting and intercept capabilities.

Summary for Kinetic Impactors

The kinetic impact method is relatively robust and would be feasible to use with moderate engineering developments. A major uncertainty is that the value of β is relatively unknown, although it has a firm lower limit of unity, applicable for highly porous NEOs from which little or no material would be ejected. A mission based on the ESA Don Quijote concept would reduce the uncertainties, especially for high-impact velocities and highly porous bodies where the uncertainties are largest.

In addition, important questions will have to be addressed about the ability to hit a small NEO at high relative velocity; those considerations may limit the intercept velocities at which kinetic impacts can be effective. The possibility of an inadvertent disruption of the NEO and the resulting consequences also need further study. This need is considered further in Chapter 6.

With the same warning time of 40 years as discussed for the gravity tractor, one could launch a series of perhaps ten 10-ton impactors to divert the NEO 30 years before impact for NEOs of order ¾ km in diameter and even more than 1 km for very-low-density NEOs. For a 10-year warning time and a crash program to launch 10 spacecraft in say 4 or 5 years, it might be possible to prevent a collision with a ½-km NEO with the gravity tractor; new, heavy-lift launchers such as the Ares cargo launcher might allow delivering 5 times more massive impactors. Multiple impactors provide robustness against random failures and the opportunity to fine-tune the results by varying the number of impacts. Even a single impactor that could be launched within 6 months might change the orbit of a 100-meter NEO, the size that is near the upper limit for use only of civil defense, with a warning time of only 1 to 2 years.

Finding: Kinetic impactors are adequate to prevent impacts on Earth by moderately sized NEOs (many hundreds of meters to 1 kilometer) with decades of advance warning. The concept has been demonstrated in space, but the result is sensitive to the properties of the NEO and requires further study.

NUCLEAR METHODS

Nuclear explosives constitute a mature technology, with well-characterized outputs. They represent by far the most mass efficient method of energy transport and should be considered as an option for NEO mitigation. Nuclear explosives provide the only option for large NEOs (> 500 meters) when the time to impact is short (years to months), or when other methods have failed and time is running out. The extensive test history of nuclear explosives demonstrates a proven ability to provide a tailored output (the desired mixture of x rays, neutrons, or gamma rays) and dependable yields from about 100 tons to many megatons of TNT-equivalent energy. Coupled with this test history is an abundance of data on the effects of the surface and subsurface blasts, including shock generation and cratering.

Various methods have been proposed for using nuclear explosions to reduce or eliminate an NEO threat; for a given mass of the NEO the warning time is a primary criterion for choosing among them. With decades of warning, the required change in velocity (ΔV) from the explosion is millimeters to a centimeter per second and can be met for NEOs many kilometers in diameter. This range of values is much less than the 25 to 50 cm/s escape velocity from moderate to large (500 to 1000 meter) bodies, so it is reasonable to assume that such a small ΔV would not lead to the target's fragmentation or to excessive ejecta (i.e., debris thrown off the object). This expectation is met in hydrodynamic simulations presented here that show that nuclear explosions can provide ΔV from 0.7 to 2.4 cm/s, for payload masses less than a ton (including the nuclear device's fuse and environmental cocoon). In models of NEOs with surface densities as in terrestrial environments, nearly 98 percent of a body remains bound as a single object through only its own weak gravity. The small amount of ejecta expands over the decades to form a large cloud of low-density debris, reducing its posed threat by another factor of 10^4 to 10^5. The amount of the ejecta depends on the surface porosity. As in the case of kinetic impacts, a dissipative, low-density surface will reduce the amount of ejecta, thus reducing the ΔV.

Alternatively, when the time to projected impact is short, it may be impossible to apply a sufficient ΔV without fragmentation, but the limiting factor is assembly and launch. A nuclear package with a new fuse (i.e., a fuse that is not designed for terrestrial use) and a new container requires a cylinder about a meter in length and 35 cm in diameter, with a mass under 220 kg. The longest lead-time item for incorporating such a device in a rocket system is the development of a container to deliver the device and a fusing system capable of operating with the timing constraints required by the spacecraft velocities near impact with the NEO. Specifications for a nuclear bus could be the same as those for a kinetic-impactor mission, but would be very challenging to construct and integrate with the booster rocket and the nuclear package in under a year. This "latency time" between the decision to act and the launch can be reduced dramatically (perhaps 100 fold) by designing and testing these critical components in advance of discovering a hazardous NEO.

Models and Uncertainties

Nuclear outputs are well determined from tests. Just as with kinetic impactors, the greatest uncertainty in their use lies in the NEO response, particularly our understanding of shock propagation through low-density material and of the large variety of NEO structures and behavior upon impact that could be encountered. Consider as examples: Asteroid Itokawa, like many asteroids, appears to consist of rubble weakly bound together by gravity. It was found to have a bulk density of about 2 g/cm^3 (Abe et al., 2006), i.e., a porosity near 40 percent. Some asteroids, such as Eros have densities near that of solids, but are probably heavily fractured (Britt et al., 2003). However, 2001 0E$_{84}$ is a large (~1-kilometer-diameter) body rotating so rapidly that it must be very strong and is therefore not very porous; (6187) 1986 DA is essentially a solid iron NEO.[1] All other known fast-spinning bodies are small (<200 meters diameter). There are also low-density objects, like asteroid Mathilde, where observed craters suggest a very porous surface with larger efficient shock dissipation. The bulk density of cometary nuclei is likely <1 g/cm^3.

NEOs have a wide range of shapes, sizes, and densities. The bulk density of those asteroids for which it is known is comparable with that of materials used in nuclear effects simulations (e.g., gravel ≈ 1.5 g/cm^3 and gravel with sand ≈1.9 g/cm^3). The sophisticated computer simulations discussed here were used to model one of many possible structures, a 1-kilometer-diameter structure with a high-density core of 2.63 g/cm^3 surrounded by a surface layer of 1.91 g/cm^3.

Experimental results indicate that high porosity can significantly reduce the shock strength and rebound of shocked material (Holsapple, 2004). The impulse from a given energy coupled into a porous surface is lower than it would be for a nonporous solid, and the ejecta is reduced. A complete and adequate crushing model is necessary to determine the shock effects on a porous body. High porosity dissipative surfaces lead to quantitatively similar uncertainties for both nuclear explosives and kinetic impactors, and an impactor mission to study asteroid structure would provide useful data for both approaches.

The limited set of conditions studied in the simulation described below begin to examine uncertainties in important physical properties, so as to understand the application of nuclear explosions to NEO orbit change. They are not exhaustive, and there is much more to learn about the effects of shape, spin, and structure. Except for NEOs 10 kilometers in diameter or larger, it is generally likely that nuclear explosives can provide a more than large enough ΔV, with little material loss and with essentially no danger of fragmentation.

[1] 2001 0E$_{84}$ and (6187) 1986 DA are catalog identifications for particular asteroids that have not yet been named.

Decades to Go—Standoff Burst

The nuclear standoff scenario utilizes the short burst of energy from a nuclear explosive to strongly heat a thin layer of an NEO's surface. As this layer accelerates away from the NEO, its main body recoils in the opposite direction and, if this "back reaction" on the NEO is large enough, alters the NEO's path to avoid collision with Earth. A nuclear explosion in space radiates most of its energy as x rays and gamma rays or as fast-moving neutrons. The proportion of x rays to neutrons is a function of the nuclear reactions that predominate in the explosion. For a given yield, fusion reactions produce more neutrons than fission explosives. Neutrons offer an advantage for the standoff scenario because they penetrate about 1,000 times deeper into the NEO's surface than do x rays and thus can heat a larger volume of material, giving a stronger impulse because more mass is ejected above escape speed. Neutron penetration is also nearly independent of the NEO's composition for atoms between carbon and iron in the periodic table. Large amounts of hydrogen in the surface (such as in comets or asteroids with hydrated minerals) more strongly limit neutron penetration.

The area of the NEO's surface that is heated by a standoff nuclear explosion depends upon the distance between the asteroid and the point of detonation; the depth of penetration depends on the distance between the surface and the detonation point. Thus, detonation close to the surface heats only a small area close to the explosion, whereas more distant explosions spread their energy over a larger area of the asteroid. The neutrons penetrate most deeply vertically underneath the explosion and, because of the increased distance, penetrate less deeply at larger angles.

A detailed simulation of energetic neutrons incident on granite (Bedrossian, 2004) found >70 percent of the incident energy was deposited in the granite (efficient deposition). More than 30 percent of the incident energy was deposited into a depth of about 15 cm. The energy required to convert rock into a hot (more than 10,000 K) plasma is high: 10 kilotons of TNT converts about 4,000 tons of surface material into plasma expanding at more than 2 km/s (Dearborn, 2004). The high efficiency of the deposition and relatively deep penetration of neutrons reduce the necessary neutron yield to near 100 kilotons of TNT equivalent. High fusion devices were tested in the Plowshares program, and the July 1962 Sedan nuclear test was more than 70 percent fusion (see DOE/NV, 209-REV 15 December 2000). If sufficient warning time is available, the largely fusion device can be chosen from tested designs and built with modern safety and security features.

To understand the action of a standoff nuclear explosion, and its ΔV capability, a member of the committee simulated the effect of a nuclear standoff detonation on homogeneous 1-kilometer-diameter NEOs with densities between 1.91 and 1.31 g/ cm^3. In these numerical models of a standoff burst about 150 meters above the NEO's surface, about 40 seconds after the burst the NEO's speed change ranged from 2.2 to 2.4 cm/s. Approximately 97.5 percent of each NEO remained intact (the NEO was held together by gravity only—it had no tensile strength), while about 2.5 percent of its mass was ejected at greater than escape speed by the rebound to the shock wave that passes through the body in reaction to the ejection of heated material. Higher porosity of the NEO will dissipate more energy, resulting in less ejecta, and less speed change. The minimum speed change for a highly porous NEO is controlled by the amount of totally vaporized material. In these models this minimum velocity change is about 0.8 cm/s for an explosion with a strong neutron output. This work is preliminary, and the results provide only the scale of what can be done. NEOs come in many more sizes, shapes, and structures than what the committee could include in this simulation.

A standoff burst is usually considered the preferred approach among the nuclear options. One clear advantage is that there is no need to maneuver for a low approach speed as might be required for a surface or just subsurface delivery. Neutron output associated with high fusion to fission ratios has many advantages including deeper neutron penetration (more impulse), high coupling efficiency, and an insensitivity to NEO composition.

Decades to Go—Small Surface Burst

Ahrens and Harris (1992, 1994) suggested using a surface or near surface nuclear explosion. NASA's 2006 study proposed the detonation of one or more sub-kiloton nuclear explosives on an NEO's surface. In this approach the yield of the explosive must be stable and well determined. At 100 kilotons, the effect of a 0.5 kiloton yield uncertainty is negligible, but not when the entire yield is 0.5 kiloton. The test base provides assurance of an effective yield between 100 tons and 1 kiloton, but not for smaller yields. The committee notes that a rendezvous mission to implant explosives may be more difficult than delivering a larger explosive package just above the surface.

As seen in Figure 5.2, yields between 100 and 500 tons provide significant speed increments to the body of the NEO with only modest amounts of ejecta (large amounts would be undesirable). Most of the ejected material has speeds in excess of 10 m/s, and should spread over many Earth-radii in only a year or two. The debris predicted from these models was not propagated along the sample orbits, but it is likely that the fraction of the ejecta that remains on a threatening orbit years later is no more than 10^{-4} (simulations done by panel member David Dearborn, Lawrence Livermore National Laboratory). As with the standoff simulations, future modeling of a more dissipative surface with very high porosity is likely to result in lower ΔV and less ejecta.

Delivering a nuclear explosive to the depth used in the simulation would be achievable with present earth penetration technology, but requires an approach speed equivalent to a rendezvous mission. Flyby speeds could be used with a fuse that fires on contact with the target and with a slightly higher-yield explosive than for rendezvous. The necessary calculations for this approach are straightforward, but current fuses must be upgraded to operate at the higher speeds.

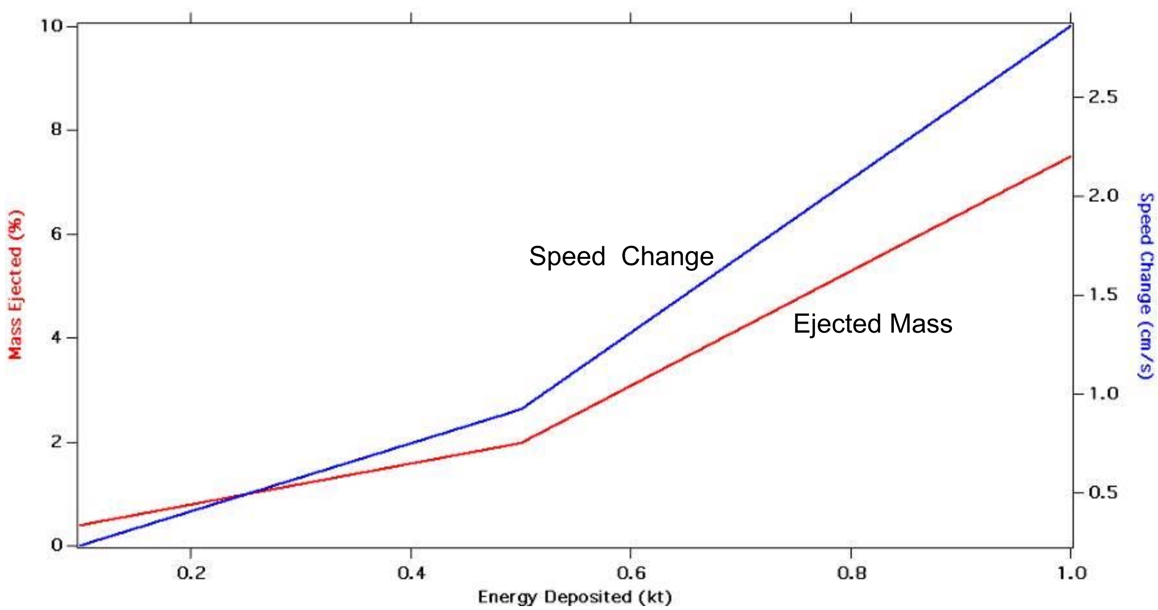


FIGURE 5.2 The speed change (blue) and ejected mass (red) for a 1-km-diameter NEO versus energy deposited on the body, measured in kilotons of equivalent TNT.

Conclusions

Nuclear explosives can provide considerable protection against a potential NEO impact. This may be the only current means to prevent an impact by a large (>500 meters in diameter) hazardous object with a warning time under a decade or by a larger (>1 km in diameter) object with a warning time of several decades. With decades of warning for such large objects, the preferred approach uses a standoff detonation. Neutron output has certain advantages (Dearborn, 2004), as the energy coupling is relatively insensitive to the surface composition and density of the NEO. The simulations show that speed changes (ΔV) of order 2 cm/s are achievable with gravitational binding mostly maintaining the NEO as a single body. About 2 percent of the body mass is ejected, evolving to such a low density that it would likely pose no threat to Earth. Very low yield surface explosives also showed great promise for speed changes of order 1 cm/s. As the NEO size decreases, and the required yield of the nuclear explosive drops below the tested regime (±100 kilotons), the kinetic impact approach will have to be used.

While the nuclear option provides considerable mitigation potential, above some size NEO tested limits will become inadequate. Although no detailed simulations have been done, NEO diameters greater than 10 kilometers are likely to be problematic for the devices in the nuclear stockpile, which go up to megatons of equivalent energy. Modeling the shock dissipation of highly porous materials appears to be the primary uncertainty for both impactors and standoff bursts. This uncertainty holds particularly true for NEOs with very low-density aggregates that can exist only in low gravity environments. At present, the simulations have not examined the affects of the range of structures, shapes, and rotational states, but with Defense Threat Reduction Agency support to extend the present studies, these simulations could be done. Currently the United States and several other nations maintain nuclear stockpiles and the infrastructure to build them for purposes of national defense. While efforts to reduce those stockpiles continue, it seems likely that they will exist for some decades. When defense concerns no longer apply, the governments involved may either accept the longer response time for a Manhattan-Project-like effort, or decide if adequate safeguards can be developed for some entity to maintain a small number of nuclear explosive packages to allow humanity to counter an NEO that could, for example, cause mass extinctions.

Finding: Unless a large flotilla (100 or more) of massive spacecraft was sent as impactors, nuclear explosions are the only current, practical means for changing the orbit of large NEOs (diameters greater than about 1 km). They also remain as a backup strategy for somewhat smaller objects if other methods have failed. They may be the only method for dealing with smaller objects when warning time is short, but additional research is necessary for these cases.

DELIVERING PAYLOADS TO NEOS

A key element of any comprehensive mitigation strategy is the ability to deliver a payload to a hazardous NEO, either via rendezvous (e.g., for characterization, for attaching an accurate tracking device, or for applying a slow push/pull technique to the NEO) or via high-speed approach (e.g., to deliver a kinetic impactor or to deliver a nuclear explosive package to change the orbit). Once an NEO has been identified as hazardous and the time to impact determined, the question becomes: Is it technologically possible to act and succeed in preventing an impact on Earth within the time available? We note that the time to design, build, and launch a mission is typically a large fraction (>1/2) of a decade, but this time could be shortened with a necessarily expensive crash program. The part that is harder to control is the time from launch to arrival at the NEO. There is a second element that is equally important for mitigation either by the gravity tractor or by a kinetic impactor and that element is the amount of mass that can be delivered to the NEO. In this section we address the issues of mass deliverable to an NEO and the time to reach the NEO after launch. We leave the discussion of crash development programs to the arena of public policy.

NEOs as a group have a very wide range of orbital properties, from nearly circular orbits with orbital periods not very different from a year to very elongated orbits with periods from less than a year to decades, if we ignore the long-period comets and to much longer periods if we include them. A complete statistical description of the time to reach an NEO with an orbit anywhere within this distribution is beyond the scope of this study so we consider only a very small number of examples. The statistical distribution of the orbits of the NEOs has been studied by Chesley and Spahr (2004), while Perozzi et al. (2001) have considered trajectories to NEOs as well as the deliverable mass. Any optimization of the trajectory to a given NEO would depend on the goal, as well as on the details of the individual orbit. While prior statistical studies will provide a start on this problem, a detailed study of possible trajectories to any specific NEO will be needed.

The warning time, the length of time from the decision to prevent an impact until the predicted time of impact, is a key parameter. For short warning times, say a decade, high-speed intercepts may be the only possible choice. For longer warning times, many decades, one can choose between a high-speed intercept and a rendezvous depending on the size and physical nature of the NEO.

The key parameters of a launch are the mass that can be launched to escape Earth's gravity and then the additional velocity that must be provided to put the spacecraft on a trajectory to the NEO of interest. The former is determined entirely by the available launch vehicles while the latter is determined by the details of the orbit of the NEO. (Note, too, that the mass of the fuel required to provide this additional velocity will come at the expense of payload mass.) The additional velocity that must be provided is usually characterized by a parameter called C3, which is a measure of this extra propulsion energy needed to change the spacecraft's trajectory. This quantity can range from almost zero to very many tens of $(km/s)^2$ for realistic missions. Values of hundreds of $(km/s)^2$ may be required for some trajectories, but for traditional scientific missions these are not considered feasible. The use of in-space propulsion, such as the engines commonly called solar-electric propulsion or nuclear-electric propulsion, can significantly reduce the mass of fuel that the spacecraft needs at launch but with a cost in time for using in-space propulsion.

Table 5.4 lists the maximum payload in tons that can be carried by various launch vehicles currently available as well as an estimate of the corresponding capability of the Ares V launcher, which is currently being developed and could be available for use in the near future. The capability of these launch vehicles is well above the capability assumed nearly a decade ago by Perozzi et al. (2001). The table includes in the first two rows data taken from published literature that provide a starting point, but which in themselves are not directly relevant. These values are for the maximum payloads that can be delivered to a low-Earth orbit (LEO, such as the orbit of the International Space Station) and to a higher orbit that is commonly used as an intermediate step before going to interplanetary space, the geostationary transfer orbit (GTO). In the third row, we list the mass that can be launched to escape Earth's gravity and in the last row, the mass that can be launched to a relatively easy-to-achieve but realistic orbit that intercepts an NEO. The differences between the corresponding entries in the last two rows—a factor of two—show that even for the NEOs in orbit easiest to reach, the penalty on payload mass is severe. For orbits harder to reach, the payload mass drops quickly to zero because of the mass needed for chemical propulsion. An alternative is to use so-called electric propulsion systems which can be used in principle at any stage beyond LEO but in practice have been used primarily beyond escape from Earth. They substantially reduce the need for fuel and thus increase the payload that can be delivered. However, the available electric power, whether generated from solar or nuclear sources, is not large with current technology so the electric propulsion systems take a long time to move the spacecraft to any desired velocity and thus significantly increase the time to reach an NEO. New technology that is under discussion and development, may improve the situation but there will always be a tradeoff between transit time and launch mass. In practice it has been used primarily for rendezvous missions, for which it can provide both initial acceleration and subsequent deceleration to the rendezvous.

TABLE 5.4 Payload Capability (in tons) of Current and Planned Launch Vehicles

	Ariane V	Atlas V	Delta IV	Proton	Zenith	Long March 5	Ares V
LEO	20	30	26	~22	~14	~25	~190
GTO	11	14	11	~6	~5	~14	~70
Escape	9	12	9	5	4	12	70
C3=10 $(km/s)^2$	5	6	5	3	2	6	35

We present some sample trajectories to illustrate what is possible with today's launch vehicles, i.e., not including Ares V. We consider two different trajectories to reach each of two NEO orbits. The first NEO orbit is like that of Apophis, but, for convenience, with the NEO starting from a different position in the orbit than Apophis is now in. The second NEO orbit ("NEO #2") was chosen to be more elongated than the first. The two different trajectories for each orbit were chosen to approximately maximize the time between the encounter of the spacecraft with the NEO and the predicted impact of the NEO on Earth, for the two cases, one each of high- and low-speed arrival at the NEO. The former corresponds, for example, to maximizing the relative speed of NEO and spacecraft at encounters for kinetic impact, and the latter to minimizing this relative speed to allow rendezvous for delivery of a subsurface nuclear device. (Formal optimization calculations were, however, not carried out.) The trajectories shown in Figure 5.3 and Table 5.5 imply launches about a decade before the predicted impact. The decision to act would of course need to be made much earlier in order to design, build, and launch the spacecraft. Note the far smaller mass that can be delivered for a rendezvous mission.

These trajectories, which are all feasible to achieve with current technology, assume launch on an Atlas V rocket with a single upper stage to place the spacecraft on the intercept trajectory. Clearly much larger masses ("payloads") can be delivered to a high-speed intercept than to a rendezvous and the difficulty of getting to a target depends in detail not only on the shape of the NEO's orbit but also on where the NEO is in its orbit at a specific time. The rendezvous trajectories require an additional propulsion system for rapid deceleration as the spacecraft nears the NEO. The intercept trajectories all make an angle of less than 30° to the orbit so that an impactor would deliver a large fraction of its momentum in the favorable direction, parallel to or exactly opposite to the NEO's motion. The trajectories for rendezvous become very different if one uses in-space propulsion, allowing near zero rendezvous speeds and allowing massive payloads but at the expense of much longer flight times than in the cases shown here. New in-space propulsion systems that have been considered and/or are under development can considerably improve the situation by shortening the flight time. Longer warning times offer several other possibilities, including gravity assists from planets.

The most challenging trajectories are those to long-period comets, largely because of the short time from discovery to impact on Earth coupled with the very elongated orbits. In general these comets would require a spacecraft that is ready to launch when the decision is made to act. Cometary impacts on Earth can occur either when the comet is inbound or when it is outbound. In Figure 5.4 and Table 5.6 we present intercept trajectories that assume launch on a Delta IV-heavy rocket with a single upper stage and a 0.5-ton payload. This payload is sufficient for a nuclear package but rather small for a kinetic impactor. The trajectories were designed to maximize the time between intercept and predicted NEO impact on Earth.

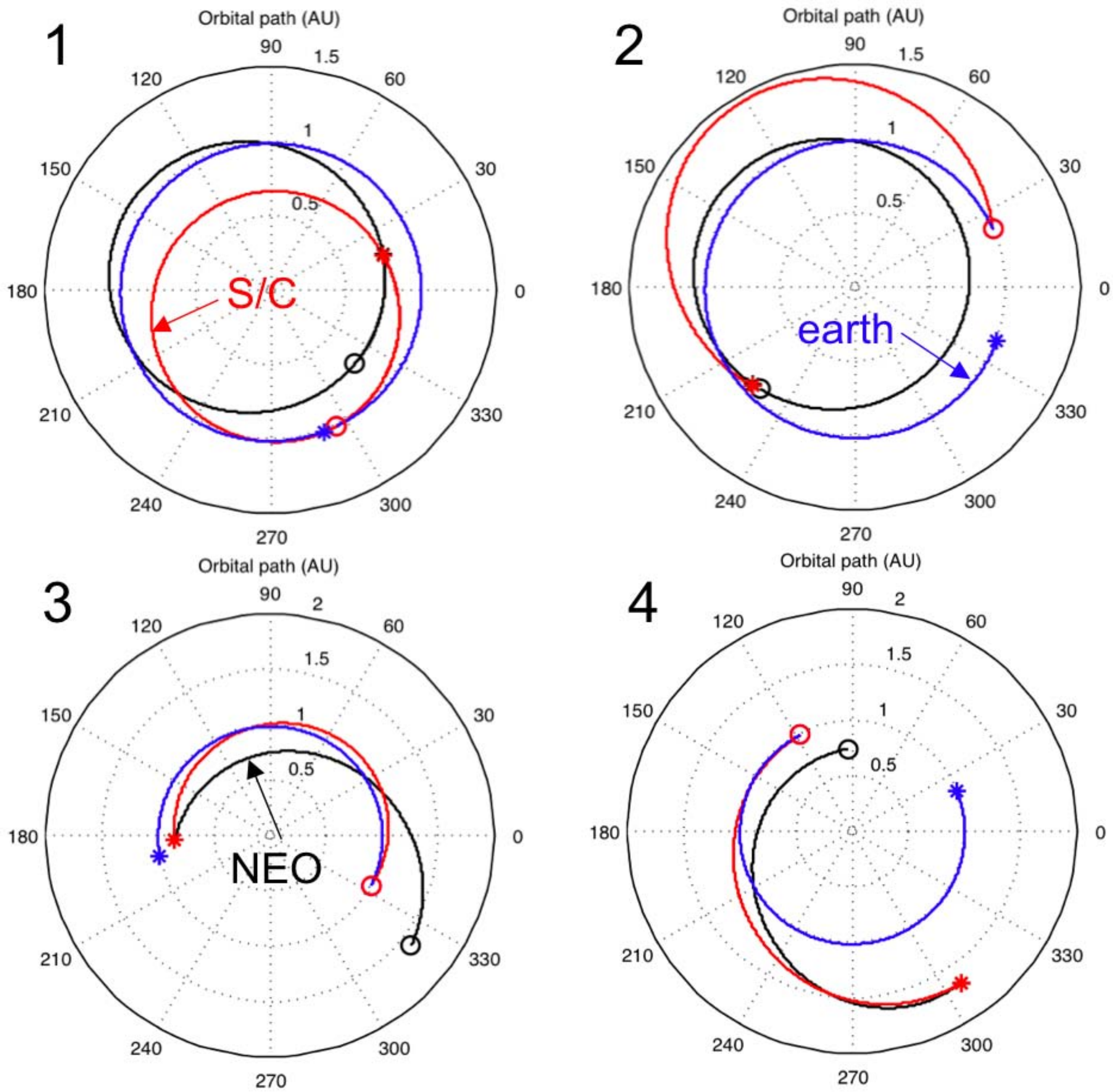


FIGURE 5.3 Sample trajectories of a spacecraft are shown in red. The sun is at the center and the distance from the sun increases to 1.5 AU at the edge of the upper panels and to 2 AU at the edge of the lower panels. Earth's orbit is shown in blue, with the launch point shown by a small circle. The NEO's orbit in each case is shown in black with a small circle at the point of intercept. Each panel corresponds to the indicated column in Table 5.5.

TABLE 5.5 Values of Key Parameters for Sample Trajectories Using Chemical Propulsion

	Apophis-like High-speed	Apophis-like Rendezvous	NEO #2 High-speed	NEO #2 Rendezvous
Launch to Earth-impact (years)	14	9.5	12	7.5
Launch to NEO (days)	360	320	220	270
Intercept velocity (km/s)	12	3.2	12	3.0
C3 $(km/s)^2$	15	70[a]	17	19
Payload Mass (tons)	6.5	0.6	5.9	4.0

[a] The large difference in these entries illustrates the great sensitivity of C3 requirements to spacecraft launch dates.

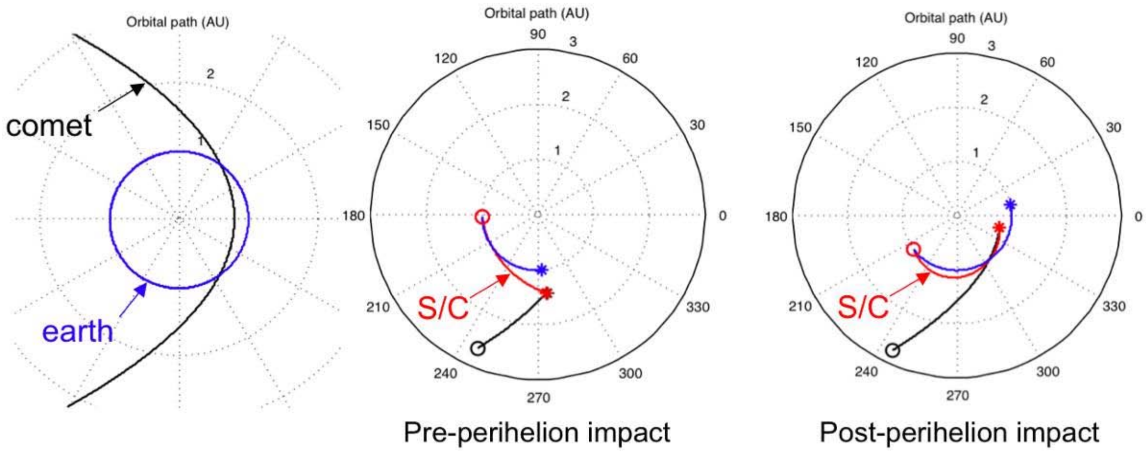


FIGURE 5.4 Intercept trajectories for a hazardous, long-period comet. The left panel shows the comet's orbit and the two places at which it intercepts Earth's orbit. The next two panels show the intercept trajectories corresponding to the two rows in Table 5.6. In other respects, the panels are similar to those in Figure 5.3.

TABLE 5.6 Parameter Values for Delivering a 500-kg Payload to a Long-period Comet

	Intercept Speed[a] (km/s)	Launch to Impact[b] (days)	Flight Time[c] (days)	Intercept to Impact Time[d] (days)
Pre-perihelion impact	37	130	95	34
Post-perihelion impact	15	200	160	40

[a] Relative speed of spacecraft and comet at impact.
[b] Time from spacecraft launch to predicted Earth impact of comet.
[c] Time from spacecraft launch to its intercept of comet.
[d] Arrival time of spacecraft at comet prior to predicted Earth impact of comet.

These trajectories to a comet are examples of a relatively easy case since they assume the comet's orbit is in the same plane as Earth's orbit. Other orbits are harder to reach. However, the key point is that intercept trajectories with reasonable flight times are feasible. A next-generation launch vehicle, such as Ares V, would make kinetic impacts feasible for some long-period comets.

In summary, current technology allows us to deliver payloads for mitigation to NEOs in a wide range of orbits. However, in cases of short warning (under, say, a decade), payloads are likely to be severely limited in mass, but may often be sufficient to deliver a nuclear device. The development of the next generation of heavy-lift launch vehicles will considerably improve the situation. The development of advanced engines for in-space propulsion will considerably improve our capability for delivering rendezvous payloads (for characterization, to act as gravity tractors, or to emplace surface explosives) when the warning time is decades.

Finding: For a wide range of impact scenarios, launch capability exists to deliver an appropriate payload to mitigate an NEO. For some scenarios, particularly short warning scenarios, the capability is inadequate. Development of foreseen heavy-lift launch vehicles, such as the Ares cargo vehicle, should enable the use of a variety of methods for NEOs up to 2 times larger than is possible with current launch vehicles

DISRUPTION

Both the kinetic impact and nuclear detonation methods are capable of including larger changes in velocity of the NEO than discussed above, particularly for smaller objects, but in those cases these methods deliver so much energy that there is a likelihood of totally disrupting the NEO (i.e., fragmenting it). Disruption has been widely proposed as a mitigation option, but disruption could make the situation worse. Specifically, if the hazardous object breaks into a small number of large fragments with only a very small spread in velocity, the multiple impacts on Earth might cause far more damage than the single, larger impact. Thus, disruption or fragmentation is a feasible strategy only if it can be shown that the hazard is truly diminished. In the case of a very large impactor (say 10-kilometer-diameter, civilization destroying) discovered without many years of warning, adequate orbital change may not be possible, leaving disruption as the only option for mitigation. This option would likely require a system on standby at all times and a decision to disrupt made long before the probability of impact was high. Even in this situation one would want assurance, from previous studies, that disruption would both succeed and reduce the hazard.

Numerous studies of catastrophic disruption of asteroids, undertaken in order to understand the evolution of the asteroid belt, have shown that the energy required for catastrophic disruption per unit mass of an asteroid has a minimum for bodies with diameters of a few hundred of meters (*e.g.*, Holsapple 2002). These calculations, of course, assume physical properties for the asteroids and those properties are not well known in any particular case. Early laboratory experiments and subsequent basic physical and numerical simulations (Housen and Holsapple, 1990; Michel et al., 2004) show that when an asteroid is catastrophically disrupted, only one large fragment remains and the size of that fragment shrinks with increasing energy of the impact. The fragments disperse at speeds in excess of the escape velocity (m/s). Furthermore, energy arguments imply that most of the fragments should disperse with velocities comparable to or greater than the escape velocity from the original body, i.e., >1 m/s for a km-sized NEO. To the extent that these calculations and laboratory experiments are relevant, they suggest that disruption might leave one much smaller object on an impact trajectory while most of the smaller pieces would spread out over a cross-section much larger than Earth within less than a year.

Thus disruption might be a useful mitigation technique. However, the uncertainties in the structure of NEOs are sufficiently large that this committee does not now have high enough confidence in the disruption approach to recommend it as a valid technique for mitigation at this time. Additional research, including a suite of independent calculations and laboratory experiments, but particularly including experiments on real comets and asteroids, might show that disruption is well enough understood to use it as a mitigation technique.

To avoid disruption, both kinetic impact and nuclear detonation approaches to deflection benefit dramatically from using multiple events. (They also allow effective orbit change of larger NEOs, but disruption is rarely an issue in that case.) This strategy also allows for adjustment of the total effect when the hazardous object's response to an event is not predictable in advance.

SUMMARY

Figure 5.5 summarizes the range of parameter space in which each of the four types of mitigation could be considered primary, emphasizing the still significant uncertainty in the boundaries between the various regimes. Other parameters (density of the NEO, details of the NEO's orbit, probability of impact at a given warning time, etc.) all play a role in the uncertainty. Furthermore, civil defense should play a role in all the regimes and one might choose to apply multiple methods in a given case, thus further blurring the distinctions. Toward the left edge of the figure, short warning times, one would likely be able to do nothing but civil defense unless disruption is shown to be reliable and toward the right edge of the figure, long warning times, the uncertainty in the prediction would likely prevent action. Toward the right half of the figure, there is often time to design, build, and launch a mitigation mission. Toward the left half, one might need a mission ready to launch on discovery of a hazardous NEO. Significant research efforts are needed to assure success in large areas of the figure.

This chapter has considered both the range of likely mitigation measures available to society and the circumstances in which each may be appropriately used, albeit with fuzzy boundaries. However, there are also issues related to reliability and robustness that need to be considered. In particular, if mitigation is needed, the stakes are much higher than for a typical scientific mission to deep space and assured success is crucial. The general principle of "do no harm" is also crucial. Assured success includes being certain that the mitigation will not increase the hazard. This assurance is particularly important when one must initiate a mission to change the orbit of an NEO before the probability of impact approaches unity, which will often be the case, since an orbit change could then, in principle, divert a near-miss object onto an impact trajectory. The principle is equally important in the much less likely circumstance of a late-discovered, large NEO for which the energy needed for the required orbit change approaches the energy needed for disruption.

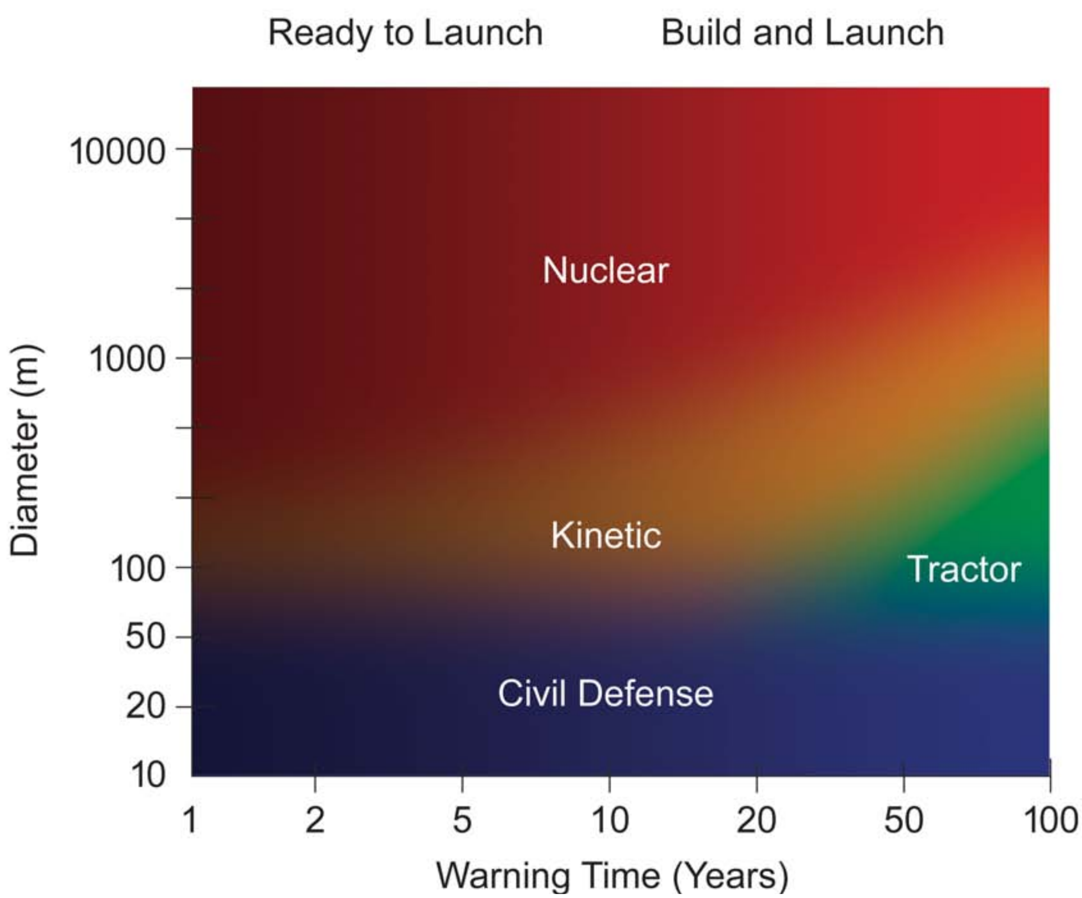


FIGURE 5.5 Approximate outline of the regimes of primary applicability of the four types of mitigation (see text for the many caveats associated with this figure). Image Courtesy of Tim Warchocki.

This need for assured success implies that, if time permits, a characterization mission prior to mitigation is highly desirable. The efficiency of orbit change in most approaches, the gravity tractor excepted, is very sensitive to some physical properties of the NEO, particularly the porosity and density in the outer tens of meters, that cannot be determined from remote sensing. An in situ characterization mission, if properly designed, can measure the key physical properties needed for orbit change. Similarly, there is a need for verification of the orbit change. For most slow-push techniques, the verification is straightforward since there is a spacecraft near the NEO for the duration. If there were an advance characterization mission, that mission could also be configured for verification. Even if there were not time for a characterization mission, there might be time to launch a verification mission that has a rendezvous with the NEO prior to the change in its orbit so as to measure this change; this approach should be implemented wherever possible.

The committee also notes that civil defense is likely needed in ALL mitigation scenarios, not just in those situations for which it is the most cost-effective approach. One aspect of civil defense is educating the public about the nature of the hazard and how individuals should respond. Public information about the hazard is crucial. For those impacts for which damage on the ground is very localized, there may nonetheless be peripheral effects on climate, probably small and of short duration but important enough that the public needs to understand them, and there may be effects on infrastructure, such as on communications, that have effects well outside the area of direct damage. Dealing with these issues is all part of civil defense preparedness.

With the current uncertainty regarding both the properties of the NEOs themselves and the efficiency of interaction with an NEO for kinetic and nuclear deflection, and even from the general standpoint of confidence of success, functional redundancy is crucial. Instead of changing the orbit of an NEO with a single kinetic impactor, a series of impactors spread slightly in time provides much more reliability and in some situations might even allow assessment of the effect of the first impactor before the second arrives. Depending on the details of the specific orbit, it might be desirable and possible to divert later impactors, but the applicability of this concept needs further study. Alternatively, as long as there is a nuclear capability, one could consider readying a nuclear mission as a late-stage backup for a kinetic impactor that might, even with some very low probability, fail. Similarly, a kinetic impactor might be a backup for a gravity tractor on the chance that the gravity tractor might suddenly have a fuel leak or some other failure after a long but incomplete period of "pulling" the NEO.

A nuclear detonation approach, however implemented, is likely to raise significant public concern. If an NEO capable of massive death and destruction were discovered with certainty to be on a collision path with Earth and there were no other way to stop it, presumably any concerns about the nuclear approach would be over-ridden. But in the early planning stages public concern might inhibit development. This is primarily a public policy, rather than a technical, question and is therefore outside the scope of this committee's task. Similarly, as noted in the section on nuclear methods, the question of whether to maintain a nuclear stockpile for NEO mitigation purposes is not a technical question. In this report, the committee has assumed that a nuclear stockpile and nuclear development capability is on hand for other purposes.

Perhaps the most significant conclusion that can be drawn is the large uncertainty in the effectiveness of the mitigation techniques because of their dependence on the physical properties of NEOs that are not well known, and because of the difficulty of scaling any laboratory experiments to this regime. At this point we cannot even reliably determine the boundaries of applicability of the various approaches. In a later chapter we address organizational aspects of the decision-making process, but we still lack information to guide that process. Any process must carry out a detailed study of where to draw the boundaries and what additional information would be needed. An applied research program, directed explicitly at the NEO hazard, could significantly reduce the uncertainties. At the lowest meaningful level for the mitigation side, this would include both numerical simulations by multiple groups and laboratory experiments.

A much larger scale effort to address mitigation of the NEO hazard will likely include activities in space. The single, most significant step in this area appears to be a kinetic impact mission on a far larger scale than the Deep Impact mission, via a much larger impactor on a much smaller target, with a second spacecraft that has a rendezvous with the target well prior to impact to characterize the target and its orbit very precisely. This second spacecraft would remain with the target until long after the impact to accurately determine the change in its orbit due to the impact. The Don Quijote mission that was studied by ESA, but is no longer under active consideration, would have addressed most of these goals. Suggestions have been made to use the rendezvous spacecraft as a gravity tractor after the primary mission, but given the different design considerations it is not yet clear whether this is a good approach or not. A demonstration flight of a gravity tractor appears to be the second most significant step since lesser knowledge of NEO behavior is needed for implementation. Both the kinetic impact and gravity tractor approaches require significant engineering study but more basic knowledge is needed for the kinetic impactor.

In cases of late discovery, the change in NEO orbit that must be made for it to miss Earth can be so large that the required impact energy is comparable to or greater than the energy to disrupt the body. Depending on how the body disrupts, the effect on Earth could, in some circumstances, be worse overall than if disruption were not attempted. Alternatively disruption might lead to less total damage to Earth but more damage to, e.g., a particular populated location. With the uncertainty in the present understanding of fragmentation and disruption, the committee does not now endorse disruption as a mitigation strategy, but suggests that further study of this issue be an important part of any research program into mitigation of the NEO hazard. (See Chapter 6.)

Finding: Mitigation of the threat from NEOs benefits dramatically from in-situ characterization of the NEO prior to mitigation, if there is time to do so.

Finding: Changing the orbit of an NEO with our current understanding is sufficiently uncertain that, in most cases, it *requires* an accompanying verification. This is easy to implement with many slow-push techniques but requires considerable additional effort for other techniques.

Recommendation: If Congress chooses to fund mitigation research at an appropriately high level, the first priority for a space mission in the mitigation area is an experimental test of a kinetic impactor along with a characterization, monitoring and verification system, such as the Don Quijote mission that was previously considered, but not funded, by ESA. This mission would produce the most significant advances in understanding and provide an ideal chance for international collaboration in a realistic mitigation scenario.

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6

Research

Dealing with the NEO impact hazard is complicated because it involves balancing its imprecisely known risks against the costs, risks and benefits of proposed responses. Since the NEO impact risk is partly probabilistic in nature, it is difficult to grasp and difficult to communicate, unless and until an object is discovered that will hit Earth on some definite date not too far in the future. However, the probabilistic risk is similar to that for other types of natural disasters like earthquakes. We have an idea of the likelihood that an earthquake of a given magnitude will strike a given region within a given time. We know the fundamental reasons why earthquakes occur (associated with plate tectonics) and know that the risks from earthquakes are particularly high in certain specific regions (e.g., near plate boundaries, in certain types of soil). However, we cannot predict with confidence the date of the next great earthquake of magnitude 7 or larger that will strike San Francisco or Tokyo. Nevertheless, we know from experience that such disasters will occur, and moreover we can assess the likely damage. The United States and other countries around the world have responded by committing to various civil defense and mitigation programs, including research programs. The U.S. federal and state governments dedicate resources to earthquake research, to improve understanding of the causes of the hazard, to better quantify risks and improve capabilities for prediction, and to increase effectiveness of mitigation measures. Likewise, an appropriate and necessary aspect of mitigation of the NEO impact hazard is a research program.

The scope of this research program would ideally be targeted to address all of the areas where uncertainties stemming from lack of knowledge and/or understanding hamper our ability to quantify and mitigate the NEO impact risk. For instance, we are uncertain as to the magnitude of the impact risk for several reasons. First, the populations of small impactors near Earth are poorly understood, so we are unsure even of the average impact rates by objects above 140 meters or above 50 meters. Second, we do not know the fundamental natures of these bodies: what they are made of, or to what extent they may be intact objects as opposed to heavily fractured, or even completely separate, components traveling together as loose, gravitationally bound aggregates. Some 15 percent of known NEOs have one or more satellites. Even given knowledge of the size, impact energy, and fundamental nature of an impacting object, the effects of the impact on Earth are uncertain. They depend on whether and how high in the atmosphere the impactor may break up before hitting the surface, and on whether an impact occurs on shallow water, on deep water, or on land, as well as on the rock types found there. In addition, the effects are not necessarily limited to local or regional effects near the time and place of the impact, but may include, for large impacts, global climate change or tsunamis. But how large an impact, and what kind of impact, is needed to cause these effects is still uncertain. A research program is needed to address all of these issues in order to assess and quantify the risks associated with the NEO impact hazard.

Our ability to mitigate the impact hazard, or even to define appropriate strategies to mitigate the hazard, likewise depends on acquisition of new knowledge and understanding that could be gained through a research program. Even if our only viable mitigation approach to an impending impact is to warn the population and to evacuate, we need better information to be able to decide: under what conditions, and when, warning should be provided, and who should evacuate. If on the other hand we have active mitigation options, like changing the orbit of an impactor, again we need better information. We need to be able to predict with confidence the response of an impactor to specific forms of applied forces, impacts of various types and speeds, or various types of radiant energy, such as x rays. The required information goes beyond basic physical characterization to determine the size and mass of the impactor and includes surface and subsurface compositions, internal structures, and the nature of their reactions to various inputs.

Just as we do not limit the scope of earthquake research to only searching for and monitoring earthquakes, we should not limit the scope of NEO hazard mitigation research to searching for and detecting NEOs. A research program is a necessary part of an NEO hazard mitigation program. This research should be carried out in parallel with the searches for NEOs, and it should be broadly inclusive of research aimed at filling the gaps in our knowledge and understanding, to improve our ability to assess and quantify impact risks as well as mitigation strategies. This research covers several areas discussed in previous chapters of this report, such as risk (Chapter 2), surveys (Chapter 3), characterization (Chapter 4), and mitigation (Chapter 5). The committee stresses that this research must be broad to encompass all of these relevant and interrelated subjects.

Recommendation: The United States should initiate a peer-reviewed, targeted research program in the area of impact hazard and mitigation of NEOs. Because this is a policy driven, applied program, it should not be in competition with basic scientific research programs or funded from them. This research program should encompass three principal task areas: surveys, characterization, and mitigation. The scope should include analysis, simulation, and laboratory experiments. This research program does not include mitigation space experiments or tests which are treated elsewhere in this report.

Some specific topics of interest for this research program are mentioned below. This list is not intended to be exhaustive:

- Analyses and simulations of ways to optimize search and detection strategies, using ground-based or space-based approaches, or combinations thereof (see Chapter 3);
- Studies of distributions of warning times versus sizes of impactors for different survey and detection approaches (see Chapter 2);
- Studies of remote-sensing data on NEOs needed to develop useful probabilistic bases for choosing active-defense strategies when warning times of impacts are insufficient to allow a characterization mission (see Chapter 4);
- Concept studies of space missions designed to meet characterization objectives including a rendezvous and/or landed mission and/or impactors;
- Concept studies of active defense missions designed to meet mitigation objectives including a test of mitigation by impact with measurement of momentum transfer efficiency to the target (see Chapter 5);
- Research to demonstrate the viability, or not, of using disruption of an NEO to mitigate against an impact;
- Technological development of components and systems necessary for mitigation;
- Analyses of data from airbursts and their ground effects as obtained by dedicated networks, including military systems and bolide observations. Also analyses and simulations to assess where, why and how objects break up in the atmosphere, effects of airbursts including pulses of electromagnetic energy and consequences for communications and other infrastructure, and effects of target material properties for land or water impacts.
- Detailed, realistic analytical analyses and simulations to determine risks of tsunami generation from water impact or airburst of various types and sizes of impactors;
- Joint analyses, when possible, of available data on airbursts and data on the corresponding surviving meteorites to establish ground truth;

- Laboratory study of impact phenomena for a wide variety of impacting and impacted material (i.e., of various physical structures and properties) at speeds of collision up to the highest attainable so as to study, for example, the transfer of momentum to the target due to ejecta of material from it;
- Leadership and organization planning, national and international;
- The economic and political implications of an NEO impact;
- Behavioral research (including national and international workshops) to study people's perception of impact risks including their mental models, and to understand their possible misconceptions and/or lack of knowledge, needed to develop appropriate plans and simulation exercises in preparation for a possible impact event.

7

National and International Coordination and Collaboration

Responding effectively to hazards posed by NEOs requires the joint efforts of diverse institutions and individuals. Thus organization plays a key role that is just as important as the technical options. Because NEOs are a global threat, efforts to deal with them would probably involve international cooperation from the outset. Here we discuss possible means to organize, both nationally and internationally, responses to those hazards. Arrangements at present are largely *ad hoc* and informal here and abroad, and involve both government and private entities.

However, the Office of Science and Technology Policy (OSTP) has been directed by Congress to "recommend a federal agency or agencies to be responsible for protecting the United States from a near-Earth object . . . expected to collide with Earth." The OSTP is directed to produce such a recommendation by October 2010.

EXISTING ORGANIZATIONS

At the national level in the United States, the Minor Planet Center (MPC) at the Harvard-Smithsonian Center for Astrophysics, sponsored by the International Astronomical Union but funded about 90 percent by NASA, collects observations of all asteroids and comets made around the world, archives them, makes them publicly available, and computes orbits for all individual, identified objects. For any object that seems to pose a threat to Earth, the MPC Director or designee has a reporting system to alert a NASA official and thence through specified government channels to the country at large. Also in the United States, individual observers and observatories are dedicated in whole or in part to discovering and observing NEOs. Further, NASA supports a group of researchers at the Jet Propulsion Laboratory (JPL) that carries out accurate, long-term predictions of asteroid orbits, quantifies threats, and notifies NASA, as does the MPC, if a "threshold" is exceeded.

The National Response Framework of the Department of Homeland Security seeks to coordinate identification of threats and disaster response with communication and recovery challenges similar to that needed for NEO threats. However, at present, NEOs are not part of the Framework.

At the international level, there is one organization, the NEODyS system in Pisa, Italy (with a mirror web site in Spain), that monitors and publicizes all potentially hazardous objects. The recent 2008 TC_3 event demonstrated that even in the absence of formal international organization, effective international communications may occur, even with limited advance warning. Formal integration of these elements, with agreed-to plans, roles, and responsibilities is needed *well in advance* of the identification of any specific threat.

NATIONAL

An effective, comprehensive approach to the NEO hazard will require significant planning, coordination, and cooperation within the United States Government.

It seems sensible to assign responsibility for this NEO hazards program to an existing governmental administrative structure, especially in view of the likely relatively small size of the undertaking. It also seems more efficient to place the program under the control of a single entity in coordination with other relevant government organizations. The coordination could be implemented via a standing committee or an Interagency task force of the appropriate agencies to organize and lead the effort to plan and coordinate any action to be taken by the United States individually, or in concert with other nations. This committee or task force would have membership from each of the relevant national agencies (NASA and NSF) and departments (Defense, Energy, Homeland Security, Justice, and State), with the chair from the lead entity. (Other relevant agencies and departments could include Transportation, Health and Human Services, the Environmental Protection Agency, the General Services Administration, and the Department of Agriculture.)

The first step of the committee or task force is to define the necessary roles and responsibilities of each in addressing the various aspects of the threat, from surveying the sky through civil defense. The lead responsibility for a given task would be assigned to the appropriate agency or department.

In view of its intrinsic international nature, a civilian agency has advantages for housing the program. Otherwise, one could envision continual internal conflict over military security and classification issues. Of course, any group will have such issues from time to time, but a civilian group could have far fewer and also would likely be more acceptable to its counterparts in other nations. In an emergency, the military could be enlisted or appointed by the President to help; the military would maintain currency with the issues through membership in the standing committee.

Among the civilian agencies and departments, NASA has the broadest and deepest familiarity with solar-system objects and its associated rendezvous missions. The National Science Foundation supports ground-based solar-system research, but traditionally responds to proposals rather than initiating and organizing complex programs (the International Geophysical Year being one of the exceptions). The Departments of Defense and of Energy, on the other hand, have by far the most important experience with nuclear explosives, necessary for some active defense, NEO orbit-changing missions. For such missions and their preparations, these departments, or at least the latter, would certainly become involved, coordination being maintained through the standing committee/task force described above. NASA is a possible choice for the lead agency. Within NASA, under its present organization, a natural home for this hazards program is the Science Mission Directorate (SMD), which deals with solar-system science. The current, small—ca. $4 million annual budget—hazards program is already housed in this directorate. But the hazards program discussed here would be more effective if it has its own director and budgetary line item(s) to ensure its viability within the much larger SMD. It would, of course, derive benefits from and provide benefits to the science and other programs in the SMD.

Organization is key, too, when mitigation requires civil defense, primarily evacuation. Experience has driven home a lesson: Without prior training for it, evacuation has chaotic and often disastrous attributes. However, training from prior emergencies can yield very successful, almost trouble-free evacuation outcomes, at least in local areas. The poster child for such success is the evacuation of San Bernardino County in the face of ferocious fires that attacked this region in the summer of 2007.

The National Response Framework, within the Department of Homeland Security, is the part of the national government that deals with civil defense. Responsibility for planning for emergencies is centered within it. This Framework is especially concerned with the coordination of the numerous local, state, regional, national and non-government organizations that are or should be involved in disaster anticipation, management, and relief of all kinds. NEOs could be added to, and considered explicitly in, this Framework and would thus become a part of the planning and implementation of disaster response of our country. Any needed legislation to achieve this goal could be linked to any national and international policies and structures dealing with disaster prevention and management. The underwriting/insurance industry might be interested in providing actuarial input relevant to these matters.

Since the details of the asteroid/comet threat are unknown, planning philosophy will be most effective if it is based on the need to be flexible and generic. This is necessary because of the wide variety of potential hazards, from airbursts through land impacts to tsunamis, with each covering a broad span of possible severities.

The chief unknown will be the size of the need, but if huge, the peril will probably be defined well in advance. In addition to planning a flexible response, a trained cadre of professionals must obtain and set up the equipment and supplies needed to sustain a displaced population. Such preparatory issues are not confined to the asteroid and comet hazard, but have common elements with all other natural hazards, such as earthquakes, fires, and hurricanes. All may be treated similarly and by the same personnel.

It makes sense, in any national activity in this civil-defense sphere, to coordinate and collaborate with other nations in the planning and, depending on circumstances, in the implementing of responses to an impending impact event.

INTERNATIONAL

The probability of a devastating impact in the United States is small compared to the likelihood of an impact in other nations, most with far fewer resources to detect, track and defend against an incoming NEO. The NEO hazard, however, is such that a single country, acting unilaterally, could potentially solve the problem. Although the United States has a responsibility to identify and defend against threats with global consequences, the United States does not have to bear the full burden for such programs. There have been several international efforts to characterize objects in the near-Earth environment, but these studies have generally been driven by scientific curiosity and were not designed to address the risk of NEOs. As NEO survey requirements evolve to fainter objects and mitigation strategies are refined, additional resources will be necessary that could be provided by other developed countries. International partnerships can be sought with other science organizations, notably but not exclusively space agencies, in the areas of surveys, characterization, and mitigation technologies. NEO discovery rates and survey completeness could be significantly enhanced through coordinated use of telescopes owned and operated by other nations. Future NEO space missions, carried out either by the United States, other nations, or a cooperation of countries could be optimized for characterization that enables development and refinement of mitigation strategies. Space missions to test such strategies could also be developed on a cooperative basis with other nations, making use of complementary capability. While a coordinated intergovernmental program is needed to address the full spectrum of activities associated with NEO surveys, characterization, and mitigation, an important first step in this direction would be to establish an international partnership, perhaps of space agencies, to develop a comprehensive strategy for dealing with NEO hazards.

Many scientists, especially among the world's planetary scientists, have been concerned for well over a decade with the danger posed to Earth from the impact of an asteroid or comet. Officials from various nations have echoed these concerns. Thus, a substantial and important component of the existing international cooperation is the informal contact between professional scientists and engineers, mainly of space-faring nations, but also including official representatives from some other countries.

International conferences and small meetings, as well as the Internet, allow experts in different aspects of space science and technology, including asteroid detection and mitigation, to personally know their counterparts in other nations. Such connections often lead to offers of, or requests for, aid in solution of common problems arising in the course of their work. Veterans of the United States or Russian space programs often participate either openly or behind the scenes in the European Space Agency and the Japanese Space Agency, and Indian and Chinese space activities. Nuclear-weapons designers in both Russia and the United States have often met to discuss use of nuclear explosives to effect asteroid orbit changes.

In the event of a sudden emergency due to discovery of a threatening NEO it is likely that people forming this international network will be the first to communicate with one another and consider responses to the threat. For instance, when an observatory in Arizona discovered NEO 2008 TC_3 only 19 hours before its impact in Sudan, the informal network of amateur and professional astronomers in many countries responded in time for thousands of observations of the object to be made and communicated to the MPC, thus allowing an extremely accurate prediction of the time (<1 min error) and location (<1 km error) of impact.

Formal integration of these elements, with agreed to plans, roles, and responsibilities is needed *well in advance* of the identification of any specific threat. The United States is in a unique position to lead the sustained effort required to marshal the international community to ensure preparedness.

Given this international community of interested and knowledgeable scientists and (at least some) concerned governments, how should the world develop a coherent program to meet this threat, in all of its aspects? One approach is to work through the United Nations, perhaps by enhancement of the existing Committee on the Peaceful Uses of Outer Space. Another approach, mentioned above, is to organize the various national, and for Europe, international, space agencies. A third approach is to organize a new group—a “standing committee”—composed of representatives of nations concerned with this problem and willing to invest in preparedness for a damaging collision. A minimum for annual contributions, or national expenditures, on this problem could be set and monitored, say, by the standing committee. The level of contributions could be fixed so that even the minimum would allow “useful” accomplishments. This committee would be open to membership by representatives of all nations that wished to contribute to addressing this problem at the minimum or a greater level. Since no nation would likely give up much, if any, of its sovereignty, even in the face of this supranational issue, the committee would develop a program and submit it for approval to the individual member countries. In the absence of a specific future impact event of concern, however, it might be hard to reach agreement (it would probably be hard enough, even in the face of imminent danger).

International collaborations perforce spawn legal issues, and organizing a hazard response is far from immune to them. Suppose, for example, two or more nations in the consortium wish to alter the orbit of a potential impactor. In case of seemingly irreconcilable differences, to whom could they appeal for adjudication of the dispute and what precedent(s) would inform such adjudication? As a second example, consider Nations A and B that, in collaboration, succeeded in altering the orbit of an imminent impactor, but, through circumstances beyond their control, changed the impact site from Nation C to Nation D (instead of causing the object to miss Earth entirely). Who decides who is responsible for the damage inflicted on Nation D and to what degree? As a last example, consider Nations A through E collaborating on a mission to change the orbit of an imminent impactor by using nuclear explosives. Suppose that one of the armada of spacecraft dispatched for this mission failed to gain orbit and crashed onto Nation F releasing damaging radioactive material. How are the damages to be assessed and by whom, and how are the responsibilities for payment to be determined and the judgment enforced?

The existing legal entity that appears most appropriate to handle these issues is the World Court. It could also deal with contract disputes involving bi- and multi-national agreements involving these issues. The nations of the world would need to agree in advance, via some type of treaty, to give jurisdiction to the Court and to abide by its findings and penalty assessments. Other alternatives could be investigated, such as a new judicial entity which could be created solely to deal with these hazard issues and which might better safeguard national sovereignty. The International Society for Space Law coordinates valuable discussion of these issues and produces recommendations for national laws and international treaties, but it has no legal standing for resolving disputes.

This legal component of the hazards issue suggests that the State Department and perhaps the Department of Justice may need to play a strong role in dealing with the international aspects of the hazards issue.

One major concern with the standing committee, and its affiliates, especially in the disaster-preparation area, is the maintenance of attention and morale given the expected exceptionally long intervals between harmful events. Countering the tendency to complacency will be a continuing challenge. This problem would be mitigated were, for example, the civil defense aspects combined with those for other natural hazards.

Recommendation: The United States should establish a standing committee with membership from each of the relevant agencies and departments, to develop a detailed plan for treating all aspects of the threat posed to Earth by NEOs, and apportioning among these agencies and departments authority and responsibility for carrying out this plan, in coordination and collaboration with other nations. The committee would be further charged with overseeing on a continuing basis the carrying out of each agency's and department's activities under this plan. The Administration should designate one agency or department as the lead; the chair of the committee should be the representative from this agency or department.

Recommendation: The United States should take the lead in organizing and empowering a suitable international entity to participate in developing a detailed plan for dealing with the NEO hazard.

The lead U.S. representative to this group could be the chair of the standing committee, or the chair's designee.

EDUCATION AND PUBLIC OUTREACH

Although popular movies raise general public awareness of the threat from NEOs, they do little to educate the public of the true risk to humanity and may result in significant misconceptions due to the highly distorted science presented. With most impacts occurring in remote locations or over oceans, they often go undetected or unreported, so that few people are aware of the true hazard associated with NEOs. Although the likelihood of a devastating impact in this century is very small, smaller objects may still do significant damage, and may only be detected near impact. Thus, mitigation efforts may be limited to civil defense warning and evacuation of threatened areas. As has been clearly demonstrated during recent hurricane and forest-fire evacuations, civil-defense authorities must have clear, well-designed plans for response. Also, the public needs to understand the threat and respond appropriately should evacuations be required. The necessary education of authorities and the general population is challenging as impacts can happen anywhere and hazardous events happen so rarely that people may not take the threat seriously. In order to increase awareness of NEOs and their potential hazard, material needs to be introduced into the curricula for middle and high school students, using Earth examples of impacts and their effects, as well as the record of impacts that can readily be seen on the Moon. Education and outreach activities about NEOs need to be coordinated to enhance community awareness through public events, displays, and activities at schools, planetariums, museums, libraries, and observatories. In addition, a publicly accessible up-to-date web site featuring latest observations, historical events, and a nationwide activity calendar would do much to reach into the broader community. Such activities could be coordinated nationally through a center chosen in a competitive manner. Film makers could also be encouraged to produce engaging, but scientifically accurate films on these general subjects; truth is usually stranger than fiction and can serve as a reliable anchor.

8

Optimal Approaches

The committee was asked to address "the optimal approach to completing the NEO census called for in the George E. Brown, Jr. Near-Earth Object Survey section of the 2005 NASA Authorization Act." The committee was also asked to address "the optimal approach" to developing a deflection (i.e., orbit change) capability. The committee concluded that there was no way to define "optimal" in a universally acceptable manner: there are too many variables involved that can be both chosen and weighted in too many plausible ways. A key question nevertheless is: given the low risk over a period of, say, a decade, how much should the United States invest now? This chapter discusses cost implications. First, a summary of the background:

Government funding, primarily through NASA, now supports a modest, ongoing program of sky surveys, to discover and track NEOs. NASA also supports analysis and archiving activities. According to NASA, total expenditures are approximately $4 million annually, which does not include any funding for Arecibo. As the committee concluded in its interim report, and confirmed in this one, current expenditures are insufficient to achieve the goals established by Congress.

The committee was asked and did perform independent cost estimates of the solutions that it considered. However, most of the survey/detection and mitigation options that were cost estimated are technically immature and cost estimates at this early stage of development are notoriously unreliable. At best, these estimates provide only crude approximations of final costs of pursuing any of these options. The committee therefore did not use these cost estimates in reaching its conclusions.

The committee has therefore outlined three possible levels of funding and a possible program for each level. These three levels are somewhat arbitrary, and separated by factors of five: $10 million, $50 million, and $250 million annually.

$10 Million Level. If only $10 million were appropriated annually, the committee concluded that an approximately optimal allocation would be:

- $4 million to continue ground-based optical surveys and to make follow-up observations on long-known and newly discovered NEOs, including determining orbits and archiving them along with the observations; the archive would continue to be publicly accessible.
- $2.5 million to support radar observations of NEOs at the Arecibo Observatory.
- $1.5 million to support radar observations at the Goldstone Observatory.
- $2 million to support research on a range of issues related to NEO hazards, including, but not necessarily limited to (see Chapter 6), study of sky distribution of NEOs and development of warning-time statistics; concept studies of mitigation missions; studies of bursts in the atmosphere of incoming objects greater than a few meters in diameter; laboratory studies of impacts at speeds up to the highest feasible to obtain; and leadership and organization planning, national and international.

The $10 million funding level would not allow completion on any time scale of the mandated survey to discover 90 percent of near-Earth objects of 140 meters in diameter or greater. Also lost would be any possibility for mounting spacecraft missions, for example to test active mitigation techniques in situ.

(A caveat: The funds designated above to support radar observations are for these observations alone; were the maintenance and operations of the radar-telescope sites not supported as at present, there would be a very large shortfall for both sites, about $10 million annually for Arecibo and likely a comparable figure for Goldstone.)

$50 Million Level. At a $50 million annual appropriations level, in addition to the tasks mentioned above, the committee notes that the remaining $40 million could be used for:

- Support of a ground-based facility, as discussed in Chapter 3, to enable completion of the congressionally mandated survey to detect 90 percent of near-Earth objects of 140 meters in diameter or greater by the delayed date of 2030.

The $50 million funding level would likely not be sufficient for the United States alone to conduct space telescope missions which might be able to carry through a more complete survey faster. In addition, this funding level is insufficient to develop and test mitigation techniques in situ. However, such missions might be feasible to undertake if conducted internationally, either in cooperation with traditional space partners or as part of an international entity created to work on the hazards issue. Accommodating both the advanced survey and a mitigation mission at this funding level is very unlikely to be feasible, save on a time scale extended by decades.

$250 Million Level. At a $250 million annual budget level, a robust NEO program could be undertaken unilaterally by the United States. For this program, in addition to the research program, a more robust survey program could be undertaken that would include redundancy via some combination of ground-and space-based approaches. This level of funding would also enable a space mission similar to ESA's proposed Don Quijote spacecraft, either alone or, preferably, as part of an international collaboration. This space mission would test in situ instrumentation for detailed characterization, as well as impact technique(s) for changing the orbit of a threatening object, albeit on only one. The target could be chosen from among those fairly well characterized by ground observations so as to check these results with those determined via the in situ instruments.

The committee assumed constant annual funding at each of the three levels. For the highest level, the annual funding would likely need to vary substantially as is common for spacecraft programs. Desirable variations with time of annual funding would likely be fractionally lower for the second level, and even lower for the first level.

How long should funding continue? The committee deems it of the highest priority to continually monitor the skies for threatening NEOs; therefore, funding stability is important, particularly for the lowest level. The second level, if implemented, would likely be needed at its full level for about four years to contribute to completion of the mandated survey. The operations and maintenance of such instruments beyond this survey has not been investigated by the committee. However, were the LSST to continue operating at its projected costs this second-level budget could be reduced. The additional funding provided in the third and highest level would probably be needed only through the completion of the major part of a Don Quijote-type mission, under a decade in total, and could be decreased gradually, but substantially, thereafter.

Finding: A $10 million annual level of funding would be sufficient to continue existing surveys, maintain the radar capability at the Arecibo and Goldstone observatories, and support a modest level of research on the hazards posed by NEOs. This level would not allow achievement of the goals established in the George E. Brown, Jr. Near-Earth Object Survey Act on any timescale. A $50 million annual level of funding for several years would likely be sufficient to achieve the goals of the George E. Brown, Jr. Near-Earth Object Survey Act. A $250 million annual level of funding if continued for somewhat under a decade, would be sufficient to accomplish the survey and research objectives, plus provide survey redundancy and support for a space mission to test in situ characterization and mitigation.

Appendixes

A

Independent Cost Assessment

The committee's statement of task required it to "include an assessment of the costs of various alternatives, using independent cost estimating." Science Applications International Corporation (SAIC) was contracted by the National Research Council to perform independent risk, cost and schedule assessments in support of the committee. Eight projects were chosen by the committee for assessment. The SAIC assessment of the eight projects was led by Joseph Hamaker with the assistance of SAIC senior scientists L. Cole Howard and Peter S. Gural.

The eight projects selected by the committee are meant to be viewed in this assessment as examples of activities that could be developed to accomplish the specified detection, characterization or mitigation goals. Other particular solutions are certainly also plausible but the ones selected for this assessment were deemed sufficiently illustrative for risk, cost and schedule assessment. While data from advocates of specific concepts were used as a starting point, in all cases SAIC performed independent analysis of the technology readiness, cost and schedules of the missions.

The NEO survey, characterization and mitigation approaches that the committee asked SAIC to assess were at various levels of definition and in some cases were largely conceptual. As a result, it is too early in the NEO program development and design of most of the eight representative projects for the committee to develop confidence in either the Projects or the SAIC's cost estimates.

As one example we note the mission to place a 0.5 meter infrared telescope in a Venus-trailing orbit costed by a special team at the Jet Propulsion Laboratory. JPL internal analysis yielded a range of approximately \$600-\$650 million, including 5 years of operations and a 20 percent contingency, whereas the SAIC analysis yielded corresponding costs of \$550 million to \$1.8 billion.

LSST is a second example in which, by contrast, the SAIC cost model predicts a significantly lower cost than the LSST Team's estimate. The LSST project estimated the construction budget as \$390 million in 2007 dollars, whereas the SAIC cost range (for a replicate telescope, construction only) was between \$140 million and \$340 million in 2009 dollars.

These examples demonstrate that the initial cost estimates produced by SAIC for this study contain many uncertainties. It was not within the scope of this committee to conduct the more thorough mission definitions required to produce more accurate cost estimates and, in particular, to resolve the above differences.

The committee concluded that the primary value of the technical and cost assessments of the eight projects was not to provide a cost estimate of the potential solutions, but to identify the technical maturity and requirements of the options. The eight projects chosen by the committee are shown in Table A.1. These included three ground-based telescope concepts for NEO detection, two space-based systems for NEO detection, one space-based NEO characterization mission, and two space-based NEO mitigation systems. The results are presented in a range of costs meant to give decision makers some idea of the inherent technological risks and the range of resources that might be required to undertake such projects., However, given the conceptual level of definition of many of these projects, the end points of the range of costs will very likely change significantly as the designs are matured.

TABLE A.1 Activities/Projects Evaluated

Activity/Project	Description	Status
Panoramic Survey Telescope and Rapid Response System (PanSTARRS 4)	4 X 1.8 M ground-based optical telescope for NEO detection either at Mauna Kea or Haleakala, Hawaii.	PS-1 existing. For NEO, we assumed a replicate of planned PS-4
Large Synoptic Survey Telescope (LSST)	1 X 8.4 M ground based optical telescope for NEO detection at Cerro Pachon, Chile.	Planned. For NEO, we assumed a replicate.
Binocular Telescope (Catalina Sky Survey II)	6 X 1.8M ground based optical telescope for NEO detection at Mt. Hopkins, AZ.	Planned. For NEO, we assumed a replicate.
0.5-Meter Infrared Space Telescope	1 X 0.5M space based telescope for NEO detection at L-1.	Proposed.
0.5-Meter Infrared Space Telescope (Ball NEO Survey)	1 X 0.5M space based telescope for NEO detection in a Venus trailing orbit.	Proposed.
Don Quijote (ESA	A spacecraft orbiter/observer and an impactor spacecraft for NEO characterization and kinetic impact mitigation.	Proposed (not active in ESA).
Gravity Tractor	A spacecraft orbiter using which uses the gravitational field between itself and the NEO to mitigate NEO orbit	Proposed.
Nuclear Deflector	A spacecraft orbiter/observer and an nuclear deflector spacecraft for NEO mitigation. We assumed the observer spacecraft is characterized by the Don Quijote orbiter.	Proposed.

A key issue in the cost and schedule assessment was ensuring that the cost and schedule estimates were as much as possible on an equal footing with each other despite the limited information available to the cost estimators for some of the projects. All of these cost and schedule estimates for the space and ground-based activities employed cost and schedule risk analysis to try to achieve this equal footing. SAIC examined the major inputs to the cost model (including mass and power contingencies, heritage assumptions, technology readiness assumptions, etc.), compared these data with past data for similar missions where analogous historical missions existed and made adjustments so that all missions were estimated on a level playing field to the extent feasible. SAIC cost and schedule estimates for each NEO committee activity were also risk adjusted using a risk rating approach, SAIC assessed technology readiness at the major subsystem level and provided an assessment of the critical technologies based on the information provided to the estimators

The results of the SAIC assessment were reviewed by the committee and significant differences both plus and minus were noted between the numbers produced by the SAIC cost modeling tools and the

Project Team estimates as described in part above. A second issue facing the committee was to decide how much time and money should be spent having SAIC reconcile the significant differences between the estimate produced by SAIC assessment and the Project Team estimates. The committee decided that based on the dispersions in the level of maturity of the eight projects, it was premature to attempt this reconciliation.

The cost risk results form the SAIC models for each mission or activity is shown in the form of cost S curves (confidence level versus cost). At this point, any comparably risk adjusted cost can be selected from the S-curves for each of the proposed projects. Choosing a single confidence level tends to automatically normalize the cost estimates across competing missions in a way that allows them to be directly compared. However, as previously stated, the entire range of the S-curve should be considered more representatives of possible outcomes given our current state of knowledge and in fact, most probable range of costs will also likely shift as the design concept mature.

Major Cost Analysis Assumptions

Understanding cost estimates requires an appreciation of the cost estimating assumptions that were made to develop the estimates. Some of the more important assumptions in this assessment were:

- The range of costs reported in this study included total life cycle cost composed of pre-implementation costs (i.e., Phase A conceptual design and Phase B preliminary design), full scale development/implementation (i.e., Phase C detailed design, Phase D production), mission operations and data analysis (i.e., Phase E operations). Collectively, the Phase A through D costs are generally referred to as acquisition costs, terminology that was used in this study.
- All costs quoted in this report have been adjusted to 2010 prices using the NASA New Start Inflation Index.
- Cost estimates of spaceflight missions are assumed to be NASA funded and include an allowance for NASA civil service labor cost and other NASA institutional costs such as center management and operations and NASA G&A and overhead (NASA "full costs").
- Ground-based observatories were assumed to be funded outside of the NASA full cost institution and management model.

Methodology for Estimating the Range of Cost and Schedule for Ground-Based Facilities

The three ground-based missions were all optical observatories and the cost of these were estimated using the Multivariable Parametric Cost Model for Ground Optical Telescope Assemblies (see "References" section below). As a cross-check, the results from the Multivariable Parametric Cost Model for Ground Optical Telescope Assembly Model were compared to analogous ground-based telescope analogies.

Just as with spaceflight projects, there are a number of basic cost considerations in estimating the cost of ground-based facilities and research activities. These include the state of technology—technology varies considerably between industries, and thus affects estimate accuracy. For a "first-of-a-kind" facility project there is a lower level of confidence that the execution of the project will be successful (all else being equal). The inherent risk and uncertainty across the range of NEO ground-based activities is not constant. Some of the ground-based facilities have more challenging scientific goals, engineering requirements and programmatic objectives. All cost and schedule estimates for the ground-based activities employed cost risk analysis to normalize for this is at the 99th percentile, but the PS4 and the Binocular telescope are also high at the 80th and 75th percentile respectively. The technology readiness of the telescopes was used to translate to the new design percentage.

Methodology for Estimating the Most Probable Range of Cost and Schedule for Space-Based Missions

The five space-based missions included two infrared telescopes, a kinetic characterization/kinetic impact mission, a gravity tractor and a nuclear deflector mission. All of these space-based missions were estimated using the NASA QuickCost model (see "References" section below). QuickCost is a model developed for NASA by SAIC that requires only a top level description of the projects being estimated to generate risk adjusted life cycle cost and schedule estimates. QuickCost was also used to estimate the development span which would be expected for missions of their size and complexity.

The QuickCost database includes approximately 100 data fields on more than120 past space science flight projects. QuickCost provides means, medians, standard deviations, and coefficients of variation and inter-quartile ranges for all 100 descriptive parameters in the model's data base. SAIC examined "cross-parameter" trends to spot outlying technical descriptions for the missions being estimated. Missions with parameter relationships which lie outside these norms were flagged for further attention to determine if there is some underlying difference in assumptions or other bias in the mission descriptions. As a result of this exercise, some missions were found to have data voids such as total spacecraft masses, power, data rates, design lives, percent new design and instrument complexity. In these cases, SAIC estimated these parameters.

For launch cost of the space-based missions, SAIC utilized the NASA Expendable Launch Services Model. (See "References" section below). This model estimates launch cost as a function of payload mass, destination (i.e., orbital inclination or escape) and payload shroud (fairing) size.

Most Probable Range of Cost and Schedule for the Eight Projects

A range of costs were estimated for each of the eight projects follows along with description including technology development requirements, technology readiness and risk rating.

The S-curves of a potential range of costs for each concept is provided in Figures A.1 to A.8. These present a top-level snapshot at this stage of the independent cost estimating process of each concept's range of potential budgeting requirements. Given the conceptual level of definition at this stage of the Project development and the fact that the reconciliation between the project team and model estimates has not been performed, clearly the endpoints of this range for most of the projects also have a high probability of changing as the designs become more defined and the basis for the difference in current estimates are understood.

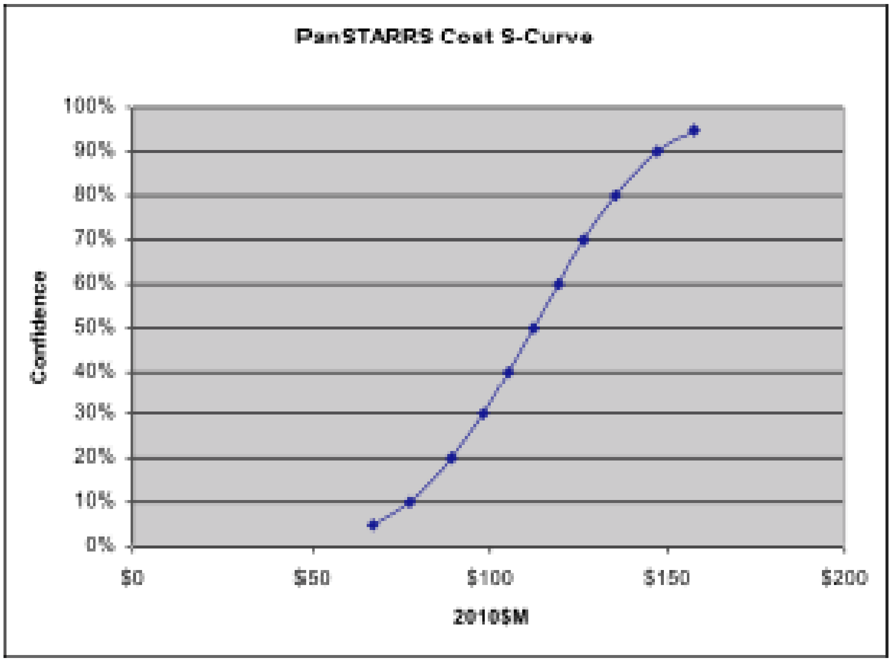

FIGURE A.1 Panoramic Survey Telescope and Rapid Response System (PanSTARRS 4) Cost S-Curve.

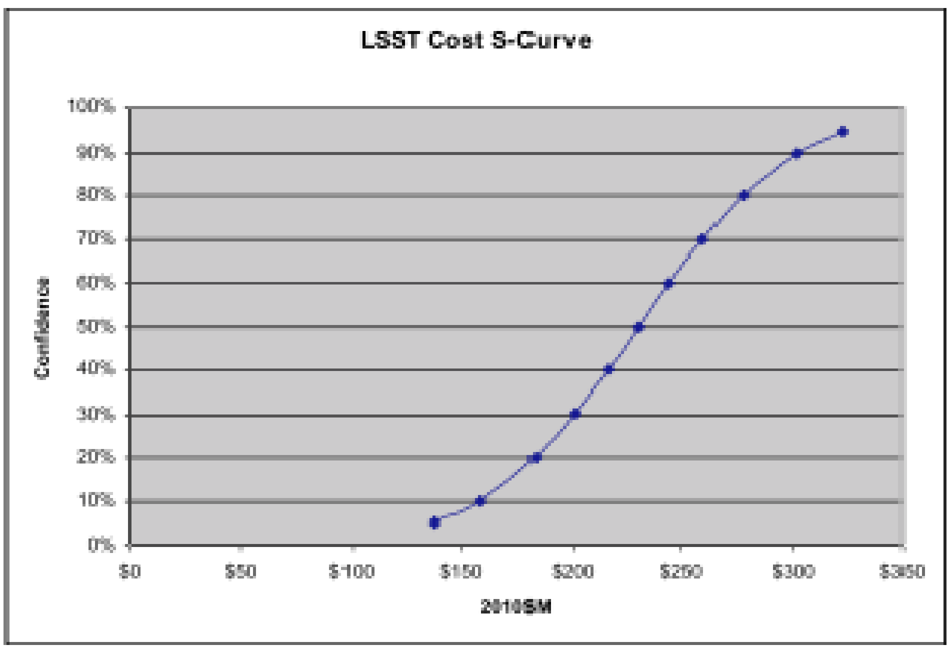

FIGURE A.2 Large Synoptic Survey Telescope (LSST) Cost S-Curve.

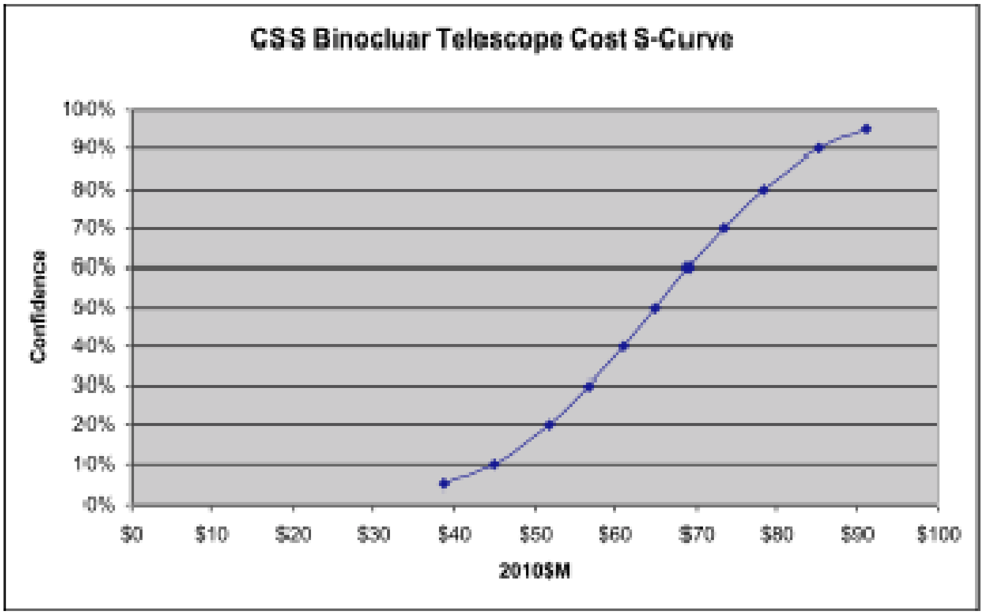

FIGURE A.3 Catalina Sky Survey (CSS) Binocular Telescope Cost S-Curve.

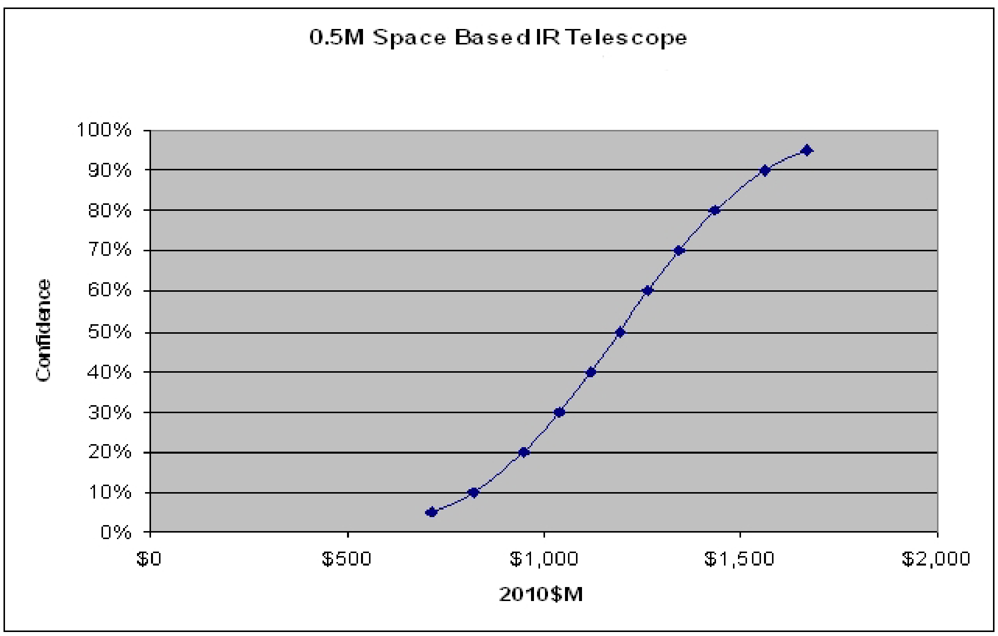

FIGURE A.4 0.5M Infrared Telescope Cost S-Curve.

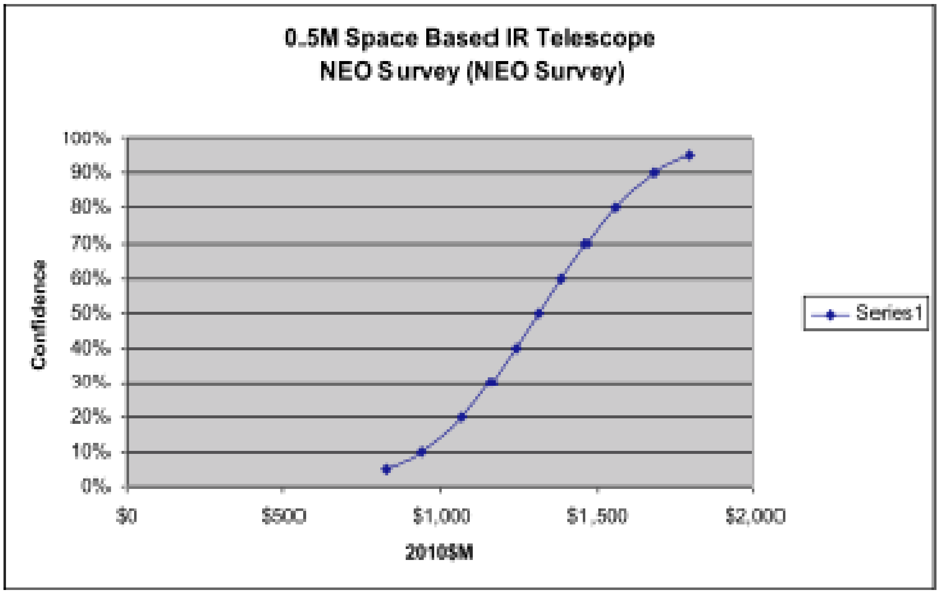

FIGURE A.5 0.5M IR Telescope (NEO Survey) Cost S-Curve.

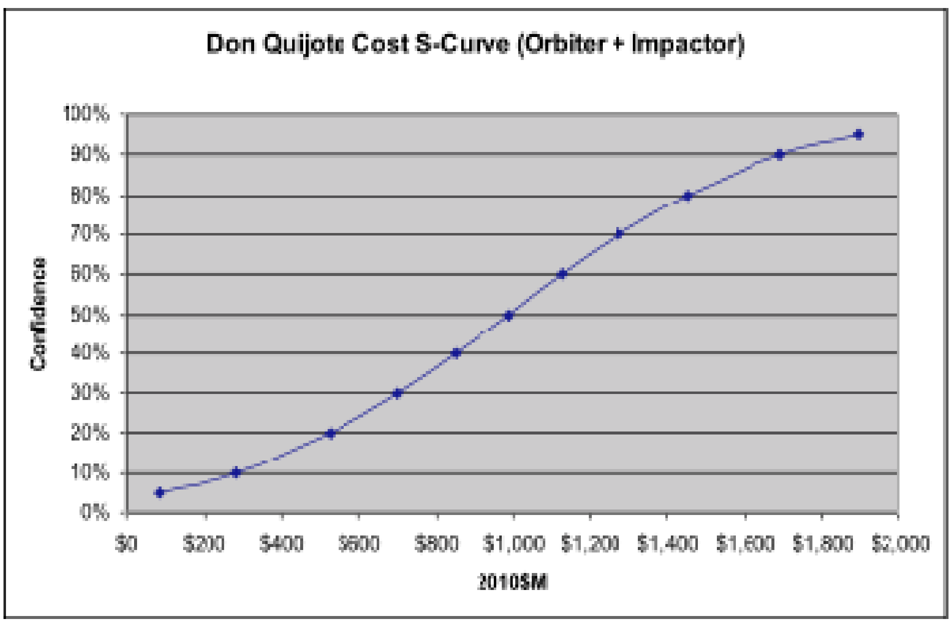

FIGURE A.6 Don Quijote Cost S-Curve (Orbiter + Impactor).

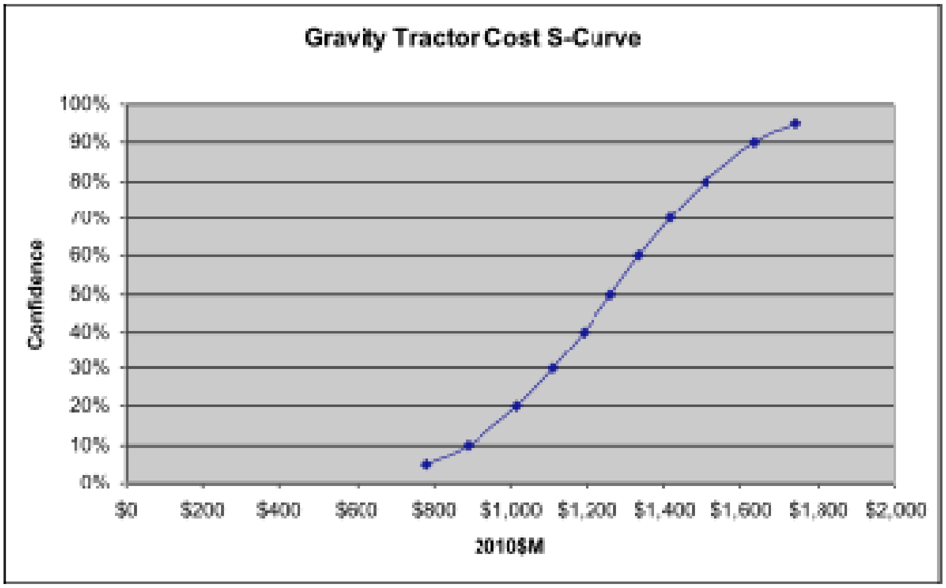

FIGURE A.7 Gravity Tractor Cost S-Curve.

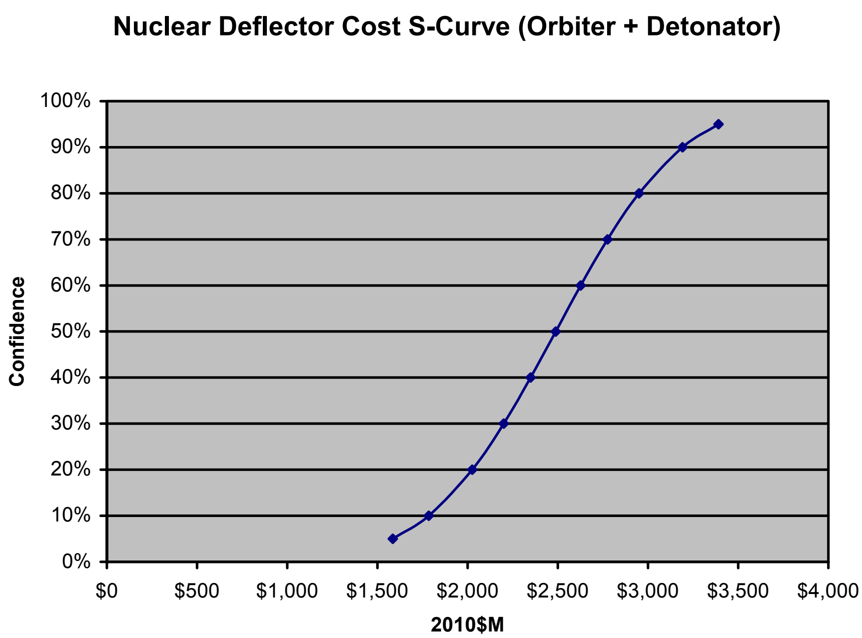

FIGURE A.8 Nuclear Deflector Cost S-Curve (Orbiter + Detonator).

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B

Letter of Request

2 June 2008

Dr. Lennard A. Fisk
Chair, Space Studies Board
National Research Council

Dear Dr. Fisk:

The legislative report accompanying the fiscal year 2008 omnibus appropriations bill for NASA established a requirement for the National Research Council (NRC) to undertake a two-phase study to review recent reports on near Earth object (NEO) detection and deflection and other relevant documentation, and to develop recommendations on optimal approaches to surveying the NEO population and to developing a deflection capability:

> In order to assist Congress in determining the optimal approach regarding the Arecibo Observatory, NASA shall contract with the National Research Council to study the issue and make recommendations. As part of its deliberations, the NRC shall review NASA's report 2006 Near-Earth Object Survey and Deflection Study and its associated March 2007 Near-Earth Object Survey and Deflection Study as well as any other relevant literature. An interim report, with recommendations focusing primarily on the optimal approach to the survey program, shall be submitted within 15 months of enactment of this Act. The final report including recommendations regarding the optimal approach to developing a deflection capability, shall be submitted with 21 months of enactment of this Act. The NRC study shall include an assessment of the costs of various alternatives, including options that may blend the use of different facilities (whether ground- or space-based), or involve international cooperation. Independent cost estimating should be utilized.

In accordance with this Congressional direction, we would like the NRC's Space Studies Board (SSB) to conduct the required analysis and prepare the required two-phase report. Terms of reference for the study activity are provided in the enclosed Statement of Task. An initial report providing findings and recommendations for the first task should be submitted no later than September 30, 2009. A second report describing the final findings and recommendations of both tasks should be submitted no later than December 31, 2009.

We would like to request that the NRC submit a plan to NASA for execution of the study described herein on this schedule. Once agreement with the NRC on the scope and cost for the proposed study has been achieved, the NASA Contracting Officer will issue a task order for implementation. Mr. Lindley Johnson will be the technical point of contact for this effort, and may be reached at (202) XXX-XXXX or lindley.johnson@XXXX.

Sincerely,

James L. Green, Director Planetary Science Division, NASA	Craig Foltz, Acting Director Astronomical Science Division, NASA

C

Committee and Staff Biographical Information

IRWIN I. SHAPIRO, *Chair,* is the former director of the Harvard-Smithsonian Astrophysical Observatory (1983-2004), where one of his institutional responsibilities was overseeing the Minor Planet Center. He, his students, and his colleagues made the first detections of asteroids and comets ever made by radar. He has also recently developed a large-screen script focusing on NEOs, which includes issues surrounding impact prevention. Dr. Shapiro was awarded nine medals and prizes for his research, and in 1997, he became the first Timken University Professor at Harvard University. His research involves applications of radio and radar techniques in astrophysics, geophysics, planetary physics, and tests of gravitational theories. Dr. Shapiro is a member of the National Academy of Sciences. His most recent NRC experience was serving on the Panel on Astronomy Education and Policy of the Astronomy and Astrophysics Survey Committee.

MICHAEL A'HEARN, *Vice Chair,* is a Distinguished University Professor at the University of Maryland, College Park. He was the principal investigator (PI) for the Deep Impact mission and is the PI for the EPOXI mission in NASA's Discovery Program and for the Small Bodies Node of NASA's Planetary Data System. His research interests include comets and asteroids, and his theoretical work focuses on the physical and chemical properties of comets. He has also worked on the development of techniques for determining sizes of cometary nuclei that combine optical and infrared measurements. Dr. A'Hearn is a member of the American Astronomical Society's Division of Planetary Sciences. His prior NRC service includes the Panel on Primitive Bodies of the Committee on a New Science Strategy for Solar System Exploration.

FAITH VILAS, *Vice Chair,* is the director of the MMT Observatory at Mt. Hopkins, Arizona. She served as chair of NASA's Small Bodies Assessment Group. She has previously worked as chief of the planetary astronomy group in NASA's Johnson Space Center (JSC) Astromaterials Research and Exploration Science Directorate and as a research scientist at JSC. From 1987 to 1988, she served as a field team participant for the Antarctic Meteorite Expedition. She was principal investigator for the Debris Collision Warning Sensors Space Transportation System flight experiment to observe orbital debris in the visible and thermal infrared spectral regions (1987-1992). Dr. Vilas was also a member of the Space Surveillance PI Team for the Mid-Course Space Experiment satellite in charge of conducting experiments to observe man-made orbital debris with visible and thermal infrared sensors. She was also a member of the Joint Science Team for the Japanese Hayabusa space probe that orbited and landed on near-Earth asteroid 25143 Itokawa. Much of her experience lies in using ground- and space-based telescopes. She was part of the science team that discovered Neptune's rings 5 years before confirmation from the 1989 Voyager mission.

ANDREW CHENG is Chief Scientist of the Space Department at the Johns Hopkins University Applied Physics Laboratory. He was responsible for the overall integrity of science returns from the Near Earth Asteroid Rendezvous mission and is the lead for science data analysis and archiving, science planning, and conflict resolution among NEAR science requirements. He was an interdisciplinary scientist for the Galileo mission to Jupiter, investigating magnetospheric physics at Jupiter, and is a co-investigator on the

Magnetospheric Imaging team on the Cassini mission to Saturn and Titan. Dr. Cheng was named Maryland Academy of Sciences Outstanding Young Scientist in 1985 and has received five NASA Group Achievement awards since then. He has authored more than 160 scientific articles. He served on the NRC Task Group on the Forward Contamination of Europa and the Committee on Planetary and Lunar Exploration.

FRANK CULBERTSON, JR., is a former astronaut and a retired captain from the U.S. Navy. He is senior vice president and deputy general manager of the Advanced Program Group at Orbital Sciences Corporation where he is responsible for human spaceflight programs, including commercial transportation services to the International Space Station (ISS). Prior to joining Orbital, Mr. Culbertson was a senior vice president at Science Applications International Corporation (SAIC), initially as program manager of the Safety, Reliability and Quality Assurance contract at NASA, before progressing to business unit general management and director of SAIC's Global Climate Change Programs. Mr. Culbertson was a NASA astronaut for 18 years in a variety of critical spaceflight and management roles for NASA's space shuttle and space station programs, including three launches aboard the space shuttle and command of the ISS. In total, he has logged more than 144 days in space and over five hours of extra-vehicular activity (space walk) experience. Mr. Culbertson also served as program manager of the Shuttle-Mir Program for 3 years and deputy program manager for operations for the ISS program.

DAVID JEWITT is a professor in the Department of Earth and Space Sciences and the Institute for Geophysics and Planetary Physics, UCLA. He has focused his research on studying the vast population of small icy bodies in the Kuiper Belt at and beyond the orbits of Neptune and Pluto. He has also studied comets and other primitive bodies of the solar system, many of which are evolved Kuiper Belt objects. Dr. Jewitt is a member of the National Academy of Sciences. He has previously served on several NRC committees, including the Committee on a New Science Strategy for Solar System Exploration and the Astronomy and Astrophysics Survey Committee.

STEPHEN MACKWELL is director of the Lunar and Planetary Institute in Houston, Texas. Prior to his appointment, Dr. Mackwell served as director of the Bayerisches Geoinstitut at the University of Bayreuth, Germany. Dr. Mackwell has served as program director for geophysics, Division of Earth Sciences, National Science Foundation (1993-1994), member, group chief and panel chair of the review panel for NASA's Planetary Geology and Geophysics Program, expert reviewer for the Department of Energy's Geosciences Research Program (1993), and expert consultant for the Division of Earth Sciences, National Science Foundation (1995). Dr. Mackwell conducts laboratory-based research into the physical, chemical, and mechanical properties of geological materials under conditions relevant to the mantle and crust of Earth and other terrestrial planets. He served on the NRC Committee on New Opportunities in Solar System Exploration.

H. JAY MELOSH is Distinguished Professor of Earth and Atmospheric Sciences and Physics at Purdue University. Some of Dr. Melosh's previous positions include professor at the Lunar and Planetary Laboratory at the University of Arizona, associate professor of planetary science at the California Institute of Technology and associate professor of geophysics at State University of New York at Stony Brook. He has made many important contributions to Earth and planetary sciences, including definitive studies of the collisional origin of the Moon and the process of impact cratering. His other major contributions include acoustic fluidization, dynamic topography, and planetary tectonics. He is active in astrobiological studies relating chiefly to microorganism exchange between the terrestrial planets. Dr. Melosh is a member of the National Academy of Sciences. He has served on the NRC Committee on Planetary and Lunar Exploration.

JOSEPH H. ROTHENBERG is currently an independent consultant. From 2002 until 2009 he was President and a member of the Board of Directors of Universal Space Network. From 1964 until 1983 he held space program technical, project and executive management positions in industry. In 1983, he joined NASA Goddard and in 1995 became Center Director, where he was responsible for space systems development and operations, and for execution of the scientific research program for NASA Earth-orbiting science missions. In January 1998, he moved to NASA Headquarters where he was named Associate Administrator for Space Flight and was in charge of NASA's human exploration and development of space. As Associate Administrator, Mr. Rothenberg was responsible for establishing policies and direction for the Space Shuttle and International Space Station programs, as well as for space communications and expendable launch services. He is widely recognized for leading the development and successful completion of the first servicing mission for the Hubble Space Telescope, which corrected the telescope's flawed optics. Mr. Rothenberg served on the NRC Committee on Assessment of Options for Extending the Life of the Hubble Space Telescope, the Committee on Meeting the Workforce Needs for the National Vision for Space Exploration, and the Beyond Einstein Program Assessment Committee.

SURVEY/DETECTION PANEL

FAITH VILAS, *Chair* (see above)

WILLIAM E. BURROWS is an aerospace writer and historian. He is former professor of journalism at New York University where he worked for 33 years and was the founder of its graduate Science, Health and Environmental Reporting Program. He covered aviation and space for The New York Times, The Washington Post, and The Wall Street Journal. He is currently a contributing editor at Air & Space/Smithsonian and the author of eleven books, including This New Ocean: The Story of the First Space Age, Deep Black: Space Espionage and National Security, and The Survival Imperative: Using Space to Protect Earth. He was recently selected for the American Astronautics Society's 2008 John F. Kennedy Astronautics Award.

PAUL ABELL is a research scientist employed by the Planetary Science Institute and assigned to the Astromaterials Research and Exploration Science Directorate at NASA Johnson Space Center. He has been studying near-Earth objects and comet-asteroid transition objects for more than 8 years and has numerous scientific publications. His primary scientific interest is determining the physical characteristics of near-Earth objects using ground-based telescopes and spacecraft sensors. Dr. Abell was a telemetry officer for the Near Earth Asteroid Rendezvous spacecraft Near-Infrared Spectrometer team and is a member of the Near-Infrared Spectrograph science team for the Hayabusa spacecraft operated by the Japan Aerospace Exploration Agency. He is also a visiting astronomer at the NASA Infrared Telescope Facility at Mauna Kea Observatory and has had extensive experience obtaining high quality spectral data of NEOs. Dr. Abell was recently involved in an internal NASA study to examine the feasibility of sending a human-led mission to a NEO using the Orion Crew Exploration Vehicle.

ROBERT F. ARENTZ is an engineer who has worked at Ball Aerospace and Technologies Corp. for 34 years and presently works in Ball's Civil and Operational Space division. For the past 3 years he has led a small team exploring ground-augmented space-based solutions using high-heritage flight hardware and commercially available sensors to detect near-Earth objects. He and his team looked at a variety of observatory orbits for detecting hard to detect "sunward" near-Earth objects. He and his team have also created cost models for their most recent infrared detection designs. For the past 10 years Mr. Arentz has participated in several concept studies for possible Discovery-class deep-space missions. His program experience includes work on Ball's Skylab instruments, the Infrared Astronomical Satellite, the Cosmic Origins Background Explorer (COBE), the near-infrared camera NICMOS now on the Hubble Space Telescope, and he contributed to some elements of the Spitzer Space Telescope.

LANCE A.M. BENNER is a research scientist at the Jet Propulsion Laboratory, California Institute of Technology, where he specializes in radar imaging of near-Earth objects. He was a NRC Postdoctoral Fellow at JPL for 3 years beginning in 1995 and has been a JPL employee since 1998. He has first-authored or co-authored more than forty papers on near-Earth objects, main-belt asteroids, and comets. He is a frequent observer at the NSF's Arecibo Observatory and at NASA's Goldstone Solar System Radar.

WILLIAM F. BOTTKE Dr. William Bottke is the Assistant Director of the Department for Space Studies at Southwest Research Institute (SwRI) in Boulder, Colorado. Bottke is also the Director of the Center for Lunar Origin and Evolution (CLOE) of NASA's Lunar Science Institute. His research interests include the collisional and dynamical evolution of small body populations throughout the solar system (e.g., asteroids, comets, irregular satellites, Kuiper belt objects, meteoroids, dust) and the formation and bombardment history of planetesimals, planets and satellites. His expertise related to near-Earth objects (NEOs) involves their delivery from their source regions in various asteroid and cometary populations to their observed orbits. By combining models of the dynamical evolution of NEOs to observational data, Bottke and colleagues have estimated the debiased orbital and size distribution of the NEO population. He received a B.S. in Physics and Astrophysics from the University of Minnesota in 1988 and a Ph.D. in Planetary Science from the University of Arizona in 1995. He has also been a postdoctoral fellow at both Caltech (1996-1997) and Cornell University (1997-2000).

ANDREW CHENG (see above)

ROBERT D. CULP is a professor of aerospace engineering sciences at the University of Colorado at Boulder. In 1966 Dr. Culp received early recognition for applying Pontryagin's Maximum Principle to optimal impulsive orbit transfer, thus completing the rigorous solution of this popular problem. From 1969 through 1975, Dr. Culp published the complete theoretical solution to the problem of optimal hyperbolic flyby. These definitive results have allowed the application of this optimal transfer technique to many multi-planet missions. He has developed less restrictive and more accurate solutions to the basic problem of satellite drag and decay. He has made significant and lasting contributions to orbit determination techniques, atmospheric entry theory, and optimal atmospheric flight mechanics. In recent years, Dr. Culp has become one of the leading authorities on space debris, satellite fragmentation modeling, hazard to resident space objects, and the space environment. He previously served on the NRC's Committee on International Space Station Meteoroid/Debris Risk Management.

YANGA (YAN) FERNANDEZ is an assistant professor of planetary science/astronomy at the University of Central Florida. Dr. Fernandez completed his doctoral thesis at the University of Maryland on the thermophysical properties of cometary nuclei. He was a Spitzer Space Telescope Fellow at the University of Hawaii from 2002 to 2005. Dr. Fernandez's research area is astronomy, specifically planetary science with an emphasis on the small bodies of the solar system. His overarching goal is to understand the thermal, physical, and compositional environment at the time of the solar system's creation. Some of Dr. Fernandez's projects involve the use of the Spitzer Space Telescope. He also uses telescopes in Arizona, Hawaii, and Chile to study active comets, dormant comets, near-Earth objects, and outer solar system objects.

LYNNE JONES is currently the Large Synoptic Survey Telescope (LSST) Science Fellow at the University of Washington, where some of her responsibilities include evaluating LSST's potential detection efficiency for near-Earth objects under various survey strategies; testing moving object processing software; and evaluating LSST's capabilities to measure light curves, photometric colors, and physical properties of asteroids. Dr. Jones is also a member of the Canada-France Ecliptic Plane Survey collaboration which has conducted an extensive wide-field, well-characterized survey for trans-Neptunian objects (TNOs). Dr. Jones previously carried out a deep survey for TNOs, developing a new digital tracking method to search for TNOs fainter than the limiting magnitude in each individual image. She was an NSF International Research Fellow at University of British Columbia from 2002 to 2004, and a Legacy Survey Fellow at UBC/Herzburg Institute of Astrophysics from 2004 to 2006.

STEPHEN MACKWELL (see above)

AMY MAINZER is a research scientist at the Jet Propulsion Laboratory where she specializes in spacecraft instrumentation. She worked at Lockheed Martin on the Spitzer Space Telescope. She was the principal investigator of a cryogenic camera called the Pointing Calibration and Reference Sensor, which serves as the fine guidance sensor for Spitzer. She worked on Spitzer part time while in graduate school. She received an NSF Graduate Research Fellowship, followed by a NASA Graduate Research Fellowship. For her thesis, she built the First Light Camera for the SOFIA airborne telescope and observed brown dwarfs. As the Wide-field Infrared Survey Explorer (WISE) deputy project scientist, she works to ensure that WISE will meet its science requirements. Dr. Mainzer's research interests include brown dwarfs, asteroids, and planetary atmospheres. She is the principal investigator of the NEOWISE task, which is an enhancement to the baseline WISE mission that will enable the discovery of new asteroids with WISE. She is also leading an effort to build the first megapixel mid-infrared array designed for high-background operations.

GORDON H. PETTENGILL is a retired professor who first came into prominence for his discovery in 1965 of the unexpected 2/3 spin/orbital period resonance of the planet Mercury, using radar astronomical techniques. Beginning with the first application of coherent Earth-based radar to studies of the Moon in 1959, his observations have embraced Mercury, Venus, Mars, several asteroids and comets, the Galilean satellites of Jupiter and the rings of Saturn. He was the principal investigator for the Radar Mapper Experiment carried out on the Pioneer Venus Orbiter from 1978 through 1981. Since then he has been the principal investigator for the Magellan (Venus-radar-mapping) mission. Dr. Pettengill has been affiliated primarily with the Massachusetts Institute of Technology, first with Lincoln Laboratory and then as professor in the MIT Department of Earth, Atmosphere and Planetary Sciences. He served as associate director (1963-1965) and later director (1968-1970) of Cornell University's Arecibo Observatory in Puerto Rico. Dr. Pettengill retired from MIT in 1995, but has remained active in research since then, primarily with the Mars Orbital Laser Altimeter experiment aboard the Mars Global Surveyor, launched in 1996 and still in orbit around that planet. He was awarded the Magellanic Premium of the American Philosophical Society and the Whitten Medal and the Fred Whipple Award, both from the American Geophysical Union. He is a member of the National Academy of Sciences. He previously served on the Committee on Planetary and Lunar Exploration (COMPLEX).

JOHN RICE is emeritus professor of statistics at the University of California at Berkeley. Dr. Rice's research interests revolve around the applications of statistics, especially to the natural sciences. He is particularly interested in modeling and analyzing data that arise from random processes. His recent research has focused on detecting objects in the outer regions of the solar system (the Kuiper Belt) and detecting gamma-ray pulsars, and developing methods to detect very rare, faint events in very large quantities of data. He is the author of Mathematical Statistics and Data Analysis, former editor of the Annals of Statistics, and the recipient of the Jerome Sacks Award for Interdisciplinary Research. Dr. Rice is a former member of the NRC's Board on Mathematical Sciences and their Applications (BMSA).

MITIGATION PANEL

MICHAEL A'HEARN. *Chair* (see above)

MICHAEL J. S. BELTON is currently President of his own research company, Belton Space Exploration Initiatives, LLC, and an emeritus astronomer at Kitt Peak National Observatory (KPNO). He was an astronomer at the KPNO Division of the National Optical Astronomy Observatories in Tucson, Arizona from 1964-2000. He is a specialist in observational and interpretive planetary science with emphasis on the application of high-resolution spectroscopy and photometric imaging from Earth-based telescopes and interplanetary spacecraft. His primary scientific interests are in the physics of cometary nuclei and the physics of planetary atmospheres particularly that of Jupiter's satellite Io. He has published in excess of 240 refereed scientific articles. He was a member of the Mariner 10 Imaging team and a co investigator on the Mariner 10 and Voyager UVS investigations. He served as the leader of the Galileo Imaging Science Team and was deputy principal investigator and member of the science teams on the CONTOUR and Deep Impact missions. Presently he is a member of the science teams on the Stardust-NExT and EPOXI (DIXI) missions. Belton is a science co-investigator in the Stardust-NEXT project. In 1995 he received the American Astronomical Society, Division of Planetary Sciences Gerard P. Kuiper Prize in Planetary Science. He is also the recipient of a number of NASA Group Achievement Awards. Dr. Belton was born in the United Kingdom in 1934, and educated at St. Andrews University in Scotland (B. Sc.[1st class Hons]. 1959) and at the University of California at Berkeley (Ph. D, 1964). He became a naturalized US citizen in 1975. In 2001 he chaired the NRC's decadal study on Solar System Exploration.

MARK BOSLOUGH is a physicist at Sandia National Laboratories. He has served as principal investigator on a number of projects involving shock/impact physics, climate change, evolutionary computing, and agent-based modeling. He has used impact experiments as a research tool to understand high-pressure equations of state, shock metamorphism, shock chemistry, evolution of planetary materials, and protection of spacecraft from micrometeorites. Since his focus shifted to computational research, he has led projects to develop a parallelized paleoclimate code, simulate impact-induced climate change, apply evolutionary computing methods, create models for conflict related to climate change, use learning algorithms for problems in physics and security, assess technology to defend Earth from an impact, understand the physics of low-altitude airbursts, and quantify the contribution of airbursts to the impact threat. He received his B.S. degree in physics from Colorado State University, and his M.S. degree and Ph.D. in applied physics (with a geophysics minor) from the California Institute of Technology.

CLARK R. CHAPMAN is a senior scientist in the Department of Space Studies at Southwest Research Institute in Boulder CO, where he has worked since 1996, following 24 years at the Planetary Science Institute in Tucson, AZ (part of SAIC). He also sits on the Board of Directors of the B612 Foundation, a not-for-profit organization that advocates for near-Earth object education, and ultimately a real-life demonstration of an asteroid deflection. Dr. Chapman is a past Chair of the Division for Planetary Sciences (DPS) of the American Astronomical Society and in 1999 he received the DPS's Carl Sagan Medal for Excellence in Public Communication in Planetary Sciences. He is a past president of Commission 15 (Physical Properties of Asteroids and Comets) of the International Astronomical Union. He is a Fellow of both the AAAS and the Meteoritical Society. Dr. Chapman was the first editor for the Planets section of the Journal of Geophysical Research. He has been on the imaging and/or spectroscopy teams of the Galileo, NEAR-Shoemaker, and MESSENGER missions. He has researched every planet in the solar system while focusing on small bodies (especially asteroids) and on impact cratering of planetary surfaces, and is currently a member of the International Astronautical Federation's Technical Committee on Near-Earth Objects. Dr. Chapman has served in some advisory capacity to many NASA NEO studies, including participating in a 2006 workshop where he presented a paper to the NASA Near Earth Object Survey and Deflection Study. He obtained his Ph.D. in planetary science at MIT, writing a thesis on spectral reflectance studies of asteroids. He previously served on the NRC Task Group on Sample Return from Small Solar System Bodies, and the Study Team on Primitive Bodies.

SIGRID CLOSE is an assistant professor in the Department of Aeronautics and Astronautics at Stanford University. Prior to coming to Stanford University, she was a project leader at Los Alamos National Laboratory and a technical staff member at the Massachusetts Institute of Technology's Lincoln Laboratory where she led programs to characterize meteoroids and meteoroid plasma using high-power radars. She also was the lead space physicist for spacecraft monitoring and unplanned space surveillance events and was a project leader for characterizing and modeling ionospheric plasma instabilities. Her current research area is in Space Weather and Satellite Systems, which includes characterizing and mitigating environmental risks to spacecraft, detecting and characterizing interstellar dust, signal processing and monitoring using RF satellite systems, and plasma modeling for remote sensing. Her honors and awards include: the Joe D. Marshall Award given by AFTAC for Outstanding Technical Briefing, MIT Lincoln Scholar from 2000 through 2004, and first place in the student paper competition at the International Union of Radio Science in 2002. She is also currently Vice Chair of Commission G. She received her Ph.D. in astronomy (space physics) from Boston University in 2004 in the area of meteoroid physics and risk assessment.

JAMES A. DATOR is a professor and director of the Hawaii Research Center for Futures Studies in the Department of Political Science at the University of Hawaii-Manoa. Dr. Dator is also the co-director of the Space and Society Department at the International Space University in Strasbourg, France, and a Fellow and member of the Executive Council of the World Academy of Art and Science. His areas of specialization include political futures studies (especially the forecasting and design of new political institutions, and the futures of law, education, and technology); and space and society, especially the design of governance systems for space settlement. Dr. Dator was an advisor to the Hawaii State Commission in 2000, and has consulted with state futures commissions for Florida, Illinois, and Oregon. He has been a futures consultant for the Federal Judicial Center and several Federal district courts; for the state judiciaries of Arizona, Florida, Hawaii, Illinois, Kansas, Massachusetts, Pennsylvania, Puerto Rico, Tennessee, and Virginia; and for the national judiciaries of New Zealand, Singapore, and the Federated States of Micronesia, as well as the American Bar Association, the American Judicature Society, numerous state bar associations, law firms, other legal organizations, industry, and the military.

DAVID S.P. DEARBORN is a research physicist at the Lawrence Livermore National Laboratory (LLNL). His current research on the diversion of asteroids by nuclear explosives mixes his background in astrophysics and nuclear weapons effects; this research creates detailed modeling of the effects of nuclear explosives on asteroids. His programmatic work has included the design and testing of both nuclear and conventional explosives. Current responsibilities include generating models and output for the DTRA Red Book, support of the LLNL reusable vehicle flight-test program, and conventional lethality studies. He has used large lasers for the study of high energy density phenomena, studied non-seismic methods for treaty verification, and designed a shuttle experiment. He is currently involved in Djehuty, a project for the full three-dimensional modeling stars, which recently led to the discovery of a new mixing mechanism that resolves a decades old conflict between predicted and observed abundances. He has received three Weapons Recognition of Excellence awards from the Department of Energy, recognizing his contributions to laser hohlraum (a laboratory device to produce blackbody radiation, used in thermonuclear testing experiments) development, his work in advancing the analysis of radar data, and for his efforts on the W87 Life Extension Program. In 2006, he received an acknowledgement from the Defense and Nuclear Technologies Directorate at LLNL for outstanding contributions of the cross discipline improvement of ICBM accuracy.

KEITH A. HOLSAPPLE is a professor in the Aeronautics and Astronautics Department at the University of Washington. With a background in engineering mechanics and numerical methods, his research interests are now focused on the planetary sciences of the small bodies of the solar system. His recent studies include the definition of the material behavior of those bodies, and models to describe those in computer studies. He has formulated and solved the problem of the equilibrium shapes, spins and tidal disruptions of solid asteroid bodies using the models of soil and rock mechanics, generalizing the well-known and classical fluid models of Maclaurin, Jacobi, Roche and others. He has been active in the studies of mitigation methods for Earth-threatening asteroids and has presented talks at various AIAA and

NASA sponsored meetings. Dr. Holsapple has also performed code calculations of mitigation by both impacts and by nuclear weapons.

DAVID Y. KUSNIERKIEWICZ is chief engineer of the Space Department of the Johns Hopkins University Advanced Physics Laboratory, where he has worked for 26 years. He has an extensive background in designing, integrating and testing power system electronics for spacecraft. Mr. Kusnierkiewicz held the position of mission system engineer for the NASA New Horizons Pluto-Kuiper-Belt Mission (launched January 19, 2006), and is still the mission and spacecraft system engineer for the NASA Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) program, which launched in December 2001. He has served on numerous review boards for NASA missions, including Lunar Reconnaissance Obiter; Lunar Robotic Explorer; Dawn, Juno, and ST-8 (part of the New Millennium Program); and he has received two NASA Group Achievement Awards. Prior to working as a system engineer, he spent 10+ years designing spaceflight hardware. Mr. Kusnierkiewicz received his B.S. and M.S. in electrical engineering from the University of Michigan-Ann Arbor.

PAULO LOZANO is an assistant professor of aeronautics and astronautics at the Massachusetts Institute of Technology (MIT). His research interests are electric propulsion, electrosprays, thruster physics, electrochemical microfabrication, engine health monitoring, and space mission design. He teaches in the areas of space, rocket and air-breathing propulsion; plasma physics; and experimental projects. Current research efforts include non-traditional configurations for Hall-effect plasma thrusters and their ability to propel spacecraft. Professor Lozano started at MIT in 2003 as a postdoctoral associate, and then became a research scientist before attaining his current position in 2006. He is a member of the American Institute of Aeronautics and Astronautics, and the American Physical Society. Professor Lozano received his M.S. and Ph.D. from MIT.

EDWARD D. McCULLOUGH is a retired principal scientist at The Boeing Company. He received his professional training in nuclear engineering through the U.S. Navy, and Bettis and Knowles Atomic Power Laboratories (gaining his Certification for Nuclear Engineering at Pearl Harbor Naval Shipyard in 1975). Mr. McCullough focused on concept development experimental chemistry and advanced technology at Rockwell Space Systems Advanced Engineering and at the Boeing divisions of Phantom Works and Integrated Defense Systems. He has researched innovative methods to reduce the development time of technologies and systems from 10 to 20 years down to 5 years. He has experienced successes in the area of chemistry and chemical engineering for extraterrestrial processing and photonics for vehicle management systems, and integrated vehicle health management and communications. Mr. McCullough has led efforts for biologically inspired multi parallax geometric situational awareness for advanced autonomous mobility and space manufacturing. He recently developed several patents, including patents for an angular sensing system; a method for enhancing digestion reaction rates of chemical systems; and a system for mechanically stabilizing a bed of particulate media. He is Chair Emeritus of the AIAA Space Colonization Technical Committee, a member of the Board of Trustees for the University Space Research Association, a member of the Science Council for Research Institute for Advanced Computer Science, and a charter member of the AIAA Space Exploration Program Committee. Mr. McCullough previously served on the NRC Committee to Review NASA's Exploration Technology Development Programs, and the Planning Committee for the Workshop on Research Enabled by the Lunar Environment.

H. JAY MELOSH (see above)

DAVID NASH, NAE, is a retired Rear Admiral in the United States Navy and president of Dave Nash and Associates, LLC, a project development firm serving businesses and governments around the world. RADM Nash has over four decades of experience in building, design and program management for both the U.S. Navy and the private sector. His experience includes the management of multi-billion dollar physical asset programs, including the U.S. Navy's shore installations worldwide and the reconstruction of Iraq's infrastructure. Most recently, RADM Nash served as director of the Iraq Program Management Office (PMO) under the Coalition Provisional Authority and later, as director of the Iraq Reconstruction Management Office (IRMO) under the U.S. State Department. Under his direction, these organizations managed the $18.4 billion Iraq infrastructure reconstruction program. RADM Nash is the recipient of numerous awards, including the Society of American Military Engineers Golden Eagle Award, the Beavers Award for Heavy Engineering Construction, the ASCE John I. Parcel-Leif J. Sverdrup Award for Civil Engineering Management, and the CERF/IIEC Henry L. Michel Award for Industry Advancement of Research. He was elected to the NAE "for leadership in the reconstruction of devastated areas after conflicts and natural disasters." RADM Nash currently serves on the NRC Board on Infrastructure and the Constructed Environment, and the Toward Sustainable Critical Infrastructure Systems: Framing the Challenges Workshop.

DANIEL J. SCHEERES is a professor in the Department of Aerospace Engineering Sciences at the University of Colorado at Boulder, and a member of the Colorado Center for Astrodynamics Research. Prior to this he held faculty positions in aerospace engineering at the University of Michigan (1999-2008) and Iowa State University (1997-1999), and was a member of the technical staff in the Navigation Systems Section at the California Institute of Technology's Jet Propulsion Laboratory (1992-1997). His research interests include the dynamics, control and navigation of spacecraft trajectories; the design of space missions; optimal control; planetary science; celestial mechanics; and dynamical astronomy. He is a Fellow of the American Astronautical Society, and is an Associate Fellow of the American Institute of Aeronautics and Astronautics. He serves on the AAS Space Flight Mechanics Committee and the AIAA Astrodynamics Technical Committee. He is a member of the Celestial Mechanics Institute and the International Astronomical Union. He is an associate editor for Celestial Mechanics and Dynamical Astronomy, the Journal of Nonlinear Science, the Journal of Guidance, Control and Dynamics, and The Journal of the Astronautical Sciences. He is the recipient of two NASA Group Awards for his work on the NEAR mission, and Asteroid 8887 is named "Scheeres" in recognition of his contributions to the scientific understanding of the dynamical environment about asteroids. He was awarded his Ph.D., M.S.E., and B.S.E. degrees in Aerospace Engineering from the University of Michigan, and holds a B.S. in Letters and Engineering from Calvin College.

SARAH STEWART-MUKHOPADHYAY is the John L. Loeb Associate Professor of the Natural Sciences in the Department of Earth & Planetary Sciences at Harvard University. She has more than 12 years of experience in studying impact cratering and conducting shock wave experiments. In 2004, she established the Shock Compression Laboratory at Harvard that focuses on Earth and planetary science topics and training new experimentalists in shock wave research. Current research includes experimental programs on shock temperature and the effects of porosity and volatility on shock wave propagation. Dr. Stewart also leads development of numerical techniques for simulations of impact events. Current work includes improvements in equations of state and strength models in the shock physics code CTH. Research interests include experimental and computational study of impact processes to interpret the resurfacing history, physical properties, and internal structure of planets. She is a recipient of a Presidential Early Career Award for Scientists and Engineers. Dr. Stewart received a B.A. in astronomy and astrophysics and physics from Harvard University in 1995 and a Ph.D. in planetary sciences (minor in astrophysics) from the California Institute of Technology in 2002.

KATHRYN C. THORNTON is assistant dean of and professor in the School of Engineering and Applied Science at the University of Virginia. Dr. Thornton has extensive human spaceflight experience and served for 12 years as a NASA astronaut, flying on four shuttle missions and performing extra-vehicular activities (i.e., spacewalks) on two of them. She also headed the NASA Johnson Space Center education working group which coordinated the educational outreach activities of astronauts and professional educators working under the "Teaching from Space" contract with Oklahoma State University. Before becoming a member of the space program, she co-authored more than 30 scientific publications and was a staff physicist for the U.S. Army Foreign Science and Technology Center for 4 years. Dr. Thornton has previously served on the NRC Aeronautics and Space Engineering Board, the Committee for Technological Literacy, and the Committee on Meeting the Workforce Needs for the National Vision for Space Exploration.

Staff

DWAYNE A. DAY, *Study Director,* a program officer for the Space Studies Board (SSB), has a Ph.D. in political science from the George Washington University and has previously served as an investigator for the Columbia Accident Investigation Board. He was on the staff of the Congressional Budget Office and also worked for the Space Policy Institute at the George Washington University. He has held Guggenheim and Verville fellowships and is an associate editor of the German spaceflight magazine *Raumfahrt Concrete,* in addition to writing for such publications as *Novosti Kosmonavtiki* (Russia), *Spaceflight*, and *Space Chronicle* (United Kingdom). He has served as study director for several NRC reports, including *Space Radiation Hazards and the Vision for Space Exploration* (2006), *Grading NASA's Solar System Exploration Program: A Midterm Review* (2008), and *Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity* (2008).

PAUL JACKSON, *Study Director,* is a program officer for the Aeronautics and Space Engineering Board (ASEB). He joined the NRC in 2006 and was previously the media relations contact for the Office of News and Public Information. He is the study director for a number of ASEB's projects, including proposal reviews for the state of Ohio and the Committee for the Review of NASA's Aviation Safety Related Programs. Mr. Jackson earned a B.A. in philosophy from Michigan State University in 2002 and an M.P.A in policy analysis, economic development, and comparative international affairs from Indiana University in 2006.

DAVID H. SMITH, *Study Director,* joined the staff of the SSB in 1991. He is the senior staff officer and study director for a variety of NRC activities, including the solar system exploration decadal survey. He also organizes the SSB's summer intern program and supervises most, if not all, of the interns. He received a B.Sc. in mathematical physics from the University of Liverpool in 1976 and a D.Phil. in theoretical astrophysics from Sussex University in 1981. Following a postdoctoral fellowship at Queen Mary College, University (1980-1982) he held the position of associate editor and, later, technical editor of *Sky and Telescope*. Immediately prior to joining the staff of the Space Studies Board, Dr. Smith was a Knight Science Journalism Fellow at the Massachusetts Institute of Technology (1990-1991).

VICTORIA SWISHER joined the SSB in 2006 as a research associate. She recently received a B.A. in astronomy from Swarthmore College. She presented the results of her research at the 2005 and 2006 AAS meetings and at various Keck Northeast Astronomy Consortium undergraduate research conferences. Her most recent research focused on laboratory astrophysics and involved studying the x rays of plasma, culminating in a senior thesis entitled "Modeling UV and X-ray Spectra from the Swarthmore Spheromak Experiment." She is currently obtaining a master's degree in nonproliferation studies at the Monterrey Institute.

ANDREA M. REBHOLZ joined the ASEB as a program associate in January 2009. She began her career at the National Academies in October 2005 as a senior program assistant for the Institute of Medicine's Forum on Drug Discovery, Development, and Translation. Prior to the Academies, she worked in the communications department of a D.C.-based think tank. Ms. Rebholz graduated from George Mason University's New Century College in 2003 with a B.A. in integrative studies–event management and has more than 7 years of experience in event planning.

LEWIS GROSWALD is a research associate and joined the SSB as the Autumn 2008 Lloyd V. Berkner Space Policy Intern. Mr. Groswald is a second-year graduate student pursuing his masters' degree in international science and technology policy at the George Washington University (GW). A graduate of GW, he studied international affairs with a double concentration in conflict and security and Europe and Eurasia as an undergraduate. Following his work with the National Space Society during his senior year at GW, Mr. Groswald decided to pursue a career in space policy, educating the public on space issues, and formulating policy.

RODNEY N. HOWARD joined the SSB as a senior project assistant in 2002. Before he joined SSB, most of his vocational life was spent in the health profession—as a pharmacy technologist at Doctor's Hospital in Lanham, Maryland, and as an interim center administrator at the Concentra Medical Center in Jessup, Maryland. During that time, he participated in a number of Quality Circle Initiatives that were designed to improve relations between management and staff. Mr. Howard obtained his B.A. in communications from the University of Baltimore County in 1983. He plans to begin coursework next year for his master's degree in business administration.

ABIGAIL A. SHEFFER joined the SSB in Fall 2009 as a Christine Mirzayan Science and Technology Policy Graduate Fellow. She enjoyed her fellowship so much that she continued with SSB to become an associate program officer. She earned her Ph.D. in Planetary Science from the University of Arizona and her A.B. in Geosciences from Princeton University.

D

Minority Opinion—Mark Boslough, Mitigation Panel Member

The original draft table of Expected Deaths Per Year by Cause (Table 2.2) included the World Health Organization[1] estimate of 150,000 deaths/year from climate change. The steering committee made a decision to remove the climate data, giving as reasons (1) caution about having any debate on climate change distract from the issue at hand and (2) irrelevance of climate-change numbers to the NEO threat.

The first reason is inappropriate. Data should not be removed from a report to avoid the potential for political controversy.

The second reason is incorrect. Climate change is more relevant than the other causes in the table, for several reasons:

- The portion of the threat above the global catastrophe threshold—which in the model we quote (Harris, 2009) constitutes about one half of the expected annual death rate—is primarily a climate change threat. Estimates of deaths from a large impact are largely based on our model-derived scientific understanding of climate change. The 91 deaths per year assumes a catastrophe threshold significantly lower than the current best estimate (3 km). It implicitly assumes a high-sensitivity climate and/or strong dependence of death rate on climate change.
- Asteroids and climate change are the only two threats in the original table that can have abrupt and global consequences, and to which everyone on the planet is exposed, regardless of their lifestyle or personal behavior. They are also both to some extent preventable, and in both cases mitigation requires international agreements and cooperation. The climate change death rate is therefore more appropriate to compare to the asteroid death rate than the other threats are. Climate can and has changed abruptly. Evidence from Greenland ice cores and other paleoclimate data show that these spontaneous changes take place much more frequently than large impacts and on time scales that can exceed human adaptive capacities.[2]
- Asteroids and climate change are the only two threats in the original table that include global catastrophe as a possibility. The best estimate of the global catastrophe threshold diameter for an asteroid is 3 km, but according to Alan Harris[3] all NEOs above this threshold, except for long-period comets, have been discovered. The best estimate of the probability of a global catastrophe this century from an asteroid impact is therefore zero. If Earth and its inhabitants are assumed to be much more sensitive to global change, then a low threshold of 1.5 km (a factor of 8 lower in kinetic yield) can be assumed. Harris estimates there are around 30 undiscovered asteroids larger than 1.5 km. The probability of impact by one of these before the end of the century is 0.0005 percent. On the other hand, recent models[4,5] suggest a

[1] A. McMichael et al., Climate change. In: Comparative Quantification of Health Risks: Global and Regional Burden of Disease due to Selected Major Risk Factors (M. Ezzati, A. Lopez, A. Rodgers, and C. Murray, eds.), World Health Organization, Geneva, 1543-1649, 2004.

[2] National Research Council, Abrupt Climate Change: Inevitable Surprises, The National Academies Press, Washington D.C., 2002, p. 230.

[3] A. Harris, personal communication, 2009.

[4] P. Huybers, Compensation between model feedbacks and curtailment of climate sensitivity, American Geophysical Union 2009 Fall Meeting.

2 percent probability of global catastrophe from anthropogenic climate change this century, assuming realistic greenhouse gas emissions scenarios and a threshold temperature change or sensitivity of 8ºC. If the threshold sensitivity is 4ºC, the probability of global catastrophe exceeds 20 percent. With sensitive assumptions, it is therefore 40,000 times more probable that we will be faced with an anthropogenic climate change catastrophe than with an asteroid catastrophe. With best assumptions it is infinitely more probable.

The WHO climate change estimate of 150,000 deaths per year is a lower bound, because of its conservative assumptions that do not include increasing temperatures since 2000. It also does not consider the probability of global catastrophe from human-triggered abrupt climate change comparable to the speed or magnitude of the Bölling/Allerød or Younger Dryas boundaries, which are not impact related.[6] The Harris (2009) asteroid estimate of 91 deaths per year is an upper bound, because it assumes a low catastrophe threshold. Inclusion of these figures for intercomparison is the only way to provide policy makers with an objective basis for prioritization and allocation of resources that is commensurate with the relative threat from various causes.

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[5] A. Sokolov, Relative contributions of uncertainty in anthropogenic emissions and climate system response to the uncertainty of projected 21st century climate, American Geophysical Union 2009 Fall Meeting, 2009.

[6] M. Boslough and A. Harris, Global catastrophes in perspective: Asteroid impacts vs. climate change, American Geophysical Union 2008 Fall Meeting, 2008.

E

Glossary and Acronym List

2008 TC_3 – An asteroid observed by the Catalina Sky Survey to be on a collision course with Earth; 2008 TC3 exploded in an airburst over Sudan on October 7, 2008

2009 HC_{82} – A near-Earth asteroid 2to 3 kilometers in diameter in a retrograde (“backwards”) orbit, discovered in 2009.

Absolute Magnitude – A specially defined quantity describing a celestial object’s intrinsic brightness

Albedo – The ratio of the light reflected by a physical object (e.g., planet or asteroid) to that received by it

Airburst –An explosion in Earth’s atmosphere of an object entering it at high speed

AsteroidFinder – A German spacecraft mission and the first payload to be launched under its new national compact satellite program. AsteroidFinder is planned to launch sometime in 2012 with a one-year baseline mission duration, will be equipped with a 30-centimeter-diameter telescope mirror, and will operate in low-Earth orbit. Its primary goals are to estimate the population of NEOs interior to Earth’s orbit, their size distribution, and their orbital properties, along with impact hazard assessment.

Blast Wave – The pressure and flow resulting from an explosion or airburst that deposits a large amount of energy into a small, localized area.

C3 – A measure of the extra energy required over that to escape Earth for a space mission. C3 is given as the square of the required excess velocity, usually in units of $(km/s)^2$.

CCD – Charge Coupled Device, an electronic memory that records the intensity of light as a variable charge. Widely used in still cameras, telescopes, and other optical devices to capture images, CCDs are analog devices. Their charges equate to shades of light for monochrome images or shades of red, green and blue when used with color filters.

Characterization – The determining of various characteristics of a celestial object, including but not limited to: orbit, rotation, size, composition, and albedo

Chemical Energy – The energy released in a chemical reaction, measured here in terms of the energy released when TNT (trinitrotoluene) is detonated.

Chicxulub Crater – An approximate 200-kilometer-diameter impact crater formed 65 million years ago in the Yucatan peninsula and associated with the extinction of the dinosaurs

Civil Defense – A mitigation option, civil defense entails protecting the population by taking precautions on the ground, such as advanced warning, evacuations, and provision of protective shelter. It is already used for natural disasters such as hurricanes

Contact Forces – A force exerted through physical contact with an object

CSS – Catalina Sky Survey, a system of three telescopes located at the Mt. Lemmon Observatory in Arizona, the Mt. Bigelow Observatory in Arizona, and the Siding Spring Observatory in Australia (funded by NASA). CSS currently discovers NEOs at the highest rate of any operational telescope system.

CSS+ – Catalina Sky Survey Binocular Telescopes, a proposed series of three binocular telescopes fully dedicated to discovering NEOs, based upon using six existing 1.8-meter-diameter primary telescope mirrors. CSS+ is currently not funded.

ΔV – "Delta-V" – Change in Velocity. Delta V (Delta "Five") also refers to a rocket launch vehicle capable of carrying heavy loads into orbit

Deep Impact – A NASA mission in which a spacecraft collided with comet Tempel-1 in July 2006, and is an example of a kinetic impact

Deep Space Network – An network of three deep-space communications facilities placed approximately 120 degrees apart around the world that supports interplanetary spacecraft missions and radio astronomy observations, as well as selected Earth-orbiting missions. Facilities are located at Goldstone in California's Mojave Desert; near Madrid, Spain; and near Canberra, Australia

Discovery Channel Telescope (DCT) – A telescope with a 4.2-meter-diameter mirror under construction in Arizona. A collaborative effort between Lowell Observatory and Discovery Communications, the telescope is designed to contribute to multiple astronomical projects, including searches for NEOs. It's approximately $14 million camera is not yet funded.

Dissipative Surface – In the context of this report, a low-density, porous surface (e.g., of an asteroid) where the energy from an impact or explosion is dissipated across the surface rather than transferring to the interior of the body

Eccentricity – A measure of how much an orbit's shape deviates from a circle. For circular orbits, e = 0. As e becomes greater, the orbit's shape becomes increasingly elongated

Electric Propulsion – A method of spacecraft propulsion using charged ions for thrust

ESRIN – The European Space Agency's (ESA) Centre for Earth Observation, located in Frascati, Italy

Flyby Trajectory – A spacecraft's flight path designed to pass in close proximity to an object but not go into orbit around or impact the object

Gamma Rays – Very high energy electromagnetic radiation

George E. Brown, Jr. Near-Earth Object Survey Act of 2005 – A congressional act mandating the discovery of 90 percent of cosmic objects 140 meters in diameter or greater

Goldstone Solar System Radar – Located in the Mojave Desert in southern California, a steerable 70-meter-diameter antenna that transmits and receives radio waves. It is part of NASA's Deep Space Network and is operated by the Jet Propulsion Laboratory under contract with NASA.

Gravity Assist – Using the gravity of a planet to change the path and/or speed of a spacecraft

GTO – Geostationary Transfer Orbit is an intermediate orbit used to move a spacecraft from Low Earth Orbit to a geostationary orbit where the spacecraft remains stable above a particular point on Earth

Hayabusa – A Japanese spacecraft mission that rendezvoused with the sub-kilometer near-Earth object Itokawa in September 2005

Heliocentric Orbit – An orbit around the Sun

Heliocentric Velocity – The velocity of a body relative to the Sun

Human Space Flight Review Committee – A committee commissioned by President Obama in May 2009 to review the current U.S. human space flight plans and programs. The Committee concluded its review in September 2009

Hydrodynamic Simulation – Computer model created to simulate the behavior of fluids in motion

Hyperbolic Approach – An approach in which one orbiting body approaches another along a hyperbolic trajectory

IAU – International Astronomical Union, the international professional society for astronomers; provides guidance for the Minor Planet Center

Impactor – A physical object that collides with a target object at a high velocity, transferring momentum and energy to alter the target object's orbit. Also called a *kinetic impactor*

Imminent Impactors – Space objects of a natural origin whose impact with Earth is imminent

Impact Energy – The amount of energy delivered by one body in an impact with another. Units are often given in megatons (MT), which refers to a comparison with the chemical energy release of a million tons of TNT. Also known as *kinetic yield*

Inclination – In this report, the angle between the plane of an orbit and the ecliptic (the plane containing Earth's orbital path).

International Monitoring System – An international network of seismic, infrasound, radionuclide and hydroacoustic stations deployed by the Department of Defense and the Comprehensive Test Ban Treaty Organization. In addition to monitoring for violations of the Treaty, its microbarograph sensors also detect airbursts from cosmic objects striking Earth's atmosphere

Iron Meteorite – A meteorite consisting primarily of metallic nickel-iron alloys

Kinetic Energy – The energy of motion.

Kinetic Yield – See Impact Energy

Lagrange Points – Discovered by Italian-French mathematician Joseph-Louis Lagrange, the Lagrange Points mark positions where the gravitational pull of two large mutually orbiting masses precisely equals the centripetal force required to keep a small body there rotating at the same angular speed as the massive ones. Objects placed near these points would orbit around them.

LEO – Low Earth Orbit, commonly between 160 to 2,000 km

LINEAR – Lincoln Near-Earth Asteroid Research program, operated by the Massachusetts Institute of Technology's Lincoln Laboratory and funded by the U.S. Air Force and NASA. It was the most successful NEO search program from 1997 to 2004. Intended to demonstrate application of technology designed for the surveillance of Earth-orbiting satellites for detecting NEOs

LONEOS – Lowell Observatory Near-Earth-Object Search, operated by the Lowell Observatory, is a 0.6-meter diameter telescope that can scan the entire sky accessible from Flagstaff, Arizona. Project funding from NASA began in 1993 and ended in 2008.

LSST – Large Synoptic Survey Telescope is a survey project under development by a consortium of institutions. It is centered on an 8.4-meter diameter mirror and will operate in Chile, scanning the entire sky every few days in visible and infrared wavelength bands. The major science goals for LSST include cataloging and characterizing all moving objects in the solar system, including identifying NEOs

Mass Drivers – A mechanism placed on the surface of an object that ejects mass from the object as propellant (see also: Contact Forces)

MPC – Minor Planet Center, a clearinghouse for positional information from observers of minor planets (including all asteroids) from all observatories across the world; operated by the Smithsonian Astrophysical Observatory, with primary support from NASA

Meteor Crater – An approximately 1.2 kilometer diameter crater located in Arizona

Momentum Transfer – The amount of momentum that one object gives to another upon collision

Monte Carlo Simulations – A class of computational algorithms that use random numbers. They are useful for simulating complex systems with a large number of unknown quantities.

NASA – National Aeronautics and Space Administration

NASA PA&E Office – NASA's Program Analysis & Evaluation Office was established in 2005 to provide objective, transparent, and multidisciplinary analysis of NASA programs to inform strategic decision-making. The office has also been charged to lead the Agency's strategic planning efforts

Near-Earth Object Program Office – Charged with coordinating the Near-Earth Object program for NASA, based at the Jet Propulsion Laboratory in Pasadena, California

NEAR Shoemaker – A NASA spacecraft mission that rendezvoused with the second largest near-Earth object, Eros, in February 2000

NEAT – Near-Earth Asteroid Tracking, a program began in 1995, was initially a collaborative effort between NASA, the Jet Propulsion Laboratory, and the U.S. Air Force. The program converted the 1-meter Ground-based Electro-Optical Deep Space Survey (GEODSS) telescope in Maui, Hawaii into the world's first fully automated asteroid-search telescope. NEAT converted other telescopes in Hawaii as well, and ended in 2007 after having detected over ~20,000 objects, ~430 of which were NEOs

NEO(s) – Near-Earth Object(s)

NEODyS – Near-Earth Objects Dynamic Site, a European data and information gathering office maintained by the University of Pisa in Italy, with a mirror site at the University of Valladolid in Spain

NEOSSat – Canada's Near-Earth Object Surveillance Satellite, a joint venture between the Canadian Space Agency (CSA) and Defense Research and Development Canada, is currently under construction. NEOSSat will track human-made satellites and orbital debris, as well as discern and track NEOs

NEOWISE – Wide-field Infrared Survey Explorer for Near-Earth Objects, a NASA spacecraft mission launched in December 2009. NEOWISE will produce a high sensitivity imaging survey of the entire sky in four infrared wavelength bands, always looking 90 degrees from the Sun

NSF – National Science Foundation

Ocean Runup – A condition in which the water level on a coastline rises above normal fluctuations

PanSTARRS (or PanSTARRS 4 or PS4) – Panoramic Survey Telescope and Rapid Response System is planned to consist of four 1.8-meter-diameter mirrors in a single imaging system, each telescope observing the same area of sky at the same time and wavelength. So far, only PanSTARRS 1 has been built.

Perigee – The point of closest approach to Earth of a body in orbit around Earth.

Perihelion – The point of closest approach to the Sun of a body in orbit around the Sun.

Photon Pressure – Pressure exerted on a body by light

Porosity – A measure of the open spaces, or voids, in a material. It is often defined as a fraction of the volume of open space over the total volume.

Proximity Detonator – A device used to detonate explosives automatically when the distance to the target becomes smaller than a predetermined value.

Radiant Energy – The energy of electromagnetic waves. Also may be used to refer to the waves themselves.

Recovery – A component of a larger response-and-recovery civil defense plan. Planning for recovery should occur before the impact

Rendezvous Trajectory – A spacecraft trajectory designed to intersect the trajectory of another body at very slow speed. It can then impact or go into orbit around the body

Semi-major axis – The semi-major axis of an ellipse (e.g., a NEO orbit) is 1/2 the length of the major axis which is the segment of a line passing thru the foci of the ellipse with endpoints on the ellipse itself.

Shoemaker-Levy 9 – A comet that broke apart and collided with Jupiter in 1994

Slow Push or Pull – Refers to a method of mitigation whereby the orbit of a target object is changed by slowly altering its velocity over a long period of time, perhaps decades, and is limited to objects of ~100 meters in diameter or smaller

Solar Energy – Radiant light from the Sun

Spaceguard Survey – Mandated by Congress to detect 90 percent of near-Earth objects 1 kilometer in diameter or greater by 2008

Spacewatch – Established in 1981, Spacewatch is one of the first NEO discovery systems, is run by the University of Arizona, and utilizes two (0.9-meter and 1.8-meter diameter) telescopes

Spall – Flakes of material ejected from a larger parent body as the result of an explosion.

Standoff Detonation – The detonation of an explosive at a distance from an object such as an NEO.

Stony Meteorite – A meteorite consisting primarily of rocky material

Technology Readiness Level (TRL) – A measure used to assess the maturity of evolving technologies (materials, components, devices). TRL 1 is the lowest level of readiness, limited to studies of a technology's basic properties. TRL 9 is the level for application of a tested and proven technology

Thermal Inertia – A term used to describe how fast an object changes temperature in response to a change in the heat applied

Thermal Pulse – An expanding wave of heated air or other material associated with an impact or an airburst event

TNT Megatons – A method of quantifying the energy released in explosions by comparing it to the equivalent energy released by a quantity of TNT. A ton of TNT is a unit of energy equal to 4.184 gigajoules.

Trajectory – The path or orbit that a moving object follows through space; usually applied in this report to a spacecraft headed toward an NEO

Tunguska Event – The exploration of a cosmic object exploded above Siberia in a region near the Podkamennaya Tunguska River in 1908 in what is termed an airburst

Vredefort Crater – A 300-kilometer-diameter crater located in South Africa, formed about 2 billion years ago