NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Near-Earth Object Survey and Deflection Analysis of Alternatives

Report to Congress

March 2007

Summary of Comments on NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

This page contains no comments

SUMMARY

Section 321 of the NASA Authorization Act of 2005 (Public Law No. 109-155), also known as the George E. Brown, Jr. Near-Earth Object Survey Act, directs the NASA Administrator to transmit an initial report to Congress not later than one year after the date of enactment that provides: (1) an analysis of possible alternatives that NASA may employ to carry out the survey program of near-Earth Objects (NEO), including ground-based and space-based alternatives with technical descriptions; (2) a recommended option and proposed budget to carry out the survey program pursuant to the recommended option; and (3) an analysis of possible alternatives that NASA could employ to divert an object on a likely collision course with Earth.

The objectives of the George E. Brown, Jr. NEO Survey Program are to detect, track, catalogue, and characterize the physical characteristics of NEOs equal to or larger than 140 meters in diameter with a perihelion distance of less than 1.3 AU (Astronomical Units) from the Sun, achieving 90 percent completion of the survey within 15 years after enactment of the NASA Authorization Act of 2005. The Act was signed into law by President Bush on December 30, 2005.

A study team, led by NASA's Office of Program Analysis and Evaluation (PA&E), conducted the analysis of alternatives with inputs from several other U.S. government agencies, international organizations, and representatives of private organizations. The team developed a range of possible options from public and private sources and then analyzed their capabilities and levels of performance including development schedules and technical risks.

Key Findings for the Survey Program:

- The goal of the Survey Program should be modified to detect, track, catalogue, and characterize, by the end of 2020, 90 percent of all Potentially Hazardous Objects (PHOs) greater than 140 meters whose orbits pass within 0.05 AU of the Earth's orbit (as opposed to surveying for all NEOs).
- The Agency could achieve the specified goal of surveying for 90 percent of the potentially hazardous NEOs by the end of 2020 by partnering with other government agencies on potential future optical ground-based observatories and building a dedicated NEO survey asset assuming the partners' potential ground assets come online by 2010 and 2014, and a dedicated asset by 2015.
- Together, the two observatories potentially to be developed by other government agencies could complete 83 percent of the survey by 2020 if observing time at these observatories is shared with NASA's NEO Survey Program.
- New space-based infrared systems, combined with shared ground-based assets, could reduce the overall time to reach the 90 percent goal by at least three years. Space systems have additional benefits as well as costs and risks compared to ground-based alternatives.
- Radar systems cannot contribute to the search for potentially hazardous objects, but may be used to rapidly refine tracking and to determine object sizes for a few

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Author: cchapman Subject: Inserted Text Date: 7/3/2007 3:28:21 PM

[Redlining by Clark R. Chapman, 3 July 2007. During the June 18th meeting at NASA Hq., Bill Claybaugh invited me to mark up this NEO Report, to reflect the serious errors in the Report discussed at that meeting. I describe here how I have suggested changes to the Report, and what I have not done.

I recommend changes (most of them very modest) to 12 of the 27 pages of the Report. These consist of deletions, additions, and rewritten sentences. They primarily address technical errors in the deflection analysis, but also address problems with the characterization analysis as it relates to deflection (in essence, serious characterization is highly desirable prior to deflecting a seriously threatening PHO by *any* of the deflection options studied in this Report, except possibly by the gravity tractor; the statistical characterization of PHOs by remote-sensing has largely already been done).

Experts in astronomical survey techniques believe that the detection analysis in the Report is obsolete. (Whether their input was made in sufficient time to be included in the study is not clear to me.) They believe that a 15-year detection survey beginning as soon as possible (2008) could discover 90% of NEOs >140 m for a cost of about $150 million. I have not marked up the Report to correct the obsolete detection analyses discussed in the Report. My only suggested change on this topic is a brief comment in the "Exemplar Survey Program" section stating the current conclusions.

I have *not* suggested additional changes that don't address the primary errors in the report. If a revised Report is issued, more corrections could be made (e.g. a footnote to Table 4 advertises further discussion of the techniques, when there is no further discussion in the Report, other than a redundant duplication of Table 4 as Table 15).

The chief errors corrected by my mark-up address these issues:

* Failure of the report to recognize that physical fragility of asteroids and their very low gravity makes them subject to possible disruption, especially by impulsive deflection techniques.

* Failure of the Report to consider the general significance of keyholes (the danger that an inexactly deflected PHO or fragment might be placed into a keyhole and later impact Earth, as well as the usefulness of keyholes in many instances to achieve deflection with much less energy [the mistaken analysis of VD17 is such a case]).

* The mistaken conclusion that minimal characterization is required for safely deflecting a PHO with a stand-off nuclear blast and that considerable characterization is required for the gravity tractor; the opposite is the case.

* Correcting the view that greatly enhanced statistical characterization of PHOs is required for designing deflection techniques (e.g. the mistaken statement that we need more statistical information on PHO spins in order to design a space tug).

* Correcting the backwards logic that we select a single deflection option first, and determine the required characterization later. Obviously, we need to characterize a threatening PHO first, and then determine what deflection option is sufficient, safe, and reliable.

* Option 7, as described in the study's pre-decisional Final Report (8 orbiter missions every 5 years) has no justification; I have marked it up to strike that interpretation of Option 7 and use a sensible description that is also in the Report.

* Striking the false statement that the analyzed scenarios are "representative" when, in fact, well over 95% of threats (larger than the "air blast limit") to be discovered by the survey will be smaller than the smallest NEO studied in the scenarios.

* Correcting errors made by lumping the radically different slow-push options together and characterizing them as generically expensive and technologically least ready when that is false as applied to the gravity tractor.]

Comments from page 2 continued on next page

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They could complete 100 percent of the survey over a 15-year span beginning in 2008.

NEOs of potentially high interest. Existing radar systems are currently oversubscribed by other missions.

- Determining a NEO's mass and orbit is required to determine whether it represents a potential threat and to provide required information for most alternatives to mitigate such a threat. Beyond these parameters, characterization requirements and capabilities are tied directly to the mitigation strategy selected.

Key Findings for Diverting a Potentially Hazardous Object (PHO):

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

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

Alternatives Considered to Detect, Track, Characterize, and Deflect/Mitigate NEOs

The following tables provide a summary of the options considered. Technical descriptions of each option, as well as other combinations of alternatives, can be found in subsequent sections of this report. For each option, Table 1 shows the percentage of PHOs that would be found by the survey by the end of 2020 and the year each option would achieve 90 percent completion, starting with the option of sharing the use of potential ground-based observatories, which will be referred to as the "Reference" architecture through the rest of this document. Details regarding the availability of assets for each option are also found in subsequent sections. Table 1 shows that individually each of the first three options fall short of meeting the Congressional goal. As shown in the last line of Table 1, the minimum survey architecture that achieves the goal would be a combination of the shared ground-based assets plus one of two dedicated asset options.

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. Determination of many other physical characteristics of a threatening NEO is highly desirable in order to ensure that a deflection operation is done safely and reliably.

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energetic

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the vast majority of threats identified during the prospective survey. The total deflection could be achieved by a series of smaller impactors, lessening the chances for fragmenting the NEO.

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The gravity tractor is the least costly and most technologically ready of the "slow push" techniques, but it is much less energetic than most others so would be most applicable for deflecting NEOs away from small keyholes, which are a common route taken by NEOs that actually strike Earth. While some other slow-push options are more energetic, they are more expensive and have the lowest level of readiness.

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Most NEO threats will involve decades of warning. But in unusual cases of short warning, there may be inadequate time to characterize and rendezvous with the threatening object, requiring advanced propulsion systems to reach them and application of more energetic and robust deflection options.

Table 1. Detection and Tracking Capability Options & Summary Results

Option*	through 2020	Year 90%
Shared ground-based (Reference)	83%	2026
Dedicated ground-based	85%	2024
Dedicated Infrared sensor in Venus-like orbit	89%	2021
Reference + One Dedicated Asset	At least 90%	Not Later than 2020

** Details of each option are found in a subsequent section of this report.*

Table 2. Characterization Options

Option*	Descriptions (O1 = Option 1)
Option 1	Use Existing Assets + Detection and Tracking Systems
Option 2	O1 + Dedicated Ground Systems
Option 3	O1 + Dedicated Space-Based Remote Sensing (L1/L2)
Option 4	O1 + Dedicated Space-Based Remote Sensing (Venus-Like Orbit)
Option 5	O1+ O2+ O3 + 2 Flyby Missions to 8 Objects
Option 6	O1 + O2 + O3 + 8 Orbiter Missions
Option 7	O1 + O2 + O3 + Orbiter~~s at a Fixed Threshold Probability of Impact~~

** Details of each option are found in a subsequent section of this report.*

Table 3. Impulsive Deflection/Mitigation Options

Impulsive Technique*	Description
Conventional Explosive (surface)	Detonate on impact
Conventional Explosive (subsurface)	Drive explosive device into PHO, detonate
Nuclear Explosive (standoff)	Detonate on flyby via proximity fuse
Nuclear Explosive (surface)	Impact, detonate via contact fuse
Nuclear Explosive (delayed)	Land on surface, detonate at optimal time
Nuclear Explosive (subsurface)	Drive explosive device into PHO, detonate
Kinetic Impact	High velocity impact

**A discussion of these techniques is found in a subsequent section of this report.*

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for Any Seriously Threatening PHO

Table 4. Slow Push Deflection/Mitigation Options

Slow Push Technique*	Description
Focused Solar	Use large mirror to focus solar energy on a spot, heat surface, "boil off" material
Pulsed Laser	Rendezvous, position spacecraft near PHO, focus laser on surface, material "boiled off" surface provides small force
Mass Driver	Rendezvous, land, attach, mine material, eject material from PHO at high velocity
Gravity Tractor	Rendezvous with PHO, fly in close proximity for extended period, gravitational attraction provides small force
Asteroid Tug	Rendezvous with PHO, attach to PHO, push
Enhanced Yarkovsky	Change albedo of a rotating PHO; radiation from sun-heated material will provide small force as body rotates

** A discussion of these techniques is found in a subsequent section of this report.*

Recommended Survey Program

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

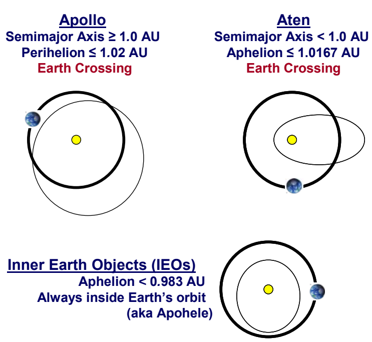
NASA recommends that the program continue as currently planned, and we will also take advantage of opportunities using potential dual-use telescopes and spacecraft—and partner with other agencies as feasible—to attempt to achieve the legislated goal within 15 years. However, due to current budget constraints,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

BACKGROUND

Asteroids and comets are the two types of potentially hazardous objects (PHO) discussed in this study. For objects in the inner solar system, astronomers can distinguish these bodies on the basis of their appearance. Moving objects that appear as a star-like point of light are known as asteroids. Moving objects that appear diffuse or those that have visible tails are known as comets. People have known about comets since antiquity. The existence of asteroids, however, was not known until about 200 years ago when telescopes became powerful enough to detect the largest such objects. It has taken several generations of improvements in telescope design to detect and understand the small bodies that orbit near Earth.

Differences in the appearance of comets and asteroids reflect in part a difference in their composition. Generally, asteroids are relatively rocky or metallic objects without atmospheres, while comets are composed in part of volatiles such as water ice that vaporizes when heated to produce a tenuous and transient atmosphere around the solid nucleus. Comets that are far from the Sun or those that have lost most of their volatiles can look like an asteroid. A volatile-rich object will develop an atmosphere only when heated sufficiently by a relatively close approach to the Sun.

The near-Earth asteroids are categorized as Apollos, Atens, Amors, and Interior Earth Objects (IEOs), depending on whether their orbits cross Earth's orbit with a period of more than one year, cross Earth's orbit with a period of less than one year, exist completely outside the Earth's orbit, or exist completely within the Earth's orbit, respectively. The distribution of these objects in the NEO population is shown in Figure 1.



Type	Near-Earth Population
Apollo	62% of known asteroids
Aten	6% of known asteroids
Amor	32% of known asteroids
IEO	6 known asteroids

Figure 1. Near Earth Asteroid Orbit Types

Near-Earth Objects (NEOs) are asteroids and comets in orbits that allow them to enter Earth's neighborhood, defined by astronomers as having a perihelion (closest approach to the Sun) of less than 1.3 AU (Astronomical Units, 1 AU is approximately 150 million km, the mean distance between the Sun and Earth). Extinct comets may make up 5-15 percent of the NEO population, and some may retain volatiles. As of December 4, 2006, using the Safeguard Survey system described elsewhere in this report, NASA has identified 701 NEOs greater than 1 km in size and 3,656 NEOs smaller than 1 km in size. Of the total number of NEOs surveyed, NASA has found only 63 comets. The estimated population of NEOs greater than 1 km in size is 1,100. The estimated population of NEOs greater than 140 meters in size is approximately 100,000 objects.

A constant power law as shown in Figure 2 can be used to estimate the number of NEOs of a particular size based on our available observations. The figure shows a hundred-fold increase in the number of NEOs as the size decreases by an order of magnitude. In terms of the goals expressed by the George E. Brown, Jr. Near-Earth Object Survey Act, NASA estimates that the population of NEOs greater than 140 meters is approximately 100,000 objects. Figure 2 also shows the approximate absolute magnitude (relative brightness) if the objects were placed at a standard distance of 1 AU from the observer, their average impact interval, and the approximate impact energy they would deliver in a collision with Earth. Given any size class of NEO, this estimate is probably accurate to within a factor of two or three, as there are not enough observations in some classes to form a statistically valid sample.

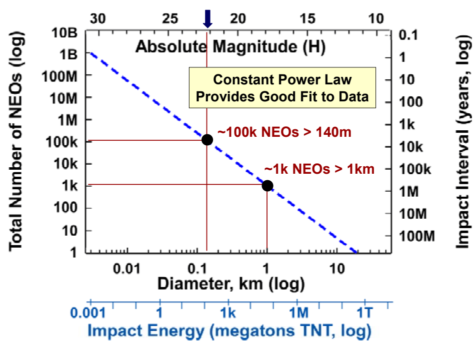


Figure 2. Frequency of NEOs by Size, Impact Energy, and Magnitude

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More relevant to this report is the definition of Potentially Hazardous Objects (PHOs), asteroids and comets that have a potential to eventually impact the Earth. A PHO is an object in our solar system that passes within 0.05 AU (about 7.5 million km) of Earth's orbit and is large enough to pass through Earth's atmosphere and cause significant damage on impact; that is, about 50 meters and larger. In this report the term PHO will be used to indicate potential threats, with the understanding that those smaller than 1 km are predominantly asteroids. Comets do not add substantially to the population below 1 km. Approximately 21 percent of the NEOs of any given size class are expected to be potentially hazardous.

In 2003, NASA chartered a Science Definition Team (SDT), which recommended an NEO survey program to produce a catalog that is 90 percent complete for PHOs larger than 140 meters. The SDT determined that impacts from objects that are 140 meters in size would only produce regional effects, while larger objects would have corresponding wider effects such as large sub-global effects from impacts of a 300-meter object and global effects from 1-kilometer object impacts. Impact of objects 10 kilometers and larger are considered an extinction-class event for Earth. A survey program that completes a 90 percent survey of 140 meter or larger PHOs would also identify virtually all of the global risk from objects greater than 1 kilometer. A survey system could be constructed to catalog hazardous objects down to the air blast limit (about 50 meters in size). However, the Science Definition Team suggested that cataloging down to 140 meters was the more prudent approach for the next-generation survey, a system which would also provide warning for 60-90 percent of objects capable of producing potentially dangerous air blasts. Essentially, the 140 meter object size is approximately where impacts transition from causing regional (e.g., a state or seaboard) to more localized (e.g. citywide) damage.

Since by this definition, objects that do not pass within 0.05 AU of Earth's orbit are not "*potentially hazardous,*" these objects are assessed (without necessity of discovery) to be no threat to Earth. Therefore, NASA recommends that the Survey's goal be modified to detect, track, catalogue, and characterize 90 percent of all PHOs greater than 140 meters by the end of 2020 rather than 90 percent of all NEOs of greater than 140 meters that pass within 1.3 AU of the Sun as expressed in the George E. Brown, Jr. Near-Earth Object Survey Act. Limiting the objects to only PHOs will reduce the required population to be surveyed and the Survey program will have a more realistic goal. However, the Survey will still provide equally effective "warning and mitigation of the hazard" and corresponds with the recommendations of the 2003 SDT report.

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STUDY APPROACH FOR NEO SURVEY PROGRAM

The PA&E study team expects that a survey system designed to detect NEOs down to 140 meters in size would discover a total of 500,000 objects (of which 400,000 would not be NEOs), to include Main Belt Asteroids, during the first five-ten years of the Survey in the course of more than two million individual observations. About 20,000 (or 20 percent) of the total estimated NEOs to be discovered will measure 140 meters or larger and be tracked as potentially hazardous. This volume of observations will require a data-processing capability that is 100 times more capable than the currently utilized cataloging system. After objects are detected, the system must be able to obtain follow-up observations, store and distribute collected data, and analyze these data for fortuitously observed but previously undetected objects. The current data management approach likely will not remain viable, and plans for the data-processing of this information must be carefully considered.

Detect and Track

Broadly, the options for the Survey Program to detect and track PHOs can be classified in three categories. Ground-based optical systems use large field of view sensors to scan the sky at night for PHOs. Space-based optical systems gather visible light from vantage points near the Earth or in Venus-like heliocentric orbits. Space-based infrared systems operate from similar vantage points, and use passively cooled infrared detectors to find and track objects. The advantages and drawbacks of each system are discussed in the following sections.

Ground-Based Optical Systems

Ground-based optical systems have several advantages over space-based systems. In general, ground-based systems are mostly based on mature technology and are relatively easy to maintain and upgrade because they are easily accessible. Consequently, these systems can be implemented using a phased approach and may take advantage of shared software. This typically means that ground systems cost less to build, verify, operate, maintain and upgrade than space-based counterparts.

Because ground-based optical systems peer through the Earth's atmosphere, drawbacks exist. Ground-based optical systems cannot operate during daylight or twilight and are subject to interference from weather, atmospheric turbulence, scattering from moonlight, and atmospheric attenuation. Significant atmospheric attenuation in the infrared-spectral region prevents these systems from determining accurate NEO sizes. These systems also will have difficulty finding objects in inner-Earth or Earth-like orbits. These objects will have fewer discovery opportunities from the ground because they are available only at the beginning and end of the night, when evening and morning twilight brightens the sky. Additionally, ground-based systems can have intangible programmatic issues related to access to the assets, as well as site and infrastructure maintenance.

Space-Based Optical Systems

Space-based optical systems rely on mature technologies with a broad foundation of existing mission heritage. Like ground-based systems, their advantages are primarily based on operating location. Space-based systems can access almost the entire sky at any given time with no interference from weather, daylight, moonlight, or atmospheric attenuation. Also, they can observe objects in inner-Earth or Earth-like orbits more easily than ground-based systems, especially if the detectors are located at the Sun-Earth Lagrange 1 stability point or in a Venus-like orbit.

Not only are space-based systems likely to be more expensive to develop than ground-based systems, space-based systems also have some additional risks. Getting a space-based system into place subjects it to possible launch and deployment failures and places it in an extreme environment that can result in a shorter lifetime (seven to ten years). This shorter lifetime is an important consideration if a NEO program is expected to continue to track objects for extended periods of time. In addition, they depend on spacecraft-to-ground data links and unique onboard software.

With the exception of technology maturity, space-based infrared systems have the same advantages as space-based optical systems. For infrared systems this technology is maturing rapidly. Space-based, passively-cooled mid-infrared systems also have additional advantages as these systems require smaller apertures than optical systems of equal detection efficiency and provide more accurate estimates of object sizes. The object size uncertainties are less than 50 percent compared with 230 percent for visual detectors. A two-band infrared system could potentially lower the size uncertainties to about 20 percent. These space-based infrared systems also are much less affected by the problem of source interference. There are about 100 times fewer infrared sources per square degree at an infrared wavelength of 8 microns compared with the number of visible sources at 0.5 microns. In addition, space-based infrared systems have lower downlink data rate requirements than space-based visible detector systems because the mid-infrared sensors would have fewer pixels (by a factor of 15) with longer exposures (also a factor of 15) so there would be ~200 times less data to downlink.

Characterization

The study team recognized that characterization of PHOs to inform the options for mitigation or deflection depended on several factors. One factor is the possible relationship between detection, tracking, and characterization elements. For example, if a ground-based survey system were to be built, its concept of operations will likely limit its ability to do follow-up characterization unless search goals are refined. If a space-based survey system (such as an infrared system in a Venus-like heliocentric orbit) is built, options for characterization include upgrading the system with certain optical filters, building a second dedicated space-based characterization system based on the design of the first, or building a dedicated ground-based system. If detection and tracking assets are available after search goals are reached, some survey systems could transition to characterization functions after detection operations are less operationally intense.

The most important factor in developing a characterization strategy is ~~to tie its requirements to a specific mitigation strategy or selected deflection options. For~~

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to understand that PHOs have a wide variety of poorly understood compositions and structures, rendering uncertain how a PHO might respond to physical interactions required to deflect it. All PHOs have very little gravity and some of them are expected to be "rubble piles" with essentially no strength. About 20% of PHOs are binaries or possess satellites. In determining what deflection option to use, we must ensure with a high level of confidence that the response of the PHO to a deflection maneuver not only results in it missing the Earth or a keyhole that would bring it back toward Earth, but also minimizes the risk that it would fragment or come apart in such a way that a sizeable fragment might strike the Earth or pass through a keyhole. The most thorough characterization would be required for any deflection option that would involve physical attachment to the body (e.g. space tug) or would impart a sudden acceleration to the body (impulsive options). Less characterization would be required for slow-push techniques and least for the Gravity Tractor, which interacts with the PHO as if it were a point-mass, without touching it.

example, if only standoff nuclear explosive alternatives are considered, little characterization beyond orbit and approximate mass of the object would be required. If a deflection approach such as a space tug becomes the deflection alternative of choice, more information on the PHO structure, composition, and kinematics would be required and a higher investment in characterization is warranted. Due to the diversity and volume of information required to support all possible mitigation alternatives, a robust program would be required to enable all deflection systems.

Two types of characterization information are necessary for mitigation, and that information is necessary for different phases of the mitigation problem. If developing a deflection option (or options) proceeds before an actual threat is identified, some understanding of the general population of targets would be necessary. For example, if the distribution of PHO sizes and composition are not well understood, it would be difficult to know if a deflection concept would perform sufficiently to eliminate most likely threats. Additionally, if concepts, such as the space tug, are chosen for development, knowing the statistical distribution of rotation rates is a key development parameter.

Second, some characterization is always needed on an actual threat once it is identified. For some alternatives, little characterization beyond mass and orbit will be required, although additional information may improve our ability to deflect such an object. Precursor missions, such as the recent Deep Impact mission or the proposed ESA Don Quixote mission, may be required to assure the successful design and implementation of a mission to divert a PHO.

Remote characterization of a PHO is useful for mitigation in two instances. The first is to provide information after a threat has been identified, but before a decision for an in-situ characterization mission would be made. The second is to provide the only available information to inform a deflection mission, particularly when insufficient time is available to first visit the PHO. As the survey catalogue reaches 90 percent completeness, the likelihood of a short warning scenario should be reduced to less than 1 percent of all warnings.

In the case of a short warning scenario, remote means must be developed to provide the required information. Models can be developed from remote observations of a large number of NEOs or from in-situ data. These models then may be used to predict the characteristics of subsequent threats as they are detected. This information may allow planners to begin designing a deflection mission without first launching an immediate in-situ mission.

The study team found that it is premature to set specific characterization requirements to enable deflection until a mitigation strategy has been determined. Therefore, the study team developed characterization options that provide a range of capabilities. These options included the use of detection and tracking assets, dedicated ground and space systems for remote observation, and in-situ missions to inform mitigation options for threats with sufficiently high impact probabilities.

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Fortunately, there already exists a good statistical sample of PHOs observed with telescopes for which information on size, shape, spin period, and approximate mineralogical composition is known. Several NEOs have had their properties further validated by spacecraft missions that have gone to them. What remains least known are the internal properties of NEOs.

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the most important

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in particular the Gravity Tractor,

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in the very unlikely case

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ANALYSIS OF ALTERNATIVES FOR NEO SURVEY PROGRAM

Detection and tracking alternatives identified by the study team as viable included optical observing systems located on the ground and optical and infrared assets located in space. For ground-based alternatives, the study team considered shared use of possible future observatories to conduct NEO surveys, such as the PanSTARRS 4 (PS4), and the Large Synoptic Survey Telescope (LSST). The study team assumed that NASA would enter partnership agreements with other government agencies regarding the shared use of those potential ground-based observatories.

The team also considered new NASA-funded facilities that would be dedicated to the search for potentially hazardous objects and would be based on the designs of these planned observatories. For this analysis, the study team assumed that any new NASA-funded ground-based observatory would be, in order to reduce development costs, a replica of either PS4 or LSST, and any new NASA-funded space-based asset would be an entirely new asset requiring full development. For the purposes of determining when the survey could be completed, acquisition of new systems was assumed to start October 1, 2007.

Ground options included:

- An architecture, which combines the sharing of the potential PS4 and LSST systems with a second dedicated NASA-funded LSST that potentially begins operations in 2015, was able to meet the goal of cataloging 90 percent of the potentially hazardous objects by 2020.
- A shared PS4, a shared LSST, and a dedicated NASA-funded PS8 that potentially begins operations in 2014 were able to catalog 90 percent of potentially hazardous objects by 2024. (PS8 is a system of two PS4 telescopes.)
- A dedicated, NASA-funded observatory based on LSST's design that potentially begins operations in 2015 was also able to catalog 90 percent of potentially hazardous objects by 2024 without the need to share the assets of the other programs.

Space-based search options included spacecraft located in low-Earth orbit, at Sun-Earth Lagrange stability points, and in heliocentric Venus-like orbits. Only an infrared system operating in a Venus-like orbit was able meet the goal specified for the NEO survey program without the contribution of shared ground-based assets. All space-based alternatives were able to meet the goals when combined with a shared PS4 and a shared LSST.

A space mission failure could delay achieving the 90 percent goal by six years (see Table 10), after which the catalog could still be completed with the shared ground-based assets. Infrared systems operating in space could provide more accurate size estimates of up to 80 percent of objects in the catalog. Observatories located in a Venus-like orbit are the most efficient at finding NEOs inside Earth's orbit, a population which has the most uncertainty yet still poses a hazard due to gravitational orbit perturbations. Additionally, by the end of 2020, infrared systems in Venus-like orbits could find 90 percent of the objects measuring down to 80 meters, exceeding the 140-meter requirement.

Selected space-based alternatives included:

- A 0.5-meter infrared system operating in a Venus-like heliocentric orbit that potentially begins operations in 2013 completes by itself 89 percent of the survey by 2020.
- The same 0.5-meter infrared system in a Venus-like orbit working in concert with a shared PS4 and a shared LSST completes 90 percent of the survey by 2017.
- A 0.5-meter infrared system operating at Sun-Earth L1 that potentially begins operations in 2013 working in concert with a shared PS4 and a shared LSST completes 91 percent of the survey by 2020.

Infrared systems with a 1.0-meter aperture complete the survey about one year earlier than the 0.5-meter alternatives described above. Optical systems with 1.0-meter and 2.0-meter apertures in Venus-like orbits, combined through partnerships with other government agencies on their potential PS4 and LSST ground-based systems, completed the survey by 2019 and 2018 respectively.

Detection and Tracking Survey Alternatives Considered

After an initial feasibility assessment of over three dozen concepts, Tables 5-7 list the detection, tracking, and data management alternatives that were considered viable for further analysis in this study.

Table 5. Description of Ground-based Survey Alternatives

Classification	Concept Name	Description
Visible - Ground	**Spaceguard**	Combined, existing ground-based detection efforts including LINEAR, NEAT, Catalina Sky, Spacewatch and LONEOS.
Visible - Ground	**Shared LSST**	Large Synoptic Survey Telescope (LSST) is a potential 8m telescope that could be operational in 2014 and would spend 75 percent of its time in survey mode.
Visible - Ground	**Shared PS4**	Potential four 1.8m Pan-STARRS telescopes searching same spot of the sky at a time with an effective aperture of 3.6m; they would spend 30 percent in survey mode.
Visible - Ground	**Dedicated LSST**	Potential rebuild of Shared LSST, dedicated to NEO search.
Visible - Ground	**Dedicated PS4**	Rebuild of Shared PS4, dedicated to NEO search.
Visible - Ground	**Dedicated PS8**	Potential system of two PS4 telescopes searching same area of the sky at a time with an effective aperture of 5.1m.
Visible - Ground	**Dedicated PS16**	Potential system of two PS8 telescopes (North and South of equator) searching differing sky regions at any given time, thus doubling the search area.
Radar - Ground	**Arecibo**	Arecibo Radio Telescope is an operational ground-based radio telescope with a 305m fixed dish.

		Continued support for Arecibo operations is being decreased by other government agencies.
Radar - Ground	**Goldstone**	Goldstone is an operational ground-based radio telescope with a 70m steerable dish. Similar or enhanced capability provided if Canberra 70m upgraded for radar by the Deep Space Network.
Radar - Ground	**Bistatic 100m**	Conceptual system composed of two 100m steerable radio antennas to be operated in a bistatic mode.

Table 6. Description of Space-based Survey Alternatives

Classification	Concept Name	Description
Visible - Space	**1m Vis Venus-like Orbit**	Concept for a space based 1m optical search telescope in Venus-like orbit (Heliocentric ~0.7AU from Sun).
Visible - Space	**2m Vis Venus-like Orbit**	Concept for a space based 2m optical search telescope in Venus-like orbit (Heliocentric ~0.7AU from Sun).
Infrared - Space	**0.5m IR L1/L2**	Concept for a space based 0.5m IR search telescope at Sun-Earth Lagrange point (L1/L2).
Infrared - Space	**1m IR L1/L2**	Concept for a space based 1m IR search telescope at Sun-Earth Lagrange point (L1/L2).
Infrared - Space	**0.5m IR Venus-like Orbit**	Concept for a space based 0.5m IR search telescope in Venus-like orbit (Heliocentric ~0.7AU from Sun).
Infrared - Space	**1m IR Venus-like Orbit**	Concept for a space based 1m IR search telescope in Venus-like orbit (Heliocentric ~0.7AU from Sun).

Table 7. Description of Data Management Alternatives

Classification	Concept Name	Description
Ops and Data Management	**Scale Existing Systems**	Expand existing Minor Planet Center (MPC) capability to support expected increases in NEO detection rates.
Ops and Data Management	**Adopt Other Systems**	Adopt system based on Futron's Space Launch & Satellite Database, Aerospace Corp.'s Space Systems Engineering Database or Analytical Graphics Inc.'s Satellite Database.
Ops and Data Management	**New Central Repository**	Proposed framework used by the US National Virtual Observatory (NVO).
Ops and Data Management	**Back-up Facility**	Grow the MPC capability as the detection rate grows using the NVO as a backup archive.

Survey Performance Simulation Results for Detection and Tracking

The results presented in this section are based on analyses where absolute performance is expected to be within 5 percent of the results shown, and within 1-2 percent for the best performing concepts. Study results are expected to have an internal relative uncertainty of 1-2 percent.

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Table 8 shows the analysis results for the performance of various ground-based optical survey options acting alone and assuming no new discoveries until the beginning of the survey program. For example, the first line of Table 8 shows that the currently operating ground-based Spaceguard observing program will catalog 14 percent of all PHOs with diameters larger than 140 meters (D > 140 m) by the end of 2020. This system would take decades beyond 2030 to achieve the goal of 90 percent completeness. On the second line of Table 8, note that the shared PS4 will reach 72 percent survey completeness for 140-meter size objects by the end of 2020. It will reach 69 percent completeness after operating for 10 years and 90 percent completeness after 2030.

Table 9 shows the analysis results for the performance of the space-based systems acting alone. The first line of Table 9 shows that a 0.5-meter IR telescope operating at the Sun-Earth L1 point could catalog 85 percent of the PHO population (D > 140 m) between 2013 and 2020, 88 percent after 10 years (2023) and 90 percent shortly thereafter.

Table 8. Ground-based Survey Performance

Survey Systems	Start	140 meter PHO Completion		
		by end of 2020	10 years	Year for 90%
Spaceguard	1998	14%	8%	>2030
PS4 (shared)	2010	72%	69%	>2030
PS4 (dedicated)	2013	72%	77%	>2030
PS8 (dedicated)	2014	74%	81%	>2030
PS16 (dedicated)	2014	77%	83%	2029
LSST (shared)	2014	75%	81%	>2030
LSST (dedicated)	2015	85%	90%	2024

Table 9. Space-based Survey Performance

Survey Systems*	Start	140 meter PHO Completion		
		by end of 2020*	10 years	Year 90%
0.5m IR @ L1	2013	85%	88%	2024
1.0m IR @ L1	2014	86%	91%	2022
0.5m IR in Venus-like	2013	89%	93%	2021
1.0m IR in Venus-like	2014	92%	95%	2020
1.0m VIS in Venus-like	2014	82%	88%	2025
2.0m VIS in Venus-like	2016	87%	94%	2022

Table 10 shows space-based alternatives used in conjunction with the reference architecture of shared ground-based systems. The fourth line of Table 10 shows that these systems could reach 91 percent by the end of 2020 provided the Spaceguard telescopes operate until the shared PS4 begins its potential operations in 2010, the shared LSST begins its potential operations in 2014, and the space-based 0.5m IR telescope at Sun-Earth L1 starts its potential operations in 2013.

Table 11 shows that the options that exceed the goals of the Survey program also provide other benefits. The middle column of the table shows that systems that operate in Venus-

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like orbits are more efficient at finding Aten and Interior Earth Objects, a potentially underrepresented population of PHOs. The final column of the table shows that for combinations of space-based visual and IR detectors, some systems will be able to estimate object sizes to better than 50 percent for more than 70 percent of the catalog by the end of 2020.

Table 10. Survey Performance of Combinations

Survey Systems*	140 meter PHO Completion	
	by end of 2020*	Year 90% complete
Shared PS4 + Shared LSST	83%	2026
Dedicated PS8 + Reference	85%	2024
Dedicated LSST + Reference	90%	2020
0.5m IR @ L1 + Reference	91%	2020
1.0m IR @ L1 + Reference	91%	2020
0.5m IR in Venus-like + Reference	97%	2017
1.0m IR in Venus-like + Reference	97%	2017
1.0m VIS in Venus-like + Reference	93%	2019
2.0m VIS in Venus-like + Reference	95%	2018

** Requirement is 90% by the end of 2020*
[+] Shared PS4 + Shared LSST = Reference

Table 11. Additional Benefits of Space Systems

Survey Systems	Diameter to 90%*	Size
0.5m IR @ L1 + Reference	125 m	77%
1.0m IR @ L1 + Reference	125 m	78%
1.0m IR in Venus-like	125 m	**
0.5m IR in Venus-like + Reference	90 m	-
1.0m IR in Venus-like + Reference	80 m	76%
1.0m VIS in Venus-like + Reference	125 m	78%
2.0m VIS in Venus-like + Reference	110 m	-

** Diameter of PHOs catalogued to 90% complete by end of 2020*
*** Not explicitly evaluated, likely 70-78%*

NASA uses the Spaceguard Survey system to find NEOs greater than 1 km in diameter. However, this system would not materially contribute to future searches because almost all objects it finds would be found much more quickly by one of the other next-generation space-based and/or ground-based systems. Assuming that a single system can cover the richest areas of the sky in one search period of approximately five days, the addition of another identical system generally adds very little benefit. Asteroids tend to cycle in and out of range of the detectors on timescales that would allow either of the two identical telescopes to "discover" a given NEO if it were observable at all. However, a second system may enable an improvement in the quality of the orbit prediction of a

NEO because the two systems acting together would enable more observations. This enhances the characterization of the NEOs.

Figure 3 shows the survey completion as a function of time for several individual and combinations of systems. The results for the PHO completeness percentages are estimated to be accurate to ±2 percent for results near 90 percent.

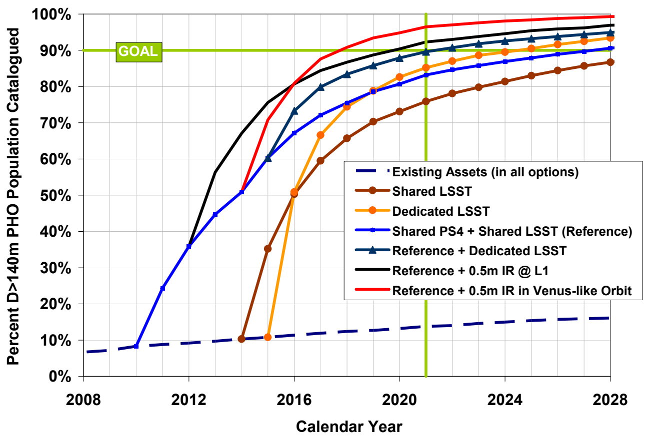

Figure 3. Survey Performance for Selected Alternative Systems

Characterization Alternatives Considered

The George E. Brown, Jr. Near-Earth Object Survey Act indicates two primary objectives for characterizing potentially hazardous objects. The first objective, to "*assess the threat,*" requires analysts to determine the orbit and approximate the mass of each PHO. Detection and tracking systems with judicious follow-up can warn of potential threats within the next 100 years, and some are able to provide very good size and mass estimates. Systems operating in the visible spectrum are limited by a factor of two for size estimates, resulting in a factor-of-eight uncertainty in mass. Infrared systems are much more accurate for determining size.

Radar may quickly and precisely characterize and determine the orbit of about 10-25 percent of the objects of interest within five years of their detection. While the number of objects observed by radar increases with time, the relative value of such observed objects dependent on radar to precisely determine the orbits of the full catalog declines over the same period. Orbits determined from optical data alone will nearly match the accuracy of radar-improved orbits after one to two decades of observation. Therefore, the utility of

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radar is limited to a relatively few "short warning" cases that may be of very high interest during the survey, and in such cases radar would be utilized if available during the first decade of the Survey.

The second objective of characterization is to "*inform mitigation.*" ~~Depending on the mitigation strategy selected, this objective may require~~ information beyond the size and orbit of PHOs. This information ~~may include the~~ structure, porosity, rotation rate, material composition, and surface features of the object. ~~The deflection alternatives considered are sensitive to the maximum mass that needs to be deflected, but some alternatives are orders of magnitude less sensitive than others.~~

Characterization by remote sensing provides some information about the diversity of objects in the population. From this information, analysts build models that can later be used to infer a limited number of characteristics of a particular object, but only in-situ encounters can provide the definitive observations necessary to calibrate the remote observations. More importantly, only in-situ visits can obtain the information needed by ~~some of the~~ deflection alternatives to mitigate a specific threat. For credible threats with sufficient warning, it is expected that in-situ characterization will always be performed to both confirm the probability of impact and to characterize the potential threat if deflection is necessary.

~~Without the selection of specific search and mitigation strategies, a specific choice of a characterization program is premature. Therefore, this~~ study analyzed a range of characterization capabilities listed in Table 12. For these options, Option 7 is similar to Option 6 in that it combines dedicated ground-based and space-based remote characterization with a number of in-situ orbiters. In Option 6, the chosen number of orbiters is eight~~, possibly one for each of the primary asteroid classes needed to calibrate remote characterization models. At least one representative of each asteroid type (which may actually number greater than eight) must be visited to contribute materially to the model verification purpose of in-situ visits.~~ In Option 7, the strategy is to send characterization missions to only credible threats.

~~For example, the Option 7 strategy may be to characterize the highest risk PHO discovered during each five-year interval. This approach, by sending a mission to a different PHO every five years, would over time visit enough representative asteroid types to validate characterization models. It would also provide in-situ orbital determination to verify or eliminate specific hazards at a routine and sustainable mission rate. However, the orbits of the targets for Option 7 are likely to be more difficult to reach than those that would likely be chosen for Option 6.~~

Table 12. Characterization Capability Options

Option	Descriptions (O1 = Option 1)
Option 1	Use Existing Assets + Detection and Tracking Systems
Option 2	O1 + Dedicated Ground Systems
Option 3	O1 + Dedicated Space-Based Remote Sensing (L1/L2)
Option 4	O1 + Dedicated Space-Based Remote Sensing (Venus-Like Orbit)
Option 5	O1+ O2+ O3 + 2 Flyby Missions to 8 Objects
Option 6	O1 + O2 + O3 + 8 Orbiter Missions
Option 7	O1 + O2 + O3 + Orbiters ~~for a Fixed Threshold Probability of Impact~~

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Any attempt to deflect a PHO requiring interaction with the body's surface will benefit greatly from

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includes the mass, shape,

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and spin axis

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, as well as presence and nature of any satellites.

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most

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safely and reliably

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for Any Seriously Threatening PHO

EXEMPLAR SURVEY PROGRAM

An exemplar NEO Survey Program, that at a minimum meets the goals specified in the George E. Brown Jr. Near-Earth Survey Act, is shown in Table 13. This program could achieve the specified goal of surveying 90 percent of the PHOs by the end of 2020 through NASA partnerships with other government agencies on potential future optical ground-based observatories: the Panoramic Survey Telescope and Rapid Response System (PanSTARRS-4 or PS4) and the LSST. Following at least one year of program formulation, NASA could build or fund the construction of a dedicated survey asset. For example, either an additional LSST, which may be operated by other organizations, or a 0.5 meter infrared (IR) satellite in a Venus-like orbit. Other options for the dedicated Survey asset would be evaluated during program formulation. All costs shown are anticipated costs to NASA.

Both the shared and dedicated assets would detect, track, and characterize NEOs. Analyses to date indicate that the estimated completion dates for development and estimated costs are sensitive to modeling errors that may vary up to three years. Note that these costs are rough 'architecture costs' that would need more rigorous analysis if a program were to be assessed for implementation.

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

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

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As this study was concluding, PS4 and LSST scientists submitted analyses demonstrating that the goal could be met 15 years after beginning in 2008 for a cost of about $150 million, superceding the analysis of the "Reference" survey shown in Table 13 [this is mis-labelled as Table 1 on pg. 19].

Table 1. Exemplar NEO Survey Program to Detect, Track, and Characterize

Exemplar Survey Program		Detect, Track, & Characterize: ≥140 meter PHOs		Total Architecture Costs* ($M) (thru the year to reach 90%)	
		Percent completed through 2020	Year to reach 90%	$FY06	$RY
Reference (Ground) Survey Assets (Shared PS-4 & Shared LSST)		83%	2026	**$469.0** (thru 2026)	**$693.5** (thru 2026)
Two of the Options for one additional, dedicated Survey Asset	***Reference plus*** a Dedicated LSST	90%	2020	**$835.5** (thru 2020)	**$1076.2** (thru 2020)
	Reference plus a Dedicated 0.5-meter IR in Venus-like orbit	97%	2017	**$1005.9** (thru 2017)	**$1239.9** (thru 2017)

** Total Architecture Costs include data management and program office costs.*

STUDY APPROACH AND ANALYSIS OF ALTERNATIVES FOR NEO DEFLECTION PROGRAM

The study considered a wide range of techniques to divert a threatening object. These alternatives were broadly classified as "impulsive" if they acted nearly instantaneously or "slow push" if they acted over an extended period of time. Launch, orbit transfer, technology development, and object characterization requirements were assessed for each of these alternatives. They were applied to a set of ~~five scenarios representing the likely range of threats.~~

A representative set of potential PHO deflection approaches was presented during a public workshop NASA held in the course of this study. This study examined a number of techniques for deflecting a PHO, and the methods considered viable have been categorized as either impulsive or slow push techniques. Table 14 provides an overview of the impulsive methods. Likewise, Table 15 shows the slow push techniques, where the velocity change results from the continuous application of a small force.

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six [or seven if you count A1 and A2 separately] scenarios representing the most challenging, though least likely, threats.

Table 14. Impulsive Mitigation Alternatives

Impulsive Technique	Description
Conventional Explosive (surface)	Detonate on impact
Conventional Explosive (subsurface)	Drive explosive device into PHO, detonate
Nuclear Explosive (standoff)	Detonate on flyby via proximity fuse
Nuclear Explosive (surface)	Impact, detonate via contact fuse
Nuclear Explosive (delayed)	Land on surface, detonate at optimal time
Nuclear Explosive (subsurface)	Drive explosive device into PHO, detonate
Kinetic Impact	High velocity impact

Table 15. Slow Push Mitigation Alternatives

Slow Push Technique	Description
Focused Solar	Use large mirror to focus solar energy on a spot, heat surface, "boil off" material
Pulsed Laser	Rendezvous, position spacecraft near PHO and focus laser on surface, material "boiled off" surface provides small force
Mass Driver	Rendezvous, land, attach, mine material and eject material from PHO at high velocity
Gravity Tractor	Rendezvous with PHO and fly in close proximity for extended period, gravitational attraction provides small force
Asteroid Tug	Rendezvous with PHO, attach to PHO, push
Enhanced Yarkovsky Effect	Change albedo of a rotating PHO; radiation from sun-heated material will provide small force as body rotates

In the impulsive category, the use of a nuclear device ~~was found to be the most effective~~ means to deflect a PHO. ~~Because of the large amount of energy delivered, nuclear devices would require the least amount of detailed information about the threatening object, reducing the need for detailed characterization.~~ While detonation of a nuclear device on or below the surface of a threatening object was found to be 10-100 times more efficient than detonating a nuclear device above the surface, the standoff detonation would be less likely to fragment the target. ~~A n~~uclear standoff ~~mission could be designed knowing only the orbit and approximate mass of the threat, and~~ missions could be carried out incrementally to reach the required amount of deflection. ~~Additional information about the object's mass and physical properties would perhaps increase the effectiveness, but likely would not be required to accomplish the goal.~~ It should be noted that because of restrictions found in Article IV of the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies*, use of a nuclear device would likely require prior international coordination. The study team also examined conventional explosives, but found they were ineffective against most threats.

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provides the most energetic

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Non-nuclear kinetic impact alternatives are the most effective non-nuclear option, transferring 10-100 times less momentum than nuclear options for a fixed launch mass. Impact velocities, varying from 10-50 km/s, produced a factor-of-three variation in deflection performance. In addition, kinetic impacts are also sensitive to the porosity, elasticity, and composition of the target and may require large performance margins if these characteristics are not well determined.

Slow push techniques analyzed in this study included a gravity tractor, which could alter the course of an object using the gravitational attraction of a massive spacecraft flying in close proximity, and a space tug, which could attach itself to a PHO and move it using high-efficiency propulsion systems. An attached space tug has generally 10-100 times more performance than the gravity tractor, but it requires more detailed characterization data and more robust guidance and control and surface attachment technologies. Slow push techniques were determined to be useful in relatively rare cases (fewer than 1 percent of expected threat scenarios). This technique could be effective in instances where small increments of velocity (less than 1 mm/s) could be applied to relatively small objects (less than 200 meters in diameter) over many decades. In general, the slow push systems were found to be at a very low technology readiness level and would require significant development efforts.

Deflection Performance Analysis

Figures 4 and 5 graphically represent deflection capabilities. The system performance required to deflect any object on a given trajectory may be described as the velocity change necessary to change its path multiplied by its mass. The "effective momentum change" performance parameter allows many different scenarios to be plotted simultaneously across a wide range of asteroid masses and required deflection velocities (ΔV). It is displayed logarithmically on the Y-axis of these figures. The logarithmic X-axis represents launch performance to place the deflection payload on an intercept trajectory. A key parameter that matches launch capability with a certain payload at a certain time (flight time) to intercept an asteroid is C3, which is equal to twice the specific (per unit mass) orbital energy and is represented in units of km^2/s^2. The launch C3 corresponding to payload capabilities of the two launch systems considered (Delta IV Heavy and Ares V) are at the top of each figure.

The lines to the right of each figure may be used to translate effective momentum change to the design parameters of PHO mass (and size) and deflection ΔV. Lines of constant object mass (and size) spaced logarithmically run diagonally across vertical lines representing a logarithmic range of deflection ΔV. As an example, following the diagonal line representing a mass of 10^{10} kg (approximately 200 m) to its extreme lower left at the vertical 1 cm/s ΔV line, this corresponds to an effective momentum change of 10^8 kg m/s on the far left.

The lines plotted represent the performance of the deflection alternatives. If an alternative has a higher effective momentum change capability than is required, it is considered "feasible" for a single-launch deflection. Therefore, using the previous example of an effective momentum change of 10^8 kg m/s and assuming that a Delta IV Heavy launch vehicle is used and that $C3 = 25\ km^2/s^2$ is required to intercept, all but the

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energetic

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All impulsive techniques are

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very large

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over long durations to cause a PHO to miss the Earth. The overwhelming majority of threatening PHOs (larger than the air blast limit of 50 m) that will be found by the detection systems evaluated in this study will be less than 100 m in size. While a gravity tractor might be useful for some cases involving the small PHOs, even a modest gravity tractor could deflect most PHOs from passing through keyholes that would result in an early return and Earth impact. Except for the gravity tractor, most

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; some are very costly.

10 km/sec kinetic interceptor and the conventional explosives would meet performance requirements. None of the slow push techniques could meet this hypothetical scenario.

Figure 4 shows that impulsive techniques using proximal nuclear explosives generally were found to provide greater potential for momentum transfer per kilogram of payload weight delivered to the threat than any other option considered. Standoff nuclear concepts, such as those producing highly concentrated and directionally focused x-rays or neutrons, were shown to present a generally lower risk of fragmenting a PHO than impulsive techniques involving direct contact, but also produce a lower effective momentum change than surface or subsurface nuclear explosives. Performance may vary significantly, depending on the type of nuclear device used and whether it is “off-the-shelf” as opposed to optimized for the PHO deflection mission. Additionally, the performance of kinetic impactors was found to be somewhat less robust than any of the nuclear explosions. However, their effectiveness depends strongly on the structure of the PHO. Kinetic impactors may also be significantly less effective for objects which are essentially loose rubble piles. Conventional explosives were found to have the lowest performance among the impulsive techniques due to their relatively low-energy density.

Figure 5 illustrates that slow push techniques may be useful for imparting momentum changes smaller than 10^9 kg m/s. The asteroid tug appears to have significantly greater performance than the gravity tractor for a given launch mass, even accounting for pulsed operation on a rotating PHO. The disadvantage of the asteroid tug is the additional complexity required to anchor the tug to the NEO, particularly if the PHO structure has not been well characterized or the target is rotating very rapidly.

These figures show that nuclear explosives and kinetic impactors were generally found to provide greater potential for momentum transfer per kilogram of payload weight delivered to the NEO than other alternatives. Additionally, these figures illustrate how the alternatives might be applied to hypothetical deflection scenarios. The inclusion of actual objects in these scenarios was chosen not because they represent actual impact threats, but because they are both publicly known and are ~~representative of~~ classes of potential threats.

The hypothetical scenarios include missions to deflect:

A. The 330-meter asteroid, Apophis, before its close approach to Earth in 2029. This scenario was divided into two design points:

  A1. For the first, knowing the asteroid’s orbit is assumed and a relatively large momentum change is required to deflect the object with the required certainty. Apophis must be deflected by at least one Earth radius or about 6,400 km to achieve a probability of collision of less than 10^{-6}.

  A2. For the second, very accurate information about the object’s orbit is assumed and the impetus necessary to divert the asteroid with certainty is substantially reduced. Apophis must be deflected by at least five km to achieve a probability of collision of less than 10^{-6}.

B. Apophis after the close approach and before the 2036 Earth encounter, assuming a predicted collision.

C. The 500-meter asteroid (VD17) that could be a threat in the year 2102.

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most challenging

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(this analysis does not consider VD17's passage through three keyholes during decades before possible impact; deflection prior to keyhole passage could reduce the required momentum by a factor of 1000 from what is presented in Figures 4 and 5)

D. A hypothetical 200-meter asteroid~~, representative of 100-meter class asteroids~~.

E. A hypothetical asteroid larger than one km in diameter.

F. A hypothetical long-period comet with a very short time (9-24 months) to impact.

The approximate performance requirements for each of the scenarios are overlaid on Figure 4 for the impulsive techniques and Figure 5 for the slow push methods.

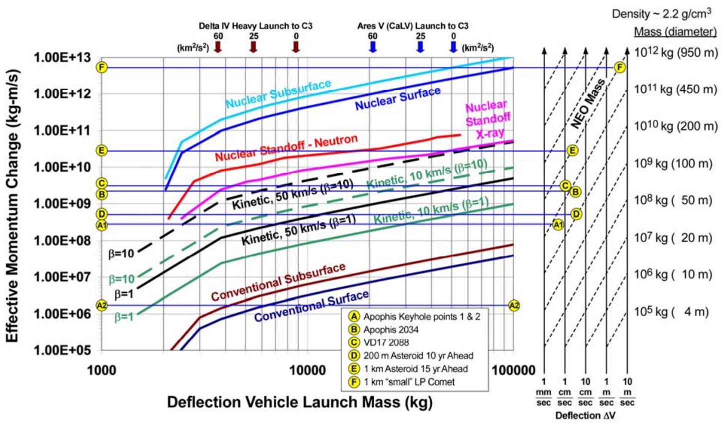

Figure 4. Deflection Performance of Impulsive Alternatives

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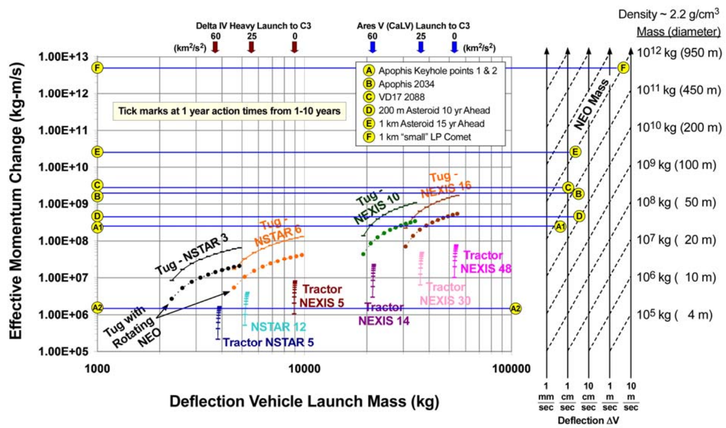

Figure 5. Deflection Performance of Slow Push Alternatives

POTENTIAL BENEFITS TO SCIENCE

NEOs are primitive bodies, primarily asteroids that probably represent almost the full range of material contained in the main asteroid belt of our solar system. The population also contains the nuclei of extinct comets, which likely still reflect the composition of all but the most volatile species and still contain a significant inventory of organic substances. The most recent National Academy of Sciences' Decadal Survey for solar system exploration summarizes the key science issues with respect to primitive bodies as follows:

- Where in the solar system are the primitive bodies found, and what range of sizes, compositions, and other physical characteristics do they represent?
- What processes led to the formation of these objects?
- Since their formation, what processes have altered the primitive bodies?
- How did primitive bodies make planets?
- How have they affected the planets since the epoch of formation?

Characterization will certainly provide new information on the sizes, compositions, and other physical characteristics of asteroids and comet nuclei. Information on the material of these objects will also provide data to understand alteration processes.

A wide area search, such as that being proposed for NEOs, will also substantially increase the identification of Kuiper Belt Objects (KBOs). For example, if 10 percent of

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the observing time on the proposed Dedicated LSST was spent in a KBO search mode, roughly 100,000 faint KBOs should be discovered. An expanded KBO database will allow the study of dynamical distributions, further resonances, the existence of a KBO demarcation beyond 50 AU, high-eccentricity/high-inclination orbits, size distributions, frequency of binary objects and collision rates, chemical compositions and the relationship of objects to dust disks around other stars. The survey will also provide a rich database of targets for future space missions.

Detection surveys such as the proposed Pan-STARRS and LSST provide unique solar-system science because they are designed to detect and perform follow-up studies of moving objects. Centaurs, Jupiter Family Comets, and certain extinct comets may be related through a common origin in the Kuiper Belt. Dedicated assets will assure that appropriate follow-up is carried out over the annual timeframes that are required to produce orbits for the slower-moving objects found in the outer solar system. Thus, a collateral result of the NEO survey program could be both the delineation of the structure of the Kuiper Belt and the discovery of many new minor planets.

It also is important to understand what a vigorous characterization effort will not do. Characterization to inform deflection missions has not identified a need for sample return from either an asteroid or comet. Asteroid and comet sample-return missions are high priorities in the Decadal Survey, but they are not included in the trade space of this study. However, a vigorous survey program would identify likely candidates for scientific visits for the sample return missions identified as a priority in the Decadal Survey. Remote characterization will allow the most interesting objects to be selected for further scientific investigation and will allow the instruments and experiments of these missions to be tailored in ways that otherwise would not have been considered. NEOs are generally among the easiest asteroids to visit, and the design of a spacecraft to work in the relatively benign environment near one AU offers less cost and risk than a mission to the main belt. A sample return mission to a NEO characterized for a deflection mission will carry substantially lower risk than a mission to an object about which much less is known.

POTENTIAL BENEFITS TO EXPLORATION

There may be future longer-term options for system-level demonstrations that could contribute to PHO deflection demonstrations. These systems, currently in development, have considerable mass, precision rendezvous and docking capability, as well as considerable performance margin.

Near-Earth Object Resources

The study team noted the connection between the goals of the Vision for Space Exploration and a program to survey the population of NEOs. Discovering and exploring resources that exist on NEOs may lead to future utilization.

Human Visits to Asteroids

The Vision for Exploration directed NASA to extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations. NEOs are one of those potential "other destinations." NASA is currently developing a new launch system, the Ares I and V launch vehicles, and a new crew exploration vehicle, the Orion. It is possible that the systems used to return humans to the Moon could be used to also visit a NEO.

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Appendix: Acronyms and Definition of Terms

Acronym	Description
AU	Astronomical Unit
D	Diameter
ESA	European Space Agency
FY	Fiscal Year
HQ	Headquarters
IEO	Interior Earth Object
IOC	Initial Operational Capability
IR	Infrared energy band
IRTF	InfraRed Telescope Facility
Isp	Specific Impulse
JPL	Jet Propulsion Laboratory
KBO	Kuiper Belt Objects
L1	First Sun-Earth Lagrange Point
LEO	Low-Earth Orbit
LINEAR	Lincoln Near Earth Asteroid Research
LONEOS	Lowell Observatory Near-Earth-Object Search
LSST	Large Synoptic Survey Telescope
MOID	Minimal Orbital Intersection Distance
MPC	Minor Planet Center
NASA	National Aeronautics and Space Administration
NEAT	Near-Earth Asteroid Tracking
NEO	Near-Earth Object
NVO	National Virtual Observatory
PA&E	Office of Program Analysis and Evaluation
Pan STARRS	Panoramic Survey Telescope & Rapid Response System
PHO	Potentially Hazardous Object
PS	Pan STARRS
Vis	Visible light band