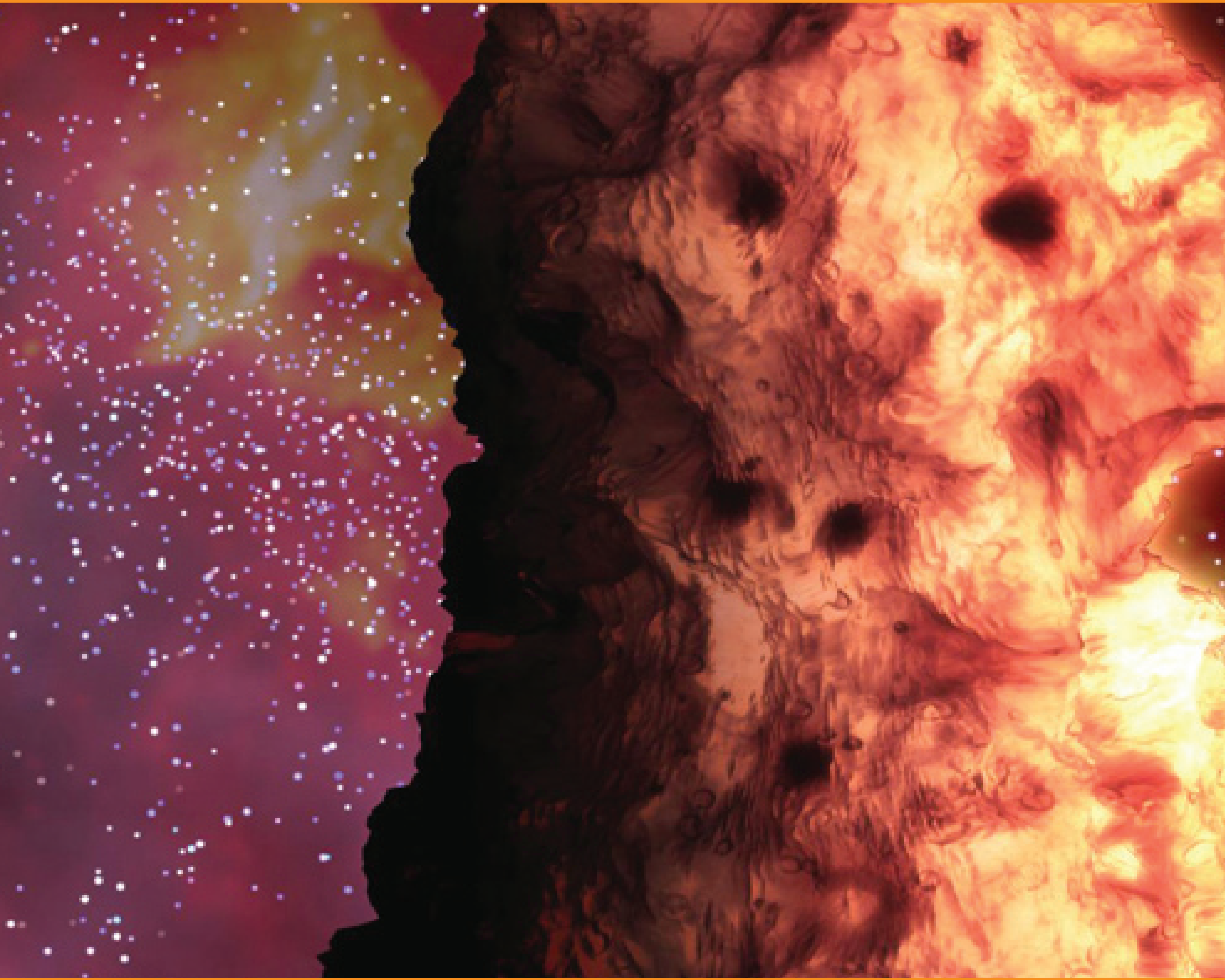
DRAFT Pre-Decisional Material

National Aeronautics and Space Administration

2006 Near-Earth Object Survey and Deflection Study



Final Report

*This is not the final report to Congress. It is available at
http://www.nasa.gov/pdf/171331main_NEO_report_march07.pdf
Please read the Context and Errata on Page 0-1 and 0-2 of this document for details.

December 2006

May 9, 2007

Context and Errata to the NEO Study Analysis Report

In the 2005 Budget Authorization Act, the U.S. Congress directed the NASA Administrator to provide an analysis of alternatives to detect, track, catalogue, and characterize potentially hazardous near-Earth objects (NEO). In addition, the legislation required the Administrator to submit an analysis of alternatives that NASA could employ to divert an object on a likely collision course with Earth. A study team derived requirements and figures of merit from the congressional direction, and used these factors to evaluate the alternatives. The team developed a range of options from public and private sources and then analyzed their capabilities, performance, life-cycle costs, schedules, and development and operations risks. This document collects the detailed results of those analyses and was prepared initially as a draft of the final report to Congress.

As the study progressed, it became clear that integrating the full extent of the analysis material with programmatic assessments would be ambitious. In October 2006, a decision was made to prepare a consolidated report to Congress,[1] and work on this document stopped. Therefore, this report is an incomplete draft, and some facts and dates related to the publication of the final report itself are incorrect. In December of 2006, NASA made the decision to distribute printed copies of this document to NASA senior management and to the study team to replace older drafts that had circulated.

Notes and Corrections

- References to the date and disposition of the final report to Congress are incorrect.
- This draft contains statements regarding planned assets of other agencies (NSF, USAF) that have not been coordinated with and do not represent the views of those agencies.
- The costs presented in this document are “architecture trade costs”, appropriate for comparison but not for budgeting.
- This document does not present programmatic options as required by Congress.
- This document contains significant examples where analyses representing different strategies and points of view are presented together. These differences are not necessarily reconciled into a comprehensive message in this document.
- This document refers to a “public workshop”, held in June 2006. This choice of nomenclature does not fully represent the structure of the meeting. Abstracts for presented papers were solicited from the public, but the meeting was by invitation only and contributors were not members of the study team.
- The “estimated total” of NEOs that may be discovered in Figure 5 should be 10-15% less. The scientific community changed the process for estimating the size of NEOs during the study, and the figure was not fully updated to match.
- The results in Section 6.17 and Figure 59 were generated using mixed assumptions for launch, orbit transfer, and threat size and the “order of magnitude” cost estimates may be incomplete. This figure will be modified if these analyses are republished.
- A close approach by Apophis is reported as 2022 on page 30, it should be 2021.
- The reference on page 50 should be to Dearborn [18] not Schweickart [17].

---

[1] NASA Near-Earth Object Survey and Deflection Analysis of Alternatives: Report to Congress. March 2007.

- The hypothetical threat Porthos has a diameter of 1 km rather than a radius of 1 km as reported in the middle of page 112.
- The study team intended to differentiate between the terms "*deflection alternative*", "*deflection campaign*", "*deflection strategy*", and "*mitigation strategy*". In its current state, the document does not consistently use these terms and meaning must sometimes be drawn from context. These terms are described here for additional clarity.
    - A ***deflection alternative*** is a technological solution for deflecting the path of a potentially threatening object. These alternatives are the primary focus subject of the congressionally directed analysis of alternatives. These alternatives along with tracking assets form a "toolkit" for deflecting specific threats.
    - A ***deflection campaign*** is the combination of (potentially) multiple missions using (perhaps) multiple deflection options to divert a potential threat. Deflection campaigns for specific threats may vary widely in the how the alternatives are combined into an effective system. Campaigns were not a primary subject of study.
    - A ***deflection strategy*** may include activities that take place when no threat is known (such as now) including development of technologies, characterization, or "waiting for a credible threat", and these strategies are not the subject of this document.
    - A ***mitigation strategy*** considers deflection options, costs, consequences, and other factors on how to respond to the general hazard of NEOs and under which circumstances to act. A mitigation strategy is formed considering the size-frequency curves, public will, available budget, cost-benefit, and many other factors. Mitigation strategies were not within the scope of this study.
- The frequency of resonant returns and keyholes, and how well keyhole events could be predicted was a source of significant discussion during the study. While the study team found that keyholes represent less than 1% of potential impacts, others have estimated their frequency to be considerably higher. This difference does not alter the study findings, but could affect the development of deflection or mitigation strategies.
- The deflection scenarios analyzed are expected to be representative of the range of potential threats. However, the scenarios were not intended to convey information regarding the predicted frequency of potential threats; this information is presented in Figure 2 and Table 1. Figures 37 and 38 may be used to evaluate the performance of the deflection options for the range of potential threat masses and deflection velocities (ΔV) required.
- While the VD17 orbit may intersect keyholes in the future, it was not treated as such for these analyses. Scenarios were not meant to comprehensively represent actual threat scenarios, and keyholes are represented by the analysis of Apophis. Keyhole cases may be further analyzed by using Figures 37 and 38 for specific deflection performance requirements.

,

2006 Near-Earth Object Survey and Deflection Study

December 28, 2006
NASA HQ, PA&E

For additional information, please contact the Office of Program Analysis and Evaluation (PA&E) at NASA Headquarters in Washington, D.C.

Table of Contents

List of Figures

List of Tables

1 Executive Summary

In the 2005 Budget Authorization Act, the U.S. Congress directed the NASA Administrator to provide an analysis of alternatives to detect, track, catalogue, and characterize potentially hazardous near-Earth objects (NEO). Congress required that the Administrator submit a program by December 28, 2006 to survey 90% of the potentially hazardous objects measuring at least 140 meters in diameter by the end of 2020. In addition, the legislation required the Administrator to submit an analysis of alternatives that NASA could employ to divert an object on a likely collision course with Earth.

A study team, led by the Office of Program Analysis and Evaluation (PA&E), derived requirements and figures of merit from the Act, and used these factors to evaluate the alternatives. The team developed a range of options from public and private sources and then analyzed their capabilities, levels of performance, life-cycle costs, schedules, and development and operations risks. This document presents the detailed results of these analyses. A summary report was submitted to Congress in December of 2006.

1.1. Survey Analysis of Alternatives

Detection and tracking alternatives identified by the study team included optical systems located on the ground and optical and infrared assets located in space. For ground-based alternatives, the study team considered sharing planned observatories such as PanSTARRS 4 (PS4), funded by the U.S. Air Force, and the Large Synoptic Survey Telescope (LSST), partially funded by the National Science Foundation. The team also considered new NASA-funded facilities that would be dedicated to the search for hazardous objects and would be based on these planned observatories. Although cost margin was applied to alternatives that leveraged planned assets, programs that rely on these projects may carry additional cost and schedule risk. Specific results include:

- An architecture, which combines the sharing of the planned PS4 and LSST systems with a second, dedicated NASA-funded LSST, was the only ground-based alternative able to meet the congressional goal of identifying 90% of the hazardous objects by 2020. This combination is estimated to have a life-cycle cost of $820M ($FY06).
- A shared PS4, a shared LSST, and a dedicated NASA-funded PS8 were able to catalog 90% of hazardous objects by 2024, with a life-cycle cost of $560M.
- A dedicated, NASA-funded observatory based on LSST’s design was also able to catalog 90% of potentially hazardous objects in 2024 without the contributions of other programs. Its estimated life-cycle cost is $870M.

Space-based search alternatives were located in low-Earth orbit, at Sun-Earth Lagrange points, and in heliocentric Venus-like orbits. Only an infrared system operating in a Venus-like orbit was able meet the congressional goals without the contribution of shared ground-based assets. All space-based alternatives were able to meet the goals when combined with a ground-based baseline of a shared PS4 and a shared LSST.

A space mission failure could delay achieving the 90% goal by up to 5 years, after which the catalog could be completed with shared ground-based assets. Infrared systems operating in space could provide more accurate size estimates of up to 80% of objects in the catalog. Observatories located in a Venus-like orbit are the most efficient at finding objects inside Earth's orbit, a potentially underestimated population. Additionally, by the end of 2020, infrared systems in Venus-like orbits can find 90% of the objects measuring over about 80 meters, exceeding the 140-meter requirement. Finally, space-based systems have much less uncertainty in the date of reaching 90% due to their superior sensitivity.

Selected space-based alternatives include:

- A 0.5-meter infrared system operating in a Venus-like heliocentric orbit completes 89% of the survey by 2020 which is within the uncertainty of the analysis. This system has a life-cycle cost of $840M ($FY06).
- A similar 0.5-meter infrared system operating in a Venus-like orbit and working in concert with a shared PS4 and a shared LSST completes 90% of the survey in 2018, with a life-cycle cost of $1B through 2018.
- A 0.5-meter infrared system operating at Sun-Earth L1 in conjunction with the baseline finishes 90% of the survey in 2020. Its life-cycle cost is $1.1B.

Infrared systems with a 1.0-meter aperture complete the survey about 1 year earlier than the 0.5-meter alternatives described above, and have life-cycle costs about $300M higher. Optical systems with 1.0-meter and 2.0-meter apertures in Venus-like orbits, combined with the baseline ground-based systems, completed the survey by 2017 and 2019 respectively, with life-cycle costs in excess of $1.7B. The visible system with a 2.0-meter aperture progressed more slowly than the 1.0-meter system due to differences in development time. Acquisition of new systems was assumed to start October 1, 2007, and delays in funding will affect the ability of some alternatives to meet the 90% completeness goal by the end of 2020.

Congress provided two 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 hazard. Detection and tracking systems with judicious follow-up are all able to provide warning, 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 provide data for much more accurate size estimates.

If detection systems must characterize the catalog, the time to complete the survey to a 90% completion level will be extended. Furthermore, the costs of these systems may increase $100M-$400M to accommodate filters and additional data processing. In addition, the smallest and faintest objects may remain visible to sensors only for a few days or weeks. Therefore, if characterization is required and it is not performed by detection systems, either formal relationships with extant observatories for "on demand" access must be negotiated or new dedicated characterization facilities will be needed.

Radar may quickly and precisely characterize and determine the orbit of about 10-25% of the objects of interest within 5 years of their detection. While the number of objects observed by radar increases with time, the relative value of 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 decades of observation. Therefore, the utility of radar is limited to a relatively few "short warning" cases that may be of very high interest during the survey. Up to $100M in funding (not included in detection and tracking life-cycle costs) may be required to maintain radar capability through 2020, as NASA and National Science Foundation funding for existing radars is currently in flux.

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 potential threats. This information may include the structure, porosity, rotation rate, material composition, and surface features of the threats. 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 be used to infer a limited number of characteristics of a particular object. 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 (with a transponder, for example) and to characterize the potential threat if deflection is necessary.

This study has determined that it is premature to set specific characterization requirements to enable mitigation until a mitigation strategy has been determined; therefore, the study has 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 of threats with sufficiently high impact probabilities. These options have life-cycle costs ranging from $50M-$8B ($FY06) over several decades.

It is expected that during the 5-10 years of a survey, a total of 500,000 objects will be discovered by more than 2 million individual observations. About 21,000 of these objects will measure 140 meters or larger and be tracked as potentially hazardous. Although this study uses an estimate of the population of potentially hazardous objects based on statistical projections, the actual number of objects will not affect the date of reaching the 90% goal as long as the objects are approximately distributed in orbits as predicted.

This volume of observations will require a data-processing capability that is 100 times more capable than current cataloguing systems. After objects are detected, the system must be able to obtain follow-up observations, store and distribute collected data, and analyze these data for observed but previously undetected objects. Currently, uncompensated or under-funded analysts perform many of these functions. Such an approach likely will not remain viable. Finally, either the NASA Survey or otherwise funded activities, such as PS4 and LSST, are expected to produce impact warnings at a rate that is 40 times greater than what is experienced today. This much higher rate of warnings will start as early as 2010.

1.2. Deflection Analysis of Alternatives

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 developed for each of these alternatives. They were applied to a set of five scenarios representing the likely range of threats over million-year timescales.

The use of nuclear explosives was found to be the most effective alternative in the near term. While an explosion on or below the surface of a threatening object is 10-100 times more effective than a detonation above the surface, the standoff detonation would be less likely to fragment the target. Nuclear options require the least amount of detailed information about the threatening object. A nuclear standoff mission could be designed knowing only the orbit and approximate mass of the threat, and most impulsive 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. The study examined conventional explosives, but found they were ineffective against most threats.

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 also are sensitive to the porosity, elasticity, and composition of the target and may require larger performance margins if these characteristics are not well determined.

Slow push techniques analyzed in this study included a gravity tractor, which would alter the course of an object using the gravitational attraction of a massive spacecraft, and a space tug, which would attach to an object 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% of expected threat scenarios), but these techniques 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.

The level of risk reduction required of a deflection campaign needs to be clearly understood, as it has a first-order impact on cost and complexity. While this report uses a goal of reducing the probability of impact to 1 in 1 million, this is not a nationally or internationally accepted threshold. Additionally, when designing the deflection campaign, planners must take into account that launch vehicles and interplanetary spacecraft fail at relatively high rates (2-5% for launches; 10+% for spacecraft) and that deflection approaches may not perform as designed. Planning for many flights of multiple spacecraft designs launched from several different launch vehicles may be necessary to achieve the reduction in impact probability projected to be required.

1.3. Summary of Findings

- Combining optical ground-based observatories currently under development with a dedicated ground-based asset can reach the congressional goal by the end of 2020. Life-cycle cost for this architecture, including a robust data-management and data-analysis infrastructure, is estimated to be $820M through 2020.
- Space-based infrared systems, combined with shared ground-based assets, could reduce the overall time to reach the 90% goal by up to 3 years, with life-cycle costs of $1.0-$1.3B through 90% completion. Space systems have additional benefits and risks over ground-based alternatives, and are generally more capable (sensitive) than 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 objects of potentially high interest. Existing radar systems are oversubscribed, and funding to operate these systems may be in flux. A budget for radar is not included in the detection and tracking life-cycle costs.
- Determining an object's mass and orbit are required to determine whether it represents a threat and to inform deflection alternatives. Beyond these parameters, characterization requirements and capabilities are tied directly to the mitigation strategy selected. Life-cycle costs for the characterization options vary by billions of dollars depending on the mitigation strategy pursued.
- While several countries have capable programs to study near-Earth objects, none of these efforts has materially influenced the results of the study team.
- Nuclear standoff explosions are assessed to be 10-100 times more effective than the non-nuclear alternatives analyzed in this study. Other techniques involving nuclear explosives may be more effective, but they run an increased risk of fracturing the target. They also carry higher development and operations risks.
- Kinetic impactors are the most mature approach and could be used in some scenarios, especially for objects that consist of a relatively small, solid body.
- Slow push deflection techniques are the most expensive, and their ability to both travel to and divert a threatening object is limited unless mission durations of many decades are available.
- Deflection campaigns may need to be 100-1,000 times more reliable than current space missions to meet mitigation requirements.
- Many potentially hazardous objects (30-80%) are in orbits that are beyond the capability of current or planned launch systems. Therefore, if these objects need to be deflected, swingby trajectories or on-orbit assembly of modular propulsion systems may be required to augment launch vehicle performance.

1.4. Summary of Program Options

The figure below shows a decision tree for selected strategy options for both parts of this study. In Step 1, a detection and tracking architecture is selected. Ground-based, space-based, and combinations of ground- and space-based systems can meet the congressional goal of detecting 90% of potentially hazardous objects 140 meters and larger by 2020. In Step 2, it is expected that search systems can provide a portion of the orbit and mass characterization required to assess the threat, but options for enhancing this capability including radar are presented. In Step 3, mitigation strategy options (including perhaps deflection demonstrations) are chosen informing the choice of further characterization in Step 4 (if required).

1. Select Detection and Tracking Architecture

other similar options exist

Option FY06 $	through 2020	LCC thru 2020*	Year 90%	LCC to 90%*
Shared ground-based (Baseline)*	83%	$0.31B	2026	$0.52B
Dedicated ground-based	85%	$0.66B	2024	$0.87B
Dedicated ground-based + Baseline	90%	$0.82B	2020	$0.82B
Infrared in Venus-like orbit	89%	$0.84B	2021	$0.86B
Infrared @ L1 + Baseline	91%	$1.1B	2020	$1.1B
Infrared in Venus-like orbit + Baseline	97%	$1.1B	2018	$1.0B

~$150M cataloguing costs in all options

1-2% uncertainty in relative performance

2. Add Orbit and Mass Characterization

Options FY06 $	LCC thru 2020*
Use search systems	$0B
Augment search systems	$100M-$400M
Dedicated ground	$100-$300M
Dedicated space	$1-$1.5B
Radar for some threats	< $100M

3. Develop a Mitigation Strategy

Options FY06 $	LCC thru 2020
No dedicated preparation	$0+
Coordinate deflection technologies w/ ESMD	$0+
Cooperate with international efforts	$50M+
Perform deflection demonstration (by 2014)	$100M+
Develop nuclear explosives technologies	?

4. Develop Characterization Further if Needed for the Mitigation Strategy ($0-$8B)

** LCC = Life-cycle cost*

2 Participants

2.1. *Study Leadership*

- Bill Claybaugh, Study Lead – NASA/HQ/PA&E
- Dan Mulville, Study Coordinator – NASA (ret)
- Marcus Shaw, Study Executive – The Aerospace Corporation/PA&E
- Lindley Johnson, NEO Observation Program Manager
- Ed Barker, Detection Lead – NASA/JSC
- Don Yeomans, Detection Co-Lead – NASA/JPL
- Tom Morgan, Characterization Lead – NASA/HQ/SMD
- Rob Gold, Characterization Co-Lead – APL/JHU
- Vern Weyers, Deflection Co-Lead – NASA (ret)
- Larry Ross, Deflection Co-Lead – NASA (ret)

2.2. *Study Team*

- Members of the 2006 NEO study working groups provided significant technical input, technical direction, and review of the study results, see Appendix B for the full study team, schedule, and structure

2.3. *Analyses*

- The JPL NEO Program Office (Steve Chesley and Paul Chodas) performed survey performance, precision orbit determination performance, and warning prediction analyses.
- David Bearden and Matt Hart, of The Aerospace Corporation, led concept development, deflection performance, and cost, risk, and schedule analyses.

2.4. *Acknowledgements*

- Survey performance model validation was performed using results from MIT/Lincoln Labs and led by Grant Stokes
- Additional technical analyses and an independent technical review were performed by NASA LaRC and led by Dan Mazanek
- Members of the June 2006 NEO Public Workshop held in Vail, Colorado provided significant technical content and many detection, characterization, and deflection concepts (See Appendix D)
- The NEO Survey Science Definition Team Report provided the foundation for this study (See Section 4.5)
- A Red Team composed of Jay Greene (NASA, retired), General Lester Lyles (USAF, retired), Dr. Lucy McFadden (University of Maryland), and Liam Sarsfield, and provided independent review of the study structure, derived requirements, study results, and this final report.

3 Introduction and Overview

3.1. Purpose

The Administrator of the National Aeronautics and Space Administration (NASA) submits this report pursuant to the requirements stated in the George E. Brown Jr. Near-Earth Object Survey Act ("the NEO Survey Act"), which Congress passed as part of Public Law No: 109-155: the 2006 NASA Authorization Act of 2005 documented in Appendix A and Reference [1].

In this Act, the Congress directed that the NASA Administrator initiate a Near-Earth Object (NEO) Survey program to detect, track, catalogue, and characterize objects larger than 140 meters in diameter, with a perihelion distance of less than 1.3 AU (Astronomical Units) from the Earth. The Survey would warn of and inform attempts to mitigate the hazard. The Survey is to be 90% complete within 15 years after the date of enactment.

3.2. Statement of Need

In the NEO Survey Act, Congress made the following findings:

- *Near-Earth objects pose a serious and credible threat to humankind, as many scientists believe that a major asteroid or comet was responsible for the mass extinction of the majority of the Earth's species, including the dinosaurs, nearly 65,000,000 years ago.*
- *Similar objects have struck the Earth or passed through the Earth's atmosphere several times in the Earth's history and pose a similar threat in the future.*
- *Several such near-Earth objects have only been discovered within days of the objects' closest approach to Earth, and recent discoveries of such large objects indicate that many large near-Earth objects remain undiscovered.*
- *The efforts taken to date by NASA for detecting and characterizing the hazards of near-Earth objects are not sufficient to fully determine the threat posed by such objects to cause widespread destruction and loss of life.*

3.3. Direction

The NEO Survey Act [Appendix A] amended the Space Act of 1958 such that

> *The Congress declares that the general welfare and security of the United States require that the unique competence of the National Aeronautics and Space Administration be directed to detecting, tracking, cataloguing, and characterizing near-Earth asteroids and comets to provide warning and mitigation of the potential hazard of such near-Earth objects to the Earth.*

In addition, it states

> *The Administrator shall 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 to assess the threat of such near-Earth objects to the Earth. It shall be the goal of the Survey program to achieve 90 percent completion 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 Congress has directed the NASA Administrator to deliver the following by one year from the law's enactment:

> *(1) An analysis of possible alternatives that NASA may employ to carry out the Survey program, including ground-based and space-based alternatives with technical descriptions.*
>
> *(2) A recommended option and proposed budget to carry out the Survey program pursuant to the recommended option.*
>
> *(3) Analysis of possible alternatives that NASA could employ to divert an object on a likely collision course with Earth.*

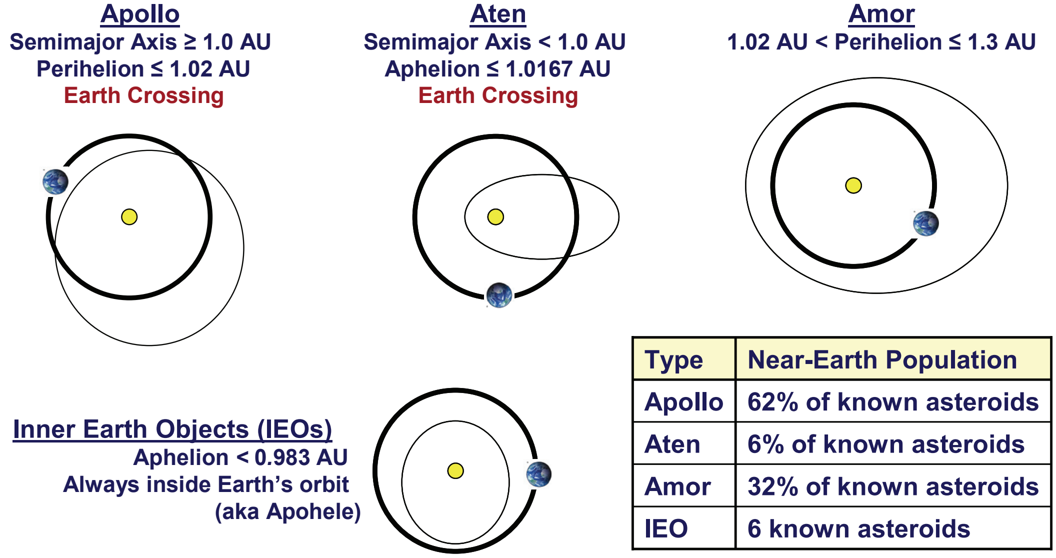
4 Background

4.1. *Asteroids and Comets*

Asteroids and comets are the two types of potentially hazardous objects discussed in this study. Astronomers distinguish these bodies on the basis of their appearance. Moving objects that appear as a star-like point of light are known as asteroids. The existence of asteroids was not known until about 200 years ago when telescopes became powerful enough to detect them. Moving objects that appear diffuse or those that have visible tails are known as comets, and because of their distinctive tails, people have known about comets since antiquity. It has taken several generations of improvements in telescope design to detect and understand the small bodies that orbit near and periodically collide with Earth.

Differences in their appearance 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 vaporize when heated. Comets that are far from the Sun or those that have lost most of their volatiles often 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 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 1 year, cross Earth's orbit with a period of less than 1 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. 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 or approximately the mean distance between the Sun and Earth). Extinct comets may make up 5-15% of the NEO population, and some may retain volatiles. [2]

More relevant to this report is the definition of Potentially Hazardous Objects (PHOs), asteroids and comets that have a potential to someday 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; that is, about 50 meters and larger. Approximately 21% of the NEOs of any given size class are expected to be potentially hazardous.

4.2. Population of Near-Earth Objects

A constant power law shown in Figure 2 can approximate the number of NEOs of a particular size. The figure shows a hundred-fold increase in the number of NEOs as the diameter decreases by an order of magnitude. Figure 2 also shows the approximate absolute magnitude (brightness) of the objects, their average impact interval, and the approximate impact energy they would deliver in a collision with Earth. [2] In any given size class, 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. 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, because comets do not add substantially to the population below 1 km.

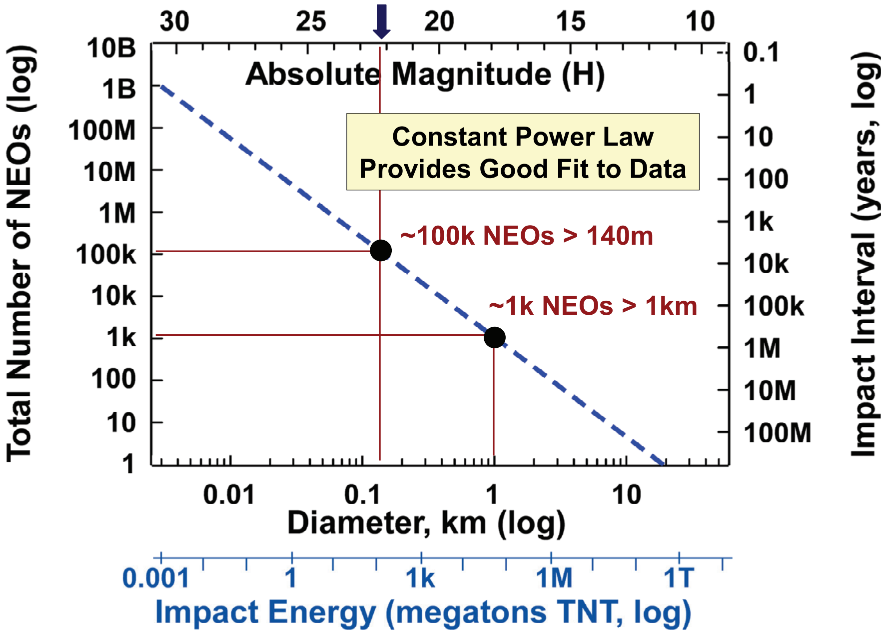


Figure 2. Frequency of NEOs by Size, Impact Energy, and Magnitude

The history of the known asteroid population is one of exponential growth. Astronomer Guiseppe Piazzi of Palermo, Sicily, discovered the first asteroid on January 1, 1801. Early asteroid discoveries usually occurred by chance while astronomers observed or searched for other objects. The number of new finds increased to five per year by 1865, 15 per year by 1895, 25 by 1910 and up to about 40 by 1930. By 2006, the number of known asteroids was about 340,000 including about 800 PHOs.

Figure 3 composed of images created by the staff of the Amragh Observatory shows a graphical history of asteroid discoveries. For many years, it was assumed that asteroids that crossed Earth's path do not exist because none had been observed. It remains to be determined if the number found inside the Earth's orbit is greater than or less the number than that expected because current observational methods are unable to reliably detect objects there. Red dots represent asteroids that cross the Earth's path, while those represented by green dots do not. Note that these dots are not to scale and the colors are intended only to give a visual cue to the pace of discovery.

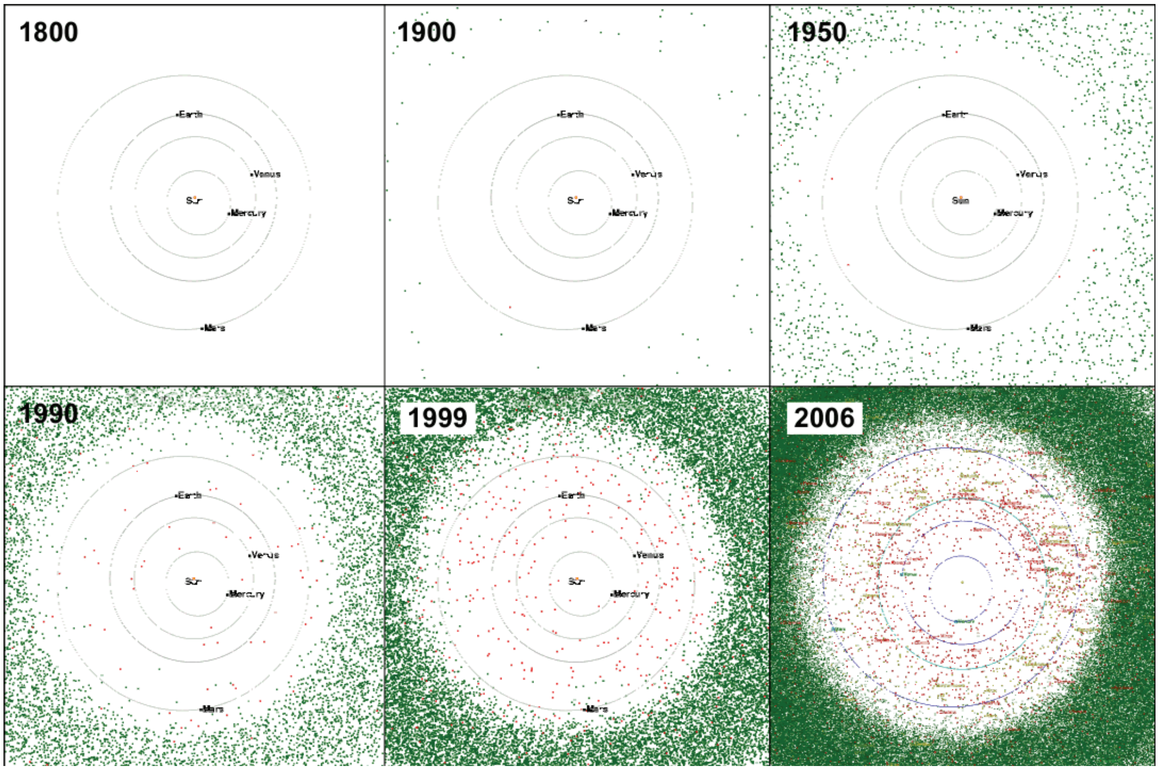


Figure 3. History of Asteroid Discoveries

Assuming comets have an enhanced signature when they come within 1.3 AU of the Sun, the majority of short-period comets probably have been found. The Spaceguard Survey has found two or three short-period comets in the last several years (see Section 4.4). Comets with orbital periods longer than 20 years only will be found when their perihelion (closest approach to the Sun) brings them close enough for their volatiles to vaporize and produce the distinctive tail. The total number of near-Earth comets is unknown, but it is estimated to be smaller than 1% of the population of near-Earth asteroids.

To estimate the performance of the detection and tracking alternatives, a synthetic population of asteroids and comets was used. This population is based on the best available estimate of the orbital distribution of objects. This study used an estimate of the NEO population developed by Bottke, et al [4], as did the Science Definition Team [2] report discussed in Section 4.5. Although the synthetic population selected for analysis may vary by as much as a factor of two, the actual number of objects will not affect the date of reaching the 90% goal as long as the objects are approximately distributed in orbits as predicted. Sensitivity to variations in the statistical population or orbital distribution of objects was not performed.

The Minimal Orbital Intersection Distance (MOID) is defined as the closest possible distance between the orbits of two objects. Assuming random values for the argument of perihelion and the longitude of node, about 20% of NEOs (about 20,000 of 100,000 NEOs ≥ 140 meters) have an Earth (MOID) smaller than 0.05 AU and, therefore, are PHOs. About 1% of the NEOs have a MOID smaller than the Moon's distance from the Earth, and the probability of having a MOID smaller than the Earth's radius is about 0.025%. This result does not imply that a collision with Earth is imminent because both the Earth and the object still must be at the same location at the same time. See Figure 2 for the frequency of impacts by size.

The Aten asteroids spend most of their time inside Earth's orbit. Currently, they account for about 6% of observed near-Earth asteroids and 13% of the Earth-crossing ones. However, observational biases may play against their discovery; thus they may be underestimated. Another potentially under-observed population of asteroids, called IEO (interior Earth objects), could exist and evolve almost entirely inside Earth's orbit, but still present a hazard. [5] These objects can be readily discovered only from orbits well inside the Earth's orbit. Only observations from vantage points inside Earth's orbit will determine if their number is accurately represented in current population estimates.

4.3. The Probability of Impact and Distribution of Sizes

The chance that an object 140 meters or larger will strike the Earth in any given year is about 0.0002 (about 1 every 5,000 years on average). The random nature of the hazard means that it is equally probable that a 140-meter object will hit the Earth in the next 50 years (~1%) or that the Earth will experience no impacts of that size in the next 23,000 years ($0.9998^{23,000} \sim 1\%$). The occurrence or absence of past events has no influence on the likelihood of future impacts.

Table 1 developed from Reference [11] reproduces a set of estimated impact frequencies and consequences for a range of PHO diameters.

Table 1. Impact Frequencies and Typical Consequences

Type of Event	Diameter of Object	Fatalities per Impact	Typical Impact Interval (years)
High altitude break-up	< 50 m	~0	annual
Tunguska-like event	> 50 m	~5,000	250 - 500
Regional event	> 140 m	~50,000	5,000
Large sub-global event	> 300 m	~500,000	25,000
Low global effect	> 600 m	> 5 M	70,000
Nominal global effect	> 1 km	> 1 B	1 million
High global effect	> 5 km	> 2 B	6 million
Extinction-class Event	> 10 km	6 B	100 million

Figure 4 projects the frequency of impacts by object size for two populations of hazards, those larger than 50 meters and those larger than 140 meters. The plot shows the percentage of impacts smaller than the corresponding diameter on the X-axis. For all threats (larger than 50 meters), there is about a 70% chance that an impacting object will be smaller than 100 meters in diameter and a 95% chance that the object will be smaller than 200 meters in diameter. These data show that threats are much more likely to be relatively small.

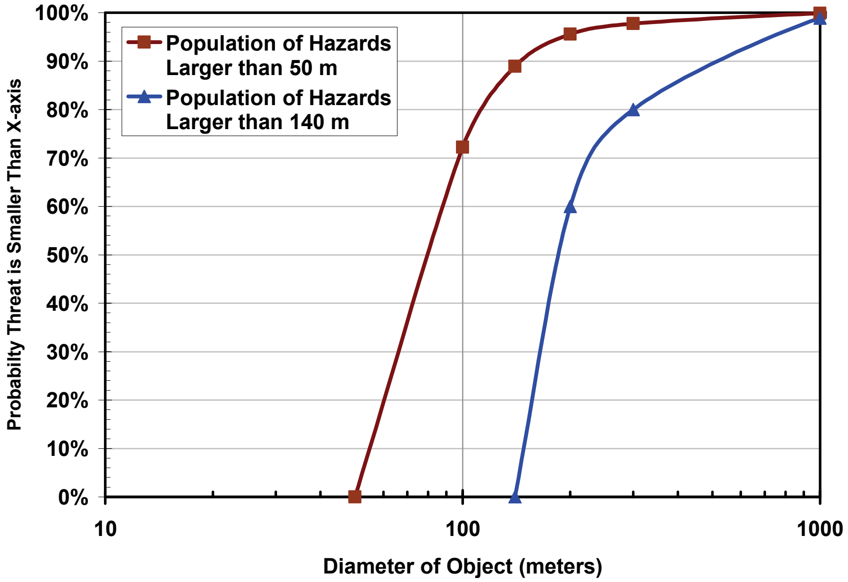


Figure 4. Frequency of Threats by Object Size and Population

Additionally, if the congressionally mandated survey detected nearly 100% of the objects measuring 140 meters and larger, the figure projects the size distribution of identified impact threats in that population. This information, in conjunction with the object's orbit, launch capability, and deflection performance, may be used as an initial filter to determine the percentage of threats that an alternative will be effective at mitigating. Rotation rate, binarity, composition, porosity, and companion objects will further narrow deflection options.

4.4. NASA Spaceguard Survey

In a 1992 report to NASA [6], a team led by David Morrison recommended that a coordinated Spaceguard Survey be initiated to discover, verify, and provide follow-up observations of Earth-crossing asteroids. This survey was expected to discover within 25 years 90% of the objects that measured more than 1 km in diameter. Three years later, another NASA study led by Eugene Shoemaker [7], recommended a search to discover 60-70% of the same size objects within 10 years. The team set a goal of obtaining 90% completeness within another 5 years.

In 1998, NASA formally accepted the goal of finding and cataloging 90% of all NEOs with sizes of 1 km or larger by 2008. This size was chosen after a study indicated that the impact of an object larger than 1 km could cause a global catastrophe [6], whereas smaller objects would likely to have local or regional consequences. The estimated population of NEOs measuring 1 km and larger is about 1,100.

The Near-Earth Object Observation (NEOO) Program, coordinated by NASA's Jet Propulsion Laboratory (JPL) in Pasadena, CA, manages NASA-sponsored efforts to detect, track, and characterize potentially hazardous asteroids and comets that approach the Earth. The progress of the survey to date is depicted in Figure 5. In addition to detecting and cataloging of NEOs, the NEOO Program is responsible for facilitating communications between the astronomical community and the public as potentially hazardous objects are discovered.

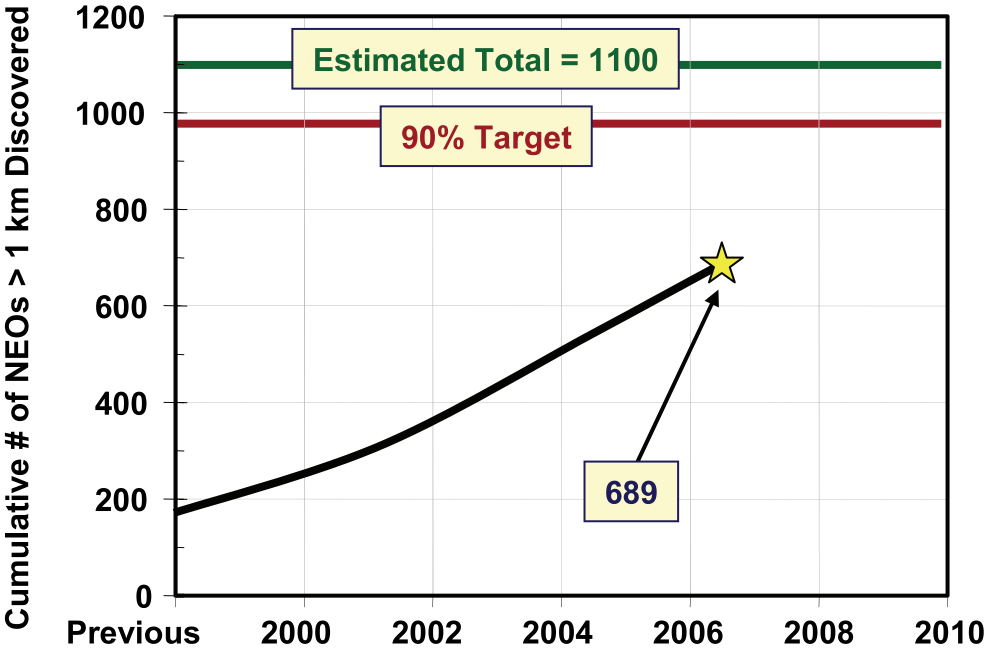


Figure 5. Spaceguard Survey Status as of 10/1/06

While current NEO surveys are dedicated to finding the largest objects, they also serendipitously find many that are sub-km in size. However, the current survey systems are not capable of performing a comprehensive search for the smaller objects as specified by the current congressional direction and recommended by the Science Definition Team.

4.5. Small Near-Earth Object Survey Science Definition Team Report

In August 2002, NASA chartered a Science Definition Team (SDT) to study the feasibility of extending the search for objects with smaller diameters. [2] The SDT report addressed the following topics:

Search size limit - The team recommended that a survey produce a catalog that is 90% complete for PHOs larger than 140 meters. Figure 6 shows the rationale for selecting 90% of objects larger than 140 meters – this fraction is calculated to eliminate 90% of the remaining sub-global risk while retiring virtually all of the global risk from objects greater than 1 km. A search system could be constructed to catalog hazardous objects down to the air blast limit (about 50 meters in diameter). However, the team suggested that cataloging down to 140 meters was the preferred approach for the next-generation survey, which also would provide warning for 60-90% of objects capable of producing potentially dangerous air blasts.

Comets - The frequency with which long-period comets closely approach the Earth is roughly one-hundredth the frequency of asteroids. This is a relatively small risk, and therefore should not be included in the goals of the next survey.

Technical feasibility and schedule - The resources made available to the effort would drive the survey; technology would not. The survey could be completed in 7-20 years.

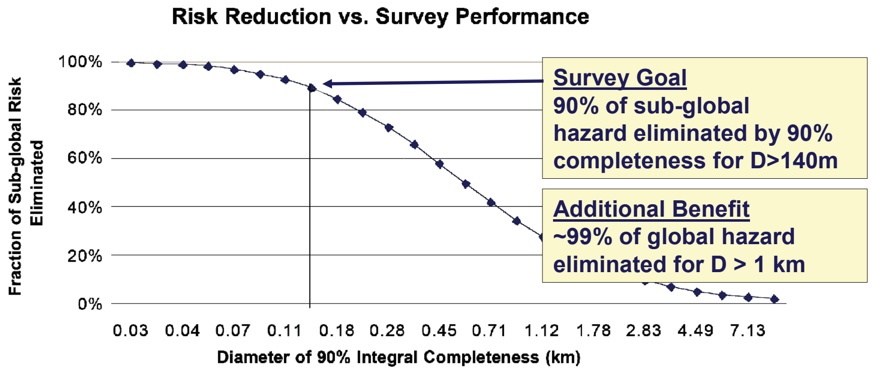


Figure 6. SDT Goal of 90% of Objects Larger than 140 meters

Survey Alternatives - The team identified a series of specific ground-based, space-based and combinations of ground- and space-based systems that could accomplish the next-generation search. The team indicated that the choice of specific systems would depend on the time allowed for the search and the resources available.

Cost - The SDT estimated that the survey systems required to eliminate 90% of the risk for sub-km NEOs would cost between \$236-\$397 million (\$FY2003) if accomplished within 20 years.

5 Survey Program Analysis of Alternatives

5.1. *Introduction*

In the NEO Survey Act, the U.S. Congress directed that NASA perform an analysis of alternatives and propose a NEO Survey Program to detect, track, catalogue, and characterize 90% of potentially hazardous objects 140 meters and larger by the end of 2020. This chapter provides an analysis of alternatives that may be used to support program decisions. The descriptions required by the Act may be found in Appendix E.

5.2. *Derived Requirements and Definitions*

Several requirements were explicit in the definition of this study. For example, Congress explicitly directed that the Survey catalogue 90% of NEOs whose diameters exceeded 140 meters by the end of 2020. Derived requirements are levels of performance, cost, schedule, or risk that are inferred or derived from explicit requirements. These include more specific technical definitions of detection, cataloguing, and characterization as well as the synthetic set of NEOs used for statistical analyses of completeness. The derived requirements drawn from the congressional language are as follows.

5.2.1. Survey Goal

Since, by definition, objects that do not pass within 0.05 AU of the Earth are not "*potentially hazardous,*" these objects are assessed (without necessity of discovery) to be no threat to Earth. Therefore, the Survey's goal will be to detect, track, catalogue, and characterize 90% of all PHOs greater or equal to 140 meters by the end of 2020, rather than 90% of all NEOs as described by the congressional language. This will amount to finding at least 18,000 of and expected 20,000 PHOs ≥ 140 meters.

Limiting the objects to only PHOs will require the Survey to find fewer objects. PHOs are brighter (on average) than NEOs because they pass closer to the Earth (by definition). Since the subset of NEOs that are PHOs are easier to find, the time to meet the goal will be reduced. However, finding 90% of PHOs will provide equally effective "*warning and mitigation of the hazard.*"

5.2.2. Detect, Track, Catalogue, and Characterize

Congressional direction uses the terms detection, tracking, cataloguing, and characterization without specifically defining them. These terms are defined to mean:

- *Detect* – Discovery of objects greater than 140 meters in diameter
- *Track* – Observing an object twice within 1 week, generally resulting in initial orbit determination and ephemeris generation
- *Catalogue* – Generating full and precise orbit determination including precovery (see Section 5.10.2) and follow-up observations. Cataloguing includes calculating uncertainties, publishing the orbit, and archiving the data. A third observation within 40 days is required.

In the congressionally directed Survey, characterization serves two purposes.

Characterization "*to assess the threat*" and "*to provide warning*" is defined as refining the orbit and approximating the mass of PHOs. This primarily will be accomplished with detection and tracking assets, although mass may be more accurately refined using other follow-up assets.

Characterization "*to provide ... mitigation options*" ties characterization requirements to mitigation. The deflection options examined in this study are broadly representative, and, therefore will help to understand the utility and cost of a range of characterization capabilities. However, this analysis does not allow one to define specific characterization requirements.

Therefore, characterization is classified into two parts.

- *Threat characterization* is defined as precision orbit determination and risk analysis using available data. Threat characterization predicts the probability of Earth impact, and provides warning, date, time, relative velocity and estimated impact energy. Appropriate alerts are issued from orbit characterization products.
- *Object characterization* is defined as all other efforts to obtain information needed for mitigation. This may include mass, size, structure, rotation rate, material, and determination of the existence of companion objects.

Object characterization may be accomplished using remote sensing assets as well as in-situ space missions. The required characterization capability will be determined by the mitigation strategy and deflection approaches selected. For some mitigation strategies, marginal remote sensing capability may be adequate to meet objectives. For other strategies, models based on remote sensing data may need to be calibrated by in-situ visits. Finally, other mitigation strategies may assume that sufficient warning will exist to conduct in-situ visits for every threat, which becomes more likely as the catalog is completed. Pending the selection of a mitigation strategy, this study examines a range of characterization capabilities and the deflection options enabled by each.

5.2.3. Resonant Returns and Keyholes

A *resonant return* is created by the gravitational interaction an object during a preceding Earth encounter [12]. The highly publicized asteroid, Apophis, which currently passes by Earth about every 7 years but is not resonant [13], offers an example of orbit resonance. It will make close approaches to Earth in 2013, 2022, 2029, and 2036.

If Apophis were to obtain a 426-day period (7:6 exterior resonance with the orbital period of Earth) due to a very specific gravitational interaction from the 2029 encounter, it would return to nearly the same point in space six revolutions and seven years later. At that point, Earth would also arrive at that point. Thus, the asteroid would have a resonant return in 2036. [14] A *keyhole* is the small area on an encounter's target plane that the asteroid must pass through to collide on a subsequent encounter. Other examples of keyholes are discussed in Reference [15].

For the 2029 encounter, Apophis must pass through a keyhole that measures 600 meters wide, an occurrence that cannot be confirmed or eliminated by current observations. However, as additional measurements are made on each successive close approach, there is a 95% probability that the 2036 impact will be ruled out after 2013 and a 99.8% probability that it will be ruled out in 2022. [15]

Few objects have nearly resonant orbits that lend themselves to keyholes, but these few objects offer a particular challenge. Experts postulate that most resonant objects were “cleared” by Earth earlier in its 4.5-billion-year history. While additional information gained by each pass usually will confirm whether the object will miss Earth, if an object becomes resonant by passing through a keyhole, very little time (6 years in the case of Apophis) will usually be available to mitigate the threat

Keyhole scenarios are expected to be “extremely rare,” less than 1% of the total possible impacts. This is due to the relatively small size of most keyholes compared with the cross-sectional area of the Earth. [16] Therefore, while the Apophis example has been well publicized, sophisticated keyhole scenarios such as this one appear to be the exception rather than the rule on human timescales. The scenario of deflecting Apophis (should it be necessary) is developed further in Section 6.13 and Reference [17].

5.3. Figures of Merit

Figures of merit (FOM) are quantitative or qualitative metrics used to differentiate the cost, risk, performance, and other features of the detection, tracking, characterization, and deflection concepts and architectures. Metrics common to all concepts include life-cycle cost, development time, development risk, and mission risk. Individual metrics for performance include the capabilities of the Survey concepts, the relative capability of various characterization options, and capabilities of the deflection systems.

Figure 7 illustrates the metrics used for the distinguishing Survey systems. Secondary figures of merit may be used to discriminate between two concepts with similar primary FOM results. Performance metrics for detection and tracking concepts include the percentage of PHOs detected by the end of 2020, and the time to detect 90% of the PHO population.

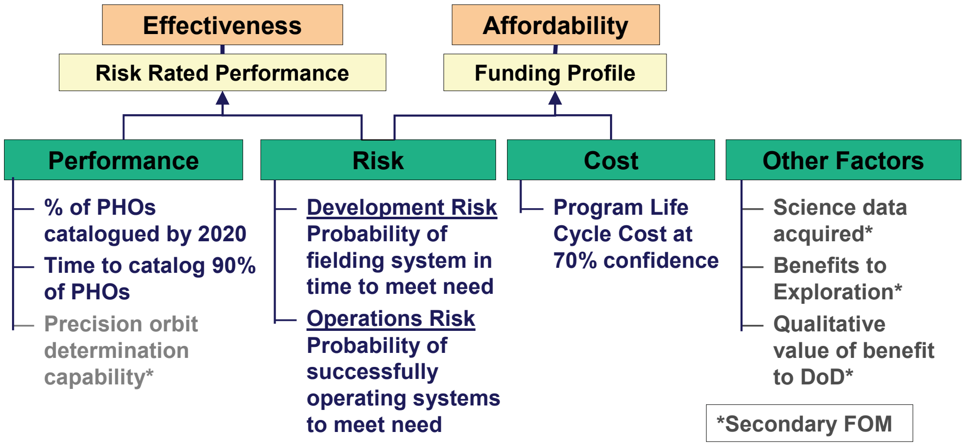


Figure 7. Detection, Tracking, and Cataloguing Figures of Merit

Risk FOMs are common to each concept. The concept risk FOM includes development and mission operations risk. Development risk is the probability that the system will be fielded in time to meet the requirement and was normalized for all schedules to the 70%

confidence level. Mission operations risk is the probability that the system will operate successfully once it has been fielded.

The life-cycle cost (LCC) figure of merit is the life-cycle cost starting at the end of conceptual design and ending at the end of mission operations. Life-cycle costs are reported at a confidence level of 70%. The secondary FOMs include identification of technology developments or capabilities that may benefit either national science goals, NASA Exploration missions, or the Department of Defense (DoD).

The characterization FOMs are shown in Figure 8. The risk, cost, and other factors are identical to those of the detection and tracking concepts, as are the effectiveness and affordability metrics. Performance for characterization is a qualitative assessment of how each concept informs the deflection options. Some characterization options provide robust information, while others provide limited amounts of data at lower confidence levels.

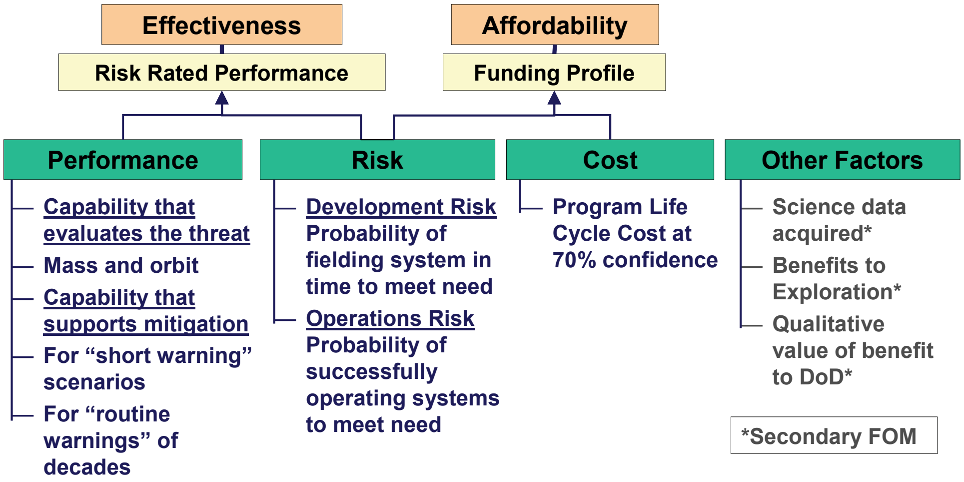


Figure 8. Characterization Figures of Merit

Some deflection options require relatively accurate characteristics, while others require less information that may be less accurate. This metric illustrates how each characterization concept ranks relative to the needs of the deflection missions. Characterization is useful only in the context of this study as to how well it informs mitigation and its performance metrics are strongly tied to mitigation decisions.

5.4. *Development of Alternatives*

5.4.1. Overview

The study team developed a set of alternatives to evaluate the variation in performance, cost, schedule, and risk across the trade space. Alternatives included leveraging current assets, collaborating with proposed survey efforts of other government agencies, and pursuing new NASA-funded assets dedicated to detection and characterization goals. The set of alternatives that the study analyzed included concepts proposed by the private and academic sectors. These included presentations from the NEO public workshop (see Appendix D), concepts similar to those examined by the NEO Science Definition Team, and multiple-element architectures. While some survey systems have the capability to do orbit follow-up and some object characterization, the goal of completing the Survey to a 90% completeness level by the end of 2020 would prohibit extensive characterization by survey systems. After the search is completed and if these assets are still operational, it is possible that they could be used to achieve additional characterization requirements.

5.4.2. Alternatives Definition Methodology

NEO study working groups developed the alternatives considered. Private-sector responses to a Request for Information (RFI) on NEO detection and characterization approaches and Internet and literature searches for related ideas augmented the Science Definition Team concepts. Furthermore, the study team developed architectures composed of combinations of multiple elements to investigate their benefits.

5.4.3. Contributions of the Science Definition Team Report

In addition to the results noted in Section 4.5, the Science Definition Team (SDT) report [3] drew the following system comparisons and summaries of SDT results:

- For a given limiting magnitude, the search system that covers the entire sky the quickest is the most efficient for discovering and cataloging undiscovered objects.
- While locating observing systems in the Northern and Southern Hemispheres provides only a modest improvement in cataloging efficiency over collocated northern telescopes, north/south systems have increased warning efficiency for relatively rare “short warning” situations.
- Search telescopes of the same type and aperture size located in low-Earth orbit (LEO) and at the second Lagrange point (exterior to the Earth on the sun-Earth line) have comparable cataloging efficiencies.
- Detector systems in Venus-like orbits have several advantages over their ground-based counterparts and spacecraft located in the Earth’s vicinity:
  - A shorter orbital period allows them to observe more objects, more often, and closer to perihelion.
  - NEOs at heliocentric distances of 1 AU or less will appear brighter due to their fuller phases.
  - These systems have an increased ability to detect potentially underrepresented population of Aten and IEO asteroids.

The SDT report ruled out space-based, infrared (IR) search systems because IR technology was not sufficiently mature. However, IR detector technologies and systems have progressed, and therefore were included in this study.

5.4.4. Alternatives Design Approach

Most alternatives were developed from existing designs or concepts. When existing designs or concepts were not available, the study team developed spacecraft-sizing algorithms to sufficiently develop the concepts for cost, risk, schedule, and performance analyses.

5.5. Alternative Approaches to Meeting Search Requirements

Broadly, the approaches to finding PHOs can be classified in three categories. Ground-based optical systems use large apertures 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.

5.5.1. 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 (some have new focal planes) 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 their space-based counterparts.

Because these optical systems must view through Earth’s atmosphere, ground systems have drawbacks. 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. These systems cannot easily operate close to the galactic plane because atmospheric turbulence and scattering cause source confusion. Significant atmospheric attenuation in the infrared-spectral region prevents these systems from accurately determining NEO sizes. These systems also will have difficulty finding objects in inner-Earth or Earth-like, orbits. They have fewer discovery opportunities because they are available only at the beginning and end of each night. Additionally, ground-based systems have intangible programmatic issues related to site and infrastructure maintenance. These issues are made worse if the telescopes are sited on foreign territory to achieve the best observing conditions and operate for decades.

5.5.2. Space-Based Optical Systems

Space-based optical systems are based on mature technologies with a broad base of existing spacecraft mission heritage. Like ground-based systems, their advantages are primarily based on where they are put to use. Because these systems are in space they 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 Sun-Earth L1 or in a Venus-like orbit.

Beyond the fact that space-based systems are historically more expensive than ground-based systems, these systems offer there are several additional drawbacks. Getting a space-based system into place subjects it to possible launch and deployment failures and places it in a hostile environment that results in a shorter lifetime (7 to 10 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 are dependent upon spacecraft-to-ground data links and unique onboard software.

5.5.3. Space-Based Infrared Systems

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 infrared systems also have additional advantages. They 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% compared with 230% for visual detectors. A two-band infrared system could lower the size uncertainties to about 20%. These space-based systems also are much less affected by the problem of source confusion. 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. Space-based infrared systems were the most capable (sensitive) of the alternatives considered.

Space-based infrared systems suffer from similar drawbacks as space-based optical systems.

5.6. Detection and Tracking Survey Alternatives Considered

Table 2, Table 3, and Table 4 list the detection, tracking, and cataloguing survey alternatives considered in this study. An initial feasibility assessment was performed on these concepts to produce a more manageable set of alternatives. The concepts not selected for further analysis are italicized and shaded in grey, and the rationale for not choosing them is described in Table 5. A corresponding alternatives trade tree is shown in Figure 9, and a pared trade tree is shown in Figure 10.

Table 2. Description of Ground-based Survey Alternatives Considered

#	Classification	Concept Name	Description
1	*Visible - Ground*	*LINEAR*	*Lincoln Near-Earth Asteroid Research (LINEAR) survey project using two 1m search telescopes.*
2	*Visible - Ground*	*NEAT*	*Near-Earth Asteroid Tracking (NEAT) survey project using 1.2m search telescope.*
3	*Visible - Ground*	*Pan-STARRS 1*	*Panoramic Survey Telescope And Rapid Response System (Pan STARRS) survey project using one 1.8m search telescope.*
4	*Visible - Ground*	*Spacewatch*	*Spacewatch survey project using 1.8m and 0.9m search telescopes.*
5	Visible - Ground	**Spaceguard**	Combined ground-based detection efforts including LINEAR, NEAT, Catalina Sky, Spacewatch and LONEOS.
6	*Visible - Ground*	*Catalina Sky Survey*	*Catalina Sky Survey project using 0.7 and 1.5 m telescopes in the north and a 0.5 m in the southern hemisphere*
7	*Visible - Ground*	*VISTA*	*Visible & Infrared Survey Telescope for Astronomy (VISTA) is a planned (2007) 4m astronomy telescope.*
8	Visible - Ground	**Shared LSST**	Large Synoptic Survey Telescope (LSST) is a planned (2014) 8m telescope, will spend 75% in survey mode.
9	*Visible - Ground*	*DCT*	*Discovery Channel Telescope (DCT) is a planned (2010) 4.2m telescope, both broad and narrow band pass.*
10	Visible - Ground	**Shared PS4**	Four 1.8m Pan-STARRS telescopes searching same spot of the sky at a time with an effective aperture of 3.6m; will spend 30% in survey mode.
11	*Visible - Ground*	*SST*	*Planned ground-based optical telescope.*
12	Visible - Ground	**Dedicated LSST**	Rebuild of Shared LSST, dedicated to NEO search.
13	Visible - Ground	**Dedicated PS4**	Rebuild of Shared PS4, dedicated to NEO search.
14	Visible - Ground	**Dedicated PS8**	Proposed system of two PS4 telescopes searching same area of the sky at a time with an effective aperture of 5.1m.
15	Visible - Ground	**Dedicated PS16**	Proposed system of two PS8 telescopes (North and South or equator) searching differing regions sky regions at any given time, thus doubling the search area.
36	*Visible – Ground*	***LONEOS***	*Lowell Observatory near-Earth Object search program using a 0.6 m telescope*
33	*Radar - Ground*	*Arecibo*	*Arecibo Radio Telescope is an operational ground-based radio telescope with a 305m fixed dish. May be closed by 2011 without additional support beyond current National Science Foundation funding.*
34	*Radar - Ground*	*Goldstone*	*Goldstone is an operational ground-based radio telescope with a 70m steerable dish. Similar or enhanced capability provided if Canberra 70m radar adopted for the Deep Space Network.*
35	*Radar - Ground*	*Bistatic 100m*	*Proposed system composed of two 100m steerable radio antennas to be operated in a bistatic mode.*

* *Italicized and shaded concepts were not considered for further detection and tracking analysis. Radars were analyzed for their contribution to precision orbit determination capability.*

Table 3. Description of Space-based Survey Alternatives Considered

#	Classification	Concept Name	Description
16	*Visible - Space*	*Hubble*	*Hubble Space Telescope is an operational 2.4m optical, space-based astronomy telescope.*
17	*Visible - Space*	*Kepler*	*Kepler is a planned (2009) 0.95m space-based astronomy telescope dedicated to the search of extra-solar planets.*
18	*Visible - Space*	*1m Vis LEO/L1/L2*	*Concept for a space based 1m optical search telescope in the near-Earth region (LEO/L1/L2).*
19	Visible - Space	**2m Vis LEO/L1/L2**	Concept for a space based 2m optical search telescope in the near-Earth region (LEO/L1/L2).
20	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).
21	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).
22	*Visible - Space*	*3m Vis LEO/L1/L2*	*Concept for a space based 3m optical search telescope in the near-Earth region (LEO/L1/L2).*
23	*Visible - Space*	*4-6m Segmented Vis*	*Concept for a space based 4-6m segmented, optical search telescope in the near-Earth region (LEO/L1/L2).*
24	*Infrared - Space*	*Spitzer*	*Spitzer Space Telescope is an operational 0.85m IR, space-based astronomy telescope.*
25	*Infrared - Space*	*JWST*	*James Webb Space Telescope (JWST) is a planned (2013) 6.5m segmented, IR, space-based astronomy telescope.*
26	*Infrared - Space*	*WISE*	*Wide-field Infrared Survey Explorer (WISE) is a planned (2010) 0.4cm IR, space-based, non-pointable survey telescope.*
27	*Infrared - Space*	*0.5m IR LEO*	*Concept for a space based 0.5m IR search telescope in low Earth orbit (LEO).*
28	*Infrared - Space*	*1m IR LEO*	*Concept for a space based 1m IR search telescope in low Earth orbit (LEO).*
29	Infrared - Space	**0.5m IR L1/L2**	Concept for a space based 0.5m IR search telescope at Sun-Earth Lagrange point (L1/L2).
30	Infrared - Space	**1m IR L1/L2**	Concept for a space based 1m IR search telescope at Sun-Earth Lagrange point (L1/L2).
31	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).
32	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).

** Italicized and shaded concepts were not considered for further analysis*

Table 4. Description of Data Management Alternatives Considered

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

5.6.1. Survey Alternatives Not Analyzed and Rationale and Why

Table 5 describes the search alternatives that the study considered, but did not analyze. The study assumed that the Spaceguard assets would continue to operate as a baseline capability at least until the proposed Survey could begin. It is assumed that the new Survey will build from this capability and that existing assets and processes will continue until replaced. While the Spaceguard goal is to detect objects 1 km or larger, some objects as small as 140 meters are detected under favorable viewing conditions.

The detection of PHOs using ground-based infrared (IR) techniques is not considered a viable option because Earth's atmosphere radiates or absorbs strongly in the IR region. Although IR characterization of bright PHOs is possible from a few select, high-altitude observatories (e.g., NASA's Infrared Telescope Facility or Keck), even the 10-meter Keck telescope only can observe objects much brighter than a 1-km PHO at typical observing distances, and therefore is of little use in the detection of smaller objects.

The returned signal strength of radar decreases as inverse fourth power of distance, and therefore has a range that is insufficient to observe most PHOs. A typical radar beam is only 1 arc minute in diameter, which does not provide the sky coverage necessary for detection. Therefore, radars are not a viable search system for PHOs, but may be desirable to rapidly improve the orbital estimates of some objects.

Classified DoD space surveillance systems were evaluated for contributions that they might make to the search for PHOs. The capabilities and requirements for six current and proposed DoD systems were studied, and this report has concluded that their capabilities, operations, and data-storage procedures are largely incompatible with Survey goals. In addition, PHO survey systems are not expected to contribute materially to satisfying any DoD requirements evaluated unless Survey goals are compromised substantially. Further discussion of the capabilities that might be shared with DoD missions and systems are discussed in Appendix O.

5.6.2. Survey Alternatives Analyzed

The alternatives analyzed in this study were developed to a level of detail to cover architectural and technology options. These options included combinations of space- and ground-based detection methods in both the visible- and infrared-spectral regions. These concepts have not been as optimized as they would be in a detailed design study.

Figure 11 provides a matrix of the multi-element alternatives evaluated. A more detailed description of these elements appears in Appendix E. The "baseline" multi-element architecture represents a collection of ground-based assets that are currently operational (i.e. Spaceguard), as well as non NASA-funded survey observatories designed to conduct surveys that are in development by agencies other than NASA and that are expected to become operational before 2020. This architecture provides a basic capability that is likely to be available regardless of a dedicated NASA survey, and thus will provide a baseline upon which NASA could build any additional capability needed to meet the Survey goals. Elements besides Spaceguard are the Pan-STARRS (PS4), being developed by the U.S. Air Force, and the Large Synoptic Survey Telescope (LSST) planned by the National Space Foundation. Both agencies have indicated a willingness to share time on the assets in exchange for partial funding of operations.

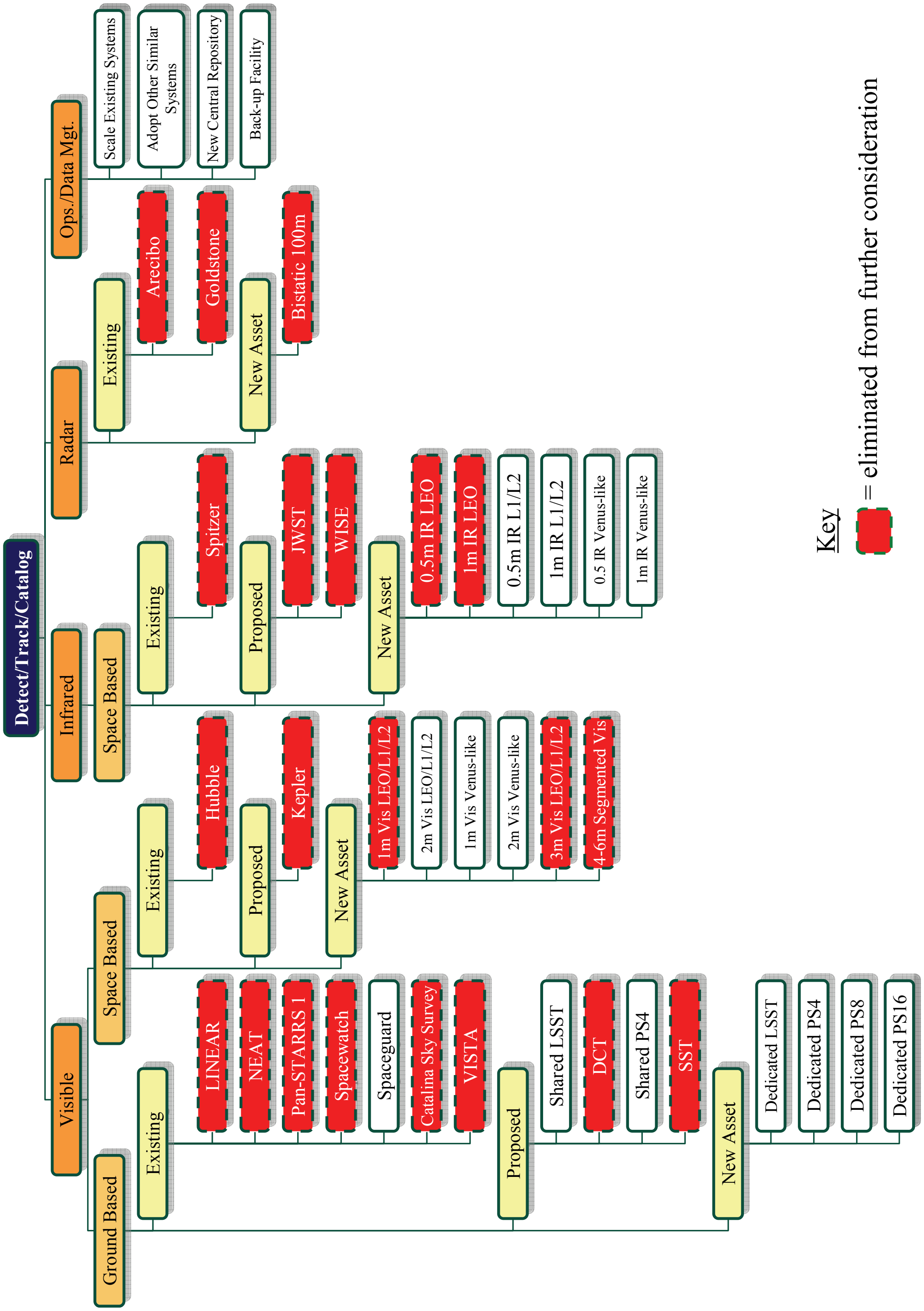


Figure 9. Complete Survey Alternatives Trade Tree

Table 5. Rationale for Detection and Tracking Alternatives not Analyzed

Concept Name	Downselect Criteria
LINEAR	Cannot detect sufficient number of 140m NEOs. Included in Spaceguard
LONEOS	Cannot detect sufficient number of 140m NEOs. Included in Spaceguard
NEAT	Cannot detect sufficient number of 140m NEOs. Included in Spaceguard
Pan-STARRS 1	Cannot detect sufficient number of 140m NEOs.
Spacewatch	Cannot detect sufficient number of 140m NEOs. Included in Spaceguard
Catalina Sky Survey	Cannot detect sufficient number of 140m NEOs. Included in Spaceguard
VISTA	Not a survey telescope. Shared time asset. Foreign owned.
DCT	Cannot detect significant number of 140m NEOs. Shared time asset.
SST	Classified project, information is unavailable. Highly constrained asset access.
Hubble	Not a survey telescope. Highly constrained asset access.
Kepler	Cannot detect significant number of 140m NEOs. Will only observe 0.25% of entire sky. Highly constrained asset access.
1m Vis LEO/L1/L2	Poor performance shown in initial analysis.
3m Vis LEO/L1/L2	Initial analysis shows no need for telescope as large. High cost/risk.
4-6m Segmented Vis	Not a survey telescope. Initial analysis shows no need for telescope as large. High cost/risk.
Spitzer	Not a survey telescope. Short lifetime.
JWST	Not a survey telescope. Highly constrained asset access.
WISE	Highly constrained asset access. Short life.
0.5m IR LEO	Earth’s thermal radiation
1m IR LEO	Earth’s thermal radiation
Arecibo	Not a survey telescope. Signal drop-off limits detection to within 0.3 AU
Goldstone	Not a survey telescope. Signal drop-off limits detection to within 0.1 AU
Bistatic 100m	Not a survey telescope. Signal drop-off limits detection to within 0.3 AU

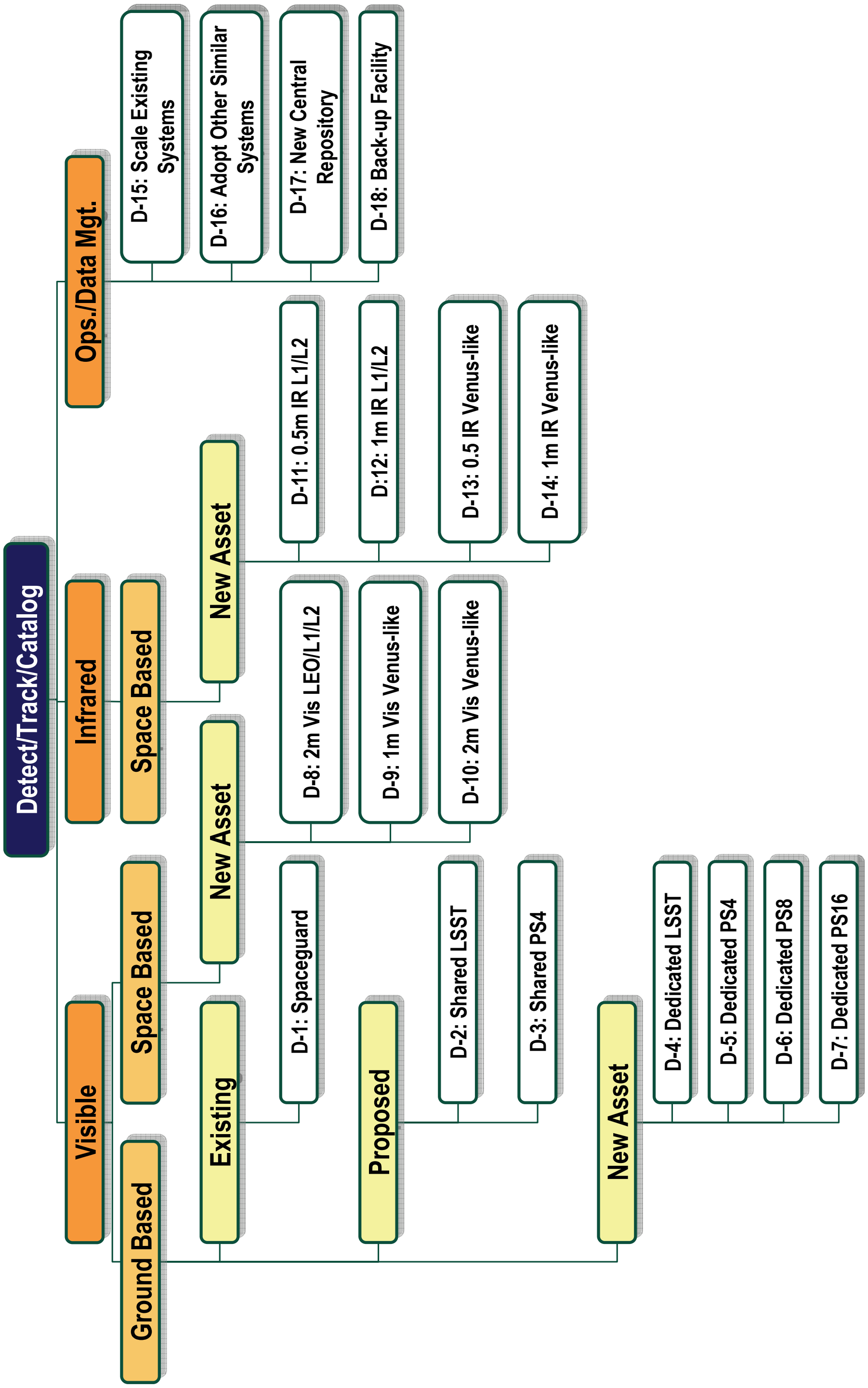


Figure 10. Pared Survey Alternatives Trade Tree

#	**Year of First Observations** **All programs start 10/1/2007**		**Spaceguard**	**Shared PS4**	**Dedicated PS4**	**PS8**	**PS16**	**Shared LSST**	**Dedicated LSST**	**0.5m IR @ L1**	**1m IR @ L1**	**0.5m IR in Venus-like Orbit**	**1m IR in Venus-like Orbit**	**1m Vis in Venus-like Orbit**	**2m Vis in Venus-like Orbit**
D-20	Spaceguard+Shared PS4	Ground-based only	**1998**	**2010**											
D-22	Spaceguard + Dedicated PS4		**2000**		**2012**										
D-23	Spaceguard + Dedicated PS8		**2000**			**2012**									
D-24	Spaceguard + Dedicated PS16		**2000**				**2012**								
D-19	Spaceguard + Shared LSST		**2000**					**2014**							
D-21	Spaceguard + Dedicated LSST		**2000**						**2016**						
D-25	Baseline (Shared PS4/LSST)		**2000**	**2010**				**2014**							
D-27	Baseline + Dedicated PS8		**2000**	**2010**		**2012**		**2014**							
D-28	Baseline + Dedicated PS16		**2000**	**2010**			**2012**	**2014**							
D-36	Baseline + Dedicated LSST		**2000**	**2010**				**2014**	**2016**						
D-32	Baseline + 0.5m IR @ L1	Ground + Space	**2000**	**2010**				**2014**		**2012**					
D-33	Baseline + 1m IR @ L1		**2000**	**2010**				**2014**			**2014**				
D-34	Baseline + 0.5m IR in Venus-like		**2000**	**2010**				**2014**				**2014**			
D-35	Baseline + 1m IR in Venus-like		**2000**	**2010**				**2014**					**2014**		
D-30	Baseline + 1m Vis in Venus-like		**2000**	**2010**				**2014**						**2014**	
D-31	Baseline + 2m Vis in Venus-like		**2000**	**2010**				**2014**							**2014**

Figure 11. Multi-Element Detection, Tracking, and Cataloguing Systems Analyzed

5.7. Survey System Elements Schedules

To assess whether the alternatives could meet the congressionally directed goal of 90% completeness by the end of 2020, schedules for each of the search alternatives were developed. Figure 12 displays the nominal development time for the detection, tracking, and cataloguing system concepts. This time does not include issues related to the development of shared systems, and assumes that all programs are fully funded during development and testing.

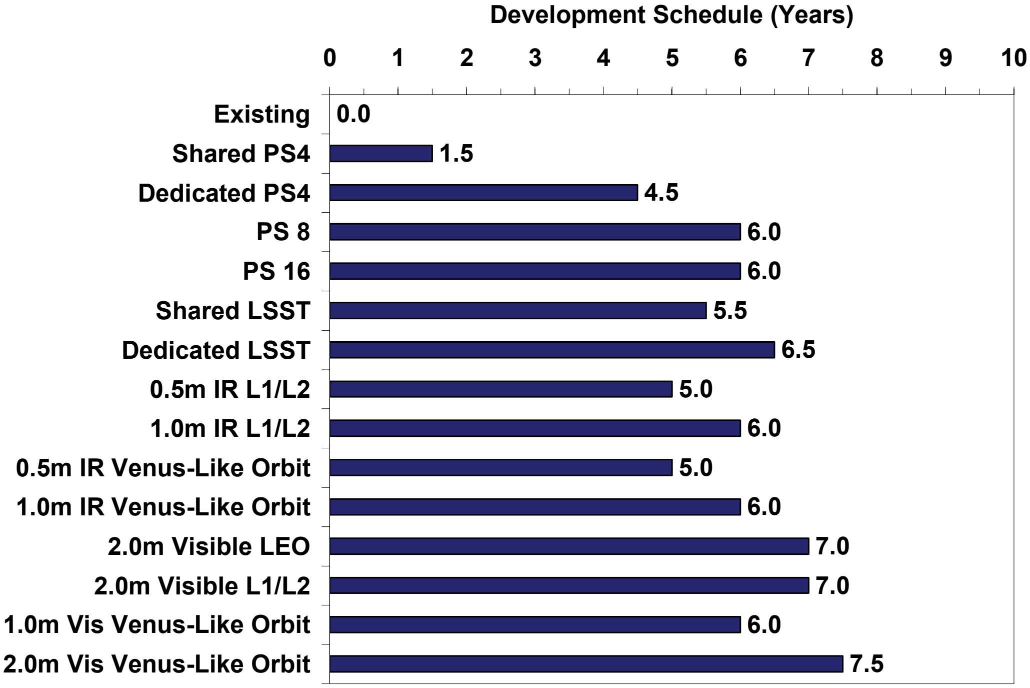


Figure 12. Detection and Tracking Nominal Development Schedules

For space assets, transit and checkout time must be added to estimate initial operational capability (IOC). Missions traveling to a Venus-like heliocentric orbit used a Venus swingby to limit required launch performance. This yielded one launch opportunity about every 13 months and caused the 0.5-meter IR system to delay its launch by about 1 year. If a more capable launch system is assumed, the launch delay due to a Venus swingby could be eliminated.

For missions stationed at Sun-Earth L1, a 3-month transit was assumed based on the Genesis, ACE, SOHO, and WMAP missions. For missions in a Venus-like heliocentric orbit, a 5-month transit was assumed (Magellan, Venera, and Pioneer Venus). For ground-based missions, checkout time was based on nominal program schedules with credit given if similar hardware had been calibrated previously. For all space missions, a checkout time of 2 months was assumed. The development of all search systems is assumed to start at the beginning of FY08. Initial operational dates are shown in Table 6 and Table 7.

Table 6. Start Date for Ground-based Survey Elements

Asset	(Months) Develop	Check	IOC*
Existing Assets	0	0	1998
Shared PS4	19	6	2010
Dedicated PS4	56	4	2013
PS 8	73	4	2014
PS 16	73	4	2014
Shared LSST	67	10	2014
Dedicated LSST	80	7	2015

* *Initial Operational Capability*

Table 7. Start Date for Space-based Survey Elements

Asset	(Months) Develop	Launch	Transit	Check	IOC*
0.5m IR @ L1	61	0	3	2	2013
1.0m IR @ L1	71	0	3	2	2014
0.5m IR @ Venus	61	13	5	2	2013
1.0m IR @ Venus	70	3	5	2	2014
1.0m Vis @ Venus	72	0	3	2	2014
2.0m Vis @ Venus	86	0	3	2	2016

* *Initial Operational Capability*

5.8. Survey Performance Simulation Results

The results presented in this section are based on the analyses described in Appendix Section H.2. Absolute performance is expected to be within 5% of the results shown, and within 1-2% for the concepts that achieve 90%. These results are expected to have a relative uncertainty of 1-2%.

Table 8 shows the analysis results for the performance of various ground-based survey options acting alone and assuming no discoveries until the beginning of the surveys. For example, the first line of Table 8 shows that the currently operating ground-based Spaceguard observing program will catalog 14% 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% completeness. On the second line of Table 8, note that the shared PS4 will reach 72% survey completeness for 140-meter size objects by the end of 2020. It will reach 69% completeness after operating for 10 years and 90% 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 beginning in 2013 could catalog 85% of the PHO population (D > 140 m) by the end of 2020, 88% after 10 years (2023) and 90% shortly thereafter.

Table 8. Ground-based Survey Performance

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

* *Continued operation of Spaceguard assets add marginally to performance*

Table 9. Space-based Survey Performance

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

Requirement is 90% completion by end of 2020

Table 10 shows space-based alternatives used in conjunction with the baseline ground-based systems. The first line of Table 10 shows that these systems could reach the 90% goal by the end of 2020 if the Spaceguard telescopes operate, the shared PS4 begins operations in 2010, the shared LSST begins operations in 2014, and the space-based IR telescope at Sun-Earth L1 starts in 2013.

Table 11 shows that the options that exceed congressional goals also provide other benefits. The middle column of the table shows that systems that operate in Venus-like orbits are more efficient at finding Aten and IEOs, a potentially underrepresented population of PHOs. The final column of the table shows that for combinations of visual and IR detectors, some systems will be able to estimate object sizes to better than 50% for more than 70% 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%
Shared PS4 + Shared LSST (Baseline)	83%	2026
Dedicated PS8 + Baseline	85%	2024
Dedicated LSST + Baseline	90%	2020
0.5m IR @ L1 + Baseline	91%	2020
1.0m IR @ L1 + Baseline	91%	2020
0.5m IR in Venus-like + Baseline	97%	2017
1.0m IR in Venus-like + Baseline	97%	2017
1.0m VIS in Venus-like + Baseline	93%	2019
2.0m VIS in Venus-like + Baseline	95%	2018

** Requirement is 90% by the end of 2020*

Table 11. Additional Benefits of Space Systems

Survey Systems	Diameter to 90%*	Size	Sees More Atens/IEOs
0.5m IR @ L1 + Baseline	125 m	77%	✓
1.0m IR @ L1 + Baseline	125 m	78%	✓
1.0m IR in Venus-like	125 m	**	✓✓
0.5m IR in Venus-like + Baseline	90 m	-	✓✓
1.0m IR in Venus-like + Baseline	80 m	76%	✓✓
1.0m VIS in Venus-like + Baseline	125 m	78%	✓✓
2.0m VIS in Venus-like + Baseline	110 m	-	✓✓

** Diameter of PHOs catalogued to 90% by the end of 2020*

*** Not explicitly evaluated, likely 70-78%*

Apart from setting the discovery floor for the next-generation search systems, the existing Spaceguard system does not materially contribute to future searches because any objects it finds would more be found more quickly by one of the next-generation search systems. Assuming that a single system can cover the richest areas of the sky in one search period (around 5 days), the addition of another identical system generally adds very little because it, too, cannot see fainter objects. Asteroids tend to cycle in and out of view 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 orbit quality because the two acting together would enable more observations and consequently provide a more precise estimation.

Figure 13 shows the survey completion as a function of time for several individual and combinations of systems. The results for the PHO completeness percentages on the following pages are estimated to be accurate to ±2% for results near 90%. Performance results for additional detection and tracking combinations are reported in Appendix I.

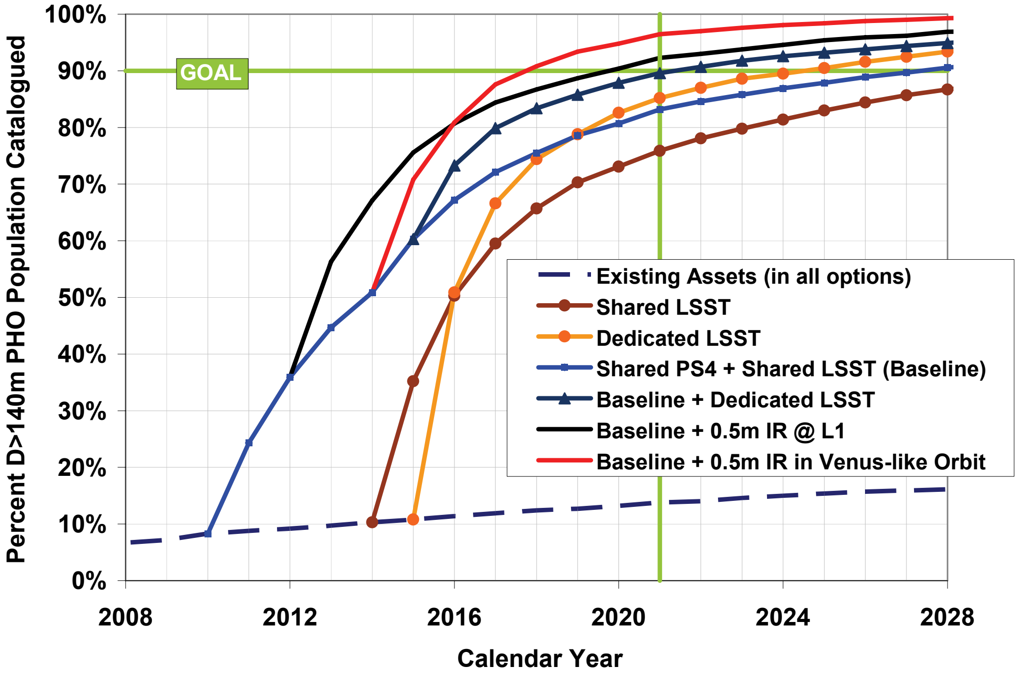


Figure 13. Survey Performance for Selected Alternative Systems

Figure 14 shows the various schedule elements that contribute to the completion date of the ground-based element alternatives.

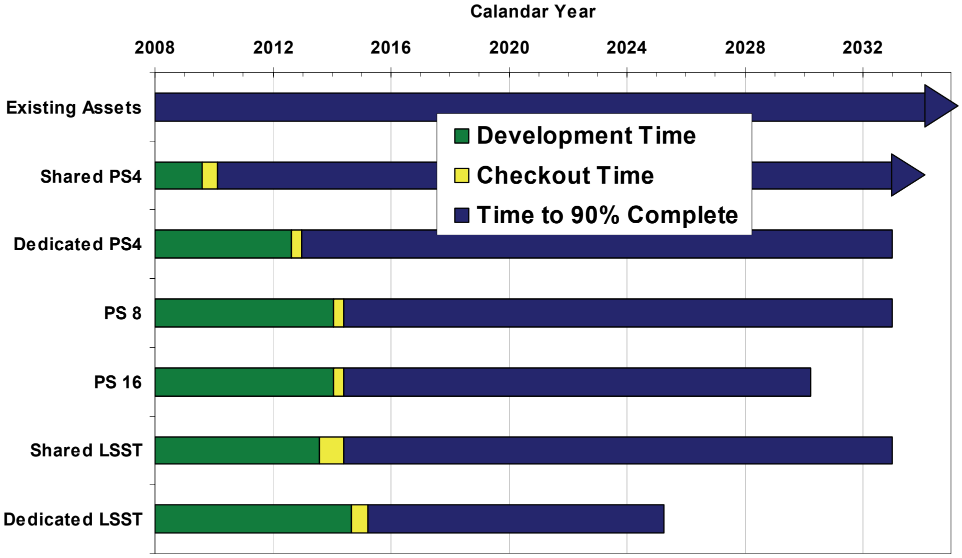


Figure 14. Constituents of Ground-Based Survey Schedules to 90%

Figure 15 shows the schedule elements that contribute to the completion date of the space-based alternatives. To reduce launch requirements, a Venus flyby was used to reach the Venus-like heliocentric orbits. This approach limited launch opportunities to about one every 13 months. How these launch opportunities may affect completion dates is illustrated in Figure 16.

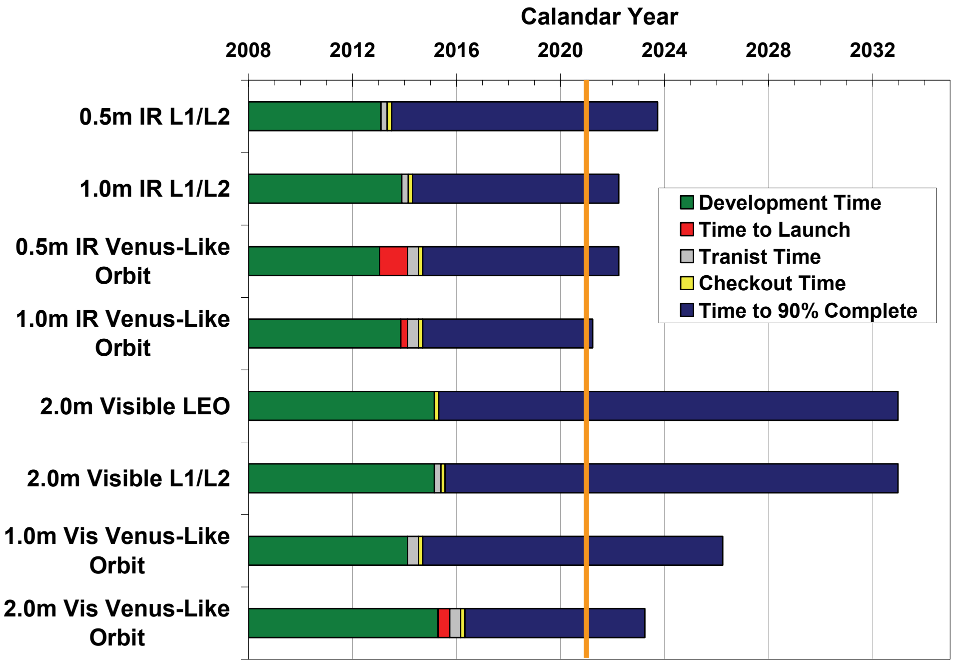


Figure 15. Constituents of Space-Based Survey Schedules to 90%

Since start dates and acquisition schedules cannot be predicted to within a year at this juncture, the completion dates for Venus-like orbits should be considered to vary by up to an additional year over the other alternatives. This is due to limited launch dates, unless a higher-performing launch vehicle is used to eliminate the Venus swingby requirement.

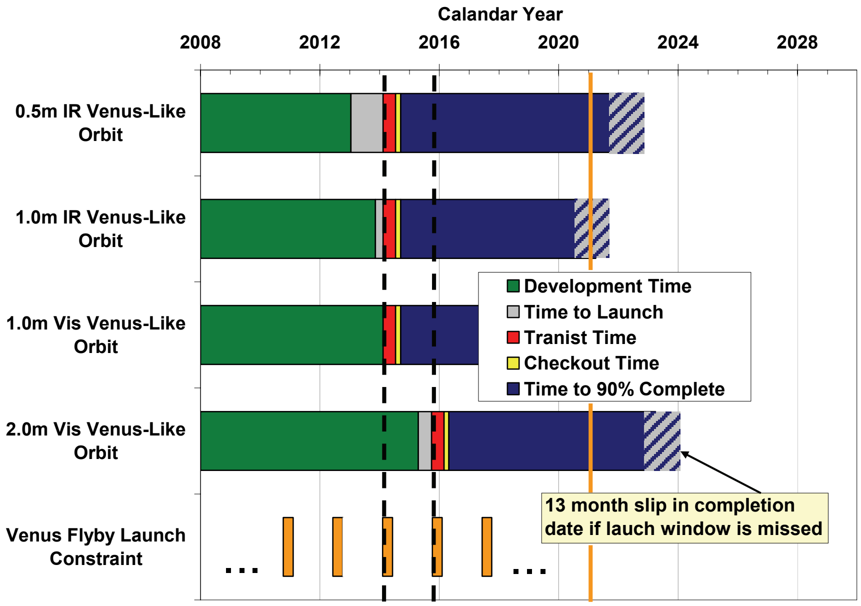


Figure 16. Possible Effect of Venus Flyby on 90% Completeness Dates

Figure 17 shows how combinations of ground-based systems contribute to reaching the 90% completeness goal. Note that existing assets in addition to Shared PS4, Shared LSST, and a Dedicated LSST reach the 90% survey goal by the end of 2020.

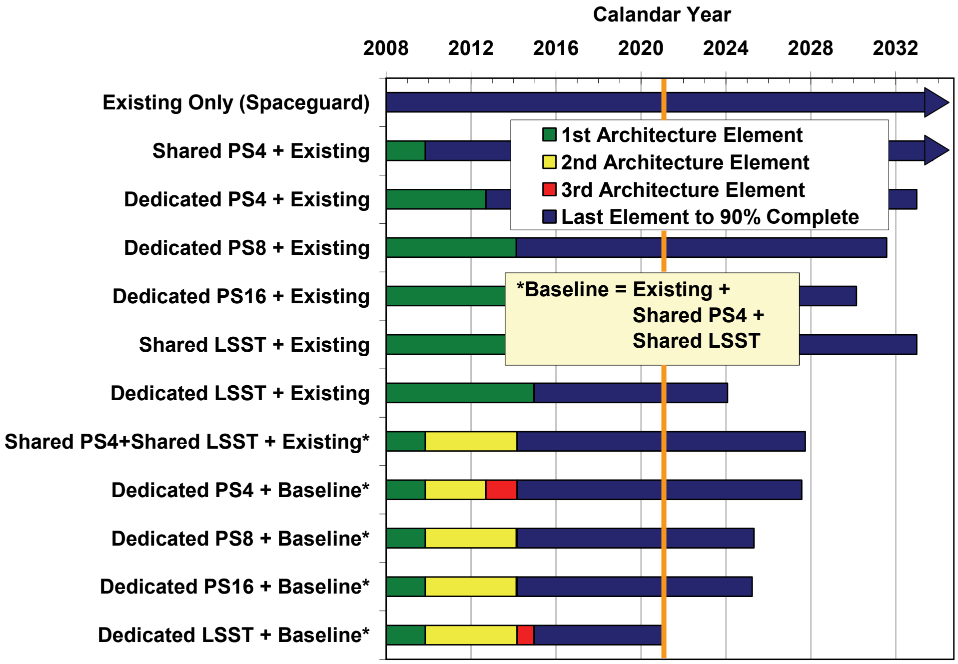


Figure 17. Survey Performance of Ground-Based Combinations

Figure 18 shows how combinations of ground-based and space-based systems contribute to reaching the 90% completeness goal. Note that except for the near-Earth visible alternatives, all of these combinations meet the goal by the end of 2020.

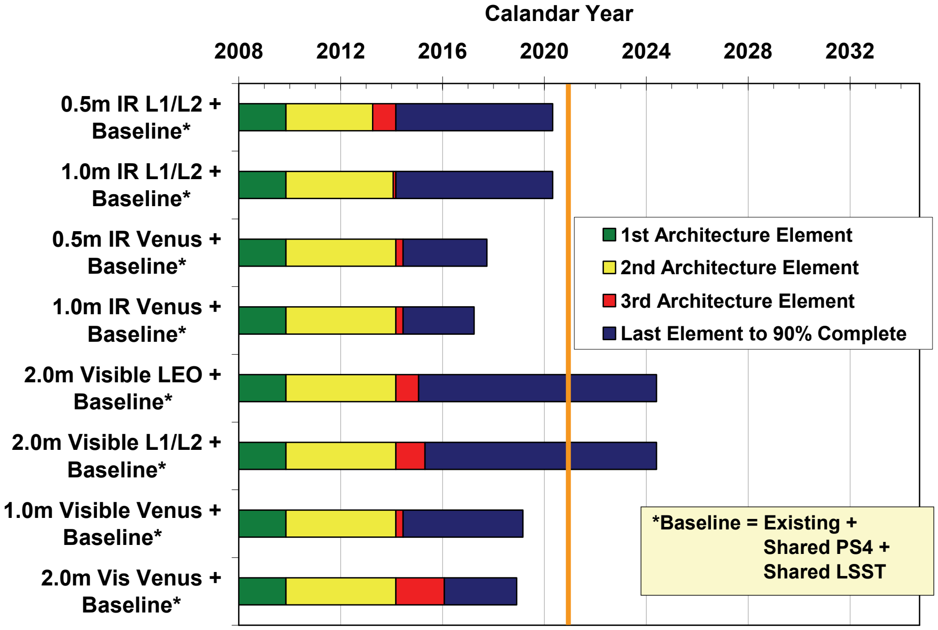


Figure 18. Survey Performance of Ground and Space Based Combinations

5.9. Orbital Uncertainty

After detection, the most important parameter affecting mitigation decisions is orbit uncertainty. If decision makers had perfect knowledge of an object's orbit and a basic understanding of its size, mitigation decisions would be much clearer. Due to radar's inability to provide active ranging at distances beyond 0.3 AU (45 million km), determining the orbits of most PHOs is limited to optical means.

Orbit uncertainty is relatively small during observations because the measurements constrain the object's position during this period. When the object's position is predicted into the future, however, orbit uncertainties grow; the farther one predicts into the future, the greater the uncertainty. The rate of uncertainty depends largely on how long the object is observed. If the object were observed for only a short period, a few weeks or months, say, and if radar-tracking data were not available, the orbit uncertainty would grow rapidly over the prediction. Unless the time to impact was very short, the encounter error ellipse could be hundreds or thousands of times larger than the Earth, leading to a small impact probability.

When an object has been observed for several orbital periods (1-10) or when radar-tracking data are available, the uncertainty in predicting the orbit is reduced substantially. Figure 19 from Reference [17] illustrates how prediction accuracy improves as the length of the interval of observation grows.

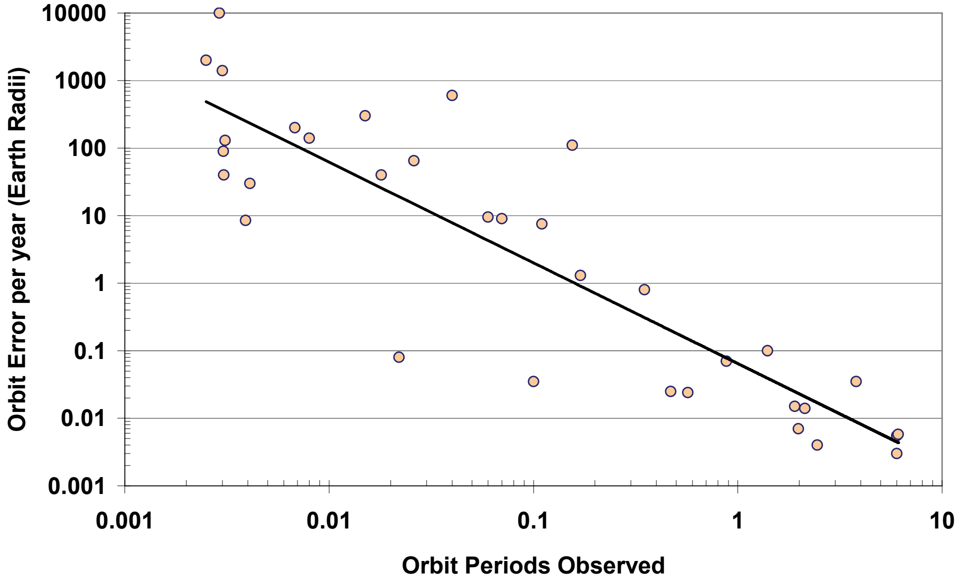


Figure 19. Orbit Prediction Accuracy Improves with Length of Observation

Currently, for a single apparition observed by an optical asset, meaningful predictions can be accurate for decades. At that point, the uncertainty region is generally stretched out more than ±0.1 AU and it is not clear that an encounter is real. If radar data are obtained, encounter predictions can extend to centuries. Once a full orbit is sampled (two or more apparitions), the meaningful predictions jump to many centuries on average, regardless of whether radar data are available. Once the survey is complete, almost every object will have multiple apparitions of data, and thus, for any random PHO, analysts could predict its location hundreds of years into the future. This would provide providing centuries of warning if the object poses a threat, assuming close planetary encounters (rare for any given object on human timescales) do not occur in the interim. [8]

After an object has been observed for several years, or if the object has approached close enough to the Earth to be observed with radar, the uncertainty in its orbit is reduced as described in Section 5.10.3. The uncertainty in the object's orbit then grows at a much slower rate when its position is predicted ahead of time, and the error ellipse will be comparable to or smaller than the size of the Earth decades into the future. The slow error growth for these objects also will allow reliable encounter predictions to extend to more than a century. Thus, once the survey is complete, a 100-year encounter prediction will be as accurate as a 10-year prediction is today assuming close planetary encounters do not occur. [8]

Much has been written on the non-gravitational forces affecting asteroid orbits. Most forces (excluding random forces such as outgassing of active bodies) can be modeled to some extent given enough observations. Even if these forces cannot be modeled, the effect of non-gravitational forces on objects that are 100 meters to 1 km in size does not materially affect impact prediction uncertainty within 50 years. [19] [20] [21] [22]

The approximate values of radial and transversal accelerations, which affect bodies in the 10-cm to 10-km size range and when solar gravity is scaled to unity, are shown in Table 12. For comparison, typical gravitational perturbations by planets and big asteroids are $GM_{planet} \sim 10^{-3}$ and $GM_{asteroid} < 10^{-9}$. Among the most difficult forces to predict is the Yarkovsky/YORP Effect, a force created by re-radiation of photons from the visible solar flux of a rotating object. As developed in Reference [19], the maximum effect of the Yarkovsky/YORP Effect on the semimajor axis of an asteroid 1-km in diameter is about 10 meters per year, and therefore constitutes a second-order effect on impact prediction uncertainty. Additional uncertainty accumulates due to the uncertainty in the mass of other celestial objects, but this effect is generally small compared with those described in Table 12.

Table 12. The Magnitude of Various Forces Acting on Asteroids

acceleration	radial	transversal
gravity	$GM_{\odot} \simeq 1$	
Yarkovsky/YORP effect	10^{-7} to 10^{-11}	10^{-8} to 10^{-12}
radiation pressure	10^{-6} to 10^{-11}	
Poynting-Robertson drag		10^{-10} to 10^{-15}
solar wind, Lorentz force, plasma drag	$< 10^{-15}$	

IAU Symposium No. 229, 2005. Non-gravitational forces acting on small bodies.
Broz, Vokrouhlicky, Bottke, Nesvorny, Morbidelli and Capek

It is a derived requirement that any deflection approach have some type of effectiveness assessment (i.e. post-action orbit determination) because predicting the object's new orbit using remote methods likely will require many years. This delay in assessing the effectiveness of the deflection attempt likely will not be acceptable unless the deflection attempt occurred many decades ahead of the predicted impact. These missions are similar to the in-situ orbit determination alternatives discussed in Section 5.10.4.

5.10. Performance of Orbit Determination Alternatives

5.10.1. Precision Orbit Determination Using Survey Assets

Simulations were developed to compare the detection efficiency of various survey elements by themselves or in combination. While the detection efficiency of the various alternatives should be considered as a primary goal, a second goal is to determine which among the viable detection surveys is best for precisely determining orbits.

To a large extent, PHO orbits are determined by optical angle data (time, right ascension, declination) taken over an interval of observation. The most accurate orbits are those that are based on the longest interval of observational data. Once a PHO has two or more observed returns to perihelion, its orbit is generally well known and in the absence of any close planetary flybys, is capable of being accurately extrapolated more than 100 years into the future.

Figure 20 shows the distribution of orbit quality among cataloged objects in the 140- to 180-meter diameter size range for a number of individual 10-year surveys. Each curve is normalized to the catalog size; thus the plot shows no information about the systems' discovery completeness. The term, dP/P, is a measure of in-track orbit accuracy calculated as the ratio of orbital period uncertainty (dP) divided by the calculated orbit period. An uncertainty in orbital period can be related to the error ellipse of the object during an Earth encounter.

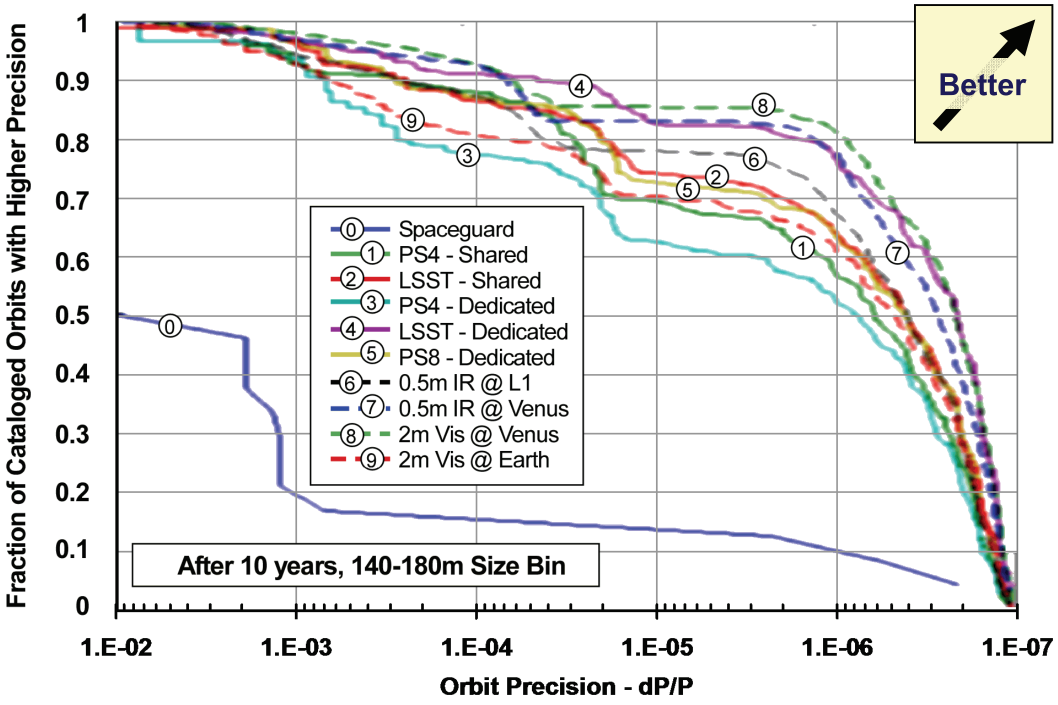


Figure 20. Comparison of Precision Orbit Capabilities of Survey Alternatives

Several conclusions can be drawn from Figure 20:

- The flattening around dP/P=5 x 10^{-6} is due to the transition from a single observed return (i.e., apparition) to multi-apparition orbits.
- Spaceguard can see very few objects at two apparitions and most have poor precision due to very short data arcs. Thus, for the next generation of search systems, the current Spaceguard Survey performs poorly at both discovery and for precisely determining orbits.
- The Venus-trailing missions have catalog precisions comparable to those of the dedicated LSST system.
- The two PS4 systems have relatively few high-precision orbits compared with the other systems, but the dedicated PS4 system also has a relatively low fraction of poorly defined orbits ($dP/P > 10^{-3}$).
- The 0.5-meter IR at Sun-Earth L1 system appears similar to LSST for high-precision orbits, but has a greater percentage of low-precision orbits.
- The 1-meter aperture systems are expected to have the same orbit precision as those with smaller apertures due to the assumption of identical sensor arrays.

For surveys with comparable discovery rates, Figure 20 may be used to distinguish the survey with the superior cataloging precision. It cannot be used to distinguish the survey with the highest cataloging performance.

5.10.2. The Role of Precovery in Precision Orbit Determination

“Precovery” is used to describe “pre-discovery” observations of an object that may be found in older archived images. Once an object has been detected and an initial orbit has been determined, astronomers can project the motion of the object backward in time and search for it in archived images. Unless a sequence of several images was taken at that time, it is very unlikely that a faint, moving object would have been detected.

To a great extent, the accuracy of an object’s orbit depends upon the time interval of the observations (see Section 5.9). Because precovery has the ability to lengthen the observational data interval of a recently discovered object, it often can be used in the orbit-determination process to dramatically improve accuracy. Precovery is particularly important when a future Earth impact cannot be immediately ruled out for a particular object whose orbit is relatively uncertain due to a short-observational interval.

Figure 21 shows how precovery observations were used to rule out an Earth impact in 2029 by the asteroid Apophis. The solid line in this figure shows the theoretical behavior expected for the 2029 impact. The probability of an impact decreases as more optical observations become available for use in the orbital estimates. If the precovery observations had not been found, the plotted circles show that orbital solutions generated from observations collected after the discovery would have followed the theoretical curve. Note that the impact probability would have been calculated to reach 12%. Additional observations would then have brought the impact probability to zero. The red-lined plot shows the evolution of the actual calculated impact probability for 2029. These calculations peaked at about 3% in late December 2004 before precovery observations collected 4 months earlier were identified in the data archives and the probability of impact was eliminated.

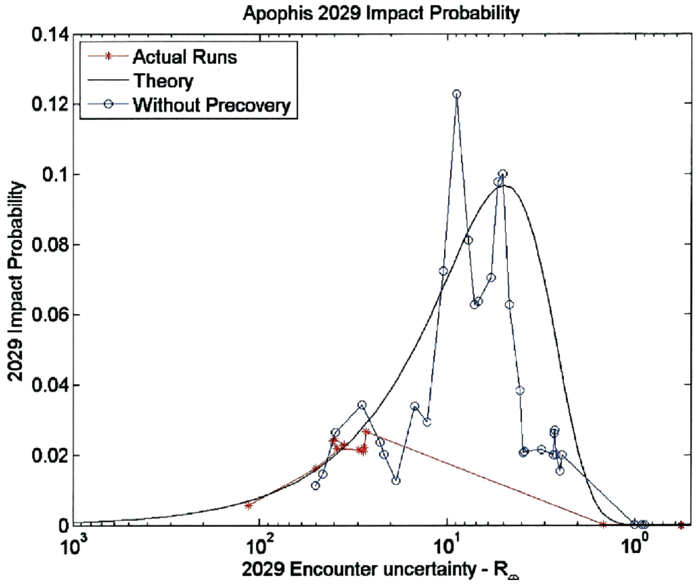


Figure 21. Value of Precovery Analysis

Currently, most precovery observations are identified in the data archives by a group of sophisticated amateur astronomers. If future surveys maintain their images in archives, or at least archive the time and positional information for each object detected, amateur astronomers could continue their work in this area. However, the potential two orders-of-magnitude increase in the detection rate may prove too rapid for this group unless personnel and funds are allocated to this task.

5.10.3. Precision Orbit Determination Using Radar

Radar observations of NEOs have been taken for several decades. Compared with optical data, these measurements are very accurate (8 meters in range, 1 mm/s in range rate). In addition, they provide radial data (observer to NEO direction) that complement angular, plane-of-sky data. Therefore, the use of radar observations can determine PHO orbits that are up to two-to-three orders of magnitude more precise, especially for those objects that have short optical observational intervals.

The value of the radar data is shown in Figure 22. In this figure, precision, given by the accuracy of the orbital period (dP), divided by the period (P), is plotted against the total interval of observation (arc length). This figure demonstrates the precision for the existing catalog of PHO orbits. The red dots show the results for orbits using only optical data. The blue stars show the improved orbital precision resulting when orbital solutions include both radar and optical data. This figure shows that the addition of radar data can make a difference of several orders of magnitude in accuracy over relatively short intervals of observation. If optical data are collected for more than about 25 years, radar and optical results converge to about the same accuracy.

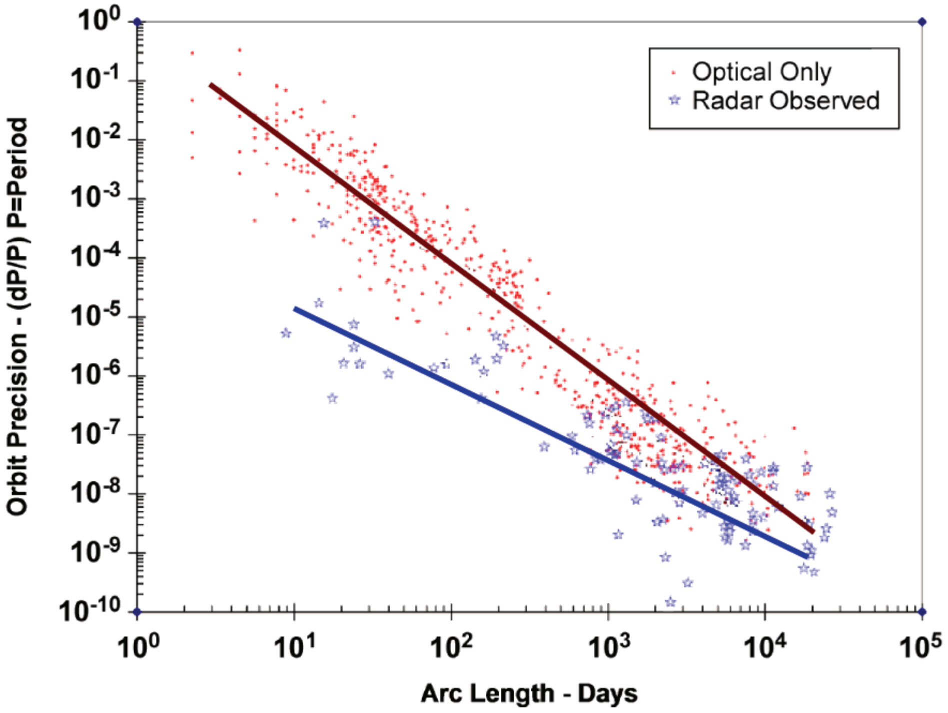


Figure 22. Orbital Precision of PHOs Observed with and without Radar

Figure 23 shows the simulated distribution of orbit quality for a typical survey with and without radar observations. The green curve shows optical-only orbits, e.g., ~75% of cataloged orbits having better than 10^{-5} precision. The blue curve reveals the orbit quality of objects that have been observed by radar, showing the substantial improvement for low-precision orbits and the more moderate improvement for orbits that already have high precision. Assuming an optimistic upper limit for ranging by existing radars of about 10% of the cataloged objects in this size bin (15 – 20 per month) over a 10-year survey, the red curve shows the quality of the combined radar and non-radar catalogs. The modest improvement relative to the green curve is because only a small fraction of objects are radar ranged and because most objects (~75%) have been optically observed at multiple apparitions.

Radar is able to rapidly generate precise orbits for recently discovered objects with short observational intervals, when those objects pass within 0.3 AU of the Earth. This information is useful in deciding whether an object is a short-term threat. For example, radar data may be important for scenarios like Apophis (see Section 5.10.2) where one may need to refine orbits relatively rapidly (less than 5 years) to determine if an object has a high probability of becoming a threat. In short, while radar does not provide a statistically impressive improvement in precisely determining orbits for the entire catalog, radar is important for a relatively few objects of high interest.

Figure 24 shows an estimate of the percentage of asteroids that pass within radar range over a given time period. This corresponds approximately to the probability that any particular asteroid will come within range of the radars during that time.

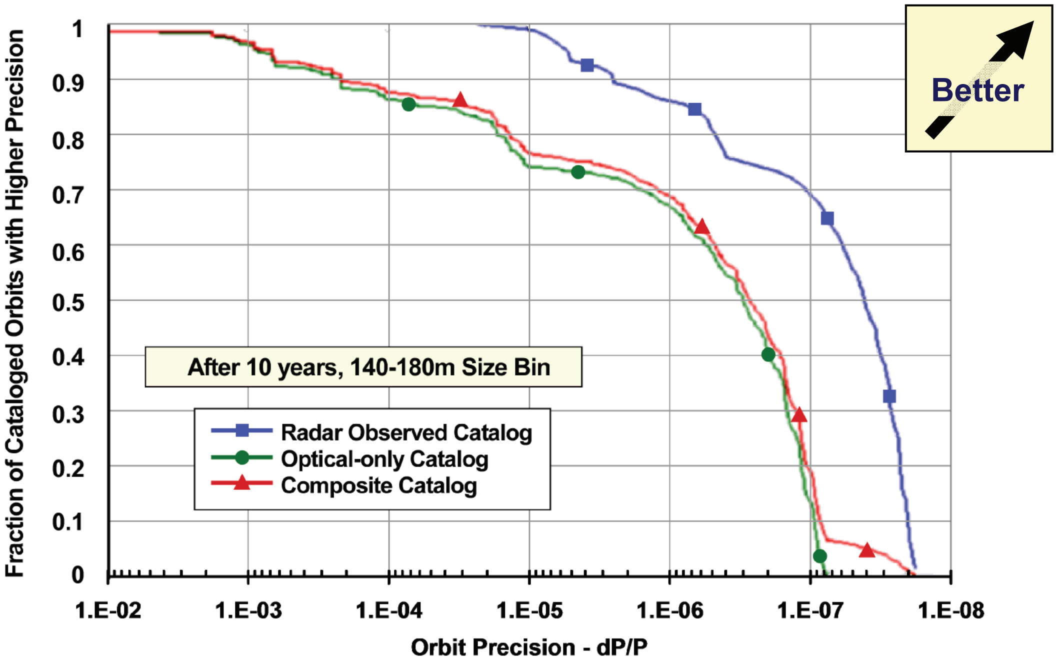


Figure 23. The Benefits of Radar Data in the Orbit Determination Process

5.10.4. Precision Orbit Determination Using a Transponder In-Situ

If an accurate orbit cannot be determined by remote means in time to make mitigation decisions, a mission to the PHO may be required. Most in-situ orbit estimates are accurate to within 1 km, sufficient to predict a potential impact many centuries into the future, assuming no planetary encounters occur. Such an in-situ orbit-determination sensor may be coupled with a spacecraft designed to characterize the threat. [9]

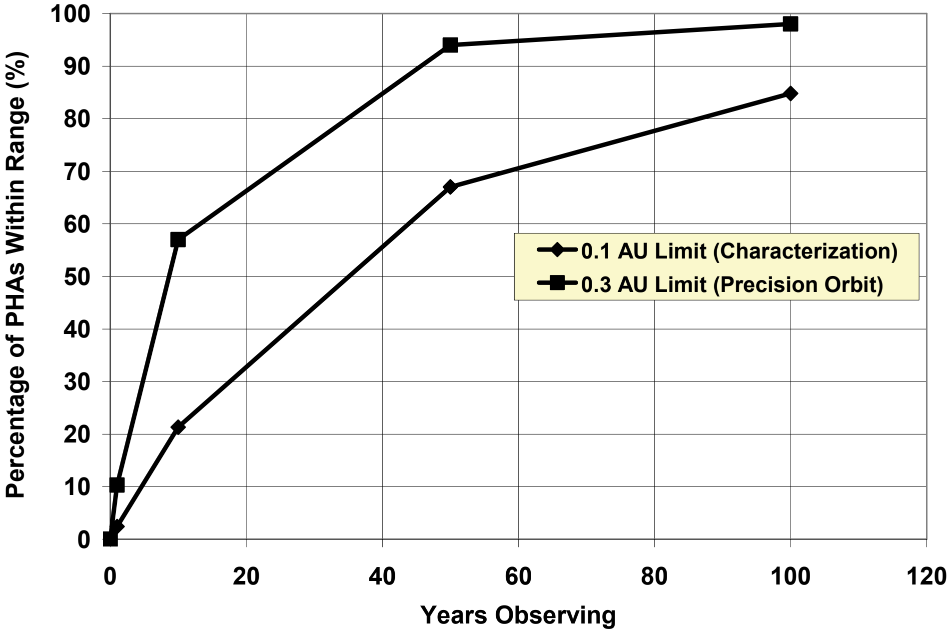


Figure 24. Percentage of Asteroids within Range of Radars

5.11. Detection and Tracking System Element Costs

Figure 25 shows the costs of the detection and tracking elements through 2020. It excludes the costs of cataloguing. Additional cost data are presented in Appendix M.

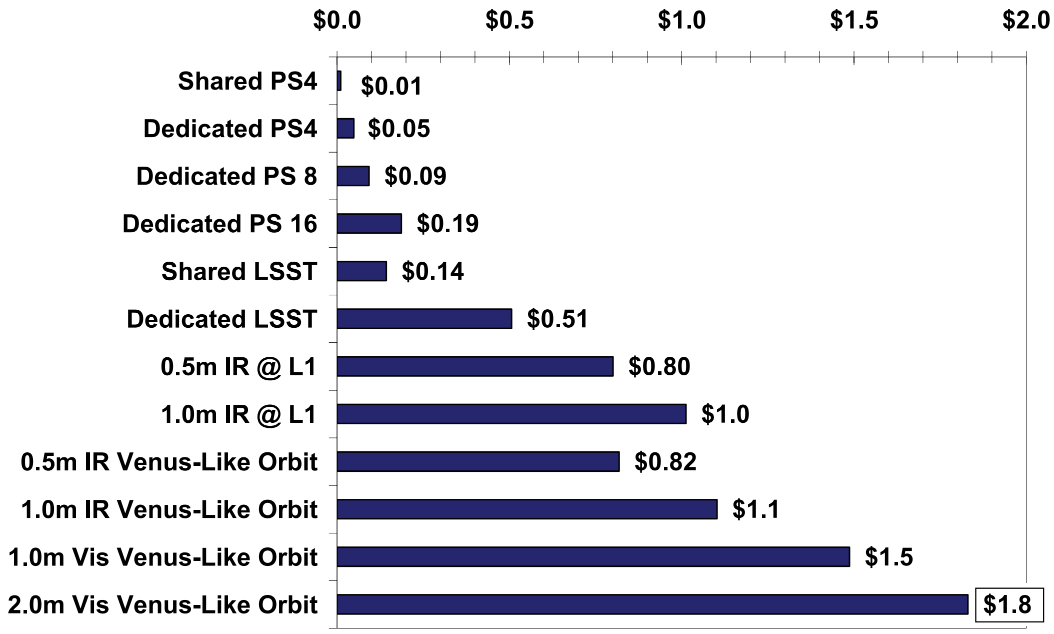


Figure 25. Survey System Elements Costs through 2020

5.12. Object Characterization Trade Space

Figure 26 illustrates the full object characterization trade space. Existing space assets that were considered likely will not be available when the Survey is operating; however, they were evaluated to understand the types of systems that may have utility. Systems that are similar to detection and tracking assets may have different filters, concepts of operations, and data processing which will require additional development. Other variations of theses systems could be considered depending on characterization requirements; however, these are considered representative of the range of systems likely to be the most useful. Five alternatives were in the initial trade space, but the study did not consider analyzing them because of the reasons listed in Table 13.

Table 13. Characterization Alternatives Not Analyzed - Rationale

Concept Name	Rationale for Lack of Further Analysis
SIM PlanetQuest	Insufficient sensitivity, cannot characterize 140m NEOs.
Kepler	Insufficient sensitivity, cannot characterize 140m NEOs. Will only observe 0.25% of entire sky.
JWST	Unable to track NEOs (fast-moving objects).
Dedicated JWST	Unable to track NEOs (fast-moving objects).
WISE	Points away from Earth, takes 6 months to survey sky.

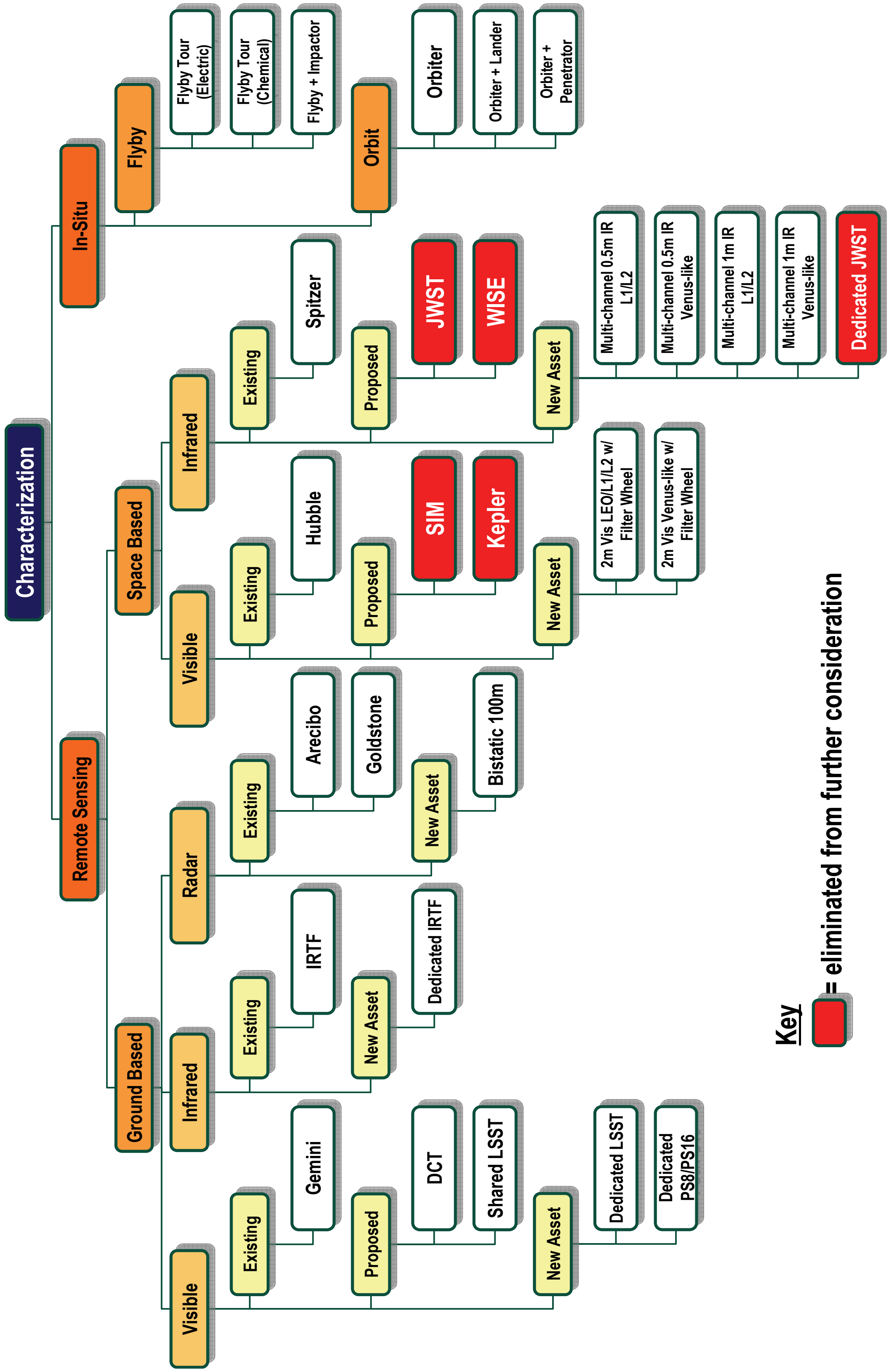


Figure 26. Complete Characterization Trade Tree

5.13. Introduction to Characterization

5.13.1. Object Characterization Parameters Useful for Deflection

Appendix Section J.1.1 describes the object characterization parameters useful for designing deflection missions and potential methods of obtaining this data using remote and in-situ means. These characteristics are tied to specific deflection alternatives in Section 6.9 and Section 6.10.

5.13.2. The Role of Characterization Using Remote Sensing

The role of characterizing objects that do not pose a specific threat to Earth is to provide a *predictive* understanding of the PHO population as a whole. Remote-sensing methods will provide the first information on any newly identified PHO. These data are indirect; therefore, key physical properties (mass, size, composition, spin-rate) must be inferred from the observations. In contrast, a NEO that has been visited by a spacecraft becomes a "standard star." The data from such a visit validates remote-sensing techniques and increases confidence in the models. In the event of "short warning" cases where schedule does not allow a dedicated visit to the PHO, this information would provide the basis for planning mitigation. These short warning cases become less probable as the Survey progresses and are improbable when the population is fully catalogued.

The methods to remotely sense PHOs are the same as those used to study the much larger population of main-belt asteroids, the principal source of NEOs. Thus, known techniques developed over many years are available to carry out these measurements. More recently, adaptive optics and radar have been used to detect asteroidal binaries. This technique can provide unique information about asteroidal masses, just as it has provided unique data on the stellar masses of binary stars. Masses of binary systems may be determined more accurately by using Kepler's law than by observational data alone.

Some of these techniques can be used at many facilities around the world using telescopes of sufficient sensitivity. Other capabilities, such as radar and polarimetry, are available at only a few locations. More important, a cadre of trained observational astronomers needs to be available should characterization work be deemed necessary.

Applying several of these remote techniques to a single NEO forms a hierarchy in the accuracy of the inferred values of the key characterization parameters. As shown in Figure 27, optical-intensity measurements of a newly discovered NEO enable an estimate of its mass to within a factor of about 50. If remotely sensed broadband colors are added, the mass estimate may be improved by a factor of eight. Adding spectroscopic observations to the mass estimates improve accuracy by a factor of five or six. Polarimetric observations can improve the accuracy by about a factor of three, and radar can improve the mass estimate by a factor of 2. Finally, very accurate mass measurements (to 1%) can be achieved only by visiting the object.

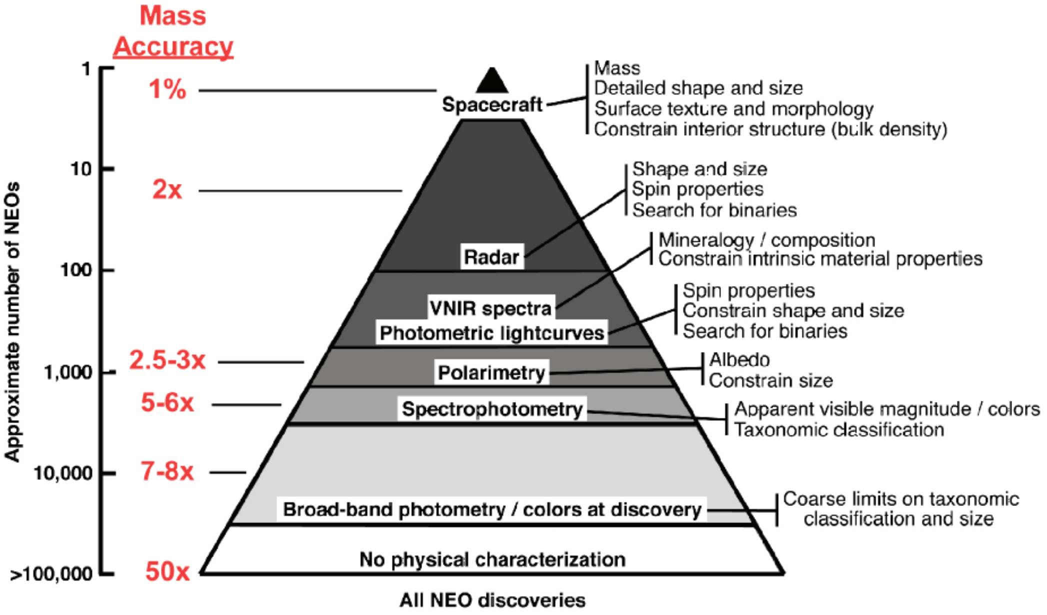


Figure 27. Distribution of Types of NEO Characterization Performed

A key issue with ground-based and non-dedicated space-based activities is access and contention for resources. Astronomical facilities and their focal-plane instruments are scheduled far in advance. On any given night, observations have been scheduled well in advance and some are tied to a particular date. Most PHOs will be discovered near opposition and are best observed while still near opposition. Therefore, capabilities for "on demand" access at major facilities must be in place to effectively use non-dedicated, ground-based remote-sensing techniques. In addition, the rate of discoveries may overwhelm current infrastructure without additional resources. The window of when PHOs may be observed is short; so dedicated facilities may be needed to gather most detailed characterization information for a significant fraction of new discoveries.

5.13.3. The Role of In-Situ Characterization Missions

Remote characterization provides data about the basic characteristics of objects in the population; however, the resulting information requires a measure of inference to determine the actual characteristics of a specific body. While the accuracy of these inferences improves with a wider range of remote characterization methods, only in-situ encounters can provide the definitive observations needed to calibrate remote observations. A much larger number of NEOs must be visited to collect statistically significant characterization information about the object population (the precise number depends on the variation allowed); therefore, it is likely that in-situ visits will be limited to model verification as opposed to model validation.

In-situ characterization of actual threats also may be critical for enabling many of the deflection options described in Chapter 6. It may eliminate the probability of impact for some threats by providing high-precision orbit determination. This will improve the reliability and effectiveness of any deflection campaign.

5.14. Object Characterization Strategy

The characterization required to provide warning of threats and inform mitigation depends on several factors. One factor is the possible relationship between detection, tracking, and characterization elements. For example if a ground-based survey system (such as LSST) is built, its concept of operations will likely limit its ability to do follow-up characterization unless search goals are compromised. 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 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 may be transitioned to contribute to characterization after detection operations are less operationally intense.

Another factor is the relative importance of committing resources to remote characterization to prepare for a potential “short warning” scenario. If short warning scenarios (less than 15 years warning) must be addressed, a statistically valid plan for sampling the diversity of the PHO population must be accomplished before the detection and tracking system can retire the threats. To enable a short warning characterization capability, models of the PHO population must be created and will likely need to be verified by in-situ visits. Model verification missions may include visits to each primary asteroid type or to specific threats as they are identified.

The most important factor in developing the characterization strategy is to tie its requirements to a specific mitigation strategy or selected deflection options. For example, if only standoff nuclear explosive alternatives are considered, little characterization beyond orbit and approximate mass is required. If a space tug becomes the highest priority, more information would be required and a higher investment in characterization is warranted. Due to the diversity of information required to support all deflection alternatives, a very robust program will be required to enable all deflection systems.

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 14. 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 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 credible threats.

For example, a strategy may be to characterize one of the highest risk PHOs discovered during 5-year intervals. This approach would involve visits to representative threats to validate models. It also would provide in-situ orbital determination to verify or eliminate specific hazards at a routine and sustainable mission rate. The orbits of the targets for Option 7 are likely more difficult to reach than those that would likely be chosen for Option 6. The capabilities of these options are evaluated against the deflection alternatives in Section 6.10.

Table 14. 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 at a Fixed Threshold Probability of Impact

5.15. Characterization Option Architectures

Table 15 provides possible timelines for candidate architectures representing each of the characterization capability options. Additional discussion of their costs is presented in Appendix Section M.4.

Table 15. Possible Characterization Option Architectures and Timelines

LCC		Start	End	Architecture Elements								
$0.1B FY06	Option 1: Use Existing Assets + Detection and Tracking Systems IOC Year (Life Cycle Cost FY06$B)	2007	2026	Existing Assets 2007 (*)	Existing Radars 2007 (*)	Shared DCT 2010 (*)	Shared LSST 2014 (0.1)					
$0.2B FY06	Option 2: Option 1 + Dedicated Ground Systems IOC Year (Life Cycle Cost FY06$B)	2007	2026	Existing Assets 2007 (*)	Existing Radars 2007 (*)	Shared DCT 2010 (*)	Shared LSST 2014 (0.1)	Dedicated IRTF 2014 (0.1)				
$1.1B FY06	Option 3: Option 1 + Dedicated Remote Sensing @ L1 IOC Year (Life Cycle Cost FY06$B)	2007	2023	Existing Assets 2007 (*)	Existing Radars 2007 (*)	Shared DCT 2010 (*)	Shared LSST 2014 (0.1)	Dedicated IRTF 2014 (0.1)	0.5m IR L1/L2 2013 (0.9)			
$1.2B FY06	Option 4: Option 1 + Dedicated Remote Sensing in Venus-like Orbit IOC Year (Life Cycle Cost FY06$B)	2007	2024	Existing Assets 2007 (*)	Existing Radars 2007 (*)	Shared DCT 2010 (*)	Shared LSST 2014 (0.1)	Dedicated IRTF 2014 (0.1)	0.5m IR Venus 2013 (1.0)			
$2.0B FY06	Option 5: O1+ O2+ O3 + 2 Flyby Missions IOC Year (Life Cycle Cost FY06$B)	2007	2023	Existing Assets 2007 (*)	Existing Radars 2007 (*)	Shared DCT 2010 (*)	Shared LSST 2014 (0.1)	Dedicated IRTF 2014 (0.1)	0.5m IR L1/L2 2013 (0.9)	Flyby Tour Electric 2013 (0.5)	Flyby Tour Electric 2015 (0.5)	
$6.7B FY06	Option 6: O1+ O2+ O3 + 8 Orbiter/Lander Missions IOC Year (Life Cycle Cost FY06$B)	2007	2031	Existing Assets 2007 (*)	Existing Radars 2007 (*)	Shared DCT 2010 (*)	Shared LSST 2014 (0.1)	Dedicated IRTF 2014 (0.1)	0.5m IR L1/L2 2013 (0.9)	NEO Orbiter 2013 (0.7)	NEO Orbiter 2015 (0.7)	Mission Every 2yrs ... (0.7)
$8.2 FY06	Option 7: Option 6 at Fixed Impact Probability Threshold (every 5 yrs) IOC Year (Life Cycle Cost FY06$B)	2007	2053	Existing Assets 2007 (*)	Existing Radars 2007 (*)	Shared DCT 2010 (*)	Shared LSST 2014 (0.1)	Dedicated IRTF 2014 (0.1)	0.5m IR L1/L2 2013 (0.9)	Lander Every 5yrs 2013 (1.0)	Mission Every 5yrs ... (1.0)	

** Costs less than $50M*

5.16. Characterization Development Schedules

Figure 28 displays the nominal development time for the characterization system alternatives. These schedules are not directly tied to any need date.

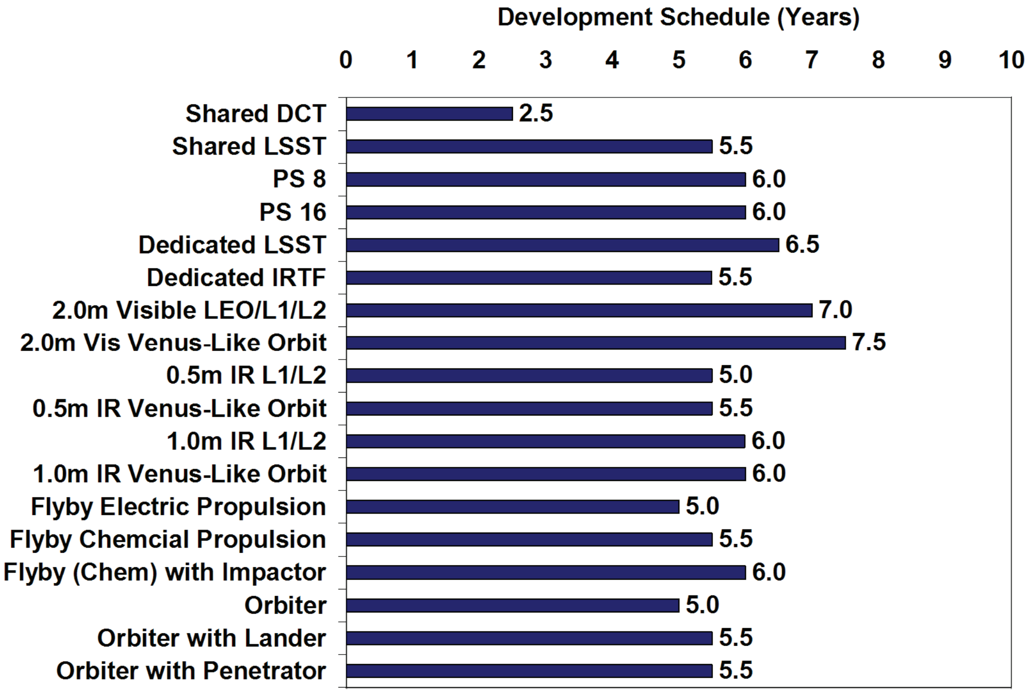


Figure 28. Characterization Systems Development Time

5.17. Characterization Elements Cost Estimates

Figure 29 displays the LCC through 2020 in FY06$B for the characterization concepts.

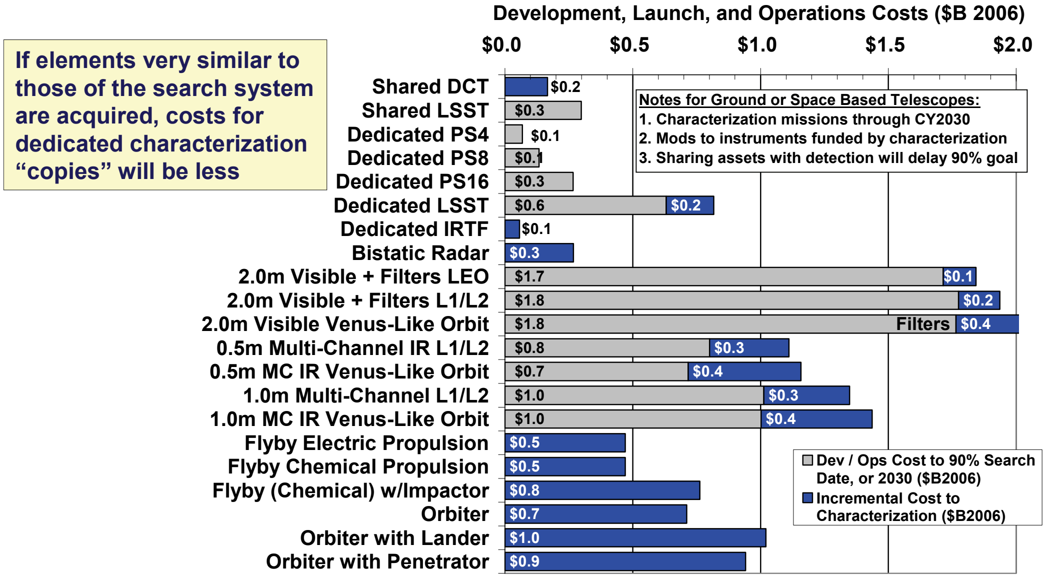


Figure 29. Characterization Alternatives Life-cycle cost Results

5.18. Performance and Cost

Table 16 displays a summary of search alternatives and their life-cycle costs through 2020. Figure 30 and Figure 31 include combined performance and life-cycle cost metrics. Figure 30 displays percentage completeness at the end of 2020 vs. the life-cycle cost of various combinations, all of which include Shared PS4 and Shared LSST as the baseline. Figure 31 displays the year of achieving 90% completeness vs. the life-cycle cost of the same systems. In each figure, related data are grouped and labeled by similar attributes.

Table 16. Summary of Detection, Tracking, and Cataloguing Alternatives

	through 2020	Cost thru 2020 (FY06)	Year 90%	Cost to 90% (FY06)
Continue Spaceguard (in all)	14%	< $0.2B	>>2030	-
Shared PS4 and shared LSST*	83%	$0.31B	2026	$0.52B
Dedicated PS8 + Baseline	85%	$0.41B	2024	$0.56B
Dedicated LSST	85%	$0.66B	2024	$0.87B
Dedicated LSST + Baseline	90%	$0.82B	2020	$0.82B
0.5m IR @ L1 + Baseline	91%	$1.1B	2020	$1.1B
1.0m IR @ L1 + Baseline	91%	$1.3B	2019	$1.3B
0.5m IR @ Venus + Baseline	97%	$1.1B	2018	$1.0B
1.0m IR @ Venus + Baseline	97%	$1.4B	2017	$1.3B
1.0m VIS @ LEO/L1 + Baseline	93%	$1.8B	2017	$1.7B
2.0m VIS @ LEO/L1 + Baseline	95%	$2.1B	2019	$2.0B

* Baseline = Existing + Shared PS4 + Shared LSST

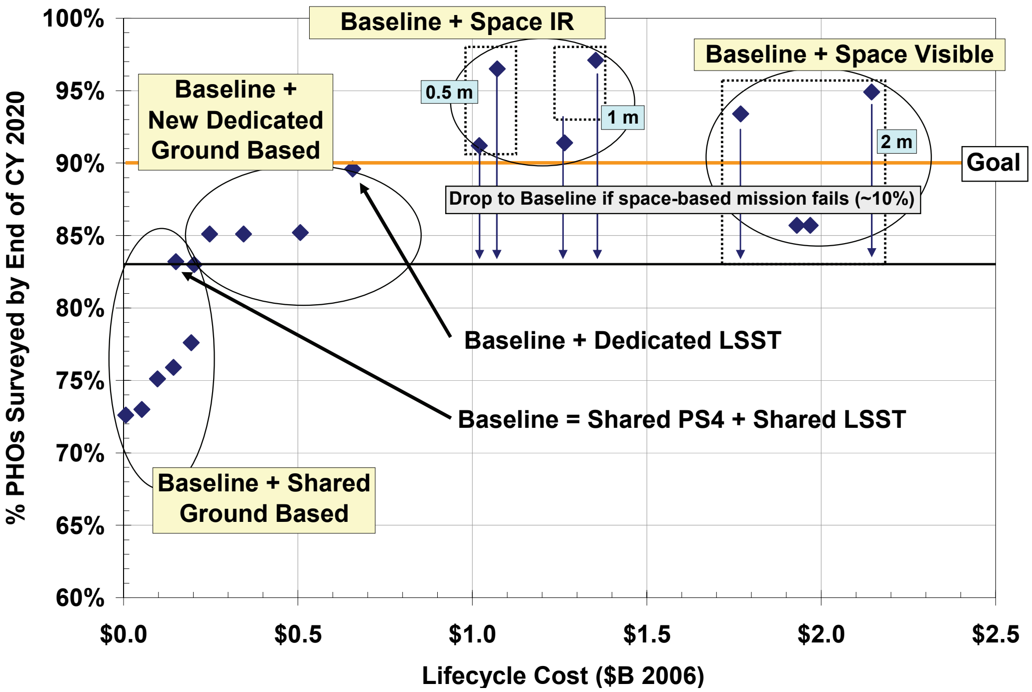


Figure 30. Survey Combinations % Completeness vs. Cost Through 2020

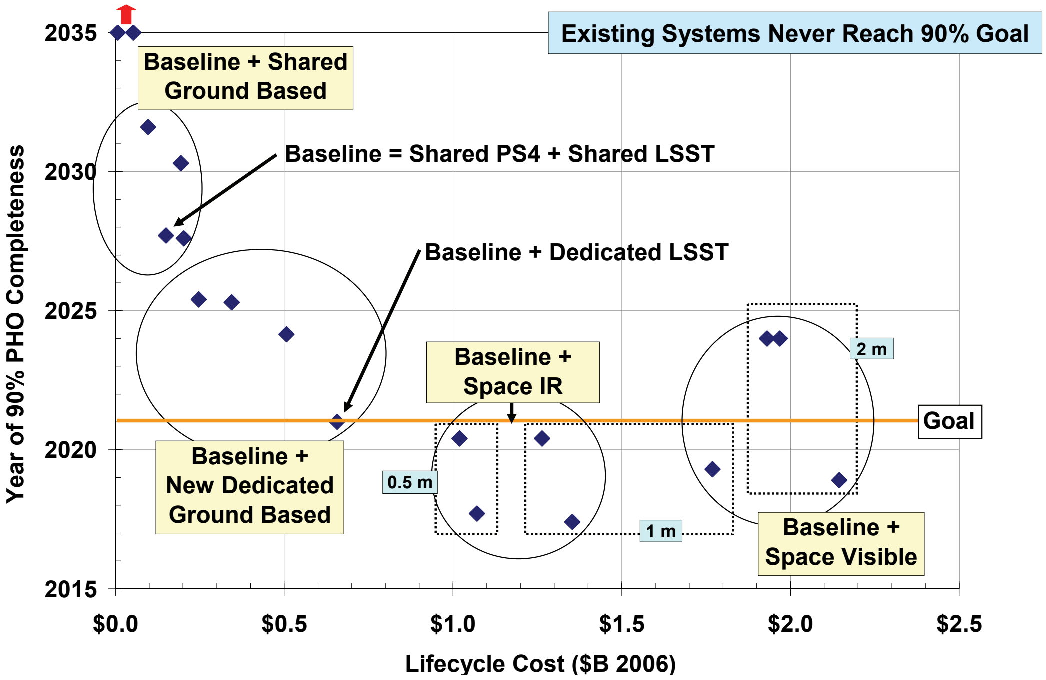


Figure 31. Survey Combinations Date of 90% vs. Life-cycle cost thru 90%

Table 17 summarizes the description and total costs of the seven characterization capability options.

Table 17. Summary of Characterization Capability Options

	Description	Cost (FY06) Period
Option 1	Use existing assets plus detection and tracking system elements. *No dedicated characterization.*	**$0.1B** 2007-2026
Option 2	Develop dedicated ground system(s) to gather and analyze data. *No in-situ missions.*	**$0.2B** 2007-2026
Option 3	Develop dedicated space system(s) to gather and analyze data at Sun-Earth L1. *No in-situ missions.*	**$1.1B** 2007-2023
Option 4	Develop dedicated space system(s) to gather and analyze data near Venus. *No in-situ missions.*	**$1.2B** 2007-2023
Option 5	Add to Options 1-3 eight (8) visits to representative NEOs using fly-bys to calibrate models.	**$2.0B** 2007-2024
Option 6	Add to Options 1-3 eight (8) visits to representative NEOs using rendezvous missions to test models.	**$6.7B** 2007-2031
Option 7	Perform Option 6 at a fixed mission rate to 8 potential threats at 5 years intervals	**$8.2B** 2007-2053

5.19. Program Elements

Part of the congressional direction was for NASA to develop a program to carry out the recommended search and characterization. The following elements are likely to be required by any such program.

Survey and Characterization Systems

- Detection and tracking system (ground and/or space based)
- Orbit improvement/follow-up systems (ground and space)
- Object characterization options (ground, space, and/or in-situ)

Infrastructure for Space-Based Elements

- Communications system
  - No new communications systems are expected to be required, but detection and tracking bandwidth needs to be considered in the NASA communications architecture
- Command and control system

Data Analysis Infrastructure

- Data cataloguing and distribution system
- Preliminary orbital determination and ephemeris generation
- "Precovery" - analysis of archived data of previous observations
- Data collection, validation, archiving
  - Requires upgrade to current Minor Planets Center or new infrastructure
- Precision orbital determination and prediction
- Earth-impact prediction and warning (alerts)
  - Requires upgrade to current JPL and NEODyS capabilities or new systems

5.20. Other Factors

5.20.1. Opportunity Science from the Survey and Characterization

NEOs are primitive bodies, primarily asteroids that represent almost the full range of material contained in the main asteroid belt. The population also contains the nuclei of extinct comets, which likely still reflect the composition of all but the most volatile species, and in particular still contain a significant inventory of organic substances.

The Decadal Survey of the Solar System 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 also will provide data to understand alteration processes.

Most searches will substantially increase the identification of Kuiper Belt Objects (KBOs). For example, if 10% of the observing time on the Dedicated LSST is spent in KBO search mode, roughly 100,000 faint KBOs will 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 also will provide a rich database of destinations for future space missions.

Detection surveys such as 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 yearly timeframes that are required to produce orbits for the slower-moving objects found in the outer solar system. Thus, a collateral result of the search 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 threat assessment and characterization effort will not accomplish. Characterization to inform deflection missions does not require sample return from either an asteroid or comet. Asteroid and comet sample-return missions are high priorities in the Decadal Survey, but are not included in the trade space of this study.

As noted, the Survey program will identify many likely candidates for scientific visits and sample return. Remote characterization will allow the most interesting objects to be selected for scientific visits and will allow the instruments and experiments of these missions to be tailored in ways that otherwise would be impossible. NEOs are generally among the easiest asteroids to visit, and the design of a spacecraft to work in the relatively benign environment near 1 AU offers less cost and risk than a mission to the main belt (crudely the difference between the Near Shoemaker mission and the Dawn mission). 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 less is known.

5.20.2. Potential Benefits to Exploration

5.20.2.1. Near-Earth Object Resources

This study has identified a loose connection between the goals of the Vision for Space Exploration and a program to survey the population of NEOs. There may come a time when Earth's resources are insufficient or too costly to support the planet's growing population. Exploring resources that exist on the Moon, other planets, or NEOs may allow further human expansion.

The survey assets examined by this study will take 5-10 years to provide an extensive map of the orbits and sizes of NEOs to 140 meters in diameter, as well as information on thousands of smaller objects. If infrared survey assets are built, these assets could be turned to the job of characterizing the composition of these objects. In addition, this study has also identified several funded efforts to survey and characterize the NEO population, which likely will come about with minimal NASA contribution.

If asteroid or comet resources prove enabling, having a map of the location and distribution of these assets may prove valuable. An analogy might be the mapping of oases to facilitate transportation across the desert. Assuming that humankind will not be ready to exploit such a map of asteroid resources for at least 30-40 years, it is very likely that this map will be created as a direct product of otherwise funded scientific surveys. If these envisioned efforts do not produce the required information, it is expected that a limited expenditure of time and resources (less than 10 years and $1B) will be needed to produce a map of asteroid and comet resources.

5.20.2.2. Human Visits to Asteroids

It is possible that the systems used to return humans to the Moon could be used to visit a NEO. While NASA has no published plans or budget to pursue such a mission, the NEO survey and characterization program could be used to help select the destination for such a mission. A visit to a NEO could be used to demonstrate technologies for lunar missions, or as an interim goal between lunar and Mars missions.

5.20.3. Potential Synergies with Department of Defense

Potential benefits to DoD and the potential of using DoD assets to augment the NEO survey are discussed in Appendix O.

5.21. Findings

- Combining optical ground-based systems currently under development with a ground-based asset dedicated to the survey would allow NASA to reach the congressional goal of 90% by the end of 2020. Life-cycle costs for the complete architecture, including data management and data analysis, are estimated to be $820M through the end of 2020.
- Space-based infrared systems, combined with shared ground-based assets, could reduce the overall time to reach the 90% goal by up to 3 years, with life-cycle costs of $1.0-$1.3B through 90% completion. Space systems have additional risks and benefits over ground-based alternatives. These benefits include improved estimation of PHO size (via IR), completeness to 90% for smaller object diameters, and an improved understanding of the population of Atens and IEOs.
- The requirement to detect 140-meter PHOs will be near the limiting magnitude of most systems considered and will require these systems to perform their own follow-up observations, unless dedicated assets are acquired. Depending on the follow-up characterization requirements, this may delay survey completeness.
- Atens and IEOs may be under-represented by current population estimates and can best be viewed from assets in a Venus-like orbit. No other vantage point considered in this study offers the opportunity to observe these objects as fully as an orbit well inside that of Earth's.
- The number of objects to be detected does not principally affect the date of completion, however, assumptions about the orbital distribution of objects may.
- Continued operation of the current Spaceguard Survey after the more advanced systems are running will not significantly improve the total discovery potential.

- Collection and storage of as much raw data as possible is important for precovery and follow up.
- Existing data systems, infrastructure, and personnel will be challenged by the increased rate of data collection (up to 100 times more than today) and by the increase in the number of objects. A significantly more robust infrastructure will be necessary to meet requirements. All architectures presented include a robust data program ($150M through 2020), but lower cost options are available depending on further definition of requirements.
- Unpaid astronomers accomplish a substantial percentage of precovery analysis. The ability of unpaid astronomers to maintain this role at the higher absolute magnitudes and at an increased rate of discovery is a significant unknown and may require incentives or substantial funding.
- Many follow-up systems that may be used to characterize PHOs are highly subscribed. They may be able to carry out "on demand" observations, which are necessary for the time that many of these objects are visible. Either "on demand" time needs to be allocated or assets need to be built or partially dedicated to follow-up observations.
- Once the survey is complete, almost every object (to about 99%) will have multiple apparitions of data and any random PHO will, as a result, have centuries of predictable encounters, providing centuries of warning if it becomes a hazard.
- Radar systems can be used to rapidly refine tracking and object size for a few objects of potentially high interest.
    - Both the Arecibo and Goldstone radars are heavily oversubscribed. Only a small percentage of their time is available for asteroid radar.
    - Near-Earth asteroid observations have been cancelled due to insufficient and difficult-to-maintain support personnel.
    - Radars may require immediate and stable funding to be available for follow-up PHO observations. This is particularly true if radar is necessary for the relatively few high-interest objects for which only radar can provide highly precise orbit and characterization data.
- The orbit and approximate mass of PHOs are necessary to determine if they are a threat. Additional requirements for characterization of hazardous objects may be derived from a specific mitigation strategy and the search system selected.
- Systems operated by the DoD were evaluated by this study. They are not expected to contribute to the congressional goals due to differences in mission requirements, concepts of operations, and procedures for data storage.
- While several countries have capable programs to study NEOs, none of these efforts has materially influenced the findings of the study team.

6 Analysis of Deflection Alternatives

6.1. Introduction and Background

If the capabilities of survey systems progress as expected, a PHO that poses a credible threat to Earth will be discovered some day. Sensors will indicate that the object could possibly strike the Earth on a specific date in the future, likely many decades or centuries in the future. Systems will continue to track the object as it proceeds toward Earth.

The probability of impact likely will start at a low level, perhaps on the order of 0.01% or less, meaning there will be one actual impact for 10,000 similar warnings. As tracking data accumulates, the recalculated probability of impact may rise, and likely will remain under 1% for some time. The probability calculation is based on both the PHO's estimated orbit and the orbit's uncertainty at the time of the predicted encounter. If the encounter is many years or decades into the future, the orbit uncertainty may be large because it grows over the prediction period. Additional uncertainty may be introduced if the PHO is perturbed by solar pressure, the Yarkovsky Effect, or if it encounters other objects before impact. Orbit uncertainty is discussed further in Section 5.9. As the object continues to be tracked and the time to impact shortens, the uncertainty will decrease and the probability of impact will change, with most threats being eliminated decades before the possible impact.

Based on this information, decisions will need to be made about how to respond to the threat and whether to launch a mission to reduce the impact probability to some acceptable level, a risk level set at 1 in 1 million in this study. An effort to mitigate the threat may require any or all of the following: time to understand the threatening object; time to debate and resolve political and policy issues; time to approve funding; time to design and build spacecraft; time to obtain the appropriate launch vehicle(s) and launch site(s); time to assess the results of the deflection attempt; and time to make additional attempts, if necessary.

This study differentiates between mitigation in general and the congressional direction to study methods of diverting (or deflecting) an object. Mitigation involves all efforts to reduce the severity of a potential impact with Earth, while deflection specifically addresses diverting the object. Therefore, these terms are not used interchangeably and deflection is generally considered to be one of several possible mitigation options,

A wide range of deflection options were considered and evaluated. Perhaps the simplest of these is the kinetic impactor, where a spacecraft is collided with the PHO to change its orbit so that the object misses Earth. Detonating a conventional or nuclear explosive as part of the deflection effort can increase a kinetic impactor's effectiveness. These are impulsive techniques that act nearly instantaneously to change the velocity of the PHO. In addition, a number of "slow push" techniques such as a space tug also were considered.

6.2. Definitions

6.2.1. Deflection Campaigns

A deflection campaign is defined as the combined series of characterization, deflection, and effectiveness assessments required to mitigate the threat. This may include multiple in-situ characterization missions, multiple deflection approaches, multiple launch systems, and multiple attempts per deflection approach. See Section 6.12 for additional discussion of this topic.

6.2.2. Launch Energy and C3

A parameter that matches launch capability with a certain payload at a certain time (flight time) to intercept an asteroid is C3. It is equal to twice the specific (per unit mass) orbital energy, with units of km^2/s^2. The implications of this parameter on the number of PHOs that can be intercepted are discussed further in Appendix L.

6.2.3. Momentum Exchange Efficiency (beta, β)

Beta factor (β) is a measure of how efficiently momentum transfers after a collision. If the impactor passes through the object or causes material to separate from the object in the direction the impactor was traveling, the beta factor would be less than 1. If a purely plastic collision occurs, that is no ejecta is produced and the impactor is absorbed, the beta factor is equal to one. If the impact ejects material in the direction from which the impacting object came, the momentum of the ejecta adds to that imparted by the impactor. For moderate ejecta production the beta factor increases to around 10. Beta factor is assumed to be ~3 for scenarios in this study, but may vary considerably with specific asteroid type and composition. [34]

6.2.4. Specific Impulse (Isp)

The specific impulse of a propulsion system is defined as the thrust produced per unit weight flow of propellant. It is a measure of propulsion system efficiency. Specific impulse is a useful value to compare the efficiency of rocket engines and is analogous to "miles per gallon" for cars. Specific impulse for space systems varies from around 200 seconds for simple monopropellant systems, to more than 450 seconds for the most energetic hydrogen-oxygen systems and several thousand seconds for low-thrust nuclear-ion propulsion. The chemical engines used in this study assume a specific impulse of 325 seconds (typical for storable propellants) and 8,700 seconds for the conceptual NEXIS ion-propulsion system.

6.3. Derived Requirements

Several requirements were explicit in the definition of this study. For example, Congress directed NASA to study alternatives capable of diverting an object on a collision course with Earth. The derived deflection requirements drawn from the congressional language are as follows.

6.3.1. Derived Deflection Distance Requirement

To assess the effectiveness of the deflection alternatives, the study needs to define deflection. In the context of this study, deflection means imparting sufficient ΔV to a PHO so that it will not strike Earth. Since there are uncertainties about an object's orbit, the amount of ΔV imparted must have sufficient margin to ensure an acceptably low probability of impact. Different scenarios may require different deflection distances to achieve this margin.

Based on the data in Figure 2, there is about a 1 in 1 million chance that an object 1 km or larger will impact the Earth in any year. This is a well-understood level of "background" risk for a well understood asteroid population. Therefore, this study chose this level to indicate a successful deflection attempt. For each scenario discussed in this study, the hypothetically threatening asteroid or comet was deflected a distance to reduce its probability of impact (at the predicted impact date) to 1 in 1 million.

6.3.2. Derived Reliability Requirement

Deflection requirements will have an effect on derived reliability requirements as any unsuccessful mission will reduce the effectiveness of the overall deflection campaign. For example, if there is a 100% probability that a particular asteroid will strike Earth in 50 years and the requirement is to reduce the probability of impact to 1 in 1 million, a deflection campaign must have less than a 1 in 1 million probability of failure. This may be compared with the historical failure rate of more than 10% of interplanetary missions. If warning time permits, deflection missions may be launched incrementally, but random and common-cause failures will continue to play a significant factor in campaign reliability. The impact of these stringent reliability requirements for mission success is developed further in Section 6.12.

6.3.3. Derived Characterization Requirements

Congressional direction states that the basis for characterization missions is twofold

- To provide "*warning*." Therefore, this relates primarily to precisely determining orbits and estimating gross mass/size.
- To inform "*mitigation*." From this statement, other requirements can be derived.

Some deflection alternatives require specific information about the hazardous object, including its shape, rotation rate/axis, multiple primary masses, and composition, while others require less. Some of this information may be gathered remotely, while other data require in-situ visits to the target.

Deflection concepts were not developed to a sufficient degree to produce specific, numerical requirements for characterization. In addition, before a deflection approach is chosen, it may be premature to invest in a broad range of characterization capabilities that may or may not support the selected approach. This is particularly true because the average impact interval of 5000 years means that any preparations for mitigation likely will be obviated (perhaps hundreds of times) by the passage of time. For this study, the team developed a range of characterization capabilities to see if they meet or exceed the notional requirements. If in-situ characterization missions are required for an alternative, the cost of those missions is included in the total cost.

6.3.4. Post-Action Effectiveness Assessment Requirements

If a deflection attempt does not end in complete failure, the PHO's orbit will be perturbed by some amount. After this attempt, the previous long-arc of observations of the object is no longer valid because the PHO will be in a different orbit. Without a radar opportunity or an in-situ aid to determine orbit, there may not be enough time using remote means to determine if the deflection attempt was sufficiently successful or if additional attempts will be required.

NASA has derived a requirement that a post-action effectiveness assessment be performed to understand if further action is required. In most cases, this will take the form of a transponder mission (launched before, with, or after the deflection attempt and possibly part of a characterization mission). This requirement does not materially affect the outcome of this analysis, but does increase by a marginal amount the cost and complexity of all the deflection alternatives.

6.4. Deflecting a Potentially Hazardous Object

Deflecting a PHO requires that the trajectory of the oncoming object be modified so that it will, with an acceptable probability, miss the Earth. Figure 32 illustrates a case where an asteroid has a 1 in 100 probability of striking the Earth some years into the future. The objective of a deflection mission might be to apply enough velocity change, ΔV, to the PHO to reduce the probability of impact to 1 in 1 million or less.

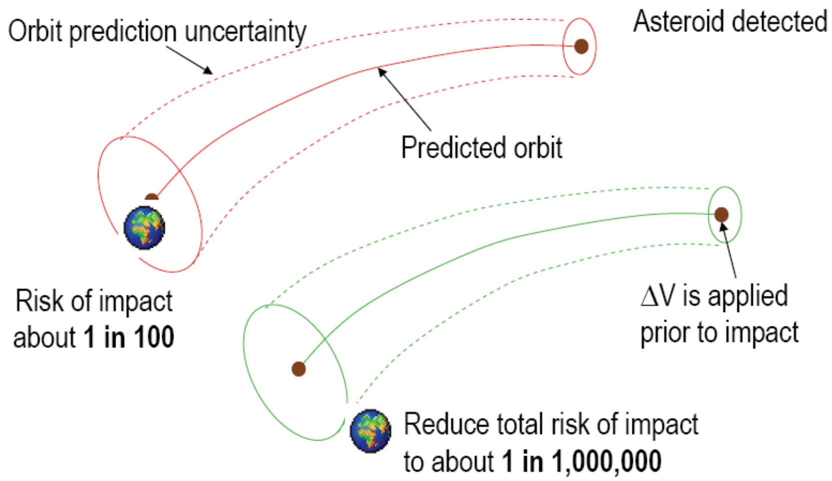


Figure 32. PHO Approach Uncertainties and Deflection Goal

To reduce the probability of impact, the velocity of the PHO must be modified, with the amount and direction of the modification dependent on the specific scenario. As Figure 33 shows, one likely approach would be to change the timing of the PHO's arrival at the intercept point, effectively slowing down or speeding up the object so that it arrives at the impact point at a slightly different time and misses Earth.

Driving a spacecraft into the PHO can change the PHO's velocity, as can activating an explosive device on, in, or near the object, or applying a relatively small force to the body over a longer period. The latter are referred to as "slow push" methods.

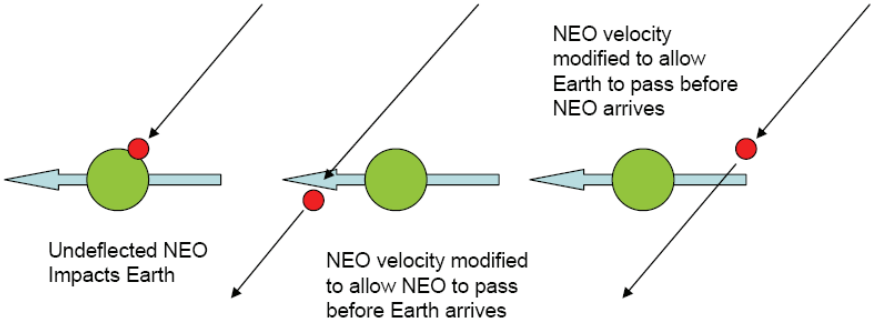


Figure 33. Illustration of PHO Deflection

Figure 34 shows how the ΔV required to deflect a hypothetical PHO changes as the object approaches Earth [23], and how the calculated probability of impact changes depending on how much ΔV is applied. The ΔV required to deflect the object also increases as the object gets closer. The cyclic variation is related to the period of the object's orbit and reflects the point in the orbit where the ΔV is applied. This case is further developed in Section 6.13.4 using the example of the 200-meter asteroid, Athos.

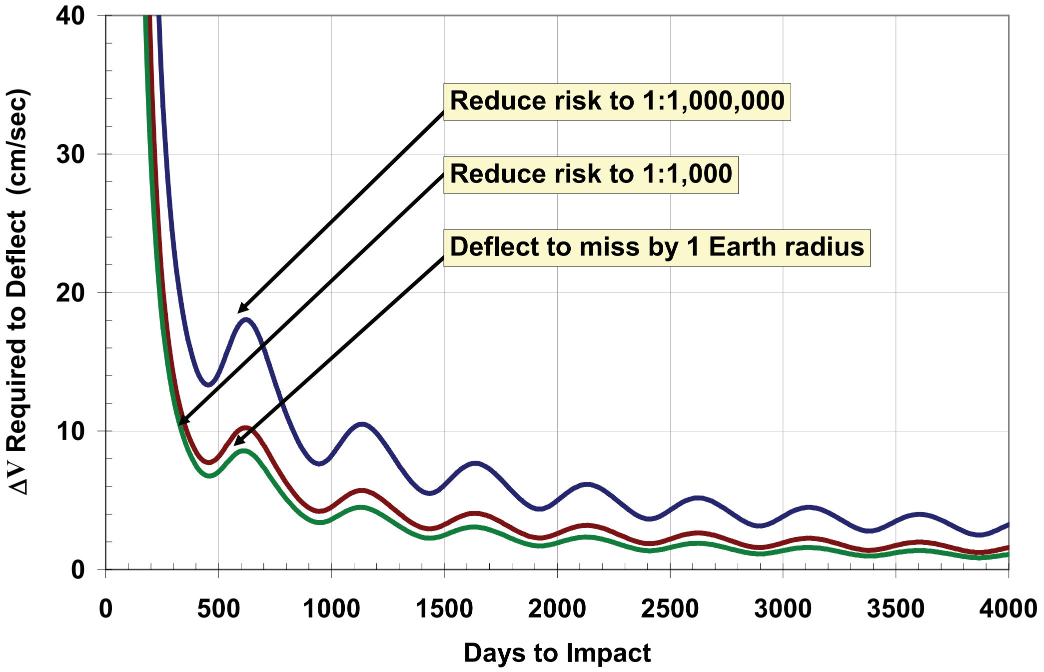


Figure 34. ΔV Required to Deflect a Hypothetical Asteroid

6.5. Deflection Mission Timelines

Table 18 shows a top-level timeline for a deflection mission. As the PHO progresses from detection to the predicted impact point, its orbit is refined. At this point, it is determined to pose a threat to Earth. If sufficient time exists, a characterization mission is launched to gain more knowledge about the object's mass and physical properties and to refine its orbit. This could take place while development begins on a deflection system, but likely will not yield results for a few years due to transit time.

Once deflections mission are designed and funded, hardware is fabricated and launched. Depending on the alternative selected, the action time at the PHO could be instantaneous or could extend over months to years. An important task will be to assess the effectiveness of the action in lowering the probability of Earth impact. If the assessment shows that the effort did not fully accomplish the goal, a second series of missions would be initiated.

Each step along this timeline will require decision making with many types of ambiguous, non-intuitive, and sometimes contradictory information. For example, funding may need to be approved well before it is certain that the PHO will actually strike Earth. It is likely that the greatest element of schedule uncertainty will be due to social rather than technical delays. [24]

Table 18. Potentially Hazardous Object Mission Timeline

	Event	Duration
●	PHO detected, orbit refined	Months to Years
○	Remote characterization performed	Days to Months
○	In-situ characterization designed, launched	2-3 Years
○	In-situ characterization performed	Months to 2 Years
●	Threat threshold exceeded Deflection action initiated	Indeterminate
●	Mission design	Months to 1 Year
●	Funding Approval	Weeks to Months
●	Hardware Fabrication and Test	1-3 Years
●	Approval of Launch(es)	Weeks to Months
●	Deflection Launch and Transit	Months to years
●	Action Time at PHO	Instant if Impulsive 5-10 Years for Slow Push
●	Assessment	Instant (with transponder)
○	Backup Action Initiated	Indeterminate (see above)
✸	Predicted Impact	

● *= Necessary event.* ○ *= Optional event.*

6.6. Figures of Merit

Figure 35 shows the figures of merit used to evaluate the deflection alternatives. The performance metrics focus on the ability of an alternative to deflect an asteroid through the transfer of momentum to the object. Performance metrics include the momentum imparted normalized to the launch mass, the time to deploy and perform the deflection, and the percentage of the PHO population against which the alternative is effective.

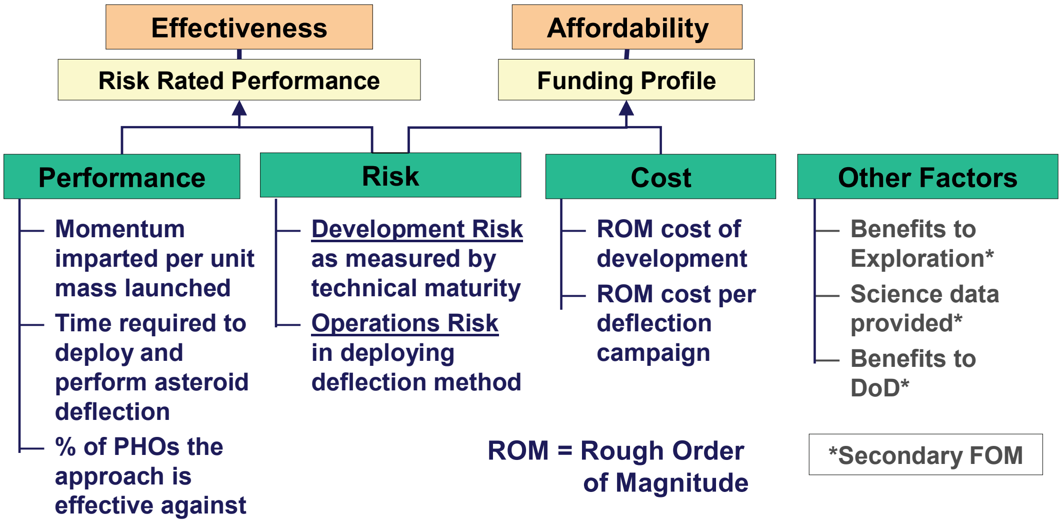


Figure 35. Deflection Figures of Merit

6.7. *Deflection Alternatives Trade Space*

6.7.1. Deflection Alternatives Trade Space

Figure 36 illustrates the deflection alternatives trade space considered in this study.

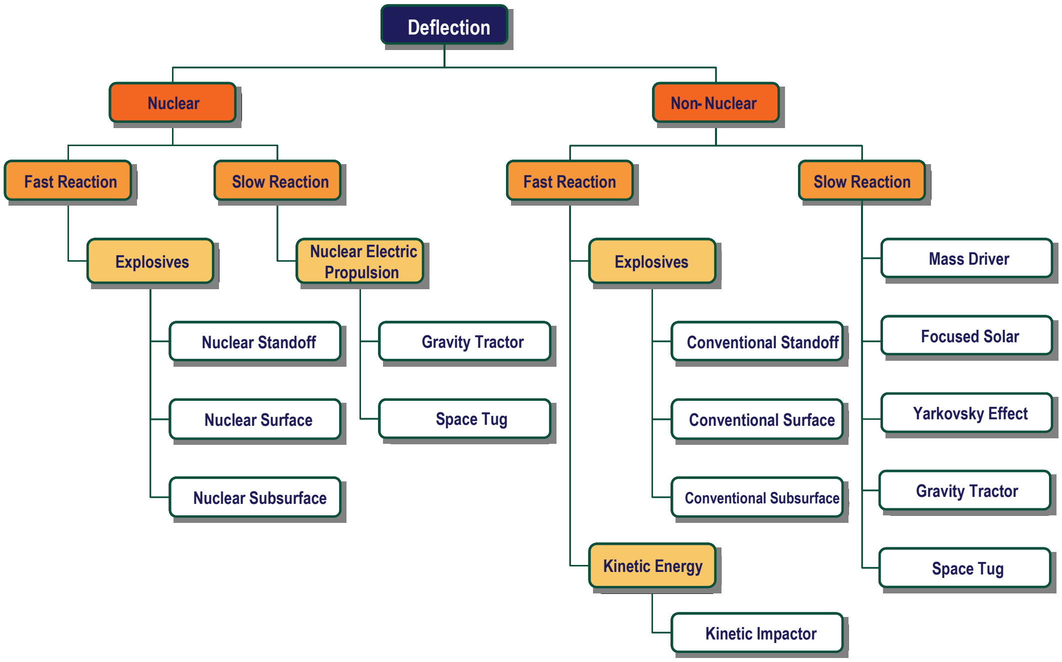


Figure 36. Deflection Alternatives Trade Tree

6.7.2. Deflection Alternatives Analyzed

A representative set of potential PHO deflection approaches was presented during the NEO public workshop described in Appendix D. NASA evaluated some of these alternatives in prior studies. [26] [27] As directed, this study has examined a number of techniques for deflecting a PHO that have been categorized as either "impulsive" or "slow push". Table 19 provides an overview of the impulsive methods, considered in this study. Likewise, Table 20 shows the slow push techniques, where the velocity change results from the continuous application of a small force. Each of these concepts is developed further in Appendix G.

Table 19. Impulsive Deflection Alternatives Considered

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

Table 20. Slow Push Deflection Alternatives Considered

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

6.8. Technology Readiness and Robustness

6.8.1. Technology Readiness

Included in the discussion of each technique is an assessment of its current level of technology readiness. This study developed the assessments by examining the readiness of technologies needed to implement each technique - an approach similar to NASA's system of Technology Readiness Levels (TRL). Reference [28] develops the concept of TRL in detail, and it can be summarized as follows:

If the technology has flown and has been demonstrated in space, it has a high level of technology readiness. If it has not been used before and requires further development before it can be implemented, the technology readiness level is low or medium.

Each of the concepts was developed using information from literature searches, inputs from the NEO public workshop, interviews with members of the community, and by performing any additional analysis required to bring each concept to a common level of detail at the element and system levels. The results for each of the individual technology risks were combined to produce one of the following scores for each technology area:

Low Level of Technology Readiness — Technologies are notional or have evolved to the point where proof-of-principle experiments have been performed. Deflection options in this range might be viable, but system-level technical and experimental verification have not been completed and documented.

Medium Level of Technology Readiness — Technologies involved have been validated at the component, breadboard, or prototype level in a laboratory experiment or a test in a relevant environment. Furthermore, analysis and testing have validated the basic concepts.

High Level of Technology Readiness – A subsystem/system prototype has been demonstrated in the space environment or in an actual test of the complete system through flight operations. Elements of the concept have been demonstrated by testing and/or actual operations, or they are thought to be readily achievable by analog.

6.8.2. Overall Effectiveness

Overall effectiveness is defined as the ability to apply the concept to the range of PHO threats, taking into account the range of orbit trajectories, ranges for PHO size and mass, and the variety of PHO types. Deflection alternatives will be evaluated as **Very High Effectiveness, High Effectiveness, Medium Effectiveness,** or **Low Effectiveness** according to their ability to address the different PHO threats. Effectiveness scores are not absolute measures; they are relative to other alternatives.

6.8.3. Readiness and Effectiveness Summaries

Table 21 combines the technology readiness scores from Table 47 in Appendix Section H.4 with assessments of the effectiveness of each alternative that uses an impulsive technique. Likewise, the results in Table 48 in Appendix Section H.4 are used to create Table 22. The rationale for each readiness and effectiveness score is discussed in Appendix Sections G.1 and G.2 respectively and are summarized in Appendix H.4.

Table 21. Impulsive Alternatives Readiness and Effectiveness Summary

"Impulsive" Concepts	Readiness	Effectiveness
Conventional Explosive - Contact	High	Medium
Conventional Explosive - Subsurface	Medium	Medium
Kinetic Impact	High	High
Nuclear Surface Contact	High	Very High
Nuclear Standoff	High	Very High
Nuclear Subsurface	Medium	Medium
Nuclear Surface Delayed	Medium	High

Table 22. "Slow Push" Alternatives Readiness and Effectiveness Summary

"Slow Push" Concepts	Readiness	Effectiveness
Enhanced Yarkovsky	Low	Low
Focused Solar	Low	Medium
Gravity Tractor	Medium	Medium
Mass Driver	Low	Medium
Pulsed Laser	Low	Medium
Space Tug	Low	Medium

6.9. Linkage of Characterization and Mitigation

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

Second, characterization is needed when an actual threat is identified. For some alternatives, little characterization beyond mass and orbit will be required, although additional information may improve performance. For others, precursor missions will be required to assure the successful design and implementation of the mission.

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

To inform such a short warning case, 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. This information may allow planners to begin designing a deflection mission without first launching an immediate in-situ mission.

Table 23 and

Table 24 show a qualitative assessment of the characterization requirements for impulsive and slow push techniques respectively. These would apply to any development and design programs, regardless of whether they were initiated ahead of an actual threat or with the discovery of one. In all cases, it is assumed that sufficient information is available about the PHO's orbit to design a deflection mission.

Table 23. Characterization Required for Impulsive Alternatives

	Mass	Spin	Density	Material Properties	Size & Shape	Surface Properties
Conventional Expl. Surface - Contact	Yes	No	Helpful	Helpful	Helpful	Helpful
Conventional Expl. Subsurface	Yes	No	Helpful	Helpful	No	No
Kinetic Impactor	Yes	No	Helpful	Helpful	Helpful	No
Nuclear (Contact)	Yes	No	Helpful	Helpful	Helpful	No
Nuclear (Standoff)	Yes	No	No	No	No	No
Nuclear Explosive (Sub-Surface)	Yes	No	Helpful	Helpful	No	No
Nuclear Explosive (Surface Delayed)	Yes	Yes	Helpful	Helpful	No	Helpful

Table 24. Characterization Required for Slow Push Alternatives

	Mass	Spin	Density	Material Properties	Size & Shape	Surface Properties
Yarkovsky	Yes	Yes	No	No	Yes	Yes
Focused Solar	Yes	Helpful	No	No	No	Yes
Gravity Tractor	Yes	Yes	No	No	Yes	No
Mass Driver	Yes	Yes	Yes	Yes	Helpful	Helpful
Pulsed Laser	Yes	Helpful	No	No	No	Yes
Space Tug	Yes	Yes	No	No	Yes	Yes

For example, if there is a factor-of-two uncertainty over the object's mass, a mission must be designed to deflect the heavier body. Similarly, the design of a slow push technique would be based on moving the largest mass anticipated and lengthening the mission duration by the scale of the uncertainty. In both cases, the weight of the payload launched from Earth and the overall cost of the campaign would increase.

In all cases, information on material properties, size, shape, albedo, rotation rate, axis of rotation, etc., reduces the uncertainties associated with the deflection mission, increases the likelihood of success, and decreases the overall cost of the effort.

6.10. Characterization Options Capabilities Matrix

The characterization options developed in Section 5.15 are connected to specific deflection alternatives in this section. If any the seven options are executed, Table 25 describes the deflection options enabled by each if no other characterization is available before the deflection mission is initiated. These primarily correspond to a “short warning” scenario where a dedicated in-situ characterization mission is not possible, except in the case of Option 7 which assumes an in-situ visit. An in-situ mission before the start of a deflection program obviates much of the need for remote characterization if sufficient time is available.

Table 25. Deflection Alternatives Enabled by Characterization Options

	Characterization Capability Options						
Deflection Alternative*	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Nuclear Subsurface[a]	Y	E	E	E	E	E	E
Nuclear Surface[b]	Y	E	E	E	E	E	E
Nuclear Surface delayed[c]	N	N	N	N	N	N	Y
Nuclear Standoff[d]	Y	E	E	E	E	E	E
Kinetic Impact[e]	Y	E	E	E	E	E	E
Subsurface Explosive[f]	Y	E	E	E	E	E	E
Surface Explosive[g]	Y	E	E	E	E	E	E
Space Tug – Non-rotating[h]	N	N	N	N	N	N	Y
Space Tug – Rotating[i]	N	N	N	N	N	N	Y
Gravity Tractor[j]	Y		E	E	E	E	E
Life-cycle cost FY06$B	**0.1**	**0.5**	**1-2**	**1-2**	**2-3**	**5-8**	**5-8**

* *rationale for scores provided below*

A column in Table 25 is marked “Y” only if the characterization option is both necessary and sufficient to enable an effective deflection. If it exceeds the requirements, it is marked “E”. If it is not sufficient, it is marked “N”. These scores do not reflect the effectiveness of the option, which may be enhanced with additional characterization.

Rationale for Scores in Table 25:

a. Nuclear subsurface is aided by information about the specific PHO’s surface and composition, but remote characterization methods likely are sufficient.

b. Nuclear surface explosions could use remotely gathered data and effectiveness would be augmented by in-situ verification.

c. A delayed surface blast cannot occur until the orbit is properly phased, and therefore will require knowledge about the PHO’s surface.

d. A nuclear standoff explosion would not require any information other than the PHO’s mass and orbit, which can be estimated by all options.

e. A kinetic impact concept would not require any information other than mass and orbit, which can be obtained by all options. If the object is highly porous, a kinetic impactor may be ineffective.

f. A conventional subsurface explosive is aided by information about a specific PHO’s surface and composition, but remote methods are likely sufficient.

g. A conventional surface explosion could use remote data and effectiveness would be augmented by in-situ verification.

h. A non-rotating space tug requires information about the surface and composition of the specific threat; remote characterization methods are likely insufficient.

i. A rotating space tug requires information about the surface and composition of the specific threat; remote characterization methods are likely insufficient.

j. A gravity tractor would be enabled with knowledge about the object’s shape and rotation, which could be obtained on station for most objects. Detection assets may be adequate depending on type and vantage point.

6.11. *Deflection Performance Analyses*

6.11.1. Deflection Performance Analysis Methodology

To compare the relative performance of the proposed asteroid deflection concepts, the change in PHO momentum, based on the maximum available launch mass, is calculated. Available momentum change for both the Delta IV Heavy (largest current launch capability) as well as the Ares V Cargo Launch Vehicle (proposed lunar cargo vehicle) will be calculated using the methods described in Sections 6.11 and H.3.

6.11.2. Deflection Performance Analysis Assumptions

Several assumptions are inherent in the following performance summary.

- Impulsive deflection concepts assume that the launch vehicle is used for direct intercept. For delayed surface methods, this is an optimistic assumption.
- During targeting maneuvers, it is assumed that 1,400 kg of propellant will be consumed. This amount of propellant is an average, which was developed across a series of simulations, and will vary for systems with system mass and operations.
- Impulsive concepts assume that the PHO will not experience large-scale fracturing. For kinetic impact concepts, collision elasticity was parameterized. Momentum efficiency was assumed to be perfectly plastic or to experience significant PHO ejecta. This assumption may not be valid when a PHO is a loose rubble pile. In this case, mass may be ejected in the direction of impact and the concepts may be less effective.
- For standoff nuclear concepts, a 200-meter asteroid, with 50% porosity, was assumed. This is based on the results from Holsapple and Gennery. [29] [30] The standoff distance was chosen as 10% of the object’s diameter, and assumes that spin axis and shape can be determined en route. There is a strong correlation between standoff distance and effectiveness, and a non-optimal standoff distance could reduce effectiveness by one-to-two orders of magnitude.

- It was assumed that current nuclear explosive technology could produce a device that yields 1-2 kt TNT per kilogram of dry mass. When considering standard nuclear explosives, it was assumed that 1% of the yield are neutrons.
- The gravity tractor standoff distance was assumed to be 1.5 times the radius of the object to be towed. Other analyses have considered a standoff distance as small as 0.5 radii. This assumption would yield a performance improvement of a factor of three, but will not alter the findings of this report.

6.11.3. Deflection Performance Analysis Results

Figure 37 and Figure 38 are graphical representations of the 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. The launch C3 corresponding to payload capabilities of the two launch systems considered 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 velocity. 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 (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 available and that C3 = 25 km^2/s^2 is required to intercept, all but the kinetic interceptor and the conventional explosives would meet performance requirements. Likewise, none of the slow push techniques could meet this hypothetical requirement.

Figure 37 shows that impulsive techniques using proximal nuclear explosives generally provide greater potential for momentum transfer per kilogram of payload weight delivered to the threat than any other option considered. Standoff nuclear concepts have 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 explosive used and whether it is "off-the-shelf" as opposed to optimized for the PHO deflection mission. The performance of kinetic impactors is somewhat less robust than any of the nuclear explosions; however, their effectiveness depends strongly on the structure of the PHO. Kinetic impactors also may be significantly less effective for loose rubble piles. Conventional explosives have the lowest performance among the impulsive techniques due to their relatively low-energy density.

Figure 38 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 generally provide greater potential for momentum transfer per kilogram of payload weight delivered to the NEO than other alternatives. Each concept is described in detail in Appendix G.

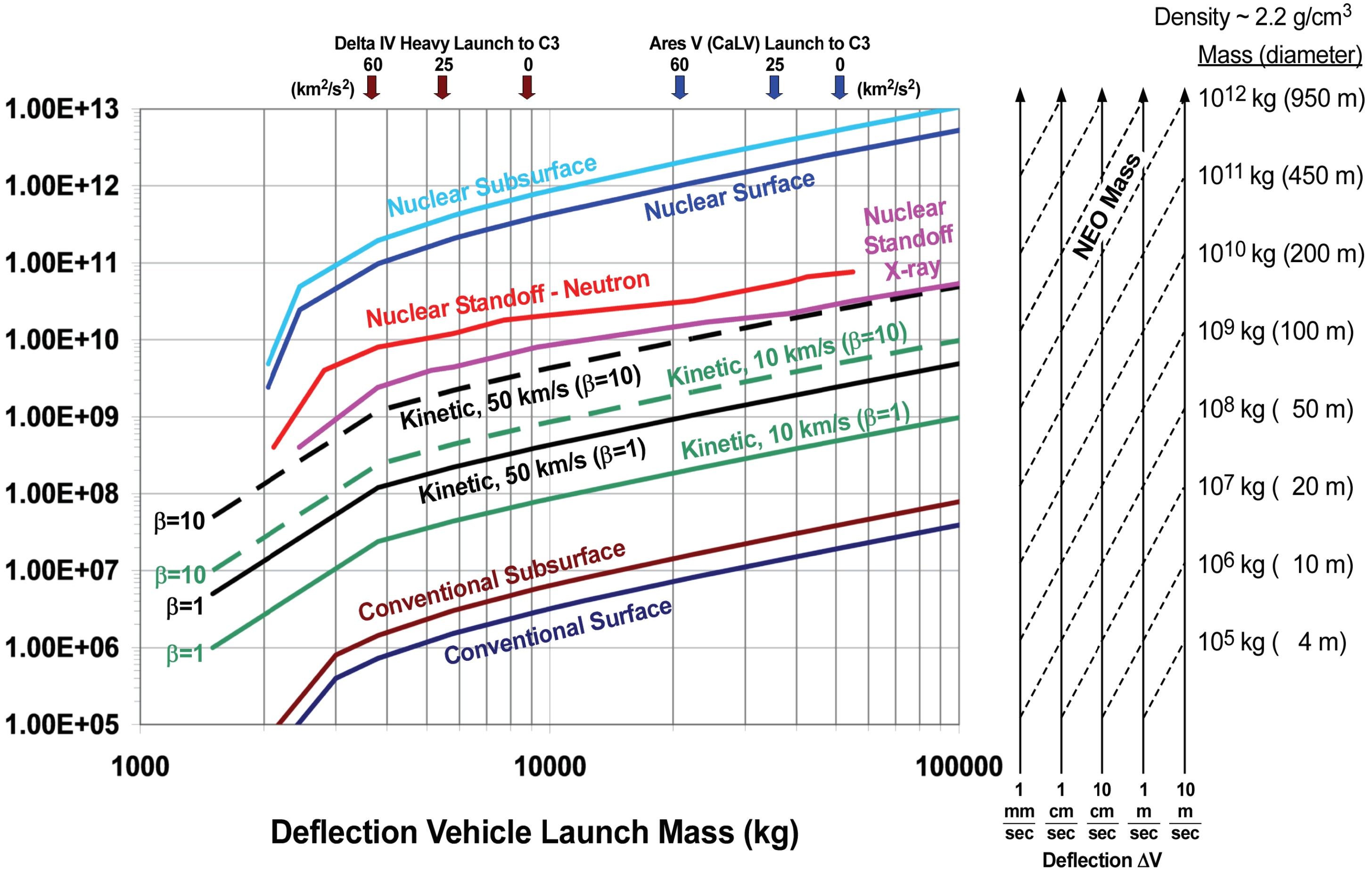


Figure 37. Deflection Performance of Impulsive Alternatives

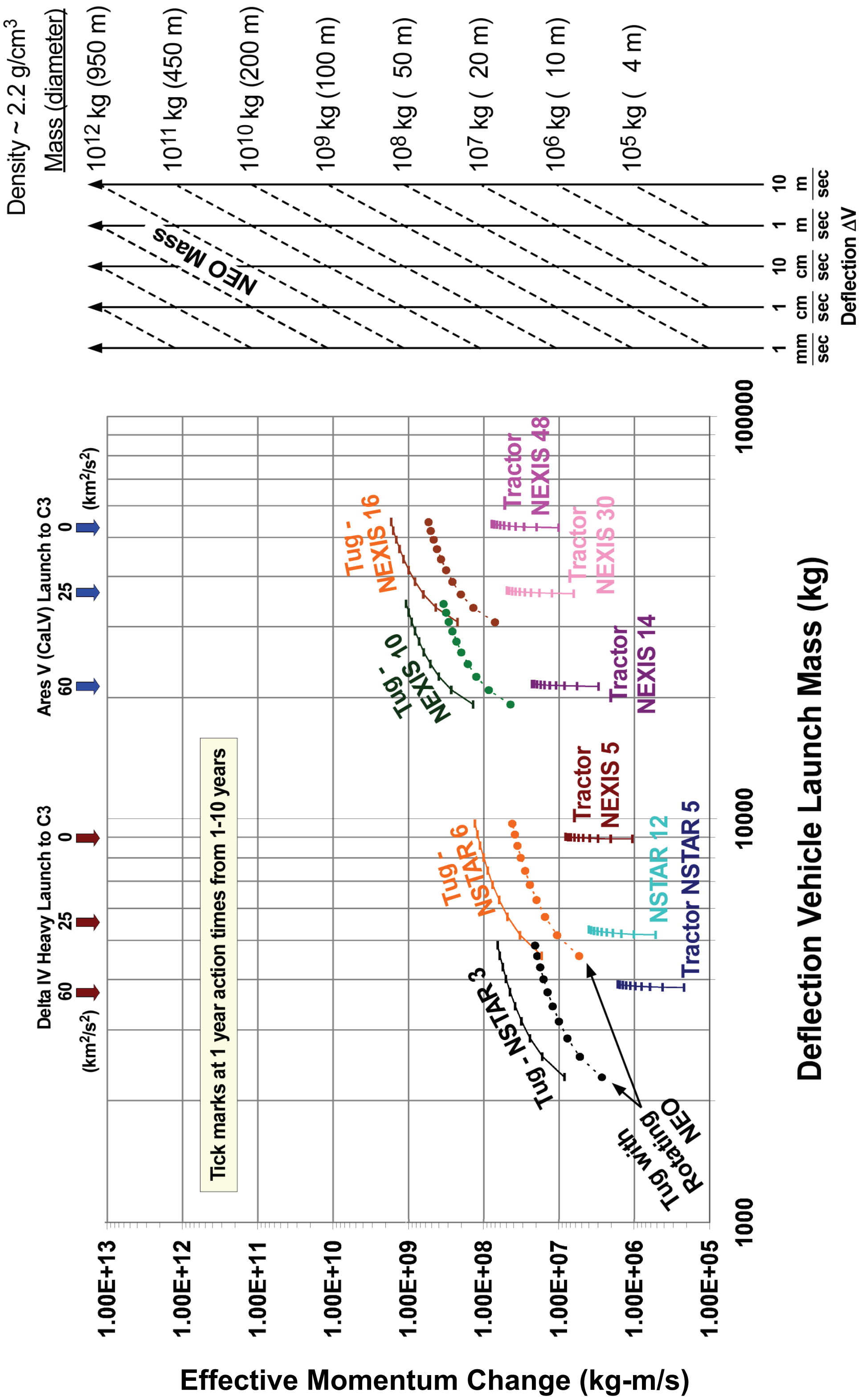


Figure 38. Deflection Performance of Slow Push Alternatives

6.12. Deflection Mission Operations Risk

6.12.1. Overview

The purpose of this section is to explore reliability requirements for deflection. For example, if the goal is to reduce the risk of impact from 1 in 1,000 to 1 in 1 million, the chance of deflection failure must be less than 1 in 1,000. This requirement is two orders of magnitude more stringent than the typical 1 in 10 chance of failure experienced by planetary missions. For higher probabilities of impact, higher reliabilities are required to meet the requirement, although an incremental mission approach may reduce the overall cost of successful deflection if sufficient time to deflect is available.

An approach is developed to illustrate mission reliability tradeoffs. This is done by generating plots overall failure risks as a function of

- Reliability of individual space missions (90-99%)
- Architecture of the deflection “campaign” (number, type of missions)
- Number of independently developed approaches
- Number of attempts for each approach

Also, it is considered that several ways may exist to increase a campaign’s reliability or chance of collateral damage:

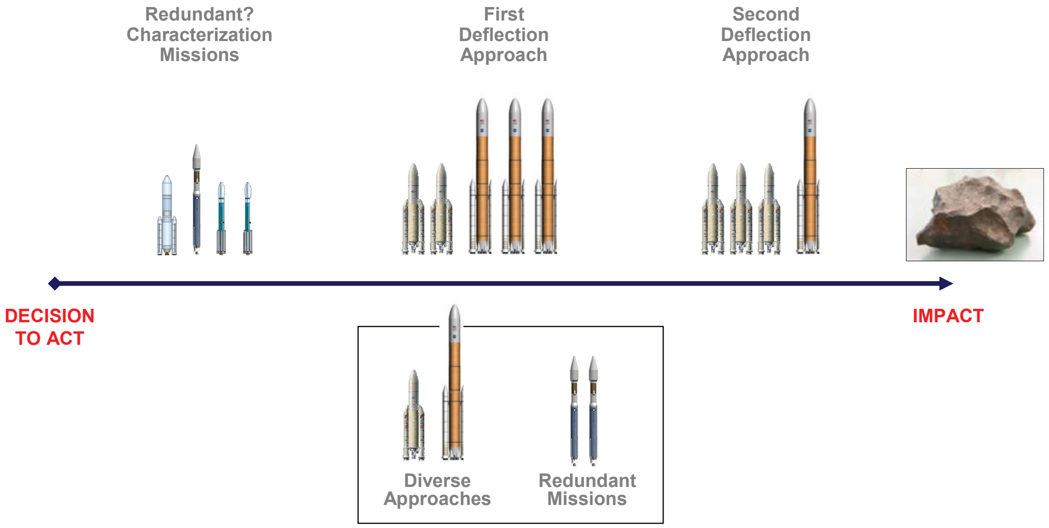
- Diverse deflection approaches to reduce risk of common-cause failures
- Redundant missions for each approach to reduce risk of random failures
- Precursor characterization missions, if time permits, to tune the deflection approach and increase reliability

The first three of these are explored in a parametric manner.

6.12.2. Notional Deflection “Campaign”

The campaign to deflect an asteroid will involve more than just a single intercept or rendezvous mission, as suggested by popular movies. If sufficient warning time is available, a series of precursor characterization missions, followed by a wave of one type of deflection mission. If the first wave fails, then a series of more robust interceptors might be launched in a second wave.

Thus, depending on the warning time and the size of the asteroid, some number of redundant missions and diverse design approaches will be needed to eliminate the threat. Figure 39 illustrates one possible scenario.



Mission Failures = Random Failures + Common Failures

Figure 39. Illustration of Types of Deflection Mission Redundancy

6.12.3. Parametric Reliability Calculations

Two basic failure modes need to be considered:

- Independent random failures
- Common-cause failures that affect all flights of a given approach

In the following parametric reliability plots it is assumed that:

- All space missions (characterization or deflection) have the same random and common-cause failure rates, except in the excursion where it is assumed that the common-cause failure rate for deflection is reduced if information is received from a successful precursor characterization mission
- Common cause modes are independent among the different characterization and deflection approaches.

6.12.4. Precursor Characterization Not Required

The risk of overall failure in this case is

$$Risk = P_n^m$$

Where

m = # of independent approaches
n = # of attempts per approach
$P_n = 1 - (1 - F_n)(1 - C)$
F = random failure rate
C = common failure rate

The overall probability of failure is plotted in Figure 40 as a function of the failure rate for a single generic space mission, assuming that 80% of the failures are random and 20% are due to a common cause in the particular design.

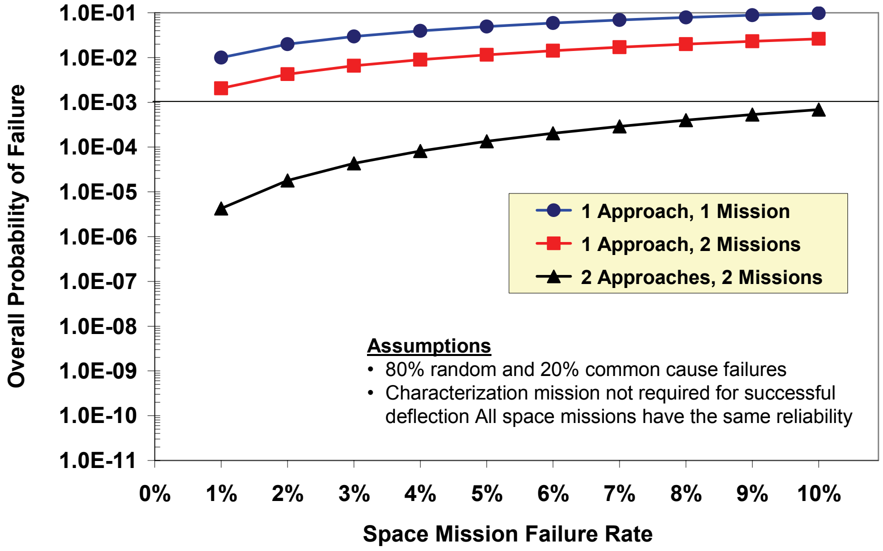


Figure 40. Chance of Deflection Failure if Characterization is Not Required

To achieve a hypothetically "required" failure rate of 0.001 or less, two or more independent interceptor designs and at least two redundant missions for each design are required. Just increasing the number of redundant missions with a single design will not reduce the overall risk below a certain level, regardless of the assumed space mission failure rate.

6.12.5. Precursor Characterization Required

The risk of overall failure in this case is

$$Risk = 1 - (1 - P_n^m)^2$$

Where

m = # of independent approaches
n = # of attempts per approach
$P_n = 1 - (1 - F_n)(1 - C)$
F = random failure rate
C = common failure rate

The risk is plotted in Figure 41 as a function of the failure rate for a single space mission, assuming that 80% of the failures are random and 20% are due to a common cause in a particular design. The overall probability of failure is higher in this case because a successful outcome depends on having at least one successful characterization mission and one successful deflection mission.

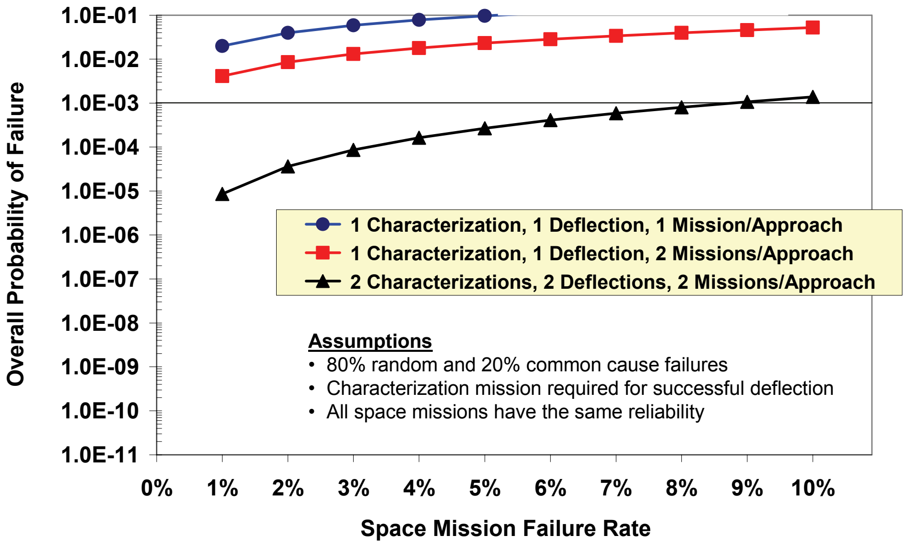


Figure 41. Chance of Deflection Failure when Characterization is Enabling

Assuming the space mission failure rate does not exceed 8%, two or more independent interceptor designs and at least two redundant missions for each design would be adequate to meet the hypothetical "requirement" of 0.001 or less.

6.12.6. Characterization Reduces Common-Cause Failure Rate

The risk of overall failure in this case is

$$Risk = (P_n^m)(P_n^m) + (1 - P_n^m)(P_n'^m)$$

Where

m = # of independent approaches
n = # of attempts per approach
$P_n = 1 - (1 - F_n)(1 - C)$
F = random failure rate
C = common failure rate
$P_n' = 1 - (1 - F^n)(1 - rC)$
r = reduction factor (0 – 1) for common failure rate for successful deflection characterization

In this case the overall probability of failure is lower because characterization improves the reliability of deflection (over the baseline reliability), but is not required for deflection, as shown in Figure 42. Unless the space mission failure rate can be reduced to less than 3%, two or more independent interceptor designs and at least two redundant missions for each design would still be necessary to meet the hypothetical 0.001 "requirement."

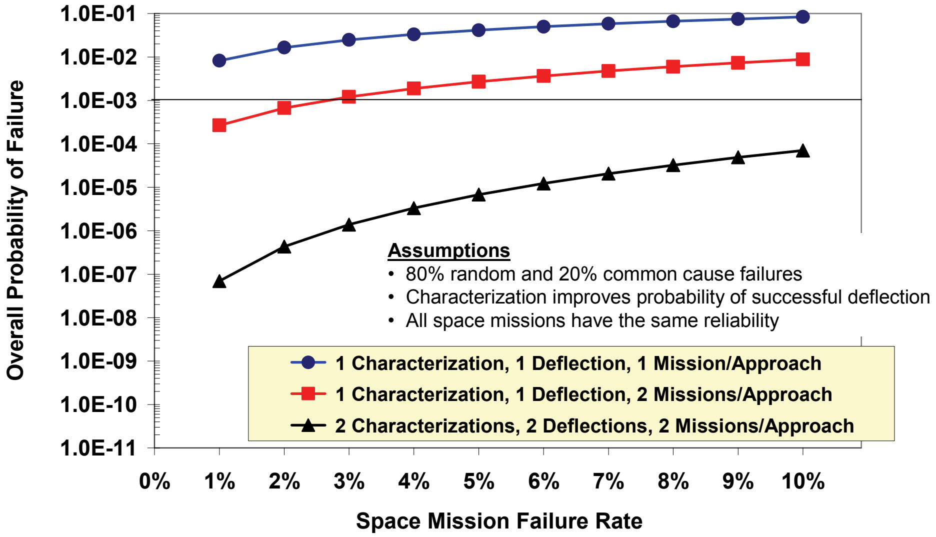


Figure 42. Chance of Deflection Failure if Characterization is Enhancing

6.12.7. Summary

Linking the reliability of the deflection method to the probability of impact reduction may seem unrelated. However, as an example, assume that the impact cannot be calculated to better than 1 in 10 in time for deflection; therefore, there are nine "near misses" for each "impact" predicted. Assume, too, that the probability rate must be reduced to 1 in 1,000. With this allowable threshold, for every 1,000 warnings, one impact will occur (likely an unacceptable level, but chosen to illustrate the example).

If no deflection missions are attempted, 100 impacts and 900 "near misses" will occur for the 1,000 warnings. If deflection campaigns are very unreliable (10% reliability, for example), 90 impacts will occur, leaving a risk of 9 in 100, well above the acceptable threshold in this example. If deflection is 99% effective, only one of the 100 actual impacts will occur and the required risk of 1 in 1,000 will be achieved. Finally, if no probability of impact is acceptable, then the deflection campaigns will need to be 100% reliable or some impacts will occur.

This analysis emphasizes that the reliability requirements for asteroid deflection are much higher than the current success rates for interplanetary missions. To achieve levels of confidence in overall mission success commensurate with significant reductions in impact probability (e.g. three orders of magnitude), diverse design approaches and multiple missions of each design will be required. If in-situ characterization is required for deflection, then reliability requirements are even more stringent.

6.13. Possible Scenarios – Application of the Alternatives

This section provides several illustrations of how the alternatives might be applied to hypothetical deflection scenarios drawn primarily from Reference [31]. The inclusion of actual objects in these scenarios does not indicate any increase or decrease in the understanding of the hazard they pose; instead they were chosen both because they are publicly known and are representative of classes of potential threats.

The scenarios include missions to deflect:

A. The 330-meter asteroid, Apophis, before its close approach to Earth in 2029 (a possible keyhole, see Section 5.2.3).

   This scenario was divided into two design points:

   A1. For the first, a relatively large momentum change is required to deflect the object with the required certainty. Apophis must be deflected by at least 1 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 therefore substantially reduced. Apophis must be deflected by at least 5 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 collision is predicted

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

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

E. A hypothetical asteroid larger than 1 km in diameter

F. A hypothetical long-period comet with a very short time (9-24 months) between detection and possible impact

Figure 37 and Figure 38 of Section 6.11 summarize the momentum capability of each alternative, with increasing launch performance. The approximate performance requirements for each of the scenarios overlaid on these to produce Figure 43 for the impulsive techniques and Figure 44 for the slow push methods.

An explanation of how to read these figures is presented in Section 6.11. A detailed analysis of how different deflection techniques would perform against these scenarios is presented in the following sections.

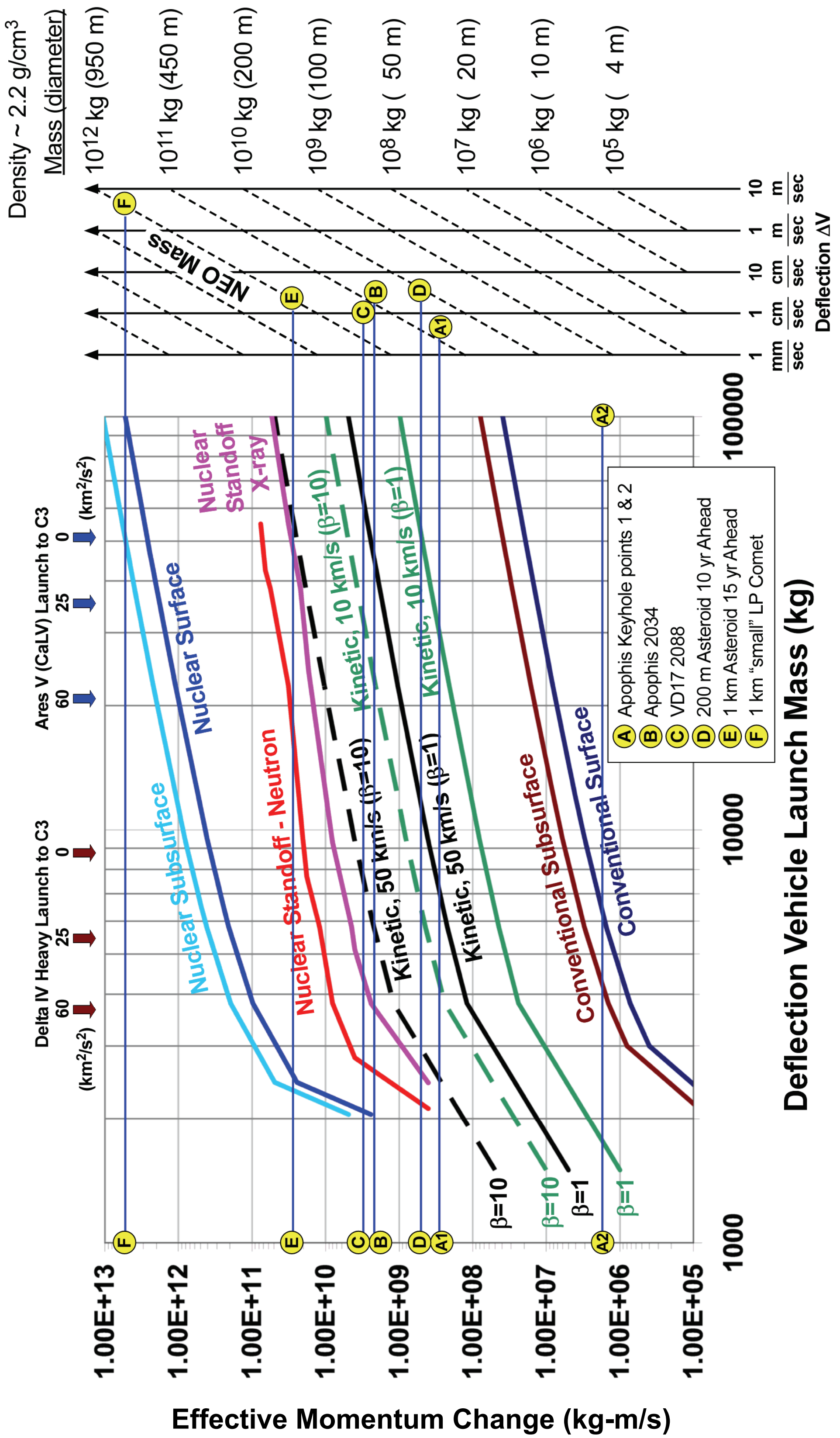


Figure 43. Momentum Capability of Impulsive Alternatives Applied to Scenarios

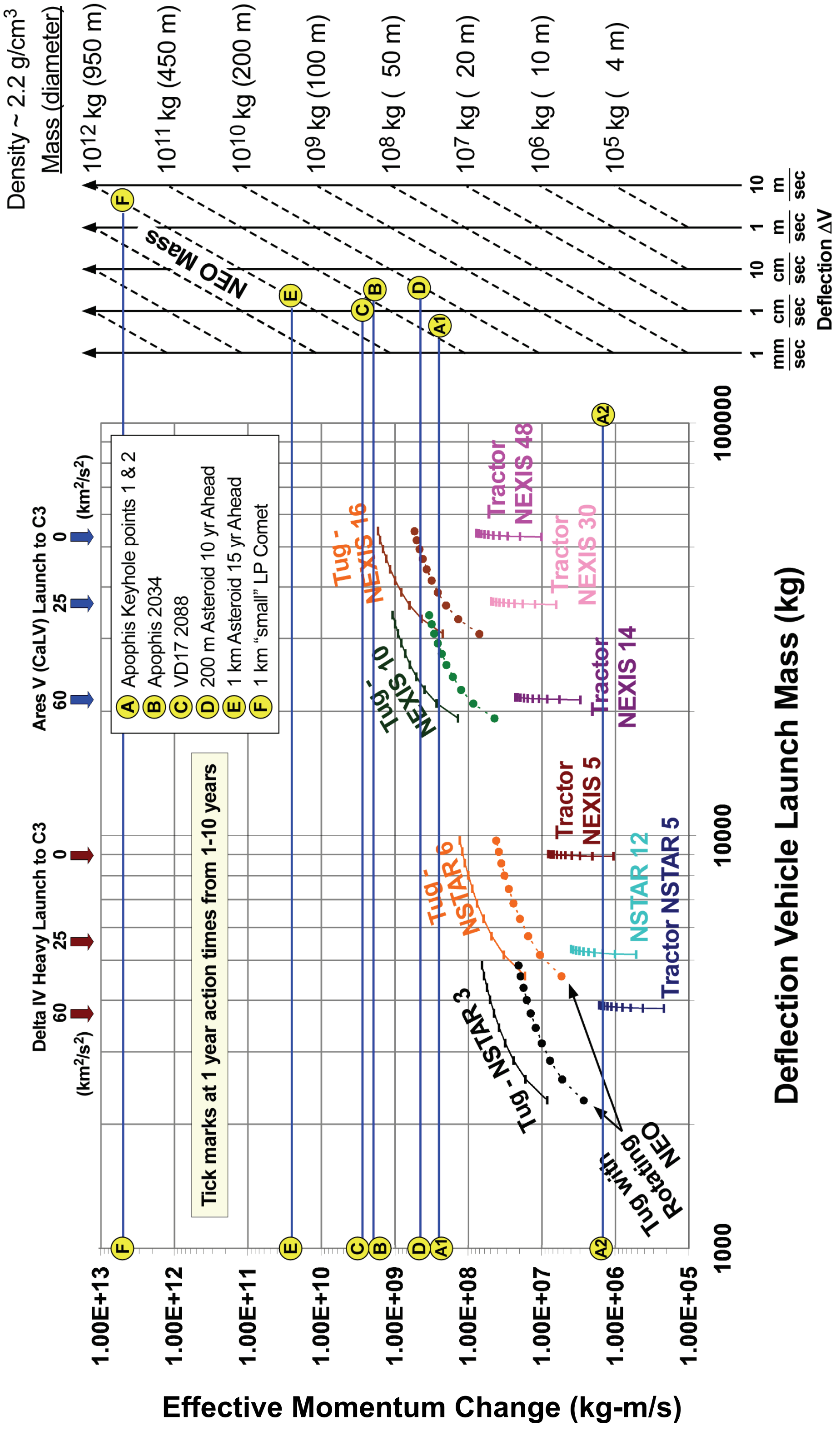


Figure 44. Momentum Capability of Slow Push Alternatives Applied to Scenarios

6.13.1. Scenario - Apophis (Deflect before 2029)

Asteroid 99942, also known as Apophis (2004 MN4), is estimated to be about 320 meters in diameter, with a mass of 4.6×10^{10} kg. Uncertainty about its diameter is currently a factor of two, which means that the mass could vary by a factor of 16 (5.8×10^{9} - 3.7×10^{11} kg). The equivalent impact energy is proportional to the mass. Specific information on its shape and rotation currently are not available. Table 26 describes this scenario further.

Table 26. Apophis before 2029 Scenario Description

Scenario	Apophis (before 2029)
Predicted Frequency	Frequency of keyholes is undetermined
Time to Act	22 years
Action Begins	6 years prior to impact
Diameter of Threat	320 m
Mass of Threat	4.6×10^{10} kg
ΔV Design Point 1	5.000 mm/s (DP1)
ΔV Design Point 2	0.026 mm/s (DP2)
Δ Momentum DP1	2.3×10^{8} kg m/s
Δ Momentum DP2	1.2×10^{6} kg m/s
Unique Features	• Keyhole scenario complicates decision to deflect in 2029

Apophis is currently predicted to have a close approach to Earth in 2029, passing within 30,000 km, with a subsequent 2.2×10^{-5} probability of impact on April 13, 2036. The probability of impact in 2036 will be strongly influenced by the precise location of the close approach in 2029. If it should pass within a 600-meter-wide “keyhole” in 2029 (see Section 5.2.3), the likelihood of impact in 2036 will be much higher. [32]

One approach for avoiding a threat in 2036 is to deflect Apophis so that it is guaranteed to miss the keyhole in 2029. An advantage of this approach is that the asteroid requires only a very relatively small change in the velocity to miss the keyhole, as shown in Figure 45. Assuming optical and radar observations are taken in 2013, 2020, and 2021, it is anticipated that one could achieve a tracking accuracy of 5 km. [16]

To take advantage of either opportunity, acquisition of a deflection system must be started years in advance to account for vehicle development and transit time to the asteroid. Consequently, such a program may need to begin with incomplete information. An in-situ characterization mission may provide better tracking accuracy early on, allowing for a less costly deflection mission or elimination of the threat entirely. Figure 45 shows that the ΔV grows substantially as the time to close approach decreases, which is typical of deflection scenarios.

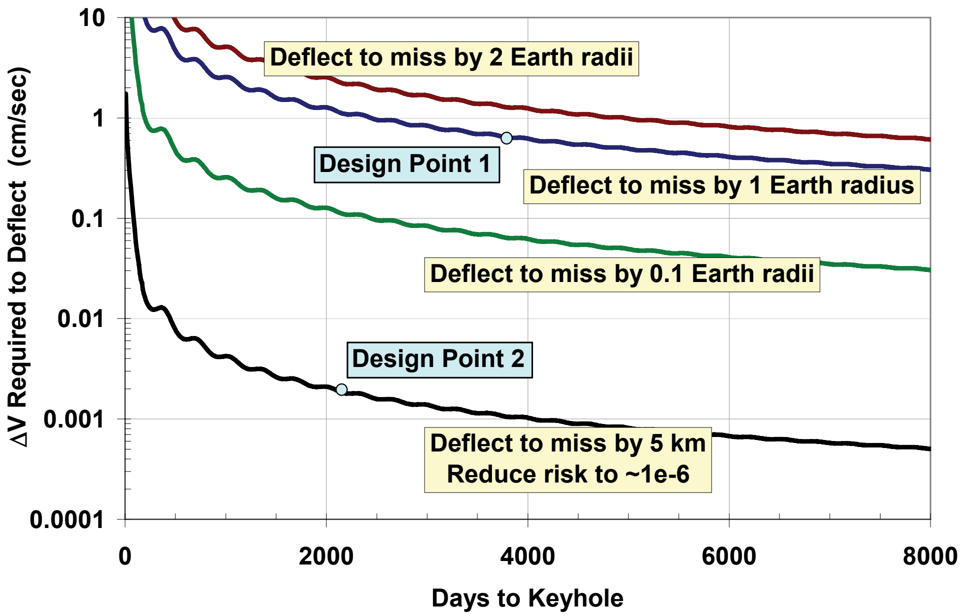


Figure 45. ΔV to Avoid the Keyhole in 2029

Two design points will be examined for this case:

1. Assuming an action time of 10 years before the asteroid arrives at the keyhole, a change in momentum of roughly 2.3 x 10^8 kg m/s would be required to alter the asteroid's velocity by 5 mm/s to reduce the impact probability to the required 1 in 1 million. In this case, it is assumed that uncertainty about the orbit is sufficient to move the orbit one Earth radius at the keyhole. This is a conservative projection as it assumes little improvement in orbital accuracy with additional observations.
2. If the error ellipse is refined by additional observations and assuming an action time of 6 years before the asteroid arrives at the keyhole and the availability of improved tracking accuracy, a change in momentum of roughly 1.2 x 10^6 kg m/s (velocity change = 0.026 mm/s) would be required to deflect Apophis, causing the refined error ellipse to miss the keyhole. This assumes that very accurate orbit information was gathered during the previous approaches (by radar) and that an orbit accuracy of 5 kilometers is achievable. This would still require that deflection preparations be initiated well before the final orbit determination is accomplished.

An on-board propulsion system that can produce a change in velocity of 1 km/s is necessary to accomplish an impact with the asteroid. Assuming a liquid propulsion system with a specific impulse of 325 seconds, an estimated 1900 kg of fuel will be required, leaving a vehicle dry mass of 5200 kg. Of the vehicle dry mass, roughly 57% of the vehicle will consist of structures and navigational systems, leaving a possible payload mass of 2,200 kg. Reference [32] designed a similar mission and proposed that an observer spacecraft be used as a second deflector; however, this would require additional launch capability.

A **performance index (P)**, defined as the momentum change delivered by the alternative, divided by the momentum change required by the scenario, will be used to help compare the various techniques.

$$\mathbf{P} = \frac{\mathbf{M}_{delivered}}{\mathbf{M}_{required}} \tag{1}$$

A performance index of 1.0 (or greater) indicates that the technique can deliver the required impulse (or more) nominally required by the scenario. Values above 1.0 indicate the amount of margin available. A performance index less than 1.0 indicates that insufficient momentum change is provided with a single launch.

Table 27 and Table 28 show the performance results of the concepts for the two design points in this scenario and the number of launches required for each launch system.

Table 27. Apophis Keyhole – Deflection Performance Design Point 1

	Performance Index (P)		**Launches Required**	
Launch Vehicle ➔ **Concept**	**Delta IV H**	**Ares V**	**Delta IV H**	**Ares V**
Nuclear Subsurface[1]	1793	17075	1	1
Nuclear Surface[1]	897	8539	1	1
Nuclear Standoff - Neutron[1]	52	244	1	1
Nuclear Standoff – X-ray[1]	19	87	1	1
Nuclear Standoff - Standard[1]	14	70	1	1
Kinetic Impact, 50 km/s, β=10[1]	9.6	80	1	1
Kinetic Impact, 10 km/s, β=10[1]	1.9	16	1	1
Kinetic Impact, 50 km/s, β=1[1]	1.0	8.0	**2**	1
Kinetic Impact, 10 km/s, β=1[1]	0.2	1.6	**6**	1
Space Tug – Non-rotating[2]	0.5	7.4	**2**	1
Space Tug - Rotating[2]	0.2	2.4	**6**	**1**
Gravity Tractor[2]	0.0	0.3	**29**	**3**
Subsurface Explosive [1]	0.0	0.1	**76**	**8**
Surface Explosive [1]	0.0	0.1	**152**	**16**

[1] Assumed to require C3=25 for an intercept trajectory

[2] Assumed to require launch C3=0 for a rendezvous using electric propulsion

If **conventional explosives** are sent on an intercept trajectory using a Delta IV Heavy with C3 = 25 km^2/s^2, a maximum of 3800 kg of explosives would arrive at the asteroid. The resulting explosion would be unable to deflect the asteroid for Design Point 1, but would be enough for Design Point 2.

Maximum intercept velocity is more beneficial for the **kinetic impact** than for any other concept. Therefore, the launch date is extremely important to allow for the maximum amount of mass to impact the asteroid. If launched at the optimum time, the relative velocity at impact can be as high as 15 km/s. Results presented are parameterized for 10 km/s and 50 km/s to allow for advances in propulsion systems or the use of swing by trajectories. Assuming that Apophis is relatively dense and that material will be ejected during impact, a beta factor can be assumed to be roughly three. [34] As discussed earlier, a kinetic deflection is dependent on the beta factor (β).

Table 28. Apophis Keyhole – Deflection Performance for Design Point 2

	Performance Index (P)		**Launches Required**	
Launch Vehicle ➔ **Concept**	**Delta IV H**	**Ares V**	**Delta IV H**	**Ares V**
Nuclear Subsurface[1]	343699	3272761	1	1
Nuclear Surface[1]	171951	1636583	1	1
Nuclear Standoff - Neutron[1]	10000	46667	1	1
Nuclear Standoff – X-ray[1]	3667	16667	1	1
Nuclear Standoff - Standard[1]	2667	13333	1	1
Kinetic Impact, 50 km/s, $\beta=10$[1]	1835	15346	1	1
Kinetic Impact, 10 km/s, $\beta=10$[1]	367	3069	1	1
Kinetic Impact, 50 km/s, $\beta=1$[1]	183	1534	1	1
Kinetic Impact, 10 km/s, $\beta=1$[1]	36	307	1	1
Space Tug – Non-rotating[2]	101	1419	1	1
Space Tug - Rotating[2]	32	452	1	1
Gravity Tractor[2]	6.8	65	1	1
Subsurface Explosive [1]	2.5	24	1	1
Surface Explosive [1]	1.3	12	1	1

[1] Assumed to require C3=25 for an intercept trajectory

[2] Assumed to require launch C3=0 for a rendezvous using electric propulsion

Nuclear explosives have the ability to transfer much more energy for a given mass than any other option. Using a Delta IV Heavy with a C3 of 25 km^2/s^2 and assuming the spacecraft defined above, the maximum mass of a nuclear explosive that could be transported to the asteroid is 2,200 kg and would provide a change in momentum of 2.0 x 10^{11} kg m/s if detonated on the surface. This would change the asteroid's velocity by 3 m/s. If the device is placed beneath the surface, it will impart twice as much momentum to the asteroid, doubling both the performance index and velocity change.

Slow push techniques create a change in momentum by incrementally moving the threatening object off its orbit. For the approaches considered here, thrust is produced by either the gravitational attraction between bodies or by the propulsion system on the spacecraft. Both of these techniques require a great deal of mass to provide the necessary thrust. For this reason, it is assumed that the launch vehicle will transport the spacecraft to a lower-energy Earth orbit and that the spacecraft's propulsion system will be used to intercept the asteroid.

A Delta IV Heavy Launch Vehicle has the ability to lift roughly 25,000 kg to a LEO orbit if launched at optimum conditions. A 3-year transit period was assumed. The fuel required by the propulsion system is calculated by assuming constant thrust over the full transit period.

The **gravity tractor** has been suggested to deliver the small momentum changes required for the keyhole deflection of Apophis. For this concept, the most mass at the PHO provides the most momentum change; therefore, an ion engine would be used to propel the vehicle. To provide enough thrust to reach the asteroid in a short period of time and rendezvous with the asteroid, eight NEXIS thrusters, similar to those used on the Jupiter Icy Moons Orbiter (JIMO), is used as the tractor's propulsion system. The propellant mass used for transit, rendezvous, and hovering would be roughly 5000 kg, allowing for a mass of 20,000 kg to produce the gravitational force on the asteroid.

Different deflection opportunities would change the available lead-time for the gravity tractor. Assuming a few years transit time for the low-thrust system, the gravity tractor may need to be launched in advance of the 2021 observation opportunity. Here, a 3-year transit time and a 6-year action time are assumed. If a mass of 20,000 kg were applied for 6 years against Apophis, it would impart a change in momentum of 4.8 x 10^7 kg m/s. This would change the asteroid velocity by 1 mm/s (0.001 m/s), insufficient to meet the 2019 opportunity (Design Point 1), but sufficient to avoid the keyhole, assuming improved tracking accuracy for the 2023 opportunity (Design Point 2). To achieve a change of one Earth radius in the short time span, the tractor's mass would need to be about 150,000 kg.

The **space tug** is another slow push technique, and its use assumes that Apophis is structurally able to support attachment. The vehicle's design could be similar to JIMO's. The JIMO vehicle used eight NEXIS ion thrusters to propel an 18,000-kg spacecraft. If a Delta IV Heavy were used to launch the spacecraft, only 7,000 kg of fuel would be required, with 4,000 kg required for the 3-year transit period and rendezvous/docking, leaving 3,000 kg of fuel to produce a change in Apophis's momentum. If the thrusters perform at full power, the active push time will be approximately 2.25 years, producing a change in momentum of 2.3 x 10^8 kg m/s. It is estimated that this would be sufficient for both the 2019 and the 2023 opportunities. A factor-of-eight increase in the mass of the PHO would increase the push time for the tractor by more than 14 years, exceeding the time available for this design. Building a system that is somewhat larger than JIMO using on-orbit assembly techniques could possibly solve the problem.

Although relatively little momentum change is required to prevent Apophis from passing through the keyhole, many of the deflection techniques are simply too massive for current lift capabilities for the first design point. If the extremely limited requirements of Design Point 2 are considered, all concepts could hypothetically deflect the threat. A mission to prevent Apophis from passing through the 2026 keyhole appears to be possible with current technologies.

6.13.2. Scenario - Apophis (Deflect after 2029)

If Apophis passes within the keyhole in 2029, a mission to deflect before the 2036 conjunction may be required. If unprepared and deflection is required, taking action within this 7-year timeframe will be a challenge from several perspectives. First, decision makers must authorize the mission and funding must be allocated. Second, spacecraft and launch vehicles (likely multiple spacecraft and multiple launch vehicles to assure success) must be designed and built. Previous studies have shown that 10 years is an ambitious schedule for a deflection of this type, [23] but less than 7 years will remain if the 2029 keyhole event occurs. Table 29 contains a summary of this scenario.

Figure 46 shows the velocity required to deflect asteroid Apophis after the 2029 close approach. The plot begins just after the 2029 close approach, approximately 2,600 days before the 2036 encounter. This analysis shows that the ΔV required to deflect Apophis in 2034 is approximately 4 cm/s in 2034, which corresponds to a momentum change requirement of 1.8 x 10^9 kg m/s. The ΔV is less than 2 cm/s in 2029 after the keyhole.

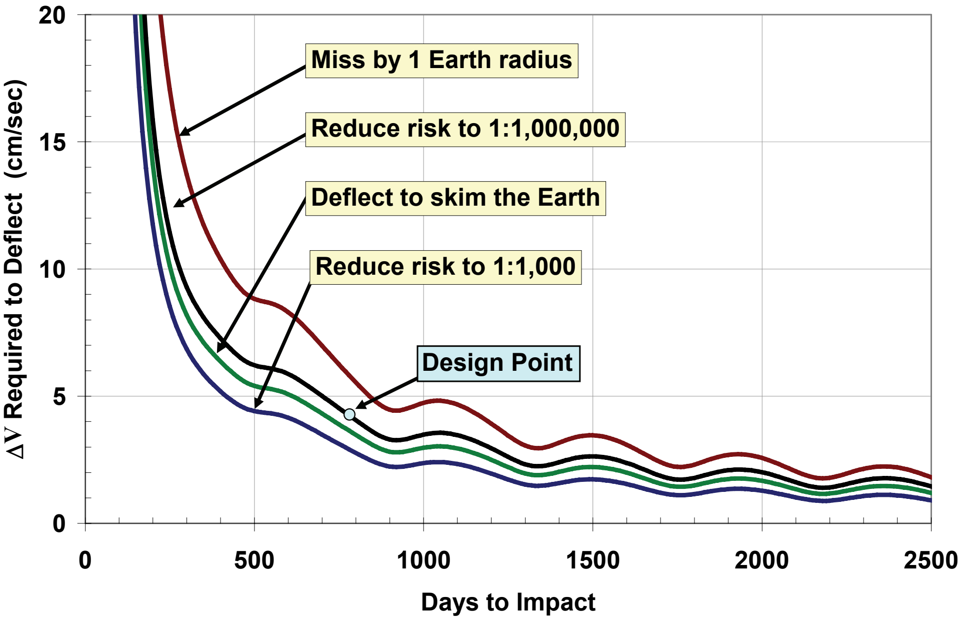


Figure 46. ΔV required to Deflect Asteroid Apophis after 2029 Keyhole

The performance required to deflect Apophis in 2034 is shown in Table 30.

Table 29. Apophis after 2029 Scenario Description

Scenario	Apophis (after 2029)
Impact Frequency	~10,000 years
Time to Act	7 years
Action Begins	2 years prior to impact
Diameter of Threat	320 m
Mass of Threat	4.6×10^{10} kg
ΔV	4 cm/s
Δ Momentum	1.8 x 10^9 kg m/s
Unique Features	• Short warning • Comparison to keyhole

Table 30. Asteroid Apophis 2034 - Deflection Performance of Alternatives

	Performance Index (P)		Launches Required*	
Launch Vehicle ➔ Concept	**Delta IV H**	**Ares V**	**Delta IV H**	**Ares V**
Nuclear Subsurface[1]	224	2134	1	1
Nuclear Surface[1]	112	1067	1	1
Nuclear Standoff - Neutron[1]	6.5	30	1	1
Nuclear Standoff – X-ray[1]	2.4	11	1	1
Nuclear Standoff - Standard[1]	1.7	8.7	1	1
Kinetic Impact, 50 km/s, β=10[1]	1.2	10.0	1	1
Kinetic Impact, 10 km/s, β=10[1]	0.2	2.0	**5**	1
Kinetic Impact, 50 km/s, β=1[1]	0.1	1.0	**9**	1
Kinetic Impact, 10 km/s, β=1[1]	0.0	0.2	**42**	**5**
Space Tug – Non-rotating[2]	0.1	0.9	**16**	**2**
Space Tug - Rotating[2]	0.0	0.3	**48**	**4**
Gravity Tractor[2]	0.0	0.0	**227**	**24**
Subsurface Explosive [1]	0.0	0.0	**605**	**64**
Surface Explosive [1]	0.0	0.0	**1209**	**127**

[1] Assumed to require C3=25 for an intercept trajectory

[2] Assumed to require C3=0 for a rendezvous using electric propulsion

* About half the number of launches is required if deflected in 2030

6.13.3. Scenario - Asteroid VD17

Asteroid VD17 is estimated to be 580 meters in diameter with a mass of 2.6×10^{11} kg. [35] A close approach with Earth is predicted for May 4, 2102 and the current probability of impact is 1.6×10^{-5}. No details are currently available on the object's rotation rate or material properties. Table 31 contains a summary of the VD17 scenario and Figure 47 shows the velocity increment that may be required.

Table 31. VD17 Scenario Description

Scenario	**VD17**
Impact Frequency	~100,000 years
Time to Act	> 90 years
Action Begins	15 years prior to impact
Diameter of Threat	580 m
Mass of Threat	2.6×10^{11} kg
ΔV	1 cm/s
Δ Momentum	2.6×10^{9} kg m/s
Unique Features	• Long warning • Moderate mass

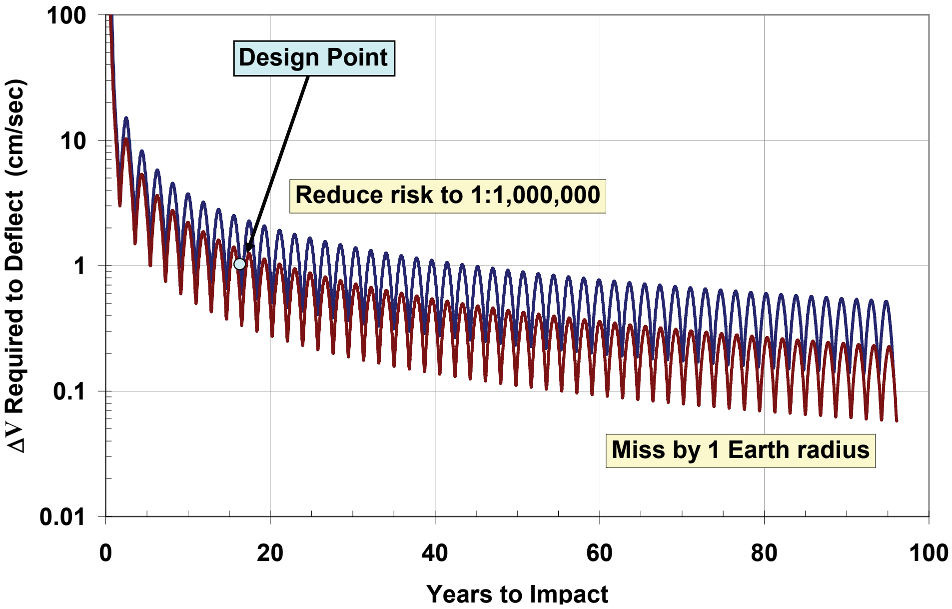


Figure 47. ΔV Required to Deflect Asteroid VD17

To deflect VD17, a change in velocity of 1 cm/s must be imparted to the asteroid roughly 15 years or more before the 2102 impact date, requiring a change in momentum of 2.6 x 10^9 kg m/s. Table 32 shows a summary of the performance parameters for this scenario.

Table 32. Asteroid VD17 - Deflection Performance of Alternatives

	Performance Index (P)		Launches Required	
Launch Vehicle ➔ **Concept**	**Delta IV H**	**Ares V**	**Delta IV H**	**Ares V**
Nuclear Subsurface[1]	159	1511	1	1
Nuclear Surface[1]	79	755	1	1
Nuclear Standoff - Neutron[1]	4.6	22	1	1
Nuclear Standoff – X-ray[1]	1.7	7.7	1	1
Nuclear Standoff - Standard[1]	1.2	6.2	1	1
Kinetic Impact, 50 km/s, β=10[1]	0.8	7.1	**2**	1
Kinetic Impact, 10 km/s, β=10[1]	0.2	1.4	**6**	1
Kinetic Impact, 50 km/s, β=1[1]	0.1	0.7	**12**	**2**
Kinetic Impact, 10 km/s, β=1[1]	0.0	0.1	**60**	**8**
Space Tug – Non-rotating[2]	0.0	0.7	**22**	**2**
Space Tug - Rotating[2]	0.0	0.2	**68**	**5**
Gravity Tractor[2]	0.0	0.0	**320**	**34**
Subsurface Explosive [1]	0.0	0.0	**855**	**90**
Surface Explosive [1]	0.0	0.0	**1709**	**180**

[1] Assumed to require C3=25 for an intercept trajectory

[2] C3=25. Rendezvous using electric propulsion likely unrealistic

* C3=25 may be optimistic by a factor of 2-4 due to launch constraints

Preliminary estimates show that if launched optimally, the necessary C3 to intercept VD17 may be as low as C3 = 25 km^2/s^2. However this is dependent on a very short launch window. If launched at a later time, the C3 needed to intercept VD17 likely will be between 50 and 100 km^2/s^2, reducing deflection performance considerably.

This example assumes that the launch delivers a C3 of 25 km^2/s^2 (a potentially optimistic assumption), with a transit time of 2 years. If a Delta IV Heavy is used, a maximum payload of 6,000 kg can be sent to this C3 and 25,000 kg can be sent to a low-Earth orbit. The Ares V launch vehicle is assumed to lift 38,000 kg to a C3 of 25 km^2/s^2 and 130,000 kg to low-Earth orbit.

Kinetic impactors use the dry mass of the vehicle to produce the change in momentum. To maximize the mass, the 6,000 kg Delta IV Heavy payload will consist of a 1,700 kg mass, and 4000 kg total dry mass will produce the change in momentum. Due the high eccentricity of VD17's orbit, the relative velocity of the impact will be on the order of 20 km/s. If an Ares V launch vehicle is used, an interceptor dry mass of 28,000 kg is possible. Using the same beta factor and relative velocity, the momentum imparted by this impact would be on the order of 1.68×10^9 kg m/s. Two to eight missions would be required to impart the required momentum depending on the value of β.

Nuclear detonations can impart the most change in momentum for a given payload. The Delta IV Heavy can deliver a 1700 kg nuclear explosive payload, and detonation on the asteroid's surface would change the asteroid's momentum by 1×10^{11} kg m/s — well exceeding the requirement. Surface detonation may fragment the asteroid. Consequently, a standoff detonation may be required to limit this possibility, reducing performance.

For this scenario, the options appear more limited than for Apophis. Nuclear and kinetic energy impactors can meet mission requirements; in some cases, more than one launch of the Ares V may be required. This scenario appears to exceed the capability of most slow push techniques and conventional explosives.

6.13.4. Scenario – Small Asteroid with Satellite

Athos is a hypothetical small asteroid in a low-inclination prograde orbit. [37] It has an orbital period of 1.3 years. Its orbit is just elliptical enough to cross Earth's path. At the time of discovery, very little is known about its specific dimensions, rotation, orientation, or material properties. It is thought to be an S-type (silicaceous) asteroid about 200 meters in diameter, with a mass of 1.1×10^{10} kg. A small satellite about one-third the size of Athos is part of the system. Table contains a summary of this scenario.

This class of asteroids represents the lower bound of those considered in this study. As Figure 48 shows, short warning times translate into relatively large ΔVs; a spacecraft that intercepts the asteroid 2 years before predicted impact would need to impart about 15 cm/s to reduce the probability of a collision to less than 1 in 1 million. The same vehicle intercepting the asteroid 10 years before impact would need to impart only 4 cm/s to achieve the same result.

Table 33. 200 Meter Class Asteroid Scenario Description

Scenario	200 m class Asteroid
Impact Frequency	~5,000 years
Time to Act	20 years
Action Begins	10 years prior to impact
Diameter of Threat	200 m
Mass of Threat	1.1×10^{10} kg
ΔV	4 cm/s
Δ Momentum	4.4×10^{8} kg m/s
Unique Features	• Moderate warning • Small mass • Launch constraints

Figure 48 shows the ΔV required to deflect Athos. Reference [23] provides details of the design of a **stand-off nuclear** deflection mission for Athos and illustrates some of the mission complexities.

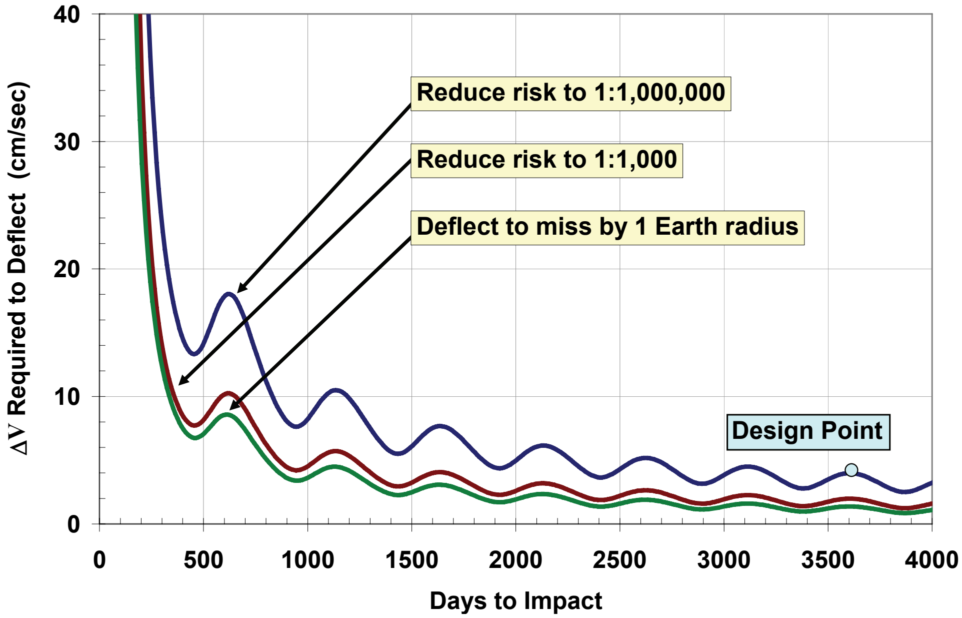


Figure 48. ΔV Required to Deflect a Hypothetical 200 m Asteroid

Many asteroids smaller than 180 meters have very short rotational periods - on the order of a few hours or minutes, as shown in Appendix Section K.5. Some of these do not have a principal axis and are tumbling. Objects of this size present considerable challenges.

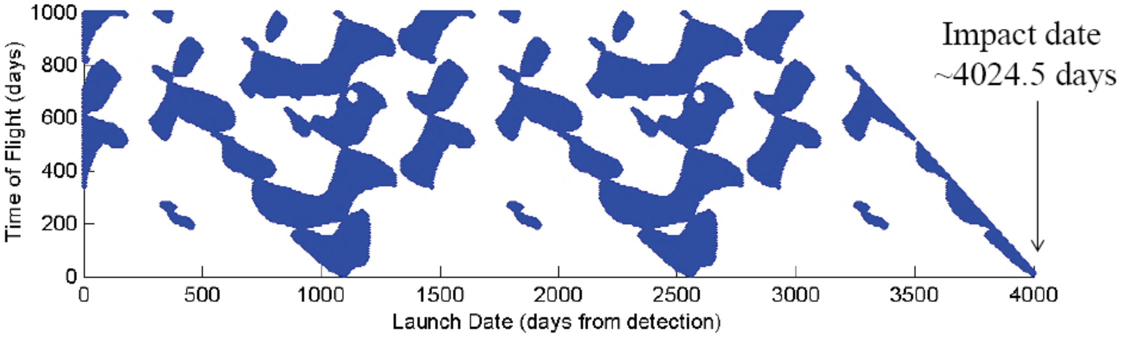


Figure 49. Launch Opportunities for Optimistic Launch Constraints

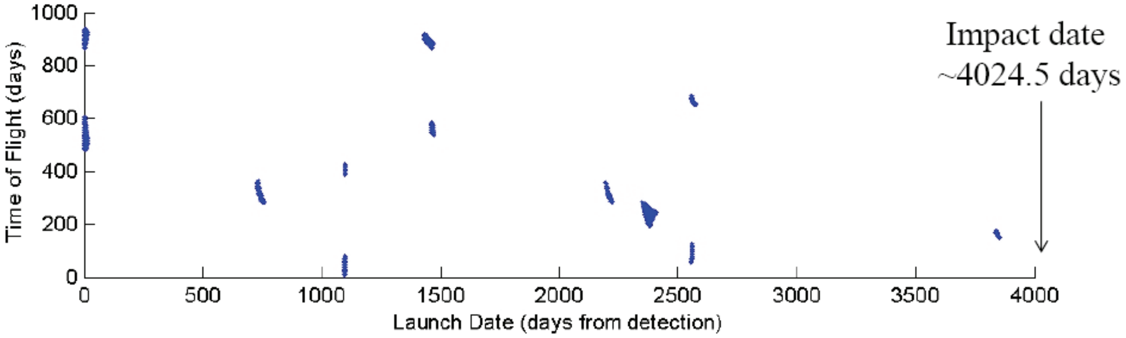
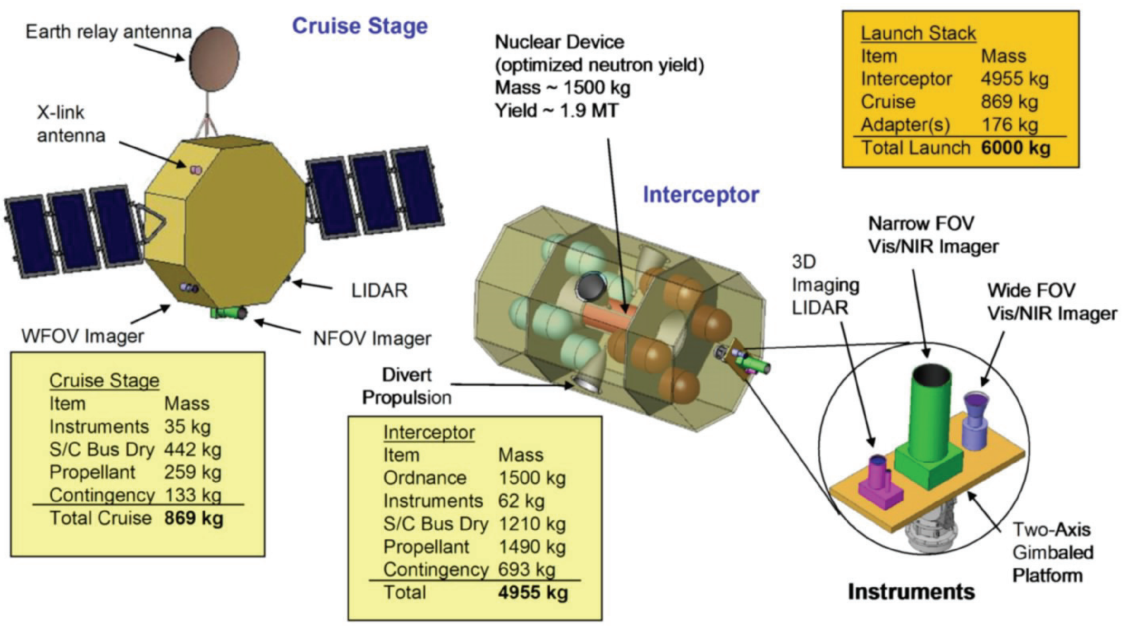


Figure 50. Opportunities for More Realistic Launch Constraints

For example, Reference [23] showed that the number of launch opportunities available depends strongly on the constraints imposed. Figure 49 and Figure 50 illustrate this point by relating launch date to time-of-flight for this example, with the shaded areas corresponding to feasible launch combinations. The results in Figure 49 constrain the C3 at Earth to less than 49 km^2/s^2 and the equivalent velocity at the PHO to less than 10 km/s. Figure 50 uses 5 km/s for the velocity constraints and includes a requirement that the spacecraft strike the PHO within 15º of its head or tail, assuring that the interceptor is directly in front of or behind the object when the explosive detonates. Note the variation in the time of flight and the great reduction in launch opportunities as constraints are added.

Since the asteroid is predicted to hit Earth 11 years after detection, a mission must be designed and launched in a short time. To reach the preferred trajectories, the launch would need to occur either 3 or 6.5 years after the asteroid's detection. Once launched, travel time to Athos is about 210 days. This example assumes that the C3 imparted by the launch vehicle will be no larger than 25 km^2/s^2. The goal is to impart a change in velocity of 5 cm/s and a change in momentum of roughly 5.5 x 10^8 kg m/s.

Figure 51 shows the spacecraft designed for this mission. The spacecraft's total mass at launch is 6,000 kg. The 1,600 kg nuclear explosive used to illustrate this case is a specially designed device, with a high neutron yield. The design, based on current technology, includes a cruise stage. It is designed to observe the detonation and then report back to Earth.



Launch Stack

Item	Mass
Interceptor	4955 kg
Cruise	869 kg
Adapter(s)	176 kg
Total Launch	**6000 kg**

Cruise Stage

Item	Mass
Instruments	35 kg
S/C Bus Dry	442 kg
Propellant	259 kg
Contingency	133 kg
Total Cruise	**869 kg**

Interceptor

Item	Mass
Ordnance	1500 kg
Instruments	62 kg
S/C Bus Dry	1210 kg
Propellant	1490 kg
Contingency	693 kg
Total	**4955 kg**

Figure 51. Athos Deflection Vehicle

Table 34 provides a summary of the performance analyses for this concept.

Table 34. 200 Meter Asteroid - Deflection Performance of Alternatives

	Performance Index (P)		**Launches Required**	
Launch Vehicle ➔ **Concept**	**Delta IV H**	**Ares V**	**Delta IV H**	**Ares V**
Nuclear Subsurface[1]	937	8926	1	1
Nuclear Surface[1]	469	4463	1	1
Nuclear Standoff - Neutron[1]	27	127	1	1
Nuclear Standoff – X-ray[1]	10	45	1	1
Nuclear Standoff - Standard[1]	7.3	36	1	1
Kinetic Impact, 50 km/s, β=10[1]	5.0	42	1	1
Kinetic Impact, 10 km/s, β=10[1]	1.0	8.4	1	1
Kinetic Impact, 50 km/s, β=1[1]	0.5	4.2	**2**	1
Kinetic Impact, 10 km/s, β=1[1]	0.1	0.8	**10**	**2**
Space Tug – Non-rotating[2]	0.3	3.9	**4**	1
Space Tug - Rotating[2]	0.1	1.2	**12**	1
Gravity Tractor[2]	0.0	0.2	**55**	**6**
Subsurface Explosive [1]	0.0	0.1	**145**	**16**
Surface Explosive [1]	0.0	0.0	**290**	**31**

[1] Assumed to require C3=25 for an intercept trajectory

[2] Assumed to require C3=0 for a rendezvous using electric propulsion

If a 1,600 kg standard nuclear explosive detonated at the best possible distance from the asteroid's surface, it would yield a momentum change of 1.5 x 10^{10} kg m/s, which would be enough to successfully deflect this asteroid. Surface and subsurface detonations would produce a momentum change of 1.5 x 10^{12} kg m/s and 3.0 x 10^{12} kg m/s, respectively. These detonations would be much more likely to fragment the asteroid than a standoff detonation.

Reference [23] also raises the issue of reliability. The reference notes that the deflection mission demands a higher probability of mission success than does a typical space mission. The initial 1-in-100 probability of Athos colliding into Earth will likely need to be reduced many orders of magnitude. This issue is considered further in Section 6.12.

It is likely that scientists will know very little about the asteroid when the mission launches; so the beta factor used to calculate the impulse given by a **kinetic impactor** is assumed to be 1.5. With this assumption, a 3,725 kg spacecraft impacting the asteroid's surface at a velocity of 10 km/s will change the momentum by 5.6 x 10^{7} kg m/s. This calculation provides a good lower bound for the impact's outcome; the beta factor may be much higher. After the first launch, a flyby observer will provide more detailed information about the asteroid's condition and tell mission planners whether the mission succeeded.

The asteroid's companion body or moon complicates the scenario. At some threshold value of ΔV, the companion (which could be on an Earth intercept trajectory as well) may separate from the primary body. Currently, the effects of such an impact on different-size bodies in a very low-gravity field are not well understood. It also is possible that if multiple deflection missions were mounted to ensure a sufficient margin and if one of the initial attempts successfully deflected the primary body but left the secondary intact, one of the trailing missions could be targeted at the companion.

A slow push technique might offer an advantage in these cases. The rate of impulse that the technique imparted would be very small, so small, in fact, that the orbit of the companion body would simply move along with the parent. The specifics of such cases are beyond the scope of this study.

Using the largest launch vehicle expected to be available at the time - the Ares V - many of the alternatives can address this scenario.

6.13.5. Scenario – 1 km-Class Asteroid

Aramis is a hypothetical large asteroid several km in size. [37] A largely C-type (carbonaceous) assemblage of solid, gravitationally bound rocks, Aramis is a classic "rubble pile." Aramis has an orbital period of 6.5 years and its orbit is elliptical. It is 1.8 x 1.2 x 0.8 km and has a mass of 1.2 x 10^{12} kg. The inherent material of the rubble pile has a density of 2.0 gm/cm^3, while the aggregate body has an overall density of about 1.3 gm/cm^3. Table 35 summarizes this scenario.

Figure 52 shows the ΔV required to deflect Aramis as a function of time. If action is taken 15 or more years before it encounters Earth, the minimum ΔV required may be less than 1 cm/s. As time to impact decreases, the ΔV increases markedly.

Table 35. 1-km Class Asteroid Scenario Description

Scenario	1-km Class Asteroid
Time to Act	17 years
Impact Frequency	~1,000,000 years
Action Begins	6 years prior to impact
Diameter of Threat	1000 m
Mass of Threat	1.2×10^{12} kg
ΔV	2 cm/s
Δ Momentum	2.4×10^{10} kg m/s
Unique Features	• Rubble pile • Large mass • Short warning

In this hypothetical case, Aramis was detected in February of 2006 and is predicted to strike Earth in May 2033. This scenario offers time to advance required technologies and to send precursor missions to better characterize the asteroid. This scenario also allows a more detailed look at how different missions react to a "rubble pile" asteroid.

Aramis has an elliptical orbit, with a period of 6.5 years. As Figure 52 shows, a ΔV of 2 cm/s will deflect the threatening asteroid 6 years ahead of impact. To obtain the necessary change in velocity, the deflection mission must impart a change in momentum of 2.4×10^{10} kg m/s by 2027.

Aramis requires a C3 of more than 50 km^2/s^2 to intercept the asteroid - a relatively large launch energy requirement. The Ares V is expected to be ready by 2020 allowing 7 years to fulfill the mission needs. If launched at the optimum time with a C3 of 60 km^2/s^2, the transit time to Aramis is about 5 years.

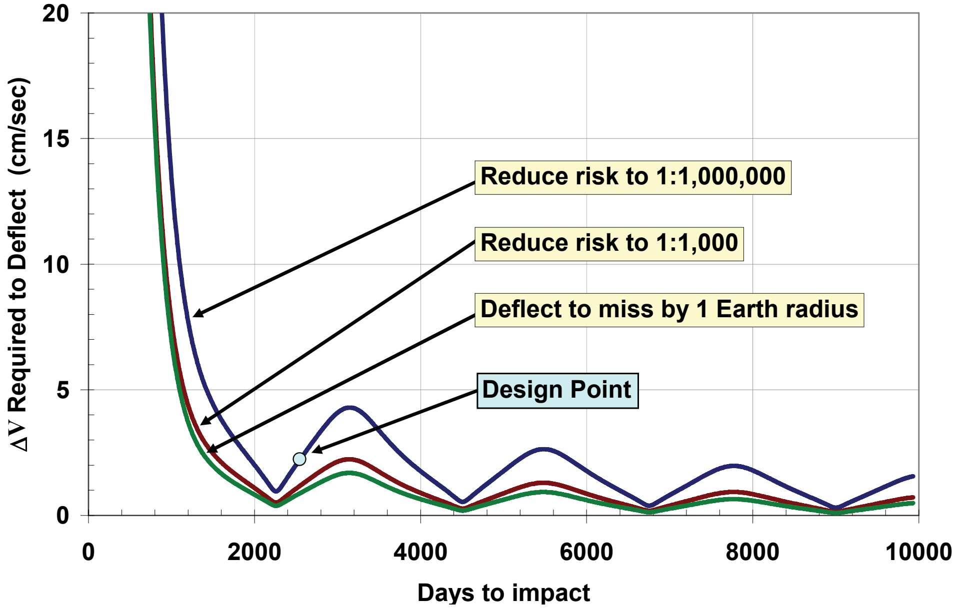


Figure 52. Velocity to Deflect a Hypothetical 1-km Asteroid

Table 36 summarizes the performance of the deflection alternatives for the 1-km asteroid Aramis which approaches Earth from a highly elliptical orbit.

Table 36. 1-km Asteroid - Deflection Performance of Alternatives

	Performance Index (P)		**Launches Required**	
Launch Vehicle ➔ **Concept**	**Delta IV H**	**Ares V**	**Delta IV H**	**Ares V**
Nuclear Subsurface[1]	8.1	92	1	1
Nuclear Surface[1]	4.1	46	1	1
Nuclear Standoff - Neutron[1]	0.3	1.3	**3**	1
Nuclear Standoff – X-ray[1]	0.1	0.7	**10**	**2**
Nuclear Standoff - Standard[1]	0.1	0.5	**15**	**2**
Kinetic Impact, 50 km/s, β=10[1]	0.1	0.4	**20**	**3**
Kinetic Impact, 10 km/s, β=10[1]	0.0	0.1	**100**	**12**
Kinetic Impact, 50 km/s, β=1[1]	0.0	0.0	**200**	**23**
Kinetic Impact, 10 km/s, β=1[1]	0.0	0.0	**1000**	**115**
Space Tug – Non-rotating[*,2]	0.0	0.0	**497**	**24**
Space Tug – Rotating[*,2]	0.0	0.0	**1561**	**75**
Gravity Tractor[2]	0.0	0.0	**6009**	**492**
Subsurface Explosive [1]	0.0	0.0	**16667**	**1478**
Surface Explosive [1]	0.0	0.0	**33334**	**2956**

[1] Assumed to require C3=60 for an intercept trajectory

[2] Assumed to require C3=25 for a rendezvous using electric propulsion

* Space Tug may have significant issues attaching to a rubble pile of any size

If a **kinetic impact** mission is launched, the entire dry mass of the vehicle will be used to change the asteroid's momentum. Because the asteroid is a "rubble pile," one can assume that the beta factor for the impact is 1.2. Additional information on the asteroid's surface strength would be needed to ensure that the interceptor did not punch through the asteroid. For this analysis, it was assumed that the interceptor would stay imbedded in the asteroid; otherwise, performance would be reduced.

For their size, **nuclear explosives** release a relatively large amount of energy. Since the asteroid is a rubble pile, imparting this large amount of energy on or below the surface may fragment the asteroid, see Section 6.14.

The Spaceguard Survey continues to reduce the unwarned threat of a 1-km asteroid. If a credible 1-km threat were discovered, this scenario shows that multiple launches of the most energetic alternatives would be needed to apply the required impulse. Lower-performing kinetic impact options, the slow push techniques, and conventional explosives are probably insufficient to address this hypothetical case.

6.13.6. Scenario – 1-km diameter Long Period Comet

Long-period comets represent a difficult mitigation challenge. Likely, they will be detected only months, not years, before impact. Furthermore, accurately determining their orbits may be difficult due to out-gassing as they approach the Sun and their higher relative velocity. Finally, these objects can be very large, with diameters of several kilometers or more. The impact velocity would be several times that of an asteroid (55-70 km/s compared with 15-20 km/s for an asteroid), meaning that the energy delivered at impact would likely be an event with global consequences. Table 37 contains a summary of this scenario.

Table 37. 1-km Comet Scenario Description

Scenario	**1 km Comet**
Time to Act	< 2 years
Impact Frequency	>> 1,000,000 years
Action Begins	1 year prior to impact
Diameter of Threat	1 km
Mass of Threat	$1\text{x}10^{12}$ kg
ΔV	500 cm/s
Δ Momentum	$5 \text{ x } 10^{12}$ kg m/s
Unique Features	• Very short warning • Moderate mass • Cometary orbit

Recent calculations have estimated comets to make up less than 1% of the total threat; however, due to their size, they offer an even more extreme example of a low-probability, high-consequence event. [6] Until they are activated by interaction with the solar wind, comets are many magnitudes fainter than comparable asteroids. If they are to be discovered before reaching Jupiter's distance from the Sun, a survey might be required to see objects seven magnitudes (more than a factor of 10) fainter than analyzed for the Survey in this study. Currently, astronomers discover them only "a few months to a year" before passing by Earth. [38]

To discover incoming km-scale comets before they reach Jupiter's distance, about thirty 10-meter aperture telescopes on Earth or about fifty to one hundred 2.5-meter spherically distributed telescopes would be required at Jupiter's distance. Although such a program does not appear practical, the study assumes that it could provide up to 30 months of warning. [39] This is very little time to mount a deflection campaign.

The hypothetical object Porthos [37] is a long-period comet in a high-inclination orbit. It is detected on February 22, 2013 and will strike on October 18, 2015 if not deflected. A classical "dirty snowball," it rotates once every 4 days. Porthos is roughly one-eighth the size of Halley's nucleus in each axis. Porthos is 2x1x1 km and has a mass of $1\text{x}10^{12}$ kg (a very small comet).

Because of the short time between discovery and predicted impact, scientists will know little about its physical characteristics and potential impact point on Earth. The comet's non-gravitational forces will add to these uncertainties, and any program to address this scenario must take such uncertainties into account. The probability of a real impact may be 1 in 1,000 or less due to the comet's high relative velocity, orbit, and relatively short observational interval.

Figure 53 shows the ΔV that might be required for such an object. Note that the required ΔV close to impact is orders of magnitude higher than for an object detected years before impact. Should a deflection effort be launched within a year (400 days) of the possible impact, a ΔV of more than 5.0 m/s to lower the impact probability to less than 1 in 1 million would be required. [34] Also note that due to the uncertainty in the orbit, a miss distance of many Earth radii may be required.

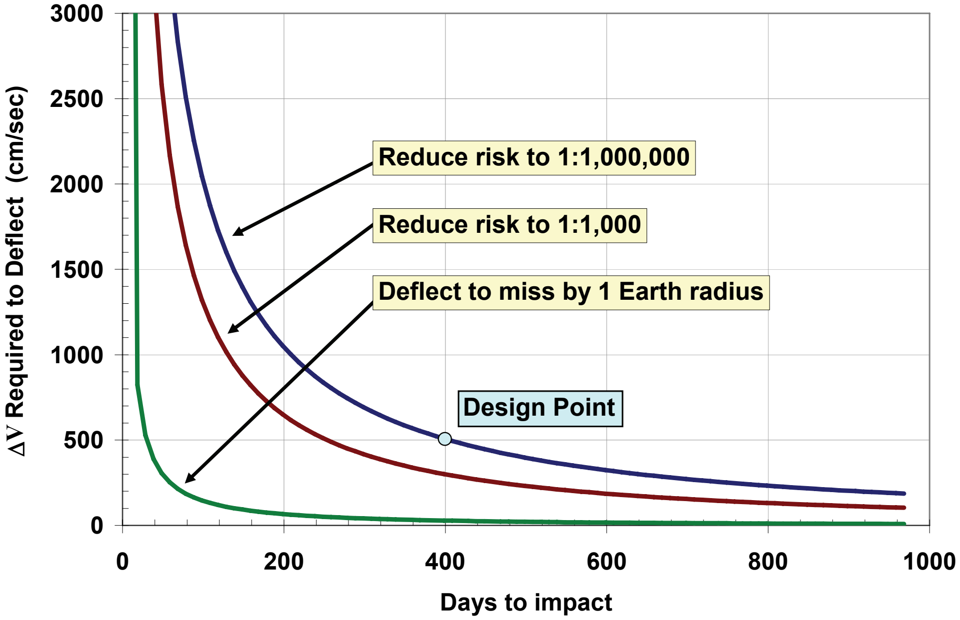


Figure 53. ΔV to Deflect a Hypothetical 1 km Long Period Comet

A comet as small as Porthos (~1-km radius) appears to be rare. If the observed frequency of short-period (SP), dynamically new (DN), and long-period (LP) comets shown in Figure 54 are typical [40], Porthos would be among the smallest.

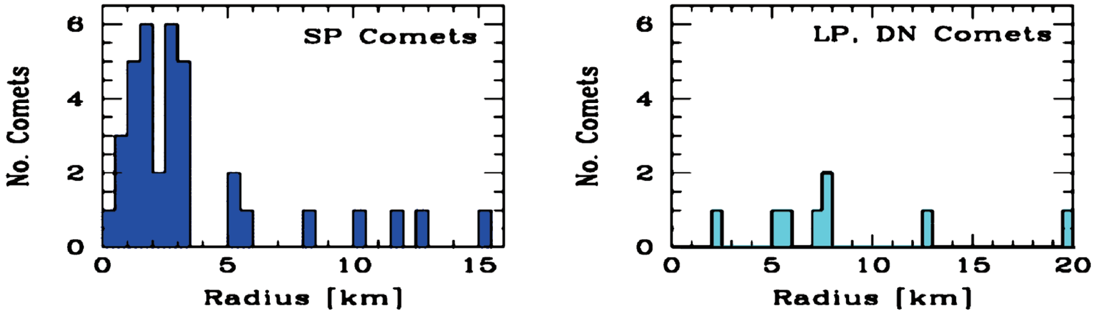


Figure 54. Frequency of Observed Comets by Size

While comets are thought to vary in mass from 10^{10} to 10^{18} kg, most are expected to fall in the range of 10^{11}-10^{14} kg. [41] At 10^{12} kg, Porthos is among the least massive comets by several orders of magnitude. However, the likelihood of a possible comet impact is highly unlikely, even compared with the threat posed by asteroids.

Table 38 shows analysis for the performance of the deflection alternatives for a 1-km long-period comet such as Porthos.

Table 38. Long Period Comet - Deflection Performance of Alternatives

	Performance Index (P)		Launches Required	
Launch Vehicle ➔ **Concept**	**Delta IV H**	**Ares V**	**Delta IV H**	**Ares V**
Nuclear Subsurface[1]	0.0	0.4	**26**	**3**
Nuclear Surface[1]	0.0	0.2	**52**	**5**
Nuclear Standoff - Neutron[1]	0.0	0.0	**625**	**157**
Nuclear Standoff – X-ray[1]	0.0	0.0	**2084**	**313**
Nuclear Standoff - Standard[1]	0.0	0.0	**3125**	**417**
Kinetic Impact, 50 km/s, β=10[1]	0.0	0.0	**4167**	**479**
Kinetic Impact, 10 km/s, β=10[1]	0.0	0.0	**20834**	**2393**
Kinetic Impact, 50 km/s, β=1[1]	0.0	0.0	**41667**	**4785**
Kinetic Impact, 10 km/s, β=1[1]	0.0	0.0	**208334**	**23921**
Space Tug – Non-rotating[2]	0.0	0.0	**103506**	**4935**
Space Tug - Rotating[2]	0.0	0.0	**325171**	**15503**
Gravity Tractor[2]	0.0	0.0	**1251833**	**102375**
Subsurface Explosive [1]	0.0	0.0	**1643008**	**307837**
Surface Explosive [1]	0.0	0.0	**3285152**	**615673**

[1] All assumed to require C3=60 for an intercept trajectory, which is very low

[2] Rendezvous to this orbit is likely infeasible. Assumed C3=25, which is very low.

In addition to deflection issues related to the mass of most comets, their high-energy trajectories pose a different, yet still difficult problem. Figure 55 shows the C3 required to arrive at Porthos and then to deflect it. The calculations include the time of flight between launch and arrival. This launch energy is in addition to the ΔV required to prevent an impact.

Figure 53 shows the relatively large ΔV that is required, while Figure 55 shows that a timely interception is even more problematic. Each curve represents a different warning time, with the X-axis values showing the corresponding time of flight, assuming a mission can be launched. The required values of C3 are well beyond the capability of current or expected launch vehicles (0-100 km^2/s^2 for current and planned launch vehicles). The assumed launch C3 of 60 km^2/s^2 (for intercept trajectories) is, therefore, considered unrealistically optimistic. However, any larger values of C3 would make the results in Table 38 that much less meaningful.

It can be concluded from Figure 55 that very early identification of a long-period comet threat is necessary to have any chance to successfully deflect it.

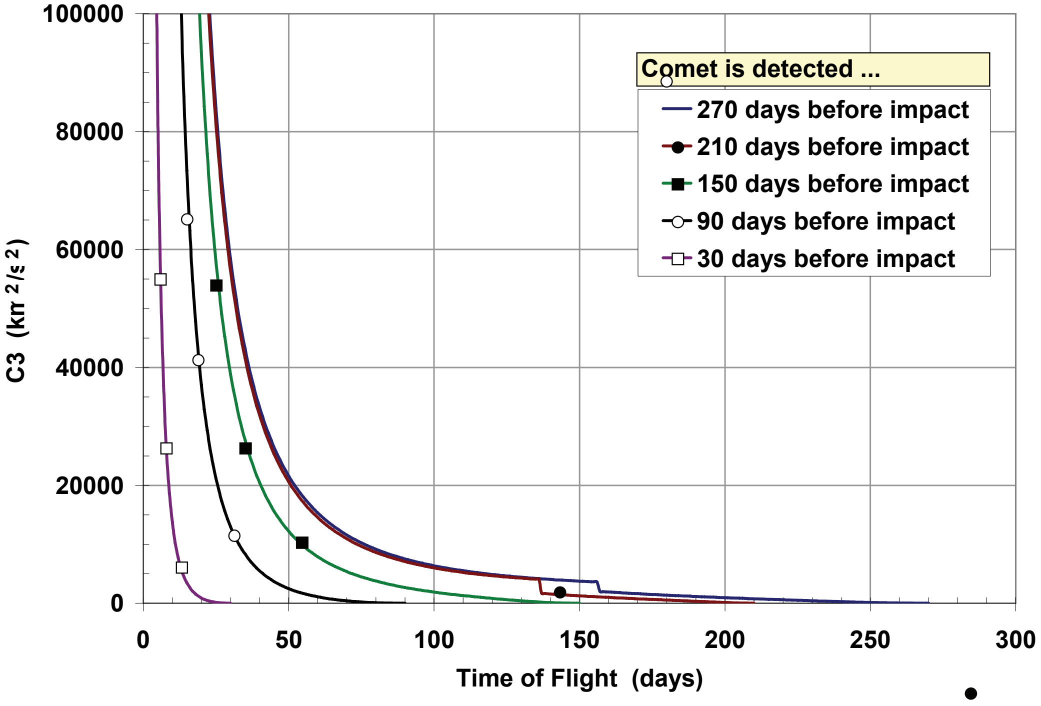


Figure 55. C3 required to Reach Porthos as a Function of Time of Flight.

6.14. Fragmentation

A mitigation approach not specifically analyzed in this report is fragmentation. If the threatening object can be broken into smaller pieces (for example, less than 10 meters in diameter), then these pieces will disintegrate in the Earth's atmosphere if they are not sufficiently diverted to miss Earth entirely.

The primary challenge with fragmentation is how to design the breakup so that most of the resulting fragments are sufficiently small. This may require extensive knowledge of the object's material properties, even more than what is required for many deflection approaches. A second challenge, also potentially requiring a higher level of knowledge, is whether the fragments will be destroyed after passing through the atmosphere. While this is likely the case for non-metallic objects, it probably is not the case for iron fragments. The literature suggest that the fragmentation approach is best suited for cases where the lead time to impact is very long, on the order of decades, and where the PHO is not very large (< 1 km) [67]. The modest size and long lead time provide margin for any slow-moving debris to travel away from the initial intercept path and pose less of a risk of Earth contact.

Any of the impulsive deflection approaches designed to alter the trajectory of an object also may fragment it. An impulsive delivery of acceleration conveys energy in a shock wave. This energy contributes to the resulting change in the object's kinetic energy. It also is the source of other changes, including heating, rotational kinetic energy (if the action line is not through the center of mass), spalling, as well as possible fracturing and dispersion of the fragments to escape velocity.

In the process of reducing the probability of Earth impact, the production of fragments may not be deleterious. For the deflection of an intact object versus one that has been fragmented, the center of mass of the system would undergo the same change in velocity. If the velocity imparted to the system is adequate in magnitude and direction, the fragmented body will achieve a miss trajectory just as an intact object would. [34] [67]

A subtle consequence of deliberate or unintended fragmentation is the fact that a second attempt might have to act on and interact with a debris cloud. Finally, while fragmentation is a possible mitigation strategy, it is not included in the congressional direction to "divert" threats and requires analyses beyond the scope of this study.

6.15. Deflection Systems Schedule Analysis

Figure 56 shows the estimated development schedules for the deflection alternatives considered. The estimates should be considered "rough order of magnitude."

A deflection campaign may consist of much more than just the development schedule, as shown in Table 18. In addition to developing one or more unique systems and launch vehicles to meet mission reliability requirements, in-situ characterization missions are required in some cases. To some extent, these missions may proceed in parallel with the development of the deflection systems. In addition, launch constraints may make it difficult to target many PHOs. Combined with transit time, these constraints could add several years to the interception time. Finally, decisions regarding deflection could be complex and controversial, particularly if nuclear materials or explosives are used. These factors must be considered in the overall schedule.

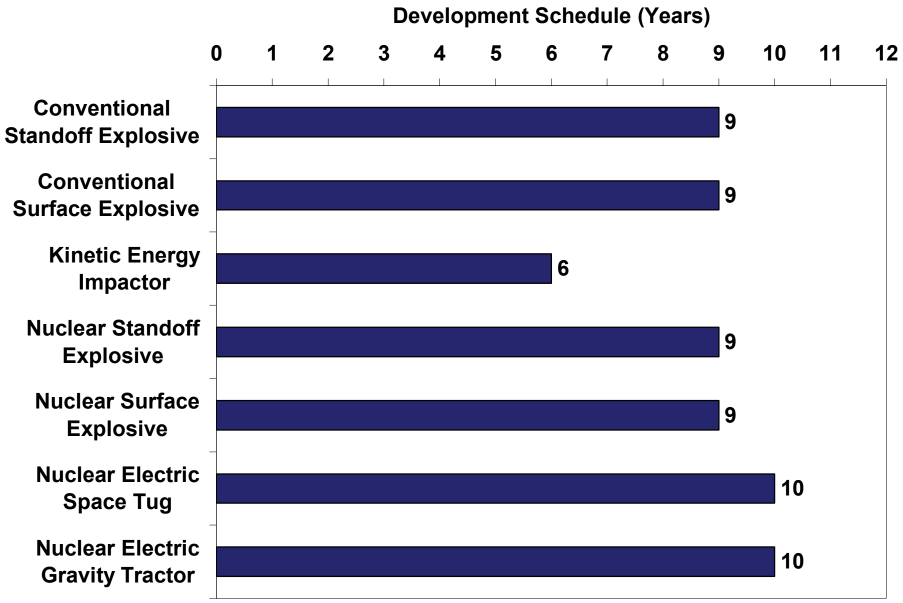


Figure 56. Deflection System Estimated Development Schedules

6.16. Deflection System Cost Analysis

Figure 57 displays the life-cycle cost (LCC) through 2030 for the deflection concepts while Figure 58 displays the recurring costs of subsequent missions. Appendix M contains more detailed cost estimates. Note that the nuclear systems do not include the cost of developing nuclear explosives for PHO deflection, and additional study as well as a specific deployment strategy and/or scenario will be required to understand the total costs of the alternatives. Costs are presented as a rough order of magnitude (ROM).

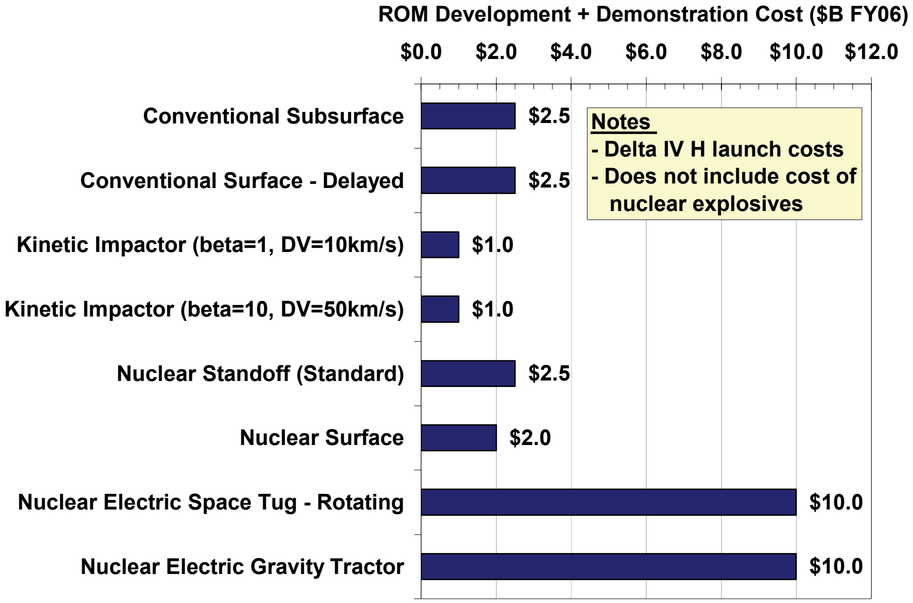


Figure 57. Deflection Concepts Development and First Mission LCC

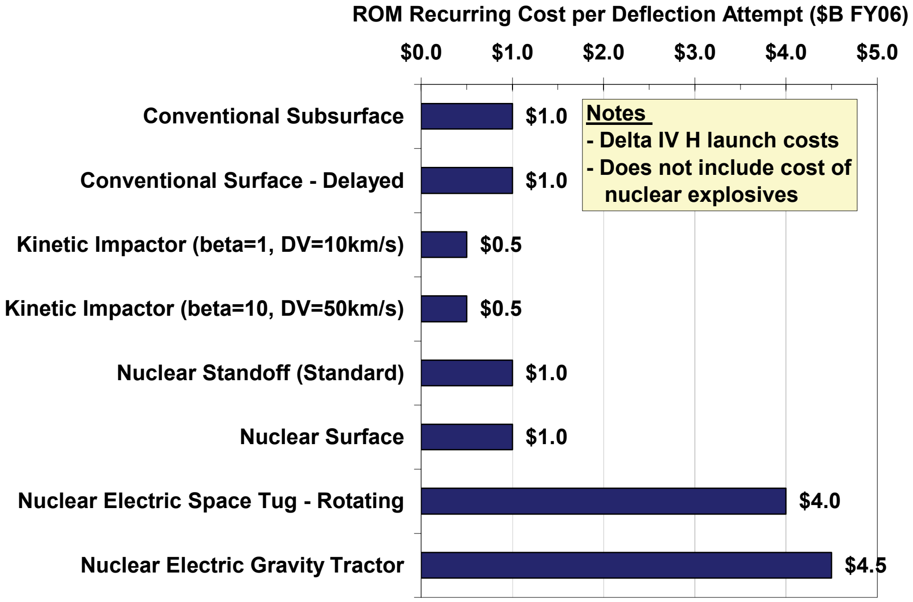


Figure 58. Deflection Mission Recurring Cost

6.17. Performance and Effectiveness vs. Cost

Figure 59 plots the range of performance vs. life-cycle cost for the alternatives. The impulsive techniques have a clear cost-performance advantage over the slow push alternatives. Nuclear options cost more than other impulsive methods, but provide several orders of magnitude more performance. This plot does not consider characterization required or the chance of mission success due to unique target characteristics.

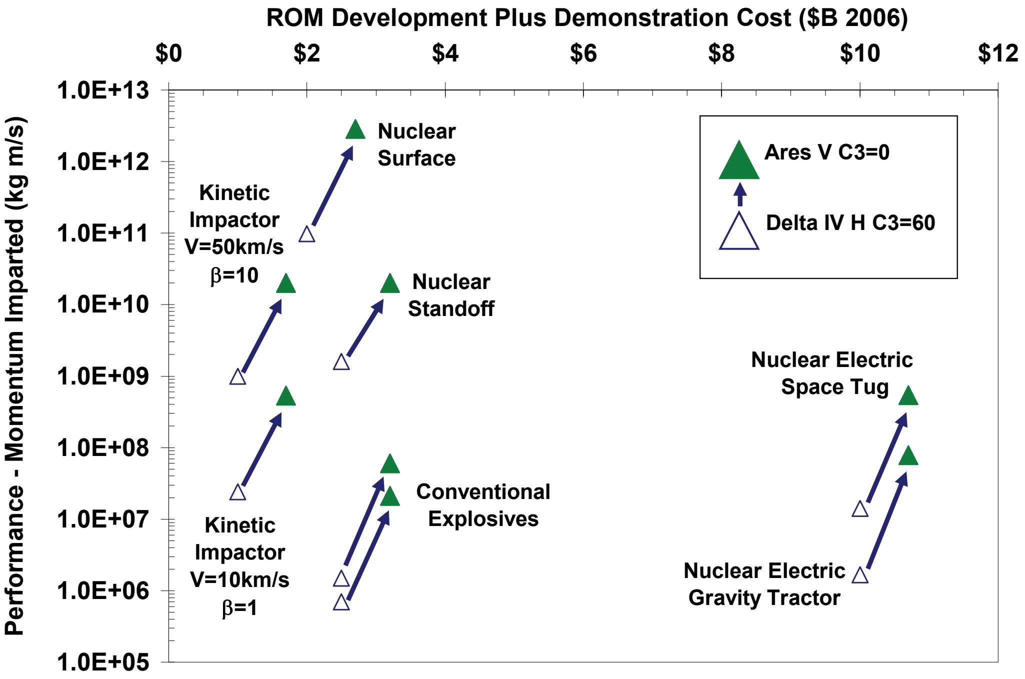


Figure 59. Deflection Performance vs. ROM Development Cost

6.18. Other Factors

Other factors are discussed in the following appendices.

- Appendix P. Potential Synergies of Deflection with Exploration
- Appendix Q. Potential Synergies of Deflection with the DoD
- Appendix R. Role of Nuclear Explosives Technology

6.19. Findings

- Nuclear standoff explosives are an effective deflection option for many threat scenarios. They minimize the possibility of fracturing the target asteroid and require only basic information on the target for mission design. Other techniques involving nuclear explosives may be more effective, but may be less reliable.
- Kinetic impactors are the most mature approach and could be used in some scenarios, especially for threats consisting of a single, small, solid mass.
- Slow push techniques are the most expensive, and their ability to divert an object is very limited unless one assumes very long action times.

- For deflection requiring physical interaction with the surface, the diversity in NEO surface properties, material types, and internal configurations must be considered. These attributes will make many possible deflection scenarios a very complex operation compared with almost any historical space mission.
- The time to impact is an important determining factor in deflection decisions. As the survey finds potential (but uncertain) threats over the next half century, questions of "short warning" (5, 10, or 20 year threats) may become germane. After the population is fully catalogued (25 or 50 years in the future), most orbit impact predictions will become more certain 100 years into the future.
- Launch vehicles and interplanetary spacecraft fail at relatively high rates (2-5% for launches, 10%+ for spacecraft). Deflection options may not perform as desired and unexpected failures can happen. Planners must consider these issues when designing a deflection campaign. It is likely that several spacecraft, several launch vehicles, several launch sites, etc. will be required to ensure mission success.
- Direct launch options may be limited. Each potential threat will be unique and the launch windows available and the launch vehicles required will depend strongly on the relative orbits of the PHO and the Earth. In many cases (as high as 70%), there may be insufficient launch capability to reach the PHO at a point where it can be deflected. Swingby trajectories or assembly of modular propulsion systems may be the only way to reach many threats.
- Survey systems that can warn of a comet threat 2 years into the future are likely technologically infeasible. In addition, these objects are probably more massive than hazardous asteroids and too distant for current or planned launch systems to deflect. It may be easier to fragment comets than asteroids, but this complex analysis is beyond the scope of this study.

7 Integrated Analyses

7.1. Warnings

7.1.1. The Torino Scale

Figure 60 is a representation of the Torino Scale [42] [43], a method for categorizing the impact hazard associated with PHOs. It is intended as a tool for astronomers and the public to assess the seriousness of collision predictions. The scale combines probability statistics and known kinetic damage potentials into a single threat value. The Palermo Technical Impact Hazard Scale [44] is a similar, but more complex, and therefore not generally used for communicating with the public.

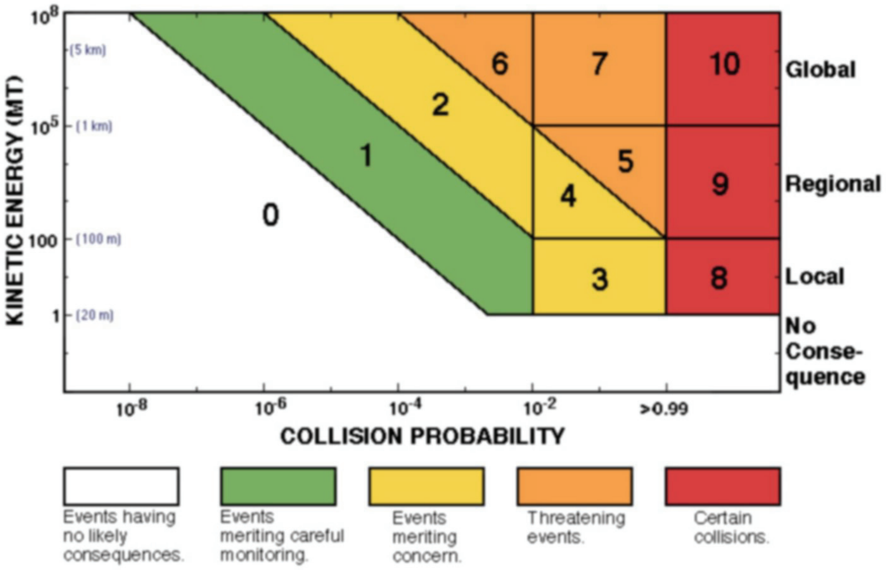


Figure 60. The Torino Impact Hazard Scale

In 1999, asteroid 1999 AN10 was the first to be rated at a non-zero value on the Torino Scale (TS). It was rated TS 1 due to a calculated probability of about 1:500,000 that the asteroid would collide in 2044, about the same as the average annual "background" risk for an untracked 1-km PHO. Subsequent tracking of the object later narrowed the range of possible future orbits and eliminated the TS 1 rating. Since the advent of automated impact-monitoring systems, such as the NASA/JPL Sentry and the University of Pisa's CLOMON2 in 2002, all PHO orbits are now systematically checked for potential future collisions. TS 1-level predictions have become fairly common, occurring at the rate of about five per year. In total, almost 20 non-zero Torino Scale warnings have been issued since the beginning of 2002.

The highest Torino Scale rating to date occurred for the 2029 close approach of asteroid Apophis, one of the objects used as an example in this report. In late 2004, Apophis became the first object to reach TS 2, and for a few days, it reached TS 4. The rating was downgraded to zero when a marginal detection was eventually located within precovery (Section 5.10.2) data. Apophis is now expected to pass close to the Earth in 2029, with no probability of impact.

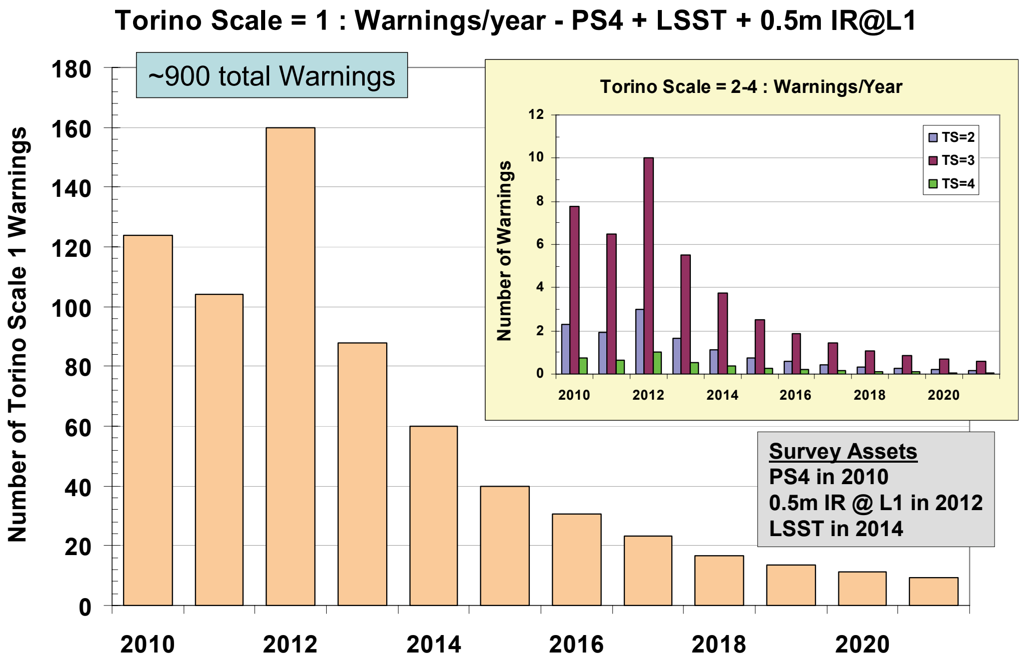
Prior to Apophis, no NEO ever had been given a Torino value higher than TS 1. For a short while in February 2006, asteroid 2004 VD17's predicted 2102 encounter with Earth was rated TS 2, making it the second asteroid to exceed TS 1. The encounter was subsequently downgraded to TS 1, and, as of August 2006, it remains the only object with a TS 1 rating.

7.1.2. Warnings Generated by the Survey

In Reference [24], a policy framework for the PHO hazard is developed, and in particular, the potential socio-economic reactions to the "cosmic impact hazard" are considered. The reaction of society to an increased number of warnings generated by the next-generation NEO Survey is one of the problems examined. The approximate number of warnings expected over the course of the SDT survey can be predicted by extrapolating the collision predictions already detected by the NASA/JPL Sentry system over the course of its first 4.5 years in operation. [45] The analysis shows that the SDT survey can be expected to increase the number of TS 1 warnings by more than an order of magnitude, to nearly 1,000. TS 2, 3, and 4 warnings will similarly increase to about 15, 50, and 5, respectively. There are fewer TS 2 warnings than TS 3 because TS 2 warnings are for larger objects, which are less common than the small objects that might be rated TS 3 or TS 4. This extrapolation also predicts a 1% chance of a TS 6 warning and a 0.7% chance of a TS 7 warning during the survey.

Using these results, and assuming that a survey detects 90% of the objects 140 meters or larger by the end of 2020, the expected warnings can be broken down further by the year during which the warning is likely to be issued. Figure 61 shows a summary of expected warnings per year and by Torino Scale. This figure shows that when the PanSTARRS 4 (PS4) survey system is deployed by the USAF, it will generate Torino Scale warnings at a rate several orders of magnitude greater than today in each class, independent of a NASA-sponsored survey.

These results do not indicate any increased risk of PHO impact. There is about a 2% chance of an actual impact of a PHO larger than 140 meters in the next 100 years. The survey program likely would predict such an event in advance. However, the transient reaction of society to 98% of the other warnings, which will eventually be withdrawn, is a matter of speculation and is possibly worth more consideration by public policy analysts. This topic and the potential economic costs are discussed further in Reference.[24]



Torino Scale = 1 : Warnings/year - PS4 + LSST + 0.5m IR@L1

~900 total Warnings

Survey Assets
PS4 in 2010
0.5m IR @ L1 in 2012
LSST in 2014

Figure 61. Representative Warnings for a Survey Completed by 2020

7.1.3. The Role, Effect, and Effectiveness of Warning Systems

The purpose of an NEO surveillance system is to generate warnings that enable a mitigation response. On the other hand, there may be social costs associated with warnings that are later withdrawn. These costs are determined by the frequency of "false" warnings, the warning horizon (time to possible impact), how long a warning remains in effect, and, least certain of all, how society reacts to them.

Reference [24] also points out that warnings have a social component, in addition to a technical one. The public receives many warnings on many topics in many forms, and the format is often as important as the message. This is particularly true if recipients are unable to personally respond to the threat.

7.2. Framework for Action Thresholds

7.2.1. Phases of Discovery

The distribution of warning times for new discoveries and the fact that two or more decade's worth of observations (sometimes much less) will yield very accurate predictions for more than 50 years (see Section 5.9) into the future provide a framework for discussing action thresholds. This is used as an overlay to probability of impact. The search and deflection problem for any newly discovered threat can be seen as one of several time-phased possibilities that depend on time of observation and predicted time to impact. This is particularly true if surveys and cataloguing are assumed to continue beyond 90% completion.

A possible framework for a newly discovered object is outlined in Table 39.

Table 39. Phases after an Object is Discovered

Phase	**Discussion of Characteristics**
Phase 1 *1-4 days after detection of an object*	• Propagation of the initial orbit has 10-100's of Earth radii (ER) of error per year • Except for very short warning impacts, all warnings carry a low calculated impact probability and then are only good for 1-10 years in the future
Phase 2 *1-4 months after detection of an object*	• During this time precovery is used and additional observations are sought • Impacts 1-10 years are << 1% but the calculated probability of impact for some rises for a time and then the risk is eliminated quickly in almost all cases • Impacts 10-40 years in the future are < 1%. The probability of impact rises for some and then is eliminated for most • Warnings for impacts 40-100 years can be made but are of very low probability
Phase 3 *1-4 years after detection, about 1 orbital period for most objects*	• Precovery has been used to the maximum extent possible • There is a 25% chance of radar observing the object during the first 4 years, rapidly improving the orbit by a factor of 1000 • 1-10 year warning threats have either passed, or have been fully eliminated or identified as threats • 10-40 year warned threats are well characterized with few "probabilistic threats" remaining (threats with a probability of impact) • Additional 30-100 year warning threats are added, and many more are eliminated

7.2.2. The Two Epochs of the NEO Problem

Taking an even broader view of these phases, two "epochs" of the NEO hazard become apparent. During the first epoch, the system is in flux. This period of "discovery and orbit refinement" lasts about 20-40 years as new objects are discovered and their orbits are refined. Short-duration (1-20 years) impact warnings are possible, but represent a small fraction of the total warnings. Changes in warning classifications are made, warnings are added, and then most are eliminated.

In the second epoch, the detection system is phased out and tracking remains the system's only function. More than 99% of objects 140 meters and larger (and many smaller objects) have been detected. Their orbits that can be accurately propagated, assuming tracking capabilities continue to be supported. Average warning times increase from decades to hundreds of years. Short-duration warnings are limited to the threat of comets, which are largely outside our current capabilities to detect with warnings exceeding 1-2 years. Comet threats are expected to be less than 1% of the already low-probability total threat and are outside the scope of this study. To gain statistically relevant benefits from the Survey, modest tracking systems must be maintained for centuries as a consequence of monitoring a 5,000-year average hazard.

It is likely that in conjunction with or following the proposed survey, many systems will be brought on line for scientific or other purposes. It is expected that these will identify and track threats below the level of potential hazard within one or two generations. To detect a high percentage of objects to this limit, the detection systems likely will need to be space-based unless unexpected advances in ground-based telescope technologies are made (see Appendix Section N.1). Some of the space-based IR alternatives evaluated for the survey can detect 90% of objects down to 80 meters.

Details of the epochs are described further in Table 40.

Table 40. Phases after the Survey is Complete

Epoch	Discussion of Characteristics
Epoch A *20-40 years after survey is initiated*	• Radar has provided a precision orbit for 75% of warned threats, but most objects have enough observations to make radar less useful • No threats have been known for less than 10 years • Newly identified threats are uncommon • If any objects have high impact probabilities, this has been known for more than 10 years • 10-40 year warned threats are either eliminated or their probability of impact is very well understood • Few 30-100+ year "probabilistic" threats remaining
Epoch B *40+ years after survey is complete*	• A century of very accurate propagation is possible • Many centuries of warning are likely • New threats are very uncommon • Precision tracking by radar is almost completely obviated

7.2.3. Amortized Cost of Unnecessary Threat Response Missions

Figure 62 shows the amortized (without inflation) cost of unnecessary characterization and deflection campaigns. The figure determines the cost over a range of rates of characterization and deflection per actual impact. The lowest cost alternative assumes one of each type of mission per impact, while the highest cost alternative assumes 1,000 characterizations and 100 deflection campaigns per impact. This translates to one characterization mission every 5 years (999 unnecessary missions) and one deflection mission every 50 years (99 unnecessary missions) for objects 140 meters and larger. This figure shows that even very high rates of unnecessary missions have relatively low-amortized costs; therefore, investing in assets to reduce the rate of unnecessary missions is likely not warranted. This figure also suggests that investment in deflection prior to an actual threat may be unwarranted unless protecting against "short warning" scenarios.

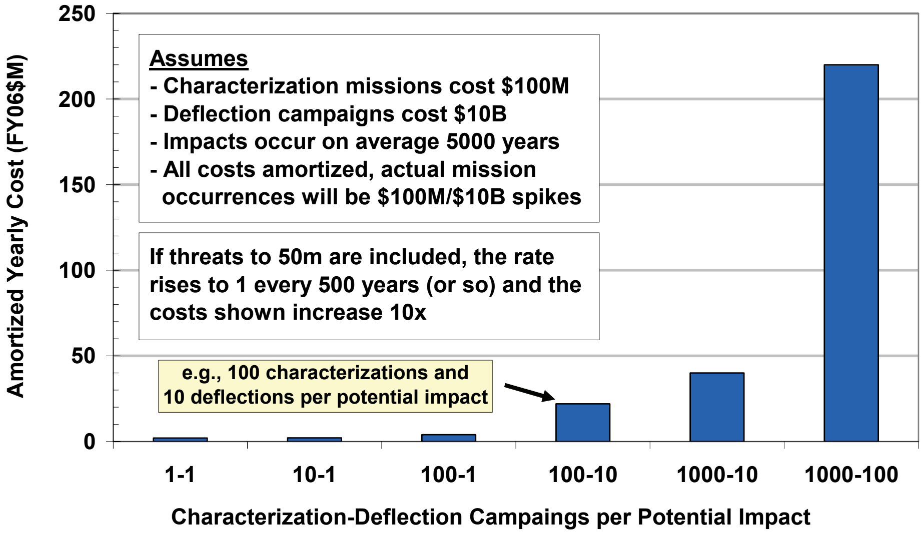


Figure 62. Amortized Cost of Unnecessary Threat Response Missions

7.3. Survey and Deflection Strategy Options

Figure 63 shows a decision tree for selected strategy options for both parts of this study. In Step 1, a detection and tracking architecture is selected. Ground-based, space-based, and combinations of ground- and space-based systems can meet the congressional goal of detecting 90% of PHOs 140 meters and larger by 2020. In Step 2, it is expected that search systems can provide a portion of the orbit and mass characterization required to assess the threat, but options for enhancing this capability including radar are presented. In Step 3, mitigation strategy options (including perhaps deflection demonstrations) are chosen informing the choice of further characterization in Step 4 (if required).

1. Select Detection and Tracking Architecture other similar options exist

Option FY06 $	through 2020	LCC thru 2020*	Year 90%	LCC to 90%*
Shared ground-based (Baseline)*	83%	$0.31B	2026	$0.52B
Dedicated ground-based	85%	$0.66B	2024	$0.87B
Dedicated ground-based + Baseline	90%	$0.82B	2020	$0.82B
Infrared in Venus-like orbit	89%	$0.84B	2021	$0.86B
Infrared @ L1 + Baseline	91%	$1.1B	2020	$1.1B
Infrared in Venus-like orbit + Baseline	97%	$1.1B	2018	$1.0B

~$150M cataloguing costs in all options *1-2% uncertainty in relative performance*

↓

2. Add Orbit and Mass Characterization

Options FY06 $	LCC thru 2020*
Use search systems	$0B
Augment search systems	$100M-$400M
Dedicated ground	$100-$300M
Dedicated space	$1-$1.5B
Radar for some threats	< $100M

↓

3. Develop a Mitigation Strategy

Options FY06 $	LCC thru 2020
No dedicated preparation	$0+
Coordinate deflection technologies w/ ESMD	$0+
Cooperate with international efforts	$50M+
Perform deflection demonstration (by 2014)	$100M+
Develop nuclear explosives technologies	?

↓

4. Develop Characterization Further if Needed for the Mitigation Strategy ($0-$8B)

** LCC = Life-cycle cost*

Figure 63. Decision Tree for Survey and Deflection Strategy Options

8 Summary

In the 2005 Budget Authorization Act, the U.S. Congress directed the NASA Administrator to provide an analysis of alternatives to detect, track, catalogue, and characterize potentially hazardous near-Earth objects (NEO). Congress required that the Administrator submit a program by December 28, 2006 to survey 90% of the potentially hazardous objects measuring at least 140 meters in diameter by the end of 2020. In addition, the legislation required the Administrator to submit an analysis of alternatives that NASA could employ to divert an object on a likely collision course with Earth.

A study team, led by the Office of Program Analysis and Evaluation (PA&E), derived requirements and figures of merit from the Act, and used these factors to evaluate the alternatives. The team developed a range of options from public and private sources and then analyzed their capabilities, levels of performance, life-cycle costs, schedules, and development and operations risks. This document presents the detailed results of these analyses. A summary report was submitted to Congress in December of 2006.

8.1. Survey Analysis of Alternatives

Detection and tracking alternatives identified by the study team included optical systems located on the ground and optical and infrared assets located in space. For ground-based alternatives, the study team considered sharing planned observatories such as PanSTARRS 4 (PS4), funded by the U.S. Air Force, and the Large Synoptic Survey Telescope (LSST), partially funded by the National Science Foundation. The team also considered new NASA-funded facilities that would be dedicated to the search for hazardous objects and would be based on these planned observatories. Although cost margin was applied to alternatives that leveraged planned assets, programs that rely on these projects may carry additional cost and schedule risk. Specific results include:

- An architecture, which combines the sharing of the planned PS4 and LSST systems with a second, dedicated NASA-funded LSST, was the only ground-based alternative able to meet the congressional goal of identifying 90% of the hazardous objects by 2020. This combination is estimated to have a life-cycle cost of $820M ($FY06).
- A shared PS4, a shared LSST, and a dedicated NASA-funded PS8 were able to catalog 90% of hazardous objects by 2024, with a life-cycle cost of $560M.
- A dedicated, NASA-funded observatory based on LSST's design was also able to catalog 90% of potentially hazardous objects in 2024 without the contributions of other programs. Its estimated life-cycle cost is $870M.

Space-based search alternatives were located in low-Earth orbit, at Sun-Earth Lagrange points, and in heliocentric Venus-like orbits. Only an infrared system operating in a Venus-like orbit was able meet the congressional goals without the contribution of shared ground-based assets. All space-based alternatives were able to meet the goals when combined with a ground-based baseline of a shared PS4 and a shared LSST.

A space mission failure could delay achieving the 90% goal by up to 5 years, after which the catalog could be completed with shared ground-based assets. Infrared systems operating in space could provide more accurate size estimates of up to 80% of objects in the catalog. Observatories located in a Venus-like orbit are the most efficient at finding objects inside Earth's orbit, a potentially underestimated population. Additionally, by the end of 2020, infrared systems in Venus-like orbits can find 90% of the objects measuring over about 80 meters, exceeding the 140-meter requirement. Finally, space-based systems have much less uncertainty in the date of reaching 90% due to their superior sensitivity.

Selected space-based alternatives include:

- A 0.5-meter infrared system operating in a Venus-like heliocentric orbit completes 89% of the survey by 2020 which is within the uncertainty of the analysis. This system has a life-cycle cost of $840M ($FY06).
- A similar 0.5-meter infrared system operating in a Venus-like orbit and working in concert with a shared PS4 and a shared LSST completes 90% of the survey in 2018, with a life-cycle cost of $1B through 2018.
- A 0.5-meter infrared system operating at Sun-Earth L1 in conjunction with the baseline finishes 90% of the survey in 2020. Its life-cycle cost is $1.1B.

Infrared systems with a 1.0-meter aperture complete the survey about 1 year earlier than the 0.5-meter alternatives described above, and have life-cycle costs about $300M higher. Optical systems with 1.0-meter and 2.0-meter apertures in Venus-like orbits, combined with the baseline ground-based systems, completed the survey by 2017 and 2019 respectively, with life-cycle costs in excess of $1.7B. The visible system with a 2.0-meter aperture progressed more slowly than the 1.0-meter system due to differences in development time. Acquisition of new systems was assumed to start October 1, 2007, and delays in funding will affect the ability of some alternatives to meet the 90% completeness goal by the end of 2020. Table 41 and Figure 64 summarize the cost-performance variation of a range of detection options.

Table 41. Summary of Detection, Tracking, and Cataloguing Alternatives

	through 2020	**Cost thru 2020 (FY06)**	**Year 90%**	**Cost to 90% (FY06)**
Continue Spaceguard (in all)	14%	< $0.2B	>>2030	-
Shared PS4 and LSST*	83%	$0.31B	2026	$0.52B
Shared PS8 + Baseline	85%	$0.41B	2025	$0.56B
Dedicated LSST	85%	$0.66B	2024	$0.87B
Dedicated LSST + Baseline	90%	$0.82B	2020	$0.87B
0.5m IR @ L1 + Baseline	91%	$1.1B	2020	$1.1B
1.0m IR @ L1 + Baseline	91%	$1.3B	2019	$1.3B
0.5m IR @ Venus + Baseline	97%	$1.1B	2018	$1.0B
1.0m IR @ Venus + Baseline	97%	$1.4B	2017	$1.3B
1.0m VIS @ LEO/L1 + Baseline	93%	$1.8B	2017	$1.7B
2.0m VIS @ LEO/L1 + Baseline	95%	$2.1B	2019	$2.0B

** Baseline = Shared PS4 + Shared LSST*

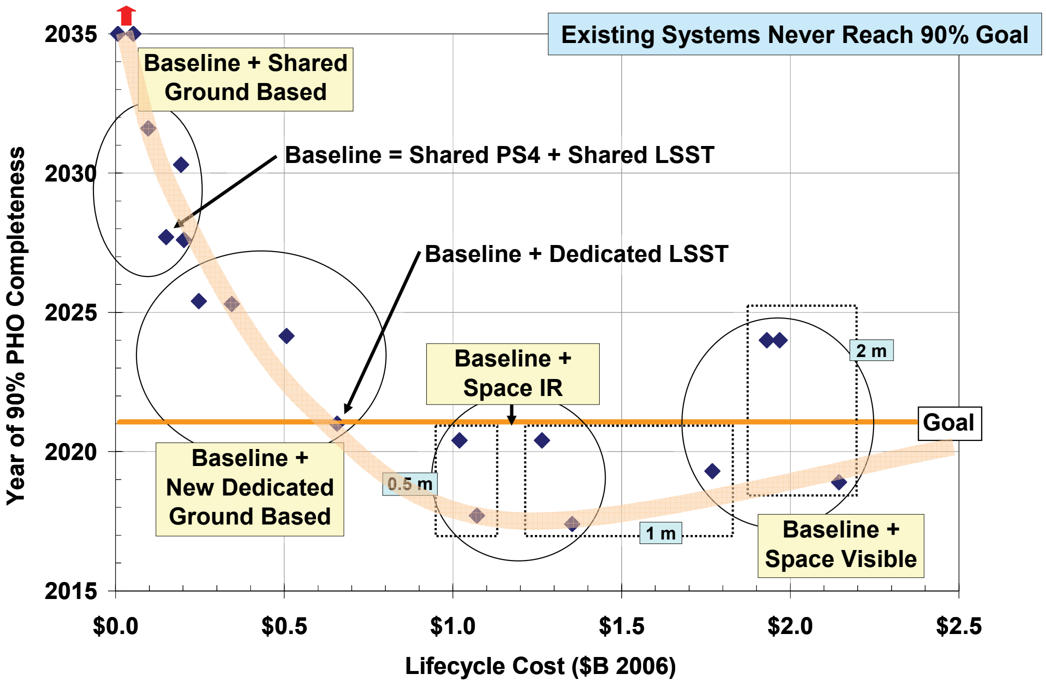


Figure 64. Year of Reaching 90% Completeness vs. Life-Cycle Cost

Congress provided two 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 hazard. Detection and tracking systems with judicious follow-up are all able to provide warning, 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 provide data for much more accurate size estimates.

If detection systems must characterize the catalog, the time to complete the survey to a 90% completion level will be extended. Furthermore, the costs of these systems may increase $100M-$400M to accommodate filters and additional data processing. In addition, the smallest and faintest objects may remain visible to sensors only for a few days or weeks. Therefore, if characterization is required and it is not performed by detection systems, either formal relationships with extant observatories for "on demand" access must be negotiated or new dedicated characterization facilities will be needed.

Radar may quickly and precisely characterize and determine the orbit of about 10-25% of the objects of interest within 5 years of their detection. While the number of objects observed by radar increases with time, the relative value of 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 decades of observation. Therefore, the utility of radar is limited to a relatively few "short warning" cases that may be of very high interest during the survey. Up to $100M in funding (not included in detection and tracking life-cycle costs) may be required to maintain radar capability through 2020, as NASA and National Science Foundation funding for existing radars is currently in flux.

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 potential threats. This information may include the structure, porosity, rotation rate, material composition, and surface features of the threats. 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 be used to infer a limited number of characteristics of a particular object. 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 (with a transponder, for example) and to characterize the potential threat if deflection is necessary.

This study has determined that it is premature to set specific characterization requirements to enable mitigation until a mitigation strategy has been determined; therefore, the study has 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 of threats with sufficiently high impact probabilities. These options have life-cycle costs ranging from $50M-$8B ($FY06) over several decades, and are summarized in Table 42.

Table 42. Summary of Characterization Capability Options

	Description	**Cost (FY06) Period**
Option 1	Use existing assets plus detection and tracking system elements. *No dedicated characterization.*	**$0.1B** 2007-2026
Option 2	Develop dedicated ground system(s) to gather and analyze data. *No in-situ missions.*	**$0.2B** 2007-2026
Option 3	Develop dedicated space system(s) to gather and analyze data at Sun-Earth L1. *No in-situ missions.*	**$1.1B** 2007-2023
Option 4	Develop dedicated space system(s) to gather and analyze data near Venus. *No in-situ missions.*	**$1.2B** 2007-2023
Option 5	Add to Options 1-3 eight (8) visits to representative NEOs using fly-bys to calibrate models.	**$2.0B** 2007-2024
Option 6	Add to Options 1-3 eight (8) visits to representative NEOs using rendezvous missions to test models.	**$6.7B** 2007-2031
Option 7	Perform Option 6 at a fixed mission rate to 8 potential threats at 5 years intervals	**$8.2B** 2007-2053

It is expected that during the 5-10 years of a survey, a total of 500,000 objects will be discovered by more than 2 million individual observations. About 21,000 of these objects will measure 140 meters or larger and be tracked as potentially hazardous. Although this study uses an estimate of the population of potentially hazardous objects based on statistical projections, the actual number of objects will not affect the date of reaching the 90% goal as long as the objects are approximately distributed in orbits as predicted.

This volume of observations will require a data-processing capability that is 100 times more capable than current cataloguing systems. After objects are detected, the system must be able to obtain follow-up observations, store and distribute collected data, and analyze these data for observed but previously undetected objects. Currently, uncompensated or under-funded analysts perform many of these functions. Such an approach likely will not remain viable. Finally, either the NASA Survey or otherwise funded activities, such as PS4 and LSST, are expected to produce impact warnings at a rate that is 40 times greater than what is experienced today. This much higher rate of warnings will start as early as 2010.

8.2. Deflection Analysis of Alternatives

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 developed for each of these alternatives. They were applied to a set of five scenarios representing the likely range of threats over million-year timescales.

The use of nuclear explosives was found to be the most effective alternative in the near term. While an explosion on or below the surface of a threatening object is 10-100 times more effective than a detonation above the surface, the standoff detonation would be less likely to fragment the target. Nuclear options require the least amount of detailed information about the threatening object. A nuclear standoff mission could be designed knowing only the orbit and approximate mass of the threat, and most impulsive 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. The study examined conventional explosives, but found they were ineffective against most threats.

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 also are sensitive to the porosity, elasticity, and composition of the target and may require larger performance margins if these characteristics are not well determined.

Slow push techniques analyzed in this study included a gravity tractor, which would alter the course of an object using the gravitational attraction of a massive spacecraft, and a space tug, which would attach to an object 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% of expected threat scenarios), but these techniques 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.

Figure 65 shows the span of deflection performance and costs for the alternatives analyzed. Deflection performance is expressed as momentum imparted to the target and covers the range of likely threats over a million-year timescales.

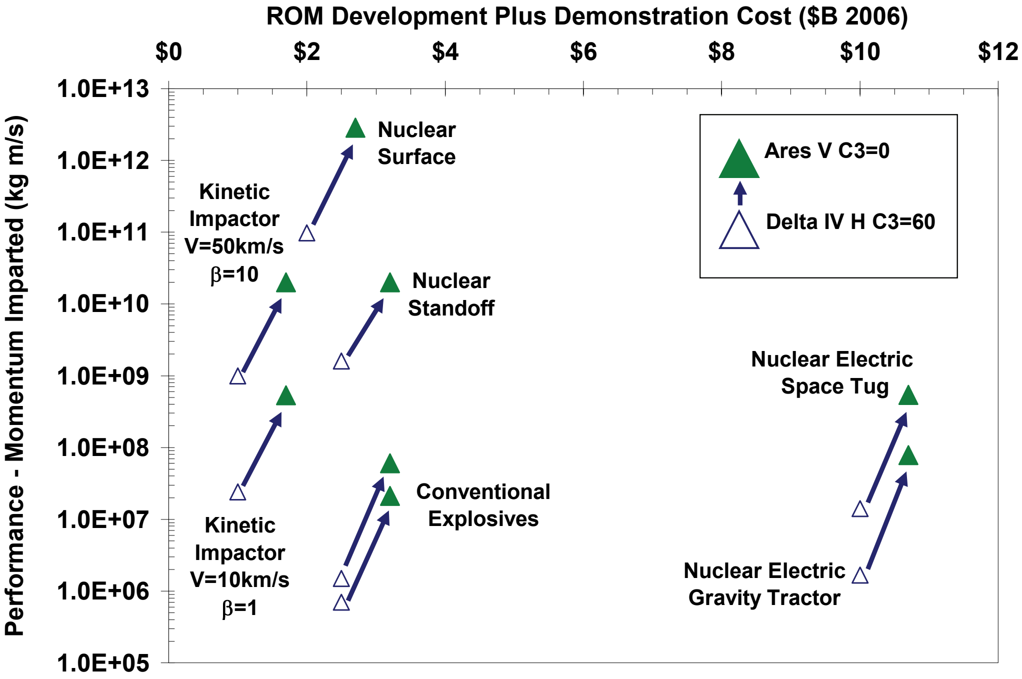


Figure 65. Deflection Performance vs. ROM Development Cost

The level of risk reduction required of a deflection campaign needs to be clearly understood, as it has a first-order impact on cost and complexity. While this report uses a goal of reducing the probability of impact to 1 in 1 million, this is not a nationally or internationally accepted threshold. Additionally, when designing the deflection campaign, planners must take into account that launch vehicles and interplanetary spacecraft fail at relatively high rates (2-5% for launches; 10+% for spacecraft) and that deflection approaches may not perform as designed. Planning for many flights of multiple spacecraft designs launched from several different launch vehicles may be necessary to achieve the reduction in impact probability projected to be required.

8.3. Summary of Findings

- Combining optical ground-based observatories currently under development with a dedicated ground-based asset can reach the congressional goal by the end of 2020. Life-cycle cost for this architecture, including a robust data-management and data-analysis infrastructure, is estimated to be $820M through 2020.
- Space-based infrared systems, combined with shared ground-based assets, could reduce the overall time to reach the 90% goal by up to 3 years, with life-cycle costs of $1.0-$1.3B through 90% completion. Space systems have additional benefits and risks over ground-based alternatives, and are generally more capable (sensitive) than 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 objects of potentially high interest. Existing radar systems are oversubscribed, and funding to operate these systems may be in flux. A budget for radar is not included in the detection and tracking life-cycle costs.
- Determining an object's mass and orbit are required to determine whether it represents a threat and to inform deflection alternatives. Beyond these parameters, characterization requirements and capabilities are tied directly to the mitigation strategy selected. Life-cycle costs for the characterization options vary by billions of dollars depending on the mitigation strategy pursued.
- While several countries have capable programs to study near-Earth objects, none of these efforts has materially influenced the results of the study team.
- Nuclear standoff explosions are assessed to be 10-100 times more effective than the non-nuclear alternatives analyzed in this study. Other techniques involving nuclear explosives may be more effective, but they run an increased risk of fracturing the target. They also carry higher development and operations risks.
- Kinetic impactors are the most mature approach and could be used in some scenarios, especially for objects that consist of a relatively small, solid body.
- Slow push deflection techniques are the most expensive, and their ability to both travel to and divert a threatening object is limited unless mission durations of many decades are available.
- Deflection campaigns may need to be 100-1,000 times more reliable than current space missions to meet mitigation requirements.
- Many potentially hazardous objects (30-80%) are in orbits that are beyond the capability of current or planned launch systems. Therefore, if these objects need to be deflected, swingby trajectories or on-orbit assembly of modular propulsion systems may be required to augment launch vehicle performance.

9 Definition of Terms

Acronym	Description
ACE	Advanced Composition Explorer
APL	Applied Physics Laboratory
AU	Astronomical Unit
D	Diameter
DCT	Discovery Channel Telescope
DoD	Department of Defense
FOM	Figure of Merit
FY	Fiscal Year
HQ	Headquarters
IEO	Interior Earth Object
IOC	Initial Operational Capability
IR	Infrared
IRTF	InfraRed Telescope Facility
Isp	Specific Impulse
JHU	Johns Hopkins University
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
JWST	James Webb Space Telescope
KBO	Kuiper Belt Objects
L1	First Sun-Earth Lagrange Point
LCC	Life-Cycle Cost
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
NEOO	Near-Earth Object Office
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
RFI	Request for Information
SDT	Science Definition Team
SIM	Space Interferometry Mission

Acronym	Description
SMD	Science Mission Directorate
SOHO	Solar and Heliospheric Observer
SST	Space Surveillance Telescope
TS	Torino Scale
Vis	Visible
VISTA	Visible and Infrared Survey Telescope
WISE	Wide-field Infrared Survey Explorer
WMAP	Wilkinson Microwave Anisotropy Probe

10 References

[1] Public Law 109-155. *http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=109_cong_public_laws&docid=f:publ155.109*

[2] Binzel, R.P., Rivkin, A.S., Lupishko, D.F. *Observed Properties of Near-Earth Objects.* White Paper. NASA NEO Workshop, Vail, Colorado. June 2006.

[3] *Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters*. Report of the Near-Earth Object Science Definition Team. Prepared at the Request of NASA Office of Space Science, Solar System Exploration Division. August 22, 2003.

[4] Bottke, W.F., Morbidelli, A., Jedicke, R., Petit, J.M., Levison, H.F., Michel, P., Metcalfe, T. S. *Debiased Orbital and Absolute Magnitude Distribution of the Near-Earth Objects.* 2002. Icarus, 156, 399.

[5] Michel, P., Zappala, V., Cellino, A., Tanga, P. *Estimated abundance of Atens and asteroids evolving on orbits between Earth and Sun*. ICARUS, 2000, Vol.143, No.2, pp.421-424

[6] *The Spaceguard Survey: Report of the NASA International NEO Detection Workshop*, Jet Propulsion Laboratory, Pasadena. Morrison, D., ed. 1992.

[7] *NASA Near-Earth Objects Survey Working Group Report*. Eugene Shoemaker, Chairman. 1994.

[8] Personal communication. Jon Giorgini, JPL. September 15, 2006.

[9] *VanCleve, J.*, LinField, R., Ebbets, D., Reitsema, H., Arentz, R., Murrow, D., Williams, B., Taylor, T., *Ranging Transponders for Precision NEO Orbit Determination*. White Paper. NASA NEO Workshop, Vail, Colorado. June 2006.

[10] Larson, S. and Beshore, E. *Observational Follow Up Needs for the Next Generation of NEO Surveys*. White Paper. NASA NEO Workshop, Vail, Colorado. June 2006.

[11] Chapman, C.R. and Morrison, D., *Impacts on the Earth by Asteroids and Comets: Assessing the Hazard.* Nature 367, 33-40. 1994.

[12] Milani, A., Chesley, S. R., and Valsecchi, G. B. *Close approaches of asteroid 1999 AN: Resonant and non-resonant returns.* A&A, 346:L65–L68.

[13] Gugliotta, G. *A New Path for Asteroids.* Washington Post. November 10, 2005.

[14] Chesley, S.R. *Potential Impact Detection for Near-Earth Asteroids: The Case of 99942 Apophis (2004 MN4)*, in Asteroids Comets, Meterors. Proceedings of IAU Symposium # 229, held August 7-12, 2005 in Buzios, Brazil.

[15] Chodas, P. W. and Yeomans, D. K. *Predicting close approaches and estimating impact probabilities for near-Earth objects.* Paper AAS 99-462, AAS/AIAA Astrodynamics Specialists Conference, Girdwood, Alaska.

[16] Personal communication with Don Yeomans, Steve Chesley, Paul Chodas, JPL.

[17] Schweickart, R. et al, *Threat Characterization: Trajectory Dynamics*, White Paper. NASA NEO Workshop, Vail, Colorado. June 2006.

[18] Dearborn, D.S. *21st Century Steam for Asteroid Mitigation.* 2004 Planetary Defense Conference. UCRL-PROC-202922. March 16, 2004.

[19] Bottke, W. F., Vokrouhlicky, D. Rubincam, D. P., and Nesvorný D. (2006) *The Yarkovsky and YORP Effects: Implications for Asteroid Dynamics*. Ann. Rev. Earth Planet. Sci., v. 34, p. 157-191.

[20] Vokrouhlický D. and Milani A. *Direct solar radiation pressure on the orbits of small near-Earth asteroids: Observable effects?* Astron. Astrophys., 362, 746–755. 2000.

[21] Rubincam D. P. *Asteroid orbit evolution due to thermal drag.* J. Geophys. Res., 100, 1585–1594. 1995.

[22] Radzievskii V. V. *About the influence of the anisotropically reemited solar radiation on the orbits of asteroids and meteoroids.* Astron. Zh., 29, 162–170. 1952.

[23] Smith P.L. et al, *Deflecting a Near-Earth Object with Today's Space Technology.* AIAA 2004-1447, 2004 Planetary Defense Conference: Protecting Earth from Asteroids. February 2004.

[24] Sommer G.S. 2004. *Astronomical Odds: A Policy Framework for the Cosmic Impact Hazard.* PhD Dissertation, RAND Graduate School. June 2004.

[25] Morrison, D. et al. *Dealing with the Impact Hazard. In Asteroids III.* Bottke et al. Editors. University of Arizona Press, Tucson, 2002, p.749.

[26] *Comet/Asteroid Protection System (CAPS): Preliminary Space-Based System Concept and Study Results.* Mazanak, et al. NASA NASA/TM-2005-213758. May 2005.

[27] *Survey of Technologies Relevant to Defense from Near-Earth Objects.* Adams, et al. NASA/TP—2004–213089. July 2004.

[28] Mankins, J. C., *Technology Readiness Levels*, NASA Advanced Concepts Office. April 6, 1995.

[29] Holsapple, K.A., *The Deflection of Menacing Rubble Pile Asteroids.* White Paper.

[30] Gennery, D.B., *Deflecting Asteroids by means of Standoff Nuclear Explosions*, AIAA 2004-1439, 2004 Planetary Defense Conference: Protecting Earth from Asteroids. February 2004.

[31] Lynch, D.K., and Peterson, G.E. *Athos, Porthos, Aramis, & D'Artagnon: Four Planning Scenarios for Planetary Protection.* AIAA-2004-1417. 2004 Planetary Defense Conference: Protecting Earth from Asteroids.

[32] Junkins, J., Singla, P, and Davis, J. *Impact Keyholes and Collision Probability Analysis for Resonant Encounter Asteroids*, White Paper. NASA NEO Workshop, Vail, Colorado. June 2006.

[33] Bodnar, J. et al, *Near-Earth Object Deflection System: Nullifying The Threat Posed By Asteroid 99942 Apophis*, White Paper. NASA NEO Workshop, Vail, Colorado. June 2006.

[34] Holsapple, K.A., *Existing Methods of Asteroid Deflection Will Work: Impacts and Nuclear Bombs*, University of Washington, 2006

[35] http://neo.jpl.nasa.gov/risk/2004vd17.html.

[36] Goebel, *Electric Propulsion Research and Development at JPL*, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit. 10 - 13 July 2005, Tucson, Arizona, AIAA 2005-3535.

[37] http://www.planetarydefense.info

[38] Chodas, P. *Warning Time for Long-Period Comets on Earth Impact Trajectories*. White Paper. 96-0609.

[39] Chapman, C.A., Durda, D.D, Gold, R. *The Comet/Asteroid Impact Hazard: A Systems Approach.* 24 February, 2001.

[40] Meech, K. J., Hainaut, O. R., Marsden, B. G. *Comet Size Distributions and Distant Activity*, in Minor Bodies in the Outer Solar System, ESO Astrophysics Symposia, ed. A. Fitzsimmons, D. Jewitt and R. M. West, Springer New York, 75-79.

[41] Dr. Sten Ostenwald, NASA/GSFC. http://www.astronomycafe.net/qadir/q918.html

[42] Morrison, D., Chapman, C.R., Steel, D., and Binzel R. P. *Impacts and the Public: Communicating the Nature of the Impact Hazard* in Mitigation of Hazardous Comets and Asteroids, (M.J.S. Belton, T.H. Morgan, N.H. Samarasinha and D.K. Yeomans, Eds), Cambridge University Press, 2004.

[43] http://neo.jpl.nasa.gov/torino_scale1.html

[44] Chesley, S.R., Chodas, P.W., Milani, A., Valsecchi, G.B., Yeomans, D.K. *Quantifying The Risk Posed By Potential Earth Impacts*. Icarus 159, 423-432 (2002)

[45] Chesley, S. R. *Asteroid Impact Prediction*, Invited lecture for Near-Earth Ojects, Our Celestial Neighbors: Opportunity and Risk, IAU Symposium 236, Prague, Czech republic, Aug. 14-18, 2006.

[46] IVOA website, 5 September 2006, http://www.us-vo.org/about.cfm

[47] IVOA website, 5 September 2006, http://www.ivoa.net/pub/info/

[48] Meadows, V. *Near Earth Asteroid Surveys and SIRTF.* White paper for NASA HQ/NEOO. January 2001.

[49] Hudson, R.S. *Three-dimensional reconstruction of asteroids from radar observations.* Remote Sensing Review, vol. 8, p. 195, 2003.

[50] Ostro, S.J.. *Planetary radar astronomy.* Review of Modern Physics, vol. 65, No. 4, Oct. 1993, pp. 1235-1280.

[51] Ostro, S.J., R.S. Hudson, M.C. Nolan, J.-L. Margot, D.J. Scheeres, D.B. Campbell, C. Magri, J.D. Giorgini, D.K. Yeomans *Radar Observations of Asteroid 216 Kleopatra.* Science, vol. 288, pp.836-839. (2000).

[52] Ostro, S.J., R.S. Hudson, R.F. Jurgens, K.D. Rosema, D.B. Campbell, D.K. Yeomans, J.F. Chandler, J.D. Giorgini, R. Winkler, R. Rose, S.D. Howard, M.A. Slade, P. Perillat, I.I. Shapiro *Radar Images of Asteroid 4179 Toutatis*. Science, vol. 270, pp. 80-83. (1995).

[53] Ostro, S.J., Giorgini, R. *The Role of Ground-based Radar in Near-Earth Object Tracking, Characterization and Threat Mitigation*. Near-Earth Object Study, Vail, Colorado. June 2006.

[54] Walker, J.D. and Chocron, S., *NEO Deflection Through Conventional Explosives*, White Paper. NASA NEO Workshop, Vail, Colorado. June 2006.

[55] Walker, J.D. and Chocron, S., *NEO Deflection through Conventional Explosives*, Southwest Research Institute. 2006.

[56] Wie, B., *Solar Sailing Kinetic Impactor Mission Concept for Impacting and Deflecting Near-Earth Asteroids*, White Paper. NASA NEO Workshop, Vail, Colorado. June 2006.

[57] Gold, R.E., *SHIELD—A Comprehensive Earth Protection System,* Phase I Report to the NASA Institute for Advance Concepts. May 28, 1999.

[58] Cleve, J. and Bank, T. *The Impact of Deep Impact*, Ball Aerospace & Technologies Corp. 2006

[59] Simonenko, V.A., Nogin, V.N., Petrov, D.V., Shubin, O.N., and Solem, J.C. *Defending the Earth against Impacts from Large Comets and Asteroids.* in Hazards Due to Comets and Asteroids, T. Gehrels, ed.; University of Arizona Press, Tucson and London, p 929-54. 1994.

[60] Holsapple K., Verbal Discussion 7-2006, and *Existing methods of asteroid deflection will work: Impacts and Nuclear Bombs*, White Paper. NASA NEO Workshop, Vail, Colorado. June 2006.

[61] Nuclear Test Ban Treaty. June 2006. http://www.mcgill.ca/iasl/research/treaties/space_law/nuclear/.

[62] Teller, E., Talley, W.K., Higgins, G.K., and Johnson, G. *The Constructive Uses of Nuclear Explosives*. McGraw-Hill, 1969.

[63] Rodger, C.J., Clilverd, M.A., Ulich, Th, Verronen, P.T., Turunen, E., and Thomson, N.R. *The Atmospheric Implications of Radiation Belt Remediation.*

Annales Geophysicae, 24, 2024-2041. 2006. http://www.ann-geophys.net/24/2025/2006

[64] Barbee, B.W., Fowler, W.T., Davis, G.W., and Gaylor, D.E., *Optimal Deflection of Hazardous Near-Earth Objects by Standoff Nuclear Detonation and NEO Mission Design*, White Paper. NASA NEO Workshop, Vail, Colorado. June 2006.

[65] Dearborn, D., Verbal Discussion July 2006, and *21st Century Steam for Asteroid Mitigation*, AIAA 2004-1427, 2004 Planetary Defense Conference

[66] Nousek, J.A., Bautz, M.W. *Science Instrument (SI) Calibration Report for the AXAF CCD Imaging Spectrometer (ACIS).* Version 2.20. January 15, 1999.

[67] Ahrens T.J. and Harris A.W., *Deflection and Fragmentation of NEAs* in Hazards due to comets and asteroids, ed. by T. Gehrels. pp 897-928. 1994.

[68] Shafer B. P. et al. *The coupling of energy to asteroids and comets* in Hazards due to comets and asteroids, ed. by T. Gehrels, pp 955-1012. 1994.

[69] Holsapple, K., An Assessment of our Present Ability to Deflect Asteroid and Comets, AIAA 2004-1413, 2004 Planetary Defense Conference.

[70] Holsapple, K.A., *Existing Methods of Asteroid Deflections Will Work: Impacts and Nuclear Bombs,* White Paper. NASA NEO Workshop, Vail, Colorado. June 2006.

[71] http://neo.jpl.nasa.gov

[72] Agle, D., NASA Scientist Use Radar to Detect Asteroid Force, http://www.jpl.nasa.gov/releases/2003/163.cfm. 2003

[73] Izzo, D. *On the Deflection of Potentially Hazardous Objects.* AAS 05-141. 15th AAS/AIAA Space Flight Mechanics Conference. January 23-27, 2005.

[74] Spitale, J.N. *Asteroid Hazard Mitigation using the Yarkovsky Effect.* Science Volume 296 p97. 5 April 2002.

[75] Schweickart, R., Chapman, C., Durda, D., Hut, P., *Threat Mitigation: The gravity tractor.* White Paper. NASA NEO Workshop, Vail, Colorado. June 2006.

[76] Lu, E.T. and Love, S.G. *Gravitational tractor for Towing Asteroids*. Nature 438, 177-178. 2005.

[77] Schweickart, R., *Threat Mitigation: The gravity tractor.* White Paper. NASA NEO Workshop, Vail, Colorado. June 2006.

[78] Valentine, L., Planetary Defense Conference, Space Studies Institute. 2004

[79] O'Learv, B. - *Mass Driver Retrieval of Earth-Approaching Asteroids.* Space Manufacturing Facilities 11, AIAA, New York, 1977, p. 157.

[80] Gerl, D.A.M., Salustri, F.A., *Design of a Mass Driver System Concept Using Open Source Principles*. White Paper. http://www.massdriver.com/

[81] Adams, R.B., et al. *Planetary Body Maneuvering: Study Architecture and Results*. AIAA 2004-1430.

[82] Friedman, G., Gertsch, R.E., Lewis, J.S., Snively, L., Valentine, L., Wingo, D. *Mass Drivers for Planetary Defense.* AIAA 2004-1450.

[83] Discussion with Retsima. NASA NEO Workshop, Vail, Colorado. June 2006.

[84] Preston R., Johnson, D.J., Edwards, S. J. A., Miller, M. D., Shipbaugh, C. Space Weapons, Earth Wars. *Appendix A. Space Based Directed Energy Weapons.* Rand Monograph MR 1209 AF. ISBN: 0-8330-2937-1.

[85] Fork, R., response to question at NASA NEO Workshop, Vail, Colorado. June 2006.

[86] Izzo D., *Strategies for Near-Earth Object Impact Hazard Mitigation*. AIAA/AAS 05-147. 2005

[87] Goebel, D. *Electric Propulsion Research and Development at JPL.* AIAA 2005-3535. 2005

[88] Polk, J., *Performance and Wear Test Results for a 20 kW-Class Ion Engine with Carbon-Carbon Grids*, AIAA 2005-4393. 2005

[89] Izzo D., *On the Deflection of Potentially Hazardous Objects.* AIAA/AAS -5-141. 2005

[90] NASA JSC Cost Estimating Handbook Reserve Examples, http://www.jsc.nasa.gov/bu2/guidelines.html

[91] Bearden, D. A., *A Complexity-Based Risk Assessment Of Low-Cost Planetary Missions: When Is A Mission Too Fast And Too Cheap?*, The Aerospace Corporation, Fourth IAA International Conference On Low-Cost Planetary Missions, JHU/APL, Laurel, MD. May 2-5, 2000.

[92] Young, P. H., *FRISK-Formal Risk Assessment of System Cost Estimates.* The Aerospace Corporation, AIAA 1992 Aerospace Design Conference. February 1992.

[93] Hamaker, J., *NASA MSFC's Engineering Cost Model (ECM).* 1989. Proc. Intl. Soc. Parametric Analysts, 10th Annual Conference, Brighton

[94] Book, S. A., *Why Correlation Matters in Cost Estimating*, The Aerospace Corporation, 32nd Annual DOD Cost Analysis Symposium, Williamsburg, VA. February 2–5, 1999

[95] *NASA Cost Estimating Handbook, Appendix M, Compilation of Models and Tools*, http://ceh.nasa.gov/webhelpfiles/Appendix_M-Compilation_of_Models_and_Tools.htm

[96] Kellogg, R. and Phan, S., *An Analogy-based Method for Estimating the Costs of Space-based Instruments*, 2003 IEEE Aerospace Conference Proceedings. March 8-15, 2003.

[97] Strope, D., *Goddard Multivariable Instrument Cost Model (MICM)*, Proceedings of the 1998 NASA Cost Symposium. September 15-17, 1998.

[98] Kellogg, R., Lao, N., and Bitten, R., *Space-Based Optical Sensor Cost Model Final Report*, Aerospace Report No. ATR-99(7626)-1. June 15, 1999.

[99] *NASA Systems Engineering Handbook, Systems Analysis and Modeling Issues*, June 1995, SP-106S, Chapter 5.2.3 Cost Estimating, Page 96.

[100] Nadis, S. *Keeper of the Objects.* Scientific American. August 2003.

[101] Binzel, R.P., Rivkin, A.S., Lupishko, D.F. *Observed Properties of Near-Earth Objects.* White Paper. NASA NEO Workshop, Vail, Colorado. June 2006.

[102] Bottke, W. F. and Melosh, H. J., 1996. *Formation of asteroid satellites and doublet craters by planetary tidal forces.* Nature 281, 51-53. 1996.

[103] Polishook, D. and Brosch, N. *Many binaries among NEAs.* White Paper. NASA NEO Workshop, Vail, Colorado. June 2006.

[104] Jenniskens, P. *Characterizing the NEO Population from Meteor Observations.* White Paper. White Paper. NASA NEO Workshop, Vail, Colorado. June 2006.

[105] Wilson, L.; Keil, K., *The Internal Structure of Asteroids.* 30th Lunar & Planetary Science Conference, March 15-29, 1999, Houston,. Abstract #1244.

[106] Tedesco, E.F., Africano, J.L., Kervin, P.W., S.D. Price. *Tracking and Characterization of NEO'S Using AMOS Ground-Based Optical Telescopes*, Planetary Defense Workshop, Livermore CA. May 22 – 26, 1995

[107] Harris, A.W., Pravec, P., *Spins and Satellites: Probes of Asteroid Interiors*. Sixth Catastrophic Disruption Workshop. Cannes, France. June 9-11, 2003.

[108] http://www.nasa.gov/mission_pages/deepimpact/main/index.html

[109] Holsapple and Schmidt, 1982 (see Gold, 1999)

[110] *CASSANDRA: A Strategy to Protect our Planet from Near-Earth Objects.* Final Report, International Space University, Summer Session Program 2005.

[111] Canavan, G., Cost and Benefit of Near-Earth Object Detection and Interception, *Hazards Due to Comets and Asteroids*, Gehrels, T., editor, University of Arizona Press, Tucson, Arizona. 1994. pp.1157-1189.

[112] Stokes, G. H., Yeomans, D. K., et. al., *Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters, Report of the Near-Earth Object Science Definition Team*, NASA Office of Space Science, Solar System Exploration Division. August 22, 2003.

[113] Kenkel, D., *Using Estimates of the Value of a Statistical Life in Evaluating Regulatory Effects.* Session 1, Valuing Statistical Lives, Valuing the Health Benefits of Food Safety: A Proceedings, Kuchler, F., editor, U.S. Department of Agriculture Economic Research Service, MP1570. April 2001.

[114] Holsapple, K. *Existing Method of Asteroid Deflection will work: Impacts and Nuclear Bombs*, White Paper. NASA NEO Workshop, Vail, Colorado. June 2006.

11 Appendices

Appendix A. George E. Brown Jr. Near-Earth Object Survey Act

Public Law No: 109-155. SEC 321

(a) Short Title.--This section may be cited as the ``George E. Brown, Jr. Near-Earth Object Survey Act''.

(b) Findings.--The Congress makes the following findings:

- (1) Near-Earth objects pose a serious and credible threat to humankind, as many scientists believe that a major asteroid or comet was responsible for the mass extinction of the majority of the Earth's species, including the dinosaurs, nearly 65,000,000 years ago.
- (2) Similar objects have struck the Earth or passed through the Earth's atmosphere several times in the Earth's history and pose a similar threat in the future.
- (3) Several such near-Earth objects have only been discovered within days of the objects' closest approach to Earth, and recent discoveries of such large objects indicate that many large near-Earth objects remain undiscovered.
- (4) The efforts taken to date by NASA for detecting and characterizing the hazards of near-Earth objects are not sufficient to fully determine the threat posed by such objects to cause widespread destruction and loss of life.

(c) Definitions.--For purposes of this section the term “near-Earth object” means an asteroid or comet with a perihelion distance of less than 1.3 Astronomical Units from the Sun.

(d) Near-Earth Object Survey

- (1) Survey program.--The Administrator shall 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 to assess the threat of such near-Earth objects to the Earth. It shall be the goal of the Survey program to achieve 90 percent completion of it’s near-Earth object catalogue (based on statistically predicted populations of near-Earth objects) within 15 years after the date of enactment of this Act.
- (2) Amendments.--Section 102 of the National Aeronautics and Space Act of 1958 (42 U.S.C. 2451) is amended--
  - (A) by redesignating subsection (g) as subsection (h);
  - (B) by inserting after subsection (f) the following new subsection:

    “(g) The Congress declares that the general welfare and security of the United States require that the unique competence of the National Aeronautics and Space Administration be directed to detecting, tracking, cataloguing, and characterizing near-Earth asteroids and comets to provide warning and mitigation of the potential hazard of such near-Earth objects to the Earth."; and

(C) in subsection (h), as so redesignated by subparagraph (A) of this paragraph, by striking 'and (f)' and inserting '(f), and (g)'.

(3) Fifth-year report.--The Administrator shall transmit to the Congress, not later than February 28 of the fifth year after the date of enactment of this Act, a report that provides the following:

(A) A summary of all activities taken pursuant to paragraph (1) since the date of enactment of this Act.

(B) A summary of expenditures for all activities pursuant to paragraph (1) since the date of enactment of this Act.

(4) Initial report.--The Administrator shall transmit to Congress not later than 1 year after the date of enactment of this Act an initial report that provides the following:

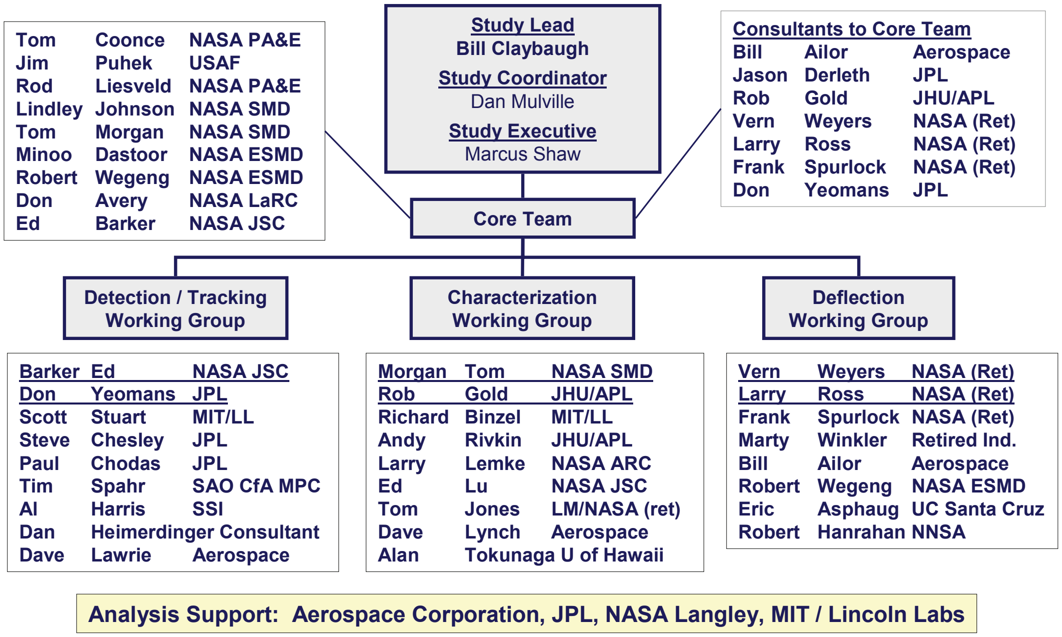
(A) An analysis of possible alternatives that NASA may employ to carry out the Survey program, including ground-based and space-based alternatives with technical descriptions.

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

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

Appendix B. Study Organization and Process

B.1. Organizational Structure



Tom	Coonce	NASA PA&E
Jim	Puhek	USAF
Rod	Liesveld	NASA PA&E
Lindley	Johnson	NASA SMD
Tom	Morgan	NASA SMD
Minoo	Dastoor	NASA ESMD
Robert	Wegeng	NASA ESMD
Don	Avery	NASA LaRC
Ed	Barker	NASA JSC

Consultants to Core Team

Bill	Ailor	Aerospace
Jason	Derleth	JPL
Rob	Gold	JHU/APL
Vern	Weyers	NASA (Ret)
Larry	Ross	NASA (Ret)
Frank	Spurlock	NASA (Ret)
Don	Yeomans	JPL

Detection / Tracking Working Group

Barker	Ed	NASA JSC
Don	Yeomans	JPL
Scott	Stuart	MIT/LL
Steve	Chesley	JPL
Paul	Chodas	JPL
Tim	Spahr	SAO CfA MPC
Al	Harris	SSI
Dan	Heimerdinger	Consultant
Dave	Lawrie	Aerospace

Characterization Working Group

Morgan	Tom	NASA SMD
Rob	Gold	JHU/APL
Richard	Binzel	MIT/LL
Andy	Rivkin	JHU/APL
Larry	Lemke	NASA ARC
Ed	Lu	NASA JSC
Tom	Jones	LM/NASA (ret)
Dave	Lynch	Aerospace
Alan	Tokunaga	U of Hawaii

Deflection Working Group

Vern	Weyers	NASA (Ret)
Larry	Ross	NASA (Ret)
Frank	Spurlock	NASA (Ret)
Marty	Winkler	Retired Ind.
Bill	Ailor	Aerospace
Robert	Wegeng	NASA ESMD
Eric	Asphaug	UC Santa Cruz
Robert	Hanrahan	NNSA

Analysis Support: Aerospace Corporation, JPL, NASA Langley, MIT / Lincoln Labs

Figure 66. NEO Study Organizational Structure

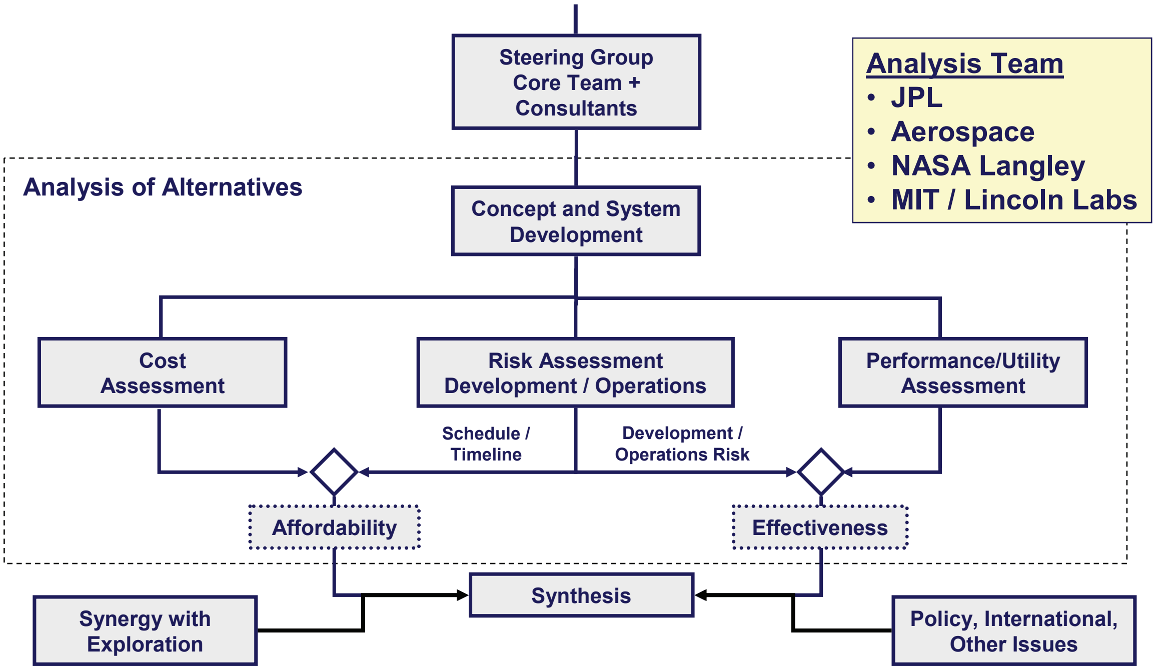


Figure 67. Analysis of Alternatives Organizational Structure

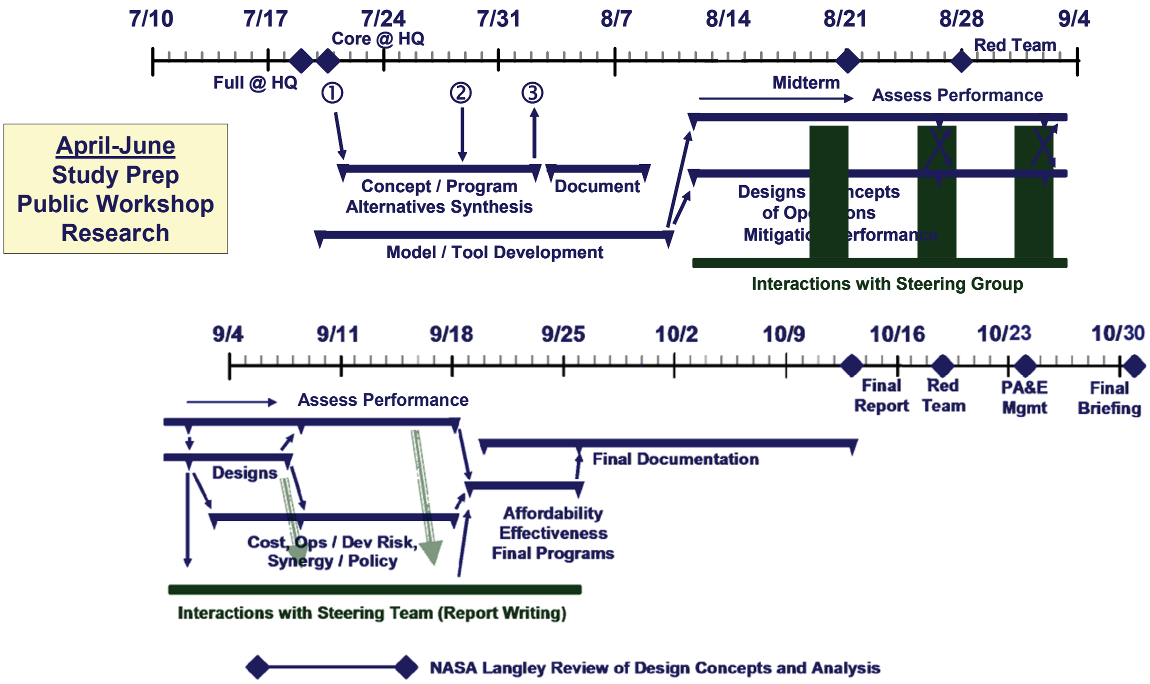


Figure 68. Study Calendar

Appendix C. Derived Requirements

Number	Requirement	Trace and Notes
1.0	**Detect, track, catalogue and characterize (Survey) near-Earth asteroids and comets,**	**Public Law "to provide warning and mitigation of the hazard.**
1.1	Survey will Survey potentially hazardous objects (PHOs), a subset of near-Earth asteroids and comets.	PHOs represent the true hazard and a more reasonable number for 2020 completion.
1.2	Track determination shall consist of at least 2 nights of observation on the same object within one week.	Sufficient orbit characterization to classify as a potential PHO.
1.3	Establish a third observation within 40 days of track determination.	Sufficient orbit characterization to classify and catalog as a PHO.
1.4	Additional observations shall be performed to quantify, improve, and update the actual PHO risk	Mitigation strategies will require more accuracy than initial PHO determination.
1.5	The system shall propagate orbits; make impact predictions, and predictions of impact energy.	Public Law "to provide warning and mitigation of the hazard.
1.6	The system shall provide warnings and alerts as appropriate to the hazard or threat condition.	Public Law "to provide warning and mitigation of the hazard.
2.0	**Plan, develop, and implement a NEO Survey program to Survey the physical characteristics of near-Earth objects equal to or greater than 140 m.**	**Public Law to assess the threat of such objects to the Earth.**
2.1	PHO mass variability shall be determined by characterizing a statistically valid number of PHOs.	All mitigation strategies will require knowledge of the mass of the PHO.
2.2	A range of solutions for characterizing other parameters of interest (size, shape, rotation rate, composition, etc.) shall be cross-checked with mitigation alternatives.	Some mitigation strategies will require detailed physical understanding of the PHO.
3.0	**Achieve 90% completion of the NEO catalogue (based on statistical predictions) within 15 years.**	**Public Law – 15 years from December 28, 2005**

4.0	**Provide alternatives to carry out the survey program with technical descriptions.**	**Public Law**
4.1	Systems must be capable of searching the entire sky down to 25th visible magnitude at least three times per lunation.	System sensitivity consistent with PHO threat definition.
4.2	Systems must have an astronometric accuracy of < 0.5 arc second.	Observation accuracy needed for sufficient orbit determination for PHO cataloguing.
4.3	The system shall minimize mean time to determine miss distance.	Provides highest accuracy information for orbit and potential keyhole events.
4.4	A fault tolerant data collection and preliminary orbit determination center must be maintained.	Architecture requires maintaining a reference and warning archive.
4.4.1	A geographically distinct "mirror" data center shall be maintained.	Provides geographic diversity to limit impact of natural disaster.
4.4.2	Offsite data backups shall be maintained.	Disaster recovery capability.
4.4.3	Capacity shall be for at least 2,000,000 observations per day for at least 500,000 NEOs, and discovery of at least 15 NEOs (3 PHOs) per day.	Matched to threat.
4.4.4	Provide web-based access to data for “precovery” (analysis of archived data) and other data mining activities.	Leverage archived data and collaboration with internationals and amateurs.
5.0	**Provide an analysis of possible alternatives to divert an object on a likely collision course with Earth.**	**Public Law**
5.1	Reduce PHO impact risk to the nominal PHO risk (~1 in one million)	Reduce PHO impact risk to the nominal background risk of PHOs.
5.2	Provide a means for verification of object diversion.	Determination whether mitigation action was successful.

Appendix D. Public Workshop

On May 15, 2006, the NEO study team solicited public input to help fulfill the requirements of this study. The workshop was held June 26-29 in Vail, Colorado and was named the Near-Earth Object (NEO) Detection, Characterization and Threat Mitigation Workshop. Participation in the workshop was by invitation only.

The study team was divided into three areas to focus discussion with the public:

- Detection, tracking and cataloging NEOs
- Characterization of NEOs, and
- Deflection or other forms of NEO threat mitigation

Interested parties were invited to submit a one-page abstract outlining concept proposals in the study focus areas by May 26, 2006. The NEO study team divided into working groups and these groups during the first week of June to review the abstracts. Invitees were chosen based upon their expertise and contribution to understanding the focus areas.

Authors of accepted abstracts received a workshop invitation by June 7, 2006, and were invited to submit a five- to 10-page white paper addressing the topic(s) of inquiry and/or detailing the proposed concept, including estimated required schedule and cost information. Most authors, except foreigners or those with other specific issues also were invited to present their papers at the workshop. The Call for Papers made it clear that concept proposals were to be evaluated only for the purposes of assessing alternatives; no proposals would be awarded funding as part of the PA&E study process.

The workshop was held over 4 days, and significantly increased the study team’s knowledge of current capabilities and plans, and provided much-needed context for both highly specialized and less-experienced team members. Spirited and extremely useful dialogue was generated on each of the 4 days, and the public input has significantly influenced and contributed to the study’s results.

Lists of external workshop attendees and their presentation or white paper topics are listed on the following pages.

Table 43. List of Vail NEO Workshop Attendees and Contributors

Full Name	Organization	Title
Abell, Paul	NASA Johnson Space Center	The Compositions Of Binary Near-Earth Objects: Implications For Their Internal Structure And Hazard Potential
Adams, Rob	NASA - MSFC	Summation Of NASA-TP-2004-213089 "Survey Of Technologies Relevant To Defense From Near-Earth Objects (NEO's)" (Paper)
Arentz, Robert	Ball Aerospace and Technologies Corp.	Invitation Only
Barbee, Brent	Emergent Space Technologies, Inc.	Optimal Deflection Of Hazardous Near-Earth Objects By Standoff Nuclear Detonation And NEO Mitigation Mission Design
Bartlett, Paul W	Honeybee Robotics	Implementation Study And Technology Development For A Near-Earth Object Deflection Mission Using Mass Drivers
Bekey, Ivan	Bekey Designs, Inc.	Extremely Large Yet Very Low Weight And Low Cost Space Based Telescopes For Detection Of 140 Meter Diameter Asteroids At 5.7 AU, And Obtaining 6 Year Warning Times For 1 km Diameter Comets
Bowell, Edward	Lowell Observatory	Searching For Neos Using Lowell Observatory's Discovery Channel Telescope (DCT)
Buie, Marc W.	Lowell Observatory	Physical Characterization Of Phas With Ground-Based Telescopes
Campbell, Donald B	Cornell University	Near-Earth Asteroid Astrometry And Characterization By Radar: Current Radar Systems And Future Possibilities
Chapman, Clark R.	Southwest Research Institute	Mitigation: Interfaces Between NASA, Risk Managers, And The Public
Conway, Bruce A	University of Illinois	Optimization Of The Deflection Of A Hazardous NEO
Cruikshank, Dale P.	NASA Ames Research Center	Determining The Physical Properties Of Near-Earth Objects (White Paper)
Davis, Jeremy J	Texas A&M University	Impact Keyholes And Collision Probability Analysis For Resonant Encounter Asteroids
Do, Khanh Q	The Boeing Company	Boeing Space-Based Characterization Sensor Concept
Doyle, Monica	SAIC	Assessment Of Current Ground-Based Telescope Cost Modeling Methodologies
Dunham, Ed	Lowell Observatory	Invitation Only
Fork, Richard L.	University of Alabama in Huntsville	Solar Powered Modelocked Lasers For Deflection Of Earth Threatening Asteroids
Gaffey, Michael J	University of North Dakota	The Compositional And Physical Characterizations Of Neos From VNIR Spectroscopy
Gertsch, Leslie S.	University of Missouri-Rolla	Distributed-Energy Blasting For NEO Mitigation
Gorevan, Stephen	Honeybee Robotics	Enabling Technology For NEO Characterization Of Return Samples
Holsapple, Keith A.	University of Washington	Existing Methods Of Asteroid Deflections Will Work: Impacts And Nuclear Bombs

Full Name	Organization	Title
Howard, Regan E	Orbital Sciences Corp.	Adapting GEO Spacecraft To Reduce The Cost Of NEO Detection, Tracking And Cataloging Missions
Huebner, Walter F.	Southwest Research Institute	White Paper: Seismology Measurements Of NEO Properties For Earth Impact Mitigation
Izenberg, Noam R.	JHU/APL	Shield: A Comprehensive Earth Protection System
Junkins, John	Texas A&M	Invitation Only
Lambert, John	Boeing	Invitation Only
Larson, Stephen M	University of Arizona	Observational Follow Up Needs For The Next Generation Of NEO Surveys
Lissauer, Jack J.	NASA Ames	Advantages Of Low-Cost Missions To Study NEO's: Why Extensive Study Will Tell Us More Than Intensive Study
McMillan, Robert Scott	University of Arizona	Spacewatch Preparations For The Era Of Deep All-Sky Surveys - White Paper
Mills, Robert	Lowell Observatory	Invitation Only
Morrison, David	Ames Research Center	Near-Earth Asteroid Trailblazer
Ostro, Steve	Jet Propulsion Laboratory	Ground-based Radar In Near-Earth Object Tracking, Characterization And Threat Mitigation
Pitchford, Brian E.	NASA/KSC	Near-Earth Object Deflection System (NEODESYS) - Nullifying The Threat Posed By Asteroid 99942 Apophis
Raeth, Peter	Ball Aerospace	Invitation Only
Reitsema, Harold J	Ball Aerospace	Neo-Vis, The Visible-Light, Near-Earth Object, Survey Mission.
Remo, John L	Sandia National Laboratories	Near-Earth Object Short Term Threat Mitigation White Paper
Ryan, Eileen V.	New Mexico Institute of Mining and Technology	Physical Characterization And Follow-Up Studies Of Faint Near-Earth Objects Using The Magdalena Ridge Observatory's 2.4-Meter Telescope
Scheeres, Daniel J	University of Michigan	Spacecraft At Small Near-Earth Objects
Schweickart, Russell	B612 Foundation	Threat Characterization: Trajectory Dynamics
Solem, Johndale	Los Alamos National Laboratory	Invited Speaker
Stuart, Joseph Scott	MIT Lincoln Laboratory	Serendipitous Discovery Of Near-Earth Asteroids With The DARPA Space Surveillance Telescope
Tedesco, Edward	University of New Hampshire	Albedos And Sizes Of NEOs Using Polarimetry
Tokunaga, Alan T.	University of Hawaii	A Dedicated Program For The Reconnaissance Of NEO Surface Reflectance Characteristics
Tyson, Anthony	University of California	LSST: Comprehensive NEO Detection, Characterization, And Orbits
VanCleve	Ball Aerospace & Technologies Corp.	NEO Retro-Reflectors And Beacons: Concepts, System Trades And Performance Issues
Whiteley, Robert J	University of Arizona	Rapid Response Characterization Of Small Neas
Wie, Bong	Arizona State University	Solar Sail Kinetic Energy Impactor

Appendix E. Descriptions of Survey Alternatives

E.1. Detailed Descriptions of Survey Alternatives

E.1.1. Spaceguard [D-1]

With 10 observatories in seven locations across the world, the Spaceguard Foundation is a dedicated international consortium in NEO observations. Telescope apertures range from 0.5 meters to 1.5 meters, with a typical field of view of 3° x 3°, which helps achieve a typical limiting magnitude (V_{lim}) of approximately about 19.5. Participation includes scientists from Italy, Germany, Australia, United Kingdom, U.S., Japan, New Zealand, Russia, Uruguay, Finland, Sweden, Canada, Spain, Czech Republic, China, and Croatia. These telescopes, all currently operational, function in the visible-wavelength range.

Spaceguard includes the following observatories or associations participating in PHO detection: LINEAR, Catalina Sky Survey, Pan-STARRS-1, Spacewatch, NEAT, Campo Imperatore NEO Survey, U.K. Spaceguard, Japan Spaceguard Association, Spaceguard Croatia, Germany Spaceguard Foundation. Two members (LINEAR and Catalina Sky Survey), alone, have accounted for approximately 70% of NEO discoveries over the last 10 years. Although the Spaceguard observatories do not coordinate their search patterns for observations, all their detections are reported through the Minor Planet Center.

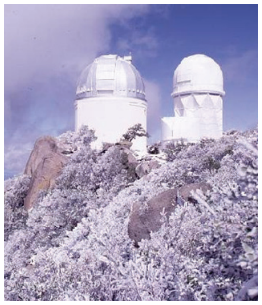
Spaceguard telescopes cannot reach limiting magnitudes to detect 140-meter PHOs and each organization maintains a separate budget. Funding varies from year-to-year.

D-1: Spaceguard

Nec cum fiducia inveniendi

S F G

Nec sine spe



Technical Description

- Consortium of ground-based NEO detection efforts
- Visible, 3° x 3° FOV (typical), V_{lim}= 19.5 (typical)
- Participation includes observatories and scientists from: Italy, Germany, Australia, UK, US, Japan, New Zealand, Russia, Uruguay, Finland, Sweden, Canada, Spain, Czech Republic, China, Croatia

CONOPS

- Operational: Currently operational
- Worldwide detection observatories: Catalina Sky Survey, Pan-Starrs-1, Spacewatch, NEAT, LINEAR, Campo Imperatore NEO Survey, UK Spaceguard, Japan Spaceguard Association, Spaceguard Croatia, Germany Spaceguard Foundation

System Sizing

Telescopes in System	10+
Locations	7+
Aperture (m)	0.5 to 1.5

Rationale for consideration

- Currently operational & active in NEO detection & surveying
- Baseline of current NEO detection capabilities

Capability

- Worldwide observation capability that reports findings to the Minor Planet Center

Pros

- Often dramatic improvements are possible when pre-discovery observations are found (e.g. Apophis 2004 March data extended observed interval 3 months and allowed the removal of the 2029 Earth impact possibility).
- Dedicated international collaboration towards this global concern

Cons

- Current telescopes cannot reach limiting magnitudes to detect 140m NEOs
- Daytime, weather, moonlight & location limit sky access
- Each organization maintains a separate budget, funding may vary year-to-year

E.1.2. Shared LSST [D-2]

Description

The Shared Large Synoptic Survey Telescope (LSST) is a planned (2014) 8.4-meter aperture telescope. It will spend about 75% of its observation time in a survey mode compatible with PHO detection. LSST is the largest aperture ground-based optical telescope currently in development. Its development is underway and has received funding from the Department of Energy (DOE), National Science Foundation (NFS), and private donations.

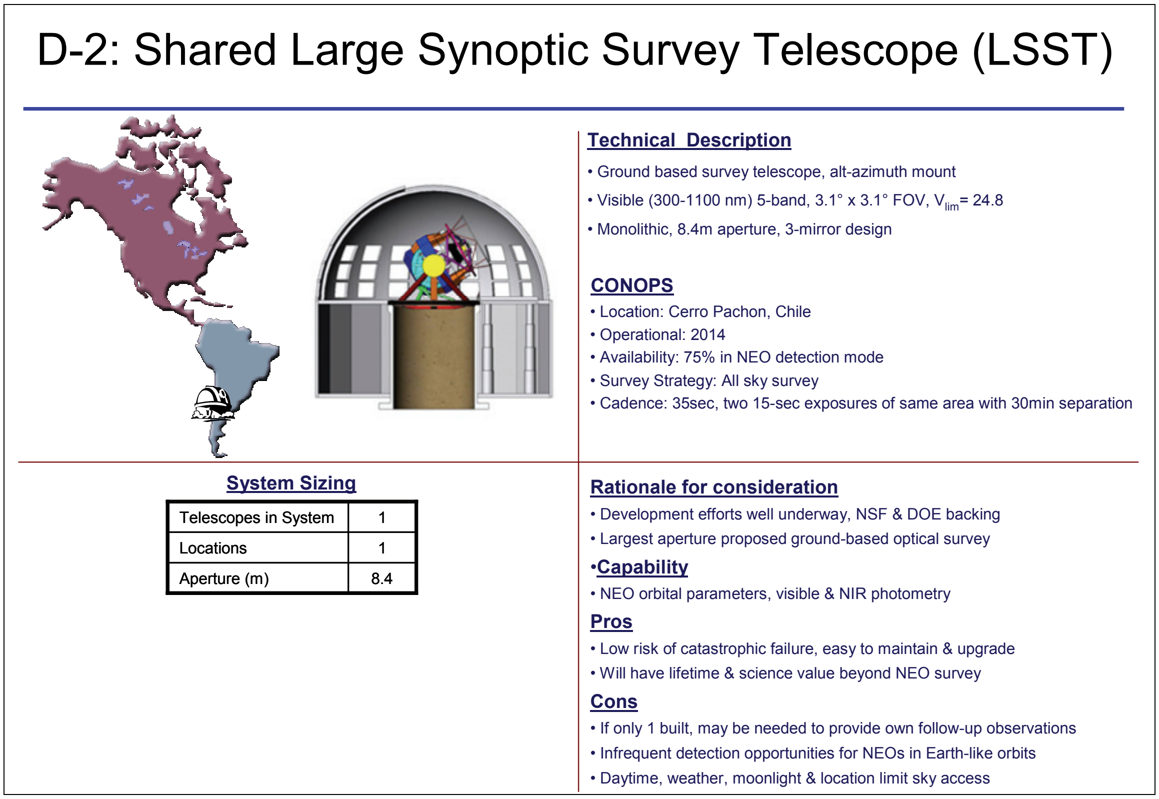
LSST is a ground-based survey telescope with an alt-azimuth mount. It performs observations in the visible and near-infrared range of the spectrum (300-1100 nm), with a 3.1° x 3.1° field of view and a limiting magnitude (V_{lim}) of approximately 24.8. The optical design consists of a monolithic three-mirror design, with an 8.4-meter diameter primary mirror (effective aperture of 6.8 meters) and uses adaptive optics to correct for atmospheric distortions. The Shared LSST is to be located at Cerro Pachón, Chile, and is expected to be operational by 2014.

LSST will spend approximately 75% of its time detecting PHOs. It will accomplish this by carrying out an automated all-sky survey, with a 35-second cadence and two 15-second exposures of the same spot in the sky. LSST will take the exposures about 30 minutes apart. LSST will have the capability to determine an asteroid’s orbital parameters and perform visible and near-infrared photometry. New instrumentation can be added to expand capabilities. LSST technology is mature and well understood. It is based on monolithic, ground-based observatories dating back centuries.

Qualitative Assessment

Shared LSST offers a low risk of catastrophic failure. As opposed to a space-based asset, it can be easily maintained and upgraded. The operation, purpose, and scientific benefits of the Shared LSST extend well beyond the proposed survey. It will have fewer opportunities to detect PHOs in Earth-like orbits because daylight, weather, moonlight, and location limit its access to the sky. LSST may be required to perform follow-up observations to determine the orbital parameters of the faintest objects within a limited time.

Requiring the Shared LSST to concentrate on follow-up observations for characterization may reduce the time Shared LSST could perform PHO-detection observations. LSST can, however, automatically perform follow-on observations while surveying the sky. That is because it can cover the entire sky in about 3 nights and therefore would typically observe a new PHO about three times within a month. Lastly, it will have a slightly less-than-optimal survey strategy and hardware since it is not purely a survey telescope.



D-2: Shared Large Synoptic Survey Telescope (LSST)

Technical Description

- Ground based survey telescope, alt-azimuth mount
- Visible (300-1100 nm) 5-band, 3.1° x 3.1° FOV, V_{lim}= 24.8
- Monolithic, 8.4m aperture, 3-mirror design

CONOPS

- Location: Cerro Pachon, Chile
- Operational: 2014
- Availability: 75% in NEO detection mode
- Survey Strategy: All sky survey
- Cadence: 35sec, two 15-sec exposures of same area with 30min separation

System Sizing

Telescopes in System	1
Locations	1
Aperture (m)	8.4

Rationale for consideration

- Development efforts well underway, NSF & DOE backing
- Largest aperture proposed ground-based optical survey

•**Capability**

- NEO orbital parameters, visible & NIR photometry

Pros

- Low risk of catastrophic failure, easy to maintain & upgrade
- Will have lifetime & science value beyond NEO survey

Cons

- If only 1 built, may be needed to provide own follow-up observations
- Infrequent detection opportunities for NEOs in Earth-like orbits
- Daytime, weather, moonlight & location limit sky access

E.1.3. Shared Pan-STARRS 4 (PS4) [D-3]

Description

The Shared Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) 4 (PS4) is an observatory under development consisting of a four 1.8-meter telescopes searching the same spot in the sky at the same time, thus combining to provide an effective aperture of 3.6 meters. It is expected to spend 30% of its observation time in survey mode. PS4 may show that it is more cost effective to build several small telescopes than to build a larger, single system. Its development is well underway and has received funding from the U.S. Air Force (USAF). The first 1.8-meter telescope (PS1) started test operations in June 2006.

PS4 is a ground-based survey telescope with an alt-azimuth mount. It performs observations in the visible and near-infrared range of the spectrum (400-1100 nm), with a 1.8° x 4.0° field of view and a limiting magnitude (V_{lim}) of approximately 24.0. Designed as a monolith mount, the telescope includes a 1.8-meter diameter primary mirror for each of the four telescopes (3.6-meter effective aperture). It uses adaptive optics to correct for atmospheric distortions. The Shared PS4 is to be located at Mauna Kea, Hawaii, and is expected to be operational by 2010.

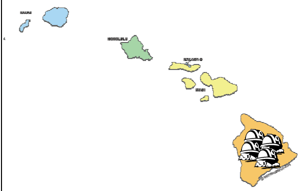
Shared PS4 will spend about 30% of its time detecting PHOs by performing an automated all-sky survey, with a 35-second cadence and two 15-second exposures of the same spot in the sky roughly 15 to 30 minutes apart. The survey strategy is a balance between PHO detection and general astronomy. Sixty-percent of surveying time will be utilized in a cadence suitable for linking solar system objects. Additionally, approximately 5% of its surveying time will be devoted to surveying PHO-rich “sweet-spots,” the sky within about 10º of the ecliptic and within about 60˚ to 90˚ from the Sun’s line of sight. The system is expected to have at least a 10-year operational lifetime.

PS4 will have the capability to determine an asteroid’s orbital parameters and perform visible and near-infrared photometry. New instrumentation can be added to expand capabilities. PS4 technology is mature and well understood and based on monolithic, ground-based observatories dating back centuries.

Qualitative Assessment

As opposed to a space-based asset, Shared PS4 runs a low risk of catastrophic failure and can be easily maintained and upgraded. PS4’s lifetime and, therefore, science value will extend beyond the completion of the PHO survey. Some of its drawbacks include infrequent opportunities to detect PHOs in Earth-like orbits and limited sky access due to daylight, weather, moonlight, and a location with limited access to the sky. Lastly, it will have a slightly non-optimal survey strategy and hardware since the asset is not purely a survey telescope.

D-3: Shared Pan-STARRS 4 (PS4)



Technical Description

- Four ground based survey telescopes, alt-azimuth mount
- Visible (400-1100 nm), 1.8° x 4.0° FOV, V_{lim}= 24.0
- Monolithic, 1.8m aperture x 4 telescopes

CONOPS

- Location: Mauna Kea, Hawaii
- Operational: 2010
- Availability: 30% in NEO detection mode
- Survey Strategy: All sky survey (when in NEO mode)
- Cadence: 35sec, two 15-sec exposures of same area with 15-30min interval
- All 4 telescopes simultaneously image same spot in sky
- 10 year operational lifetime

System Sizing

Telescopes in System	4
Locations	1
Aperture (m)	1.8 x 4
Effective Aper. (m)	3.6

Rationale for consideration

- Development efforts well underway, backing of USAF
- May be more economically feasible to build coordinated set of small telescopes than a single larger one

•Capability

- NEO orbital parameters, visible & NIR photometry

Pros

- Low risk of catastrophic failure, easy to maintain & upgrade
- Will have lifetime & science value beyond NEO survey

Cons

- Shared, thus non-optimal survey strategy
- Infrequent detection opportunities for NEOs in Earth-like orbits
- Daytime, weather, moonlight & location limit sky access

E.1.4. Dedicated LSST [D-4]

Description

The Dedicated Large Synoptic Survey Telescope (LSST) is a possible rebuild of the Shared LSST, and would be dedicated and optimized for PHO search. A copy of a proposed ground-based telescope, dedicated to the PHO survey, would reduce the cost of developing a new telescope, while guaranteeing that it spent 100% of its observation time in survey mode. The Dedicated LSST will have the same basic design as the Shared

LSST, but optimization for PHO detection and an increased exposure time to 22.5 seconds will increase its limiting magnitude (V_{lim}) to approximately 25.4. Dedicated operation will allow time for the follow up of faint PHOs when necessary.

The Dedicated LSST was assumed to be located at San Pedro Mártir in Mexico’s Baja Peninsula, the Shared LSST’s runner-up location. It would be operational by 2016. The Dedicated LSST would spend 100% of its observation time detecting PHOs. The Dedicated LSST would have the capability to determine an asteroid’s orbital parameters. New instrumentation can be added to expand capabilities.

Qualitative Assessment

The Dedicated LSST provides redundancy to the Shared LSST. The Shared LSST could be leveraged for follow-on observations of PHOs, thus the Dedicated LSST would not need to slow its survey to perform follow-up observations. If both the Shared and Dedicated LSST image the same PHO, it would provide a parallax view of the PHO, allowing for greater accuracy in determining an object’s orbit. Because it is a ground-based asset, it has a lower risk of catastrophic failure as opposed to a space-based asset. It can be easily maintained and upgraded. A Dedicated LSST’s lifetime and, therefore, science value will extend beyond the completion of the PHO survey. Some of its drawbacks include infrequent opportunities to detect PHOs in Earth-like orbits and limited sky access due to daylight, weather, moonlight, and location.

D-4: Dedicated LSST

Technical Description

- Ground based survey telescope, alt-azimuth mount
- Visible (300-1100 nm) 5-band, 3.1° x 3.1° FOV, V_{lim}= 25.4
- Monolithic, 8.4m aperture, 3-mirror design

CONOPS

- Location: San Pedro Mártir, Mexico
- Operational: 2016
- Availability: 100% in NEO detection mode
- Survey Strategy: All sky survey
- Cadence: 50sec, two 22.5-sec exposures of same area with 30min separation
- Shared LSST would still be available for follow-on observations

System Sizing

Telescopes in System	1
Locations	1
Aperture (m)	8.4

Rationale for consideration

- Optimized for NEO detection versus shared asset
- Largest aperture proposed ground-based optical survey

Capability

- NEO orbital parameters, visible & NIR photometry

Pros

- Can leverage shared LSST for follow-on observations & co-survey
- Low risk of catastrophic failure, easy to maintain & upgrade

Cons

- Infrequent detection opportunities for NEOs in Earth-like orbits
- Daytime, weather, moonlight & location limit sky access

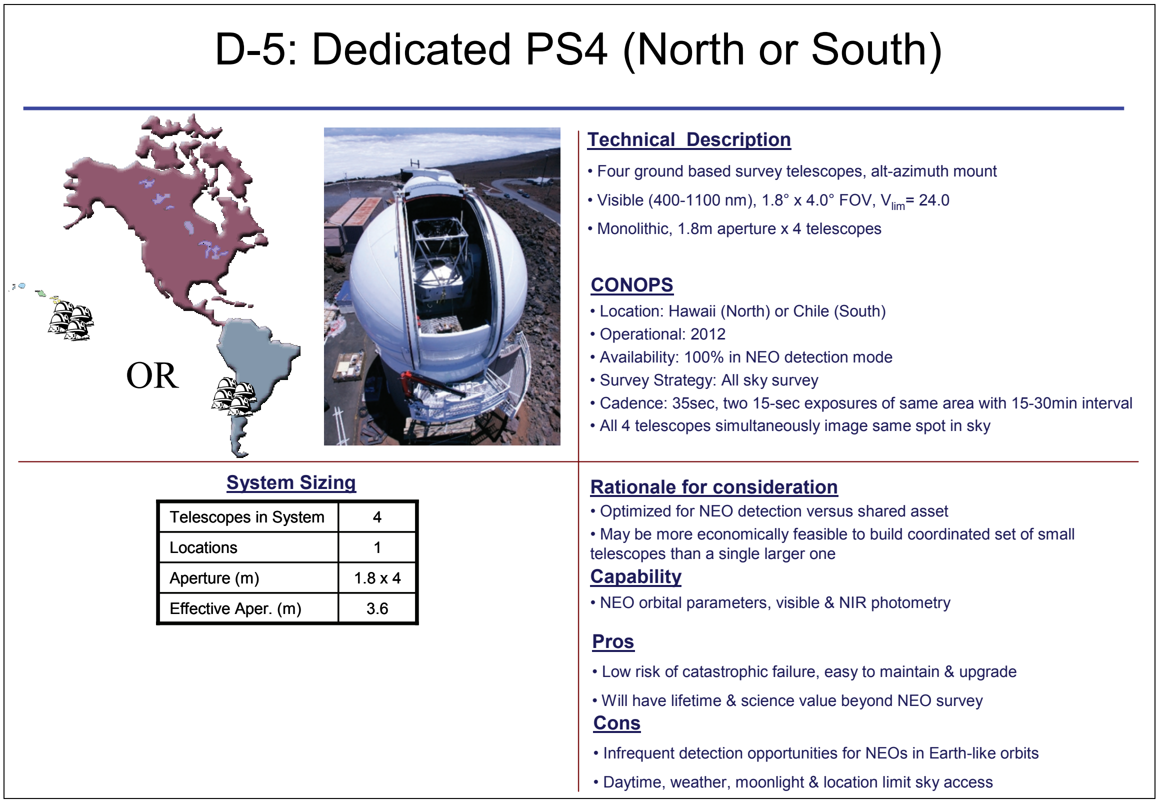
E.1.5. Dedicated Pan-STARRS 4 (PS4) [D-5]

Description

The Dedicated PS4 is a possible rebuild of the Shared PS4 dedicated to PHO search. Copying a proposed ground-based telescope dedicated to the PHO survey would save money and guarantee that the telescope would spend 100% of its observation time in survey mode. The Dedicated PS4 would have the same design as the Shared PS4. The Dedicated PS4 is to be located either in Hawaii (Northern Hemisphere) or in Chile (Southern Hemisphere). It would be operational by 2012 and will spend 100% of its time detecting PHOs. The Dedicated PS4 will be able to determine an asteroid's orbital parameters. New instrumentation can be added to expand capabilities. Dedicated operation will allow for the critical follow-up of faint PHOs when necessary.

Qualitative Assessment

The Dedicated PS4 will provide redundancy to the Shared PS4. If both the Shared and Dedicated PS4 in different hemispheres image the same PHO, they would provide a parallax view of the PHO, which would enhance observers' ability to accurately determine an object's orbit. As a ground-based asset, it also has a low risk of catastrophic failure, especially compared with a space-based asset; it can be easily maintained and upgraded. A Dedicated PS4's lifetime and, therefore, science value will extend beyond the completion of the PHO survey. As with other ground-based observatories, it has drawbacks. As with the others, it will have limited opportunities to detect PHOs in Earth-like orbits because of limited access to the sky due to daylight, weather, moonlight, and location.



D-5: Dedicated PS4 (North or South)

OR

Technical Description

- Four ground based survey telescopes, alt-azimuth mount
- Visible (400-1100 nm), 1.8° x 4.0° FOV, V_{lim}= 24.0
- Monolithic, 1.8m aperture x 4 telescopes

CONOPS

- Location: Hawaii (North) or Chile (South)
- Operational: 2012
- Availability: 100% in NEO detection mode
- Survey Strategy: All sky survey
- Cadence: 35sec, two 15-sec exposures of same area with 15-30min interval
- All 4 telescopes simultaneously image same spot in sky

System Sizing

Telescopes in System	4
Locations	1
Aperture (m)	1.8 x 4
Effective Aper. (m)	3.6

Rationale for consideration

- Optimized for NEO detection versus shared asset
- May be more economically feasible to build coordinated set of small telescopes than a single larger one

Capability

- NEO orbital parameters, visible & NIR photometry

Pros

- Low risk of catastrophic failure, easy to maintain & upgrade
- Will have lifetime & science value beyond NEO survey

Cons

- Infrequent detection opportunities for NEOs in Earth-like orbits
- Daytime, weather, moonlight & location limit sky access

E.1.6. Dedicated Pan-STARRS 8 (PS8) [D-6]

Description

The Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) 8 (PS8) is a proposed system consisting of two dedicated PS4 observatories, for a total of eight 1.8-meter telescopes searching the same spot in the sky at the same time, with an effective aperture of 5.1 meters. PS8 would be dedicated to PHO search. PS8 may show it is more cost effective to build several small telescopes than it is to build a larger, single system.

PS8 would be composed of two identical observatories. Although its design is based on that of the PS4, doubling the number of 1.8-meter telescopes to eight increases its limiting magnitude (V_{lim}) to 24.4. PS8 would be located either in Hawaii (Northern Hemisphere) or Chile (Southern Hemisphere) and is expected to be operational by 2012. PS8 will spend 100% of its time searching for PHOs. The PS8 would have the capability to determine an asteroid's orbital parameters. New instrumentation could be added to expand capabilities.

Qualitative Assessment

PS8 offers a low risk of catastrophic failure, as opposed to a space-based asset, and can be easily maintained and upgraded. PS8's lifetime and, therefore, science value would extend beyond the completion of the PHO survey. Its drawbacks are similar to those of other ground-based assets discussed in previous sections.

Design parameters are similar to those for PS4 except that eight telescopes are used.

E.1.7. Dedicated Pan-STARRS 16 (PS16) [D-7]

Description

The Dedicated Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) 16 (PS16) is a proposed system consisting of two PS8 observatories, one located in the Northern Hemisphere and the other in the Southern Hemisphere. Each PS8 observatory, equipped with a total of eight 1.8-meter telescopes, would search the same spot in the sky at the same time, with an effective aperture of 5.1 meters. PS16 would be dedicated to PHO search and, by observing a PHO from both hemispheres, would provide a parallax view of the asteroid. PS8 may show it is more cost effective to build several small telescopes than a larger, single system.

PS16 would be composed of two identical observatories based on the PS8 design. Their geographic separation (Northern and Southern Hemispheres) would allow parallax viewing. One of the two observatories would be located in Hawaii (PS16 North) and the other in Chile (PS16 South). The full PS16 system could be operational by 2012. PS16 will spend 100% of its time detecting PHOs. Each PS16 observatory would have the capability to independently determine an asteroid's orbital parameters. Planners expect the two observatories to provide greater accuracy in determining orbits. New instrumentation can be added to expand capabilities.

Qualitative Assessment

PS16 offers a lower risk of catastrophic failure, especially compared with a space-based asset. PS16 can be easily maintained and upgraded. If both the PS16 North and South observatories image the same PHO, they would provide a parallax view of the PHO and allow for greater accuracy in determining orbits. PS16's lifetime and, therefore, science value will extend beyond the completion of the PHO survey. Its drawbacks include infrequent opportunities to detect PHOs in Earth-like orbits and limited sky access due to daylight, inclement weather, moonlight, and location. Lastly, the operation of two identical facilities in different hemispheres may present operational challenges due to shared personnel between the two distant locations, although observatory automation may mitigate these issues.

Design parameters are similar to those for PS4 except that 16 telescopes are used.

E.1.8. 2-meter Visible (Vis) LEO/L1/L2 [D-8]

Description

The 2-meter Visible LEO/L1/L2 concept is a space-based, survey telescope that would scan the sky to search of NEOs. It can be placed into low-Earth Orbit (LEO) or at the Sun-Earth L1 or L2 point. This concept has the largest aperture of any space-based, optical system considered in this study to increase detection rate. This detection asset will search for PHOs and can be used to calculate their orbital parameters. This design traces its heritage to other visible, space-based telescopes, and would be similar to the proposed design of NEO-VIS.

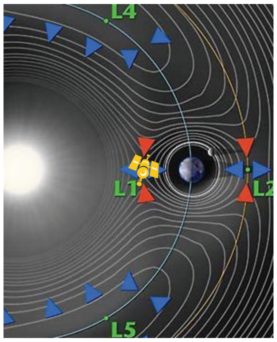
The telescope would have a 2.0-meter aperture that detects light in the visible spectrum. It would have a field of view of 2.81° x 2.81°, and be able to achieve a limiting magnitude (V_{lim}) of approximately 23.6. A Delta II 2920 would place the spacecraft in a low-Earth orbit or an Atlas V 401 would deliver it to a L1/L2 orbit. It would be operational around 2014. It is dedicated to PHO detection and the full bandpass is used to maximize detection. This spacecraft would use both onboard- and ground-image processing.

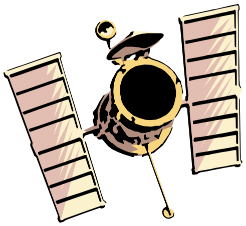
Qualitative Assessment

The benefit of a space-based visible sensor is that the asset is not limited to night-only observations. Because this asset will be deployed closer to the Earth, as compared with Venus-like orbit concepts, it will be less complex and easier to operate. There is significant heritage for space-based visible observatories and these telescopes can achieve relatively wide fields of view due to mature technology. Thermal requirements for optical LEO/L1/L2 concepts also are less strict than they are for IR systems.

At the same time, space-based systems have a higher risk of catastrophic failure when compared with ground assets and are extremely difficult to maintain or upgrade in case of failures or unforeseen circumstances. The observatory's location at LEO/L1/L2 is not optimal for PHO detection because it will have fewer opportunities to discover asteroids with Earth-like orbits, especially when compared with an observatory in a ~0.7AU, Venus-like orbit. Higher data rates are required with optical systems when compared with IR systems, especially with a larger aperture. The spacecraft would not be designed to store all raw data for precovery. In addition, it only provides limited photometric information about PHOs, which makes it difficult to determine an object's size.

D-8: 2m Vis LEO/L1/L2





	P/L	S/C
Dry Mass (kg)	1255	2599
Wet Mass (kg)		2599
Power (W)	367	1311

Technical Description
- Space-based survey telescope (Hubble-like)
- Visible, 2.81° x 2.81° FOV, V_{lim}= 23.6
- 2 m aperture (a little smaller than Hubble)
- Earth-based orbit, all of which have virtually identical detection performance
  - LEO ~ 1000 km orbit
  - L1 / L2 ~ 1.5x10^6 km

CONOPS
- Location: Earth-Sun L1 (nearly identical detection performance at LEO or L2)
- Operational: 2014
- Availability: 100% in NEO detection mode
- Launch Vehicle: Atlas V 401 for L1/L2, Delta II 2920 for LEO
- Full bandpass used to maximize detection
- On-board image processing coupled with ground image processing
- 10 year mission life

System Sizing

	Dry Mass (kg)	% of Dry Mass
Payload	1255	48%
Spacecraft Bus	1344	52%
ACDS	266	10%
C&DH	74	3%
Power	225	9%
Propulsion	0	0%
Structure & Mechanisms	580	22%
TT&C	102	4%
Thermal	96	4%

Rationale for Consideration
- Space-based asset with greater access to sky
- Provide comparison with space-based IR platforms

Capability
- NEO orbital parameters

Pros
- Can conduct survey at all times (vs. night only on ground)
- Build on heritage spacecraft (Kepler, Hubble)
- Less strict thermal requirements on optics than IR

Cons
- Higher data rates required than IR
- Non-optimal NEO survey location, especially for Earth-like orbits
- Higher risk of catastrophic failure vs. ground based asset
- Very difficult or impossible to maintain or upgrade

E.1.9. 1-meter Visible (Vis) Venus-like [D-9]

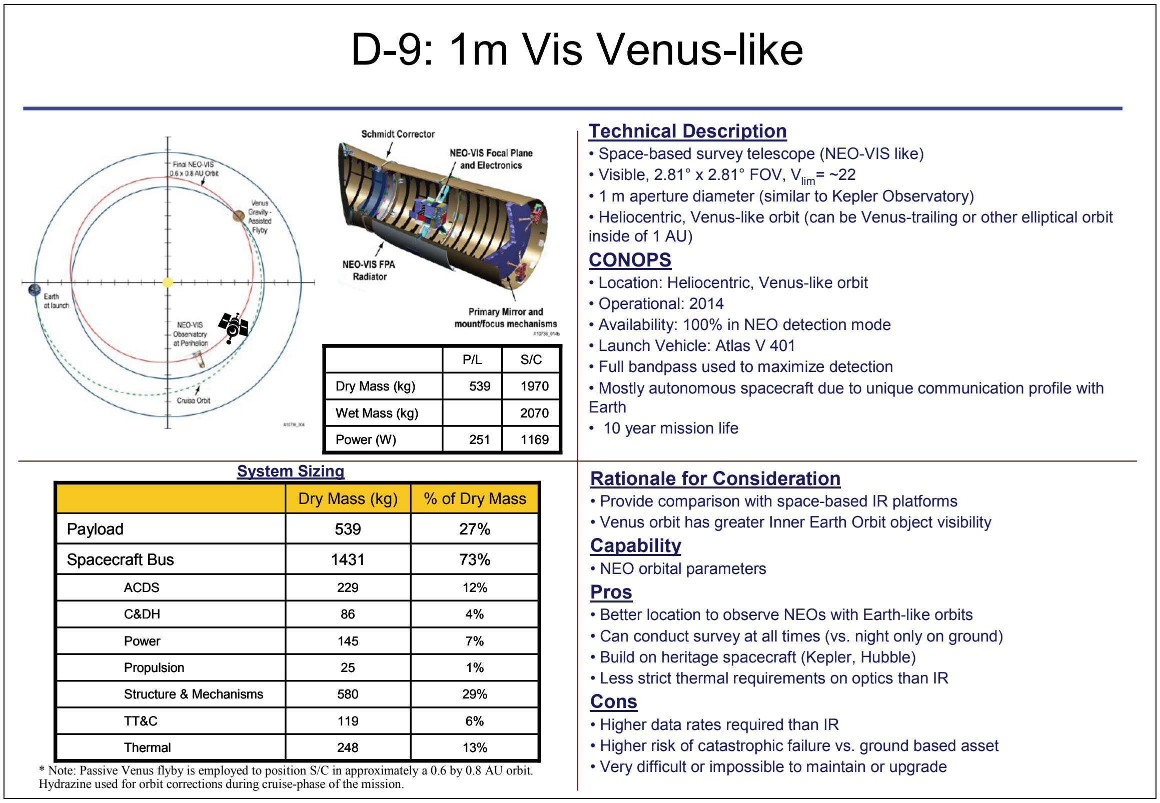
Description

The 1-meter Visible (Vis) Venus-like concept is a space-based, survey telescope that would scan the sky in search of NEOs. It is based on the proposed NEO-VIS design and would orbit the Sun in a ~0.7 AU heliocentric, Venus-like orbit. This option is included to provide a comparison with space-based IR platforms. The selected orbit also offers greater visibility of IEOs. This detection asset will search for PHOs and can be used to calculate their orbital parameters. This design is based on other visible, space-based telescopes, and would be similar to the proposed NEO-VIS design.

The telescope would have a 1.0-meter aperture that detects light in the visible spectrum. It would have a field of view of 2.81° x 2.81°, capable of achieving a limiting magnitude (V_{lim}) of approximately 22. An Atlas V 401 would launch the spacecraft. It would become operational around 2014. A passive Venus flyby is employed to position the spacecraft in approximately a 0.6 by 0.8 AU orbit. Hydrazine propulsion is used only for orbital corrections during the mission's cruise phase. It is a dedicated PHO detection asset that uses the full bandpass to maximize detection. The spacecraft has an operational life of 10 years.

Qualitative Assessment

The benefit of a space-based visible sensor is that more time can be spent on detection; in other words, it is not limited to night-only observations. The Venus-like orbit yields a greater detection rate and enables the observation of IEOs. A significant heritage exists for space-based visible observatories. In addition, larger fields of view can be achieved due to mature technology. Compared with IR systems, thermal requirements also are less restrictive. At the same time, space-based systems have a higher risk of catastrophic failure and are extremely difficult or impossible to maintain or upgrade in the event that they fail. Venus-like orbit-based systems will be larger than Earth-orbiting systems and higher data rates are required.



D-9: 1m Vis Venus-like

	P/L	S/C
Dry Mass (kg)	539	1970
Wet Mass (kg)		2070
Power (W)	251	1169

Technical Description

- Space-based survey telescope (NEO-VIS like)
- Visible, 2.81° x 2.81° FOV, V_{lim}= ~22
- 1 m aperture diameter (similar to Kepler Observatory)
- Heliocentric, Venus-like orbit (can be Venus-trailing or other elliptical orbit inside of 1 AU)

CONOPS

- Location: Heliocentric, Venus-like orbit
- Operational: 2014
- Availability: 100% in NEO detection mode
- Launch Vehicle: Atlas V 401
- Full bandpass used to maximize detection
- Mostly autonomous spacecraft due to unique communication profile with Earth
- 10 year mission life

System Sizing

	Dry Mass (kg)	% of Dry Mass
Payload	539	27%
Spacecraft Bus	1431	73%
ACDS	229	12%
C&DH	86	4%
Power	145	7%
Propulsion	25	1%
Structure & Mechanisms	580	29%
TT&C	119	6%
Thermal	248	13%

* Note: Passive Venus flyby is employed to position S/C in approximately a 0.6 by 0.8 AU orbit. Hydrazine used for orbit corrections during cruise-phase of the mission.

Rationale for Consideration

- Provide comparison with space-based IR platforms
- Venus orbit has greater Inner Earth Orbit object visibility

Capability

- NEO orbital parameters

Pros

- Better location to observe NEOs with Earth-like orbits
- Can conduct survey at all times (vs. night only on ground)
- Build on heritage spacecraft (Kepler, Hubble)
- Less strict thermal requirements on optics than IR

Cons

- Higher data rates required than IR
- Higher risk of catastrophic failure vs. ground based asset
- Very difficult or impossible to maintain or upgrade

E.1.10. 2-meter Visible (Vis) Venus-like [D-10]

Description

The 2-meter Visible (Vis) Venus-like concept is a space-based, survey telescope that would scan the sky to search for NEOs. It is based on the proposed NEO-VIS design and would orbit the Sun in a ~0.7 AU heliocentric, Venus-like orbit. This option is included to allow comparison with space-based IR platforms. The selected orbit also offers greater visibility of IEOs and its larger aperture increases the detection rate. This detection asset will search for PHOs and can be used to calculate their orbital parameters. This design is based on other visible, space-based telescopes, and would be similar to the proposed NEO-VIS design.

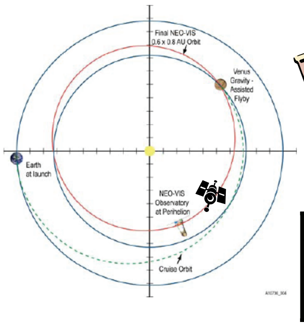
The telescope would have a 2.0-meter aperture that detects light in the visible spectrum. It would have a field of view of 2.81° x 2.81°, capable of achieving a limiting magnitude (V_{lim}) of approximately 23.6. The spacecraft would be launched by a Delta IV Medium+ (5,4) and would be operational around 2014. A passive Venus flyby is employed to position the spacecraft in a 0.6 by 0.8 AU orbit. Hydrazine propulsion is used only for orbital correction during the mission's cruise phase. It is a dedicated PHO detection asset, using the full bandpass to maximize detection. The spacecraft would be primarily autonomous due to a unique communications profile and is designed for 10 years of operations.

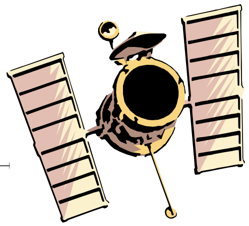
Qualitative Assessment

Compared with a ground sensor, a space-based visible sensor can spend more time searching for objects because it is not limited to night-only observations. The Venus-like orbit yields a greater detection rate and enables the observation of objects primarily inside Earth's orbit. Space-based visible observatories enjoy a long history and can achieve larger fields of view due to mature technology. In addition, their thermal requirements are less restrictive.

At the same time, space-based systems have a higher risk of catastrophic failure than do ground assets and are extremely difficult or impossible to maintain or upgrade. Venus-like orbit-based systems will be larger than Earth-orbiting systems. Compared with IR systems, they also will require higher data rates. The spacecraft would not be able to store all raw data for precovery. In addition, it only provides limited astrometric information about PHOs, which makes it more difficult to determine an object's size.

D-10: 2m Vis Venus-like





	P/L	S/C
Dry Mass (kg)	1255	2903
Wet Mass (kg)		3056
Power (W)	367	1311

Technical Description

- Space-based survey telescope
- Visible, 2.81° x 2.81° FOV, V_{lim}= 23.6
- 2m aperture diameter (a little smaller than Hubble Observatory)
- Heliocentric, Venus-like orbit (can be Venus-trailing or other elliptical orbit inside of 1 AU)

CONOPS

- Location: Heliocentric, Venus-like orbit
- Operational: 2014
- Availability: 100% in NEO detection mode
- Launch Vehicle: Delta IV Medium+ (5,4)
- Full bandpass used to maximize detection
- Mostly autonomous spacecraft due to unique communication profile with Earth
- 10 year mission life

System Sizing

	Dry Mass (kg)	% of Dry Mass
Payload	1255	43%
Spacecraft Bus	1648	57%
ACDS	266	9%
C&DH	100	3%
Power	169	6%
Propulsion	38	1%
Structure & Mechanisms	648	22%
TT&C	138	5%
Thermal	289	10%

* Note: Passive Venus flyby is employed to position S/C in approximately a 0.6 by 0.8 AU orbit. Hydrazine used for orbit corrections during cruise-phase of the mission.

Rationale for Consideration

- Provide comparison with space-based IR platforms
- Venus orbit has greater Inner Earth Orbit object visibility

Capability

- NEO orbital parameters

Pros

- Better location to observe NEOs with Earth-like orbits
- Can conduct survey at all times (vs. night only on ground)
- Build on heritage spacecraft (Kepler, Hubble)
- Less strict thermal requirements on optics than IR

Cons

- Higher data rates required than IR
- Higher risk of catastrophic failure vs. ground based asset
- Very difficult or impossible to maintain or upgrade

E.1.11. 0.5-meter Infrared (IR) L1/L2 [D-11]

Description

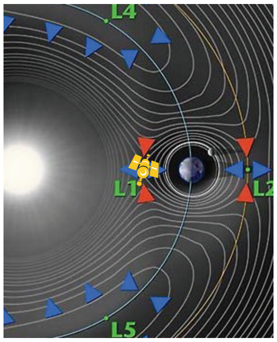
The 0.5-meter Infrared (IR) L1/L2 concept is a space-based, infrared survey telescope that would scan the sky in search of NEOs. It is based on the proposed NEOCam design, with an orbit at the Sun-Earth L1 point. This option is included due to PHO signatures that are stronger in the IR-spectral bandpass; consequently, they would be easier to detect with this asset. This detection asset will search for PHOs and can be used to calculate their orbital parameters. This design is based on other infrared, space-based telescopes, and would be similar to the proposed NEOCam design.

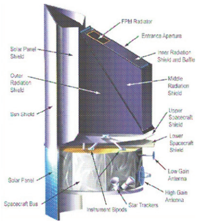
The telescope would have a 0.5-meter aperture that detects light in the infrared region between 6-10 μm. It would have a field of view of 1.7° x 6.8°, capable of achieving a limiting magnitude (V_{lim}) of approximately 23.6-25.4. Because the spacecraft would be placed in an L1 orbit, the IR detectors would be passively cooled. A Delta II 7920 would launch the spacecraft, which is expected to become operational around 2012. It is a dedicated PHO detection asset, using the full bandpass to maximize detection. The spacecraft has a 10-year operational life.

Qualitative Assessment

The benefit of a space-based infrared sensor, especially compared with a ground sensor, is that atmospheric absorbance would not block incoming IR light. Besides PHO signatures are stronger in the IR wavelengths, which results in less source confusion and a lower spacecraft data rate. The solar avoidance zone also is smaller for IR detectors. At the same time, space-based systems have a higher risk of catastrophic failure and are extremely difficult or impossible to maintain or upgrade. The observatory's location at LEO/L1/L2 is not optimal for PHO detection. It will have fewer opportunities to discover asteroids with Earth-like orbits, especially when compared with an observatory in a ~0.7AU, Venus-like heliocentric orbit. Compared with IR systems, the system requires higher data rates. In addition, infrared space systems enjoy less historical flight heritage, although it will be able to use detector technologies developed for JWST and the Wide-field Infrared Survey Explorer (WISE).

D-11: 0.5m IR L1/L2





	P/L	S/C
Dry Mass (kg)	259	600
Wet Mass (kg)		600
Power (W)	84	302

Technical Description

- Space-based survey telescope (NEOCam-like)
- Infrared (6-10 μm), 1.7° x 6.8° FOV, V_{lim}= 23.6-25.4
- 0.5m aperture
- Passively cooled
- Earth-based orbit, cannot be LEO due to cooling requirements
  L1 / L2 ~ 1.5×10^6 km

CONOPS

- Location: Earth-Sun L1 (nearly identical detection performance at L2)
- Operational: 2012
- Availability: 100% in NEO detection mode
- Launch Vehicle: Delta II 2920
- Full bandpass used to maximize detection
- 10 year mission life

System Sizing

	Dry Mass (kg)	% of Dry Mass
Payload	259	43%
Spacecraft Bus	341	57%
ACDS	109	18%
C&DH	18	3%
Power	62	10%
Propulsion	0	0%
Structure & Mechanisms	113	19%
TT&C	15	2%
Thermal	23	4%

Rationale for Consideration

- NEO signature is stronger in IR domain, easier to detect
- Provide comparison with space-based Vis platforms

Capability

- NEO orbital parameters

Pros

- No atmospheric absorbance in IR vs. ground-based asset
- Can conduct survey at all times (vs. night only on ground)
- Less source confusion and lower data rate than Vis
- Can look as close as ~55 degrees from Sun

Cons

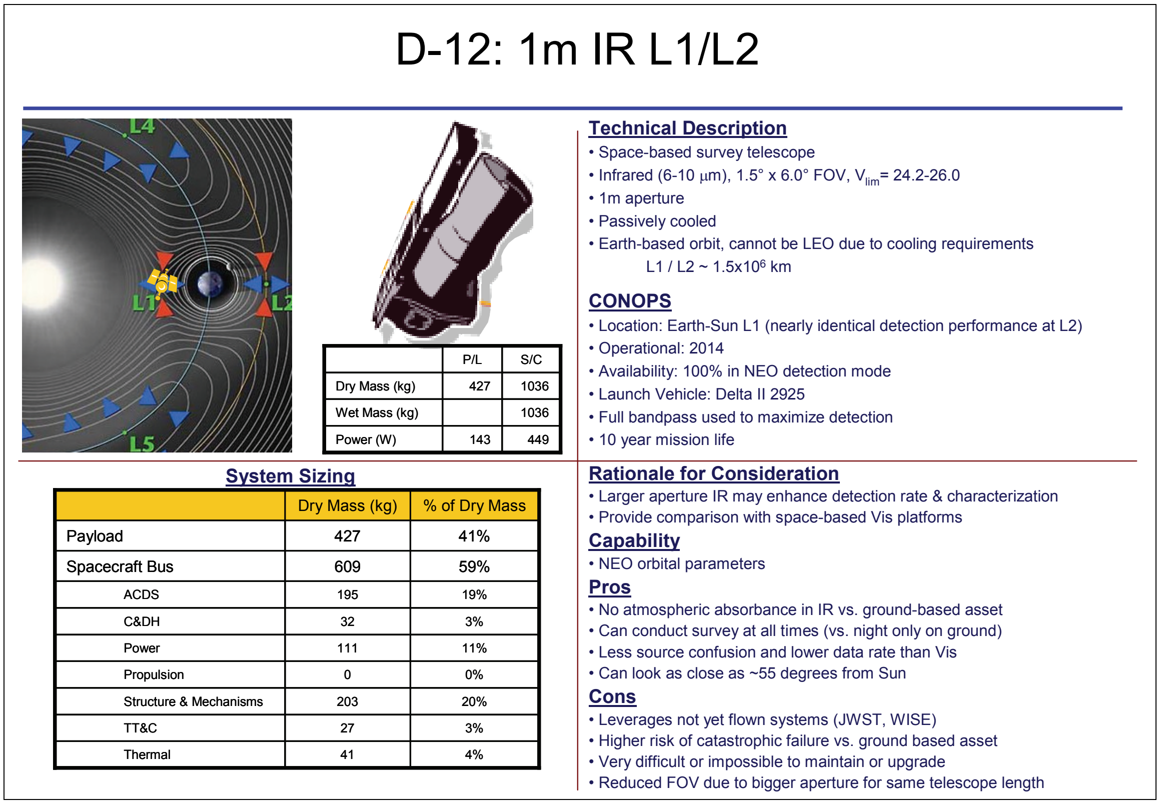
- Leverages not yet flown systems (JWST, WISE)
- Higher risk of catastrophic failure vs. ground based asset
- Very difficult or impossible to maintain or upgrade

E.1.12. 1-meter Infrared (IR) L1/L2 [D-12]

Description

The 1-meter Infrared (IR) L1/L2 concept is a space-based, infrared survey telescope that would scan the sky in search of NEOs. It is based on the proposed NEOCam design, with an orbit at the Sun-Earth L1 point. The study team included this option because PHO signatures are stronger in the IR-spectral bandpass; so these objects would be easier to detect with this asset. It also has a larger aperture that could enhance the PHO detection rate. This detection asset will search for PHOs and can be used to calculate their orbital parameters. This design has heritage to other infrared, space-based telescopes, and would be similar to the proposed NEOCam design.

The telescope would have a 1.0-meter aperture that detects light in the infrared region between 6-10 μm. It would have a field of view of 1.5° x 6.0°, capable of achieving a limiting magnitude (V_{lim}) of approximately 24.2-26.0. The IR detectors are passively cooled because of its L1 orbit. A Delta II 2925 would launch the spacecraft, which is expected to become operational around 2014. It is a dedicated PHO detection asset, using the full bandpass to maximize detection. The spacecraft has a 10-year operational life.



D-12: 1m IR L1/L2

Technical Description

- Space-based survey telescope
- Infrared (6-10 μm), 1.5° x 6.0° FOV, V_{lim}= 24.2-26.0
- 1m aperture
- Passively cooled
- Earth-based orbit, cannot be LEO due to cooling requirements
  L1 / L2 ~ $1.5\text{x}10^6$ km

CONOPS

- Location: Earth-Sun L1 (nearly identical detection performance at L2)
- Operational: 2014
- Availability: 100% in NEO detection mode
- Launch Vehicle: Delta II 2925
- Full bandpass used to maximize detection
- 10 year mission life

	P/L	S/C
Dry Mass (kg)	427	1036
Wet Mass (kg)		1036
Power (W)	143	449

System Sizing

	Dry Mass (kg)	% of Dry Mass
Payload	427	41%
Spacecraft Bus	609	59%
ACDS	195	19%
C&DH	32	3%
Power	111	11%
Propulsion	0	0%
Structure & Mechanisms	203	20%
TT&C	27	3%
Thermal	41	4%

Rationale for Consideration

- Larger aperture IR may enhance detection rate & characterization
- Provide comparison with space-based Vis platforms

Capability

- NEO orbital parameters

Pros

- No atmospheric absorbance in IR vs. ground-based asset
- Can conduct survey at all times (vs. night only on ground)
- Less source confusion and lower data rate than Vis
- Can look as close as ~55 degrees from Sun

Cons

- Leverages not yet flown systems (JWST, WISE)
- Higher risk of catastrophic failure vs. ground based asset
- Very difficult or impossible to maintain or upgrade
- Reduced FOV due to bigger aperture for same telescope length

Qualitative Assessment

The benefit of a space-based infrared sensor is that atmospheric absorbance does not block the incoming IR light. Besides PHO signatures are stronger in the IR wavelengths, resulting in less source confusion and a lower spacecraft data rate. The solar avoidance zone is also smaller for IR detectors. On the flip side, however, space-based systems have a higher risk of catastrophic failure compared with ground assets and are extremely difficult or impossible to maintain or upgrade. In addition, infrared space systems have less historical flight heritage, even though they could use detector technologies developed for the James Webb Space Telescope and the Wide-field Infrared Survey Explorer (WISE).

E.1.13. 0.5-meter IR Venus-like [D-13]

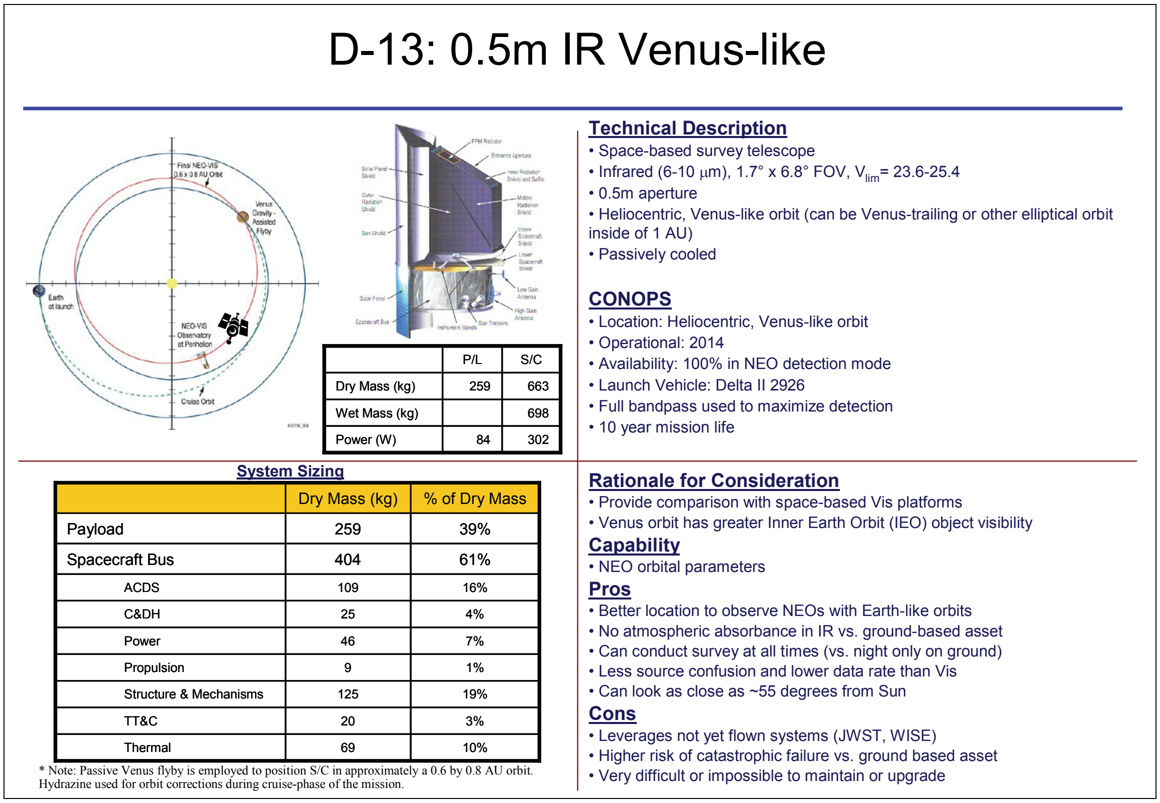
Description

The 0.5-meter IR Venus-like concept is a space-based, infrared survey telescope that would scan the sky searching for NEOs. Its design is based on the proposed NEOCam, but it would orbit the Sun in a ~0.7 AU heliocentric, Venus-like orbit. The team included this option because PHO signatures are stronger in the IR-spectral bandpass; therefore, these objects would be easier to detect with this asset. This concept's orbit also offers greater visibility of IEOs. This detection asset will search for PHOs and can be used to calculate their orbital parameters. This design traces its heritage to other infrared, space-based telescopes, and would be similar to the proposed NEOCam design.

The telescope would detect light in the infrared region between 6-10 μm. It would have a field of view of 1.7° x 6.8° and capable of achieving a limiting magnitude (V_{lim}) of about 23.6-25.4. The IR detectors are passively cooled because the spacecraft would be in a heliocentric orbit. Operational around 2014, the spacecraft would travel to space by way of a Delta II 2926. A passive Venus flyby is employed to position the spacecraft in approximately a 0.6 by 0.8 AU orbit. Hydrazine propulsion is used only for orbital correction during the mission's cruise phase. A dedicated PHO-detection asset, it would use a full bandpass to maximize detection. The spacecraft has a 10-year operational life.

Qualitative Assessment

The benefits of a space-based infrared sensor are comparable to those of other IR-based systems; namely, no atmospheric absorbance can block incoming IR light. The Venus-like orbit yields a greater detection rate and enables the observation of objects in Earth-like orbits. Besides the fact that PHO signatures are stronger in the IR wavelengths, these systems offer less source confusion and a lower spacecraft data rate. The solar avoidance zone also is smaller for IR detectors. As with other space-based systems, this asset runs a higher risk of catastrophic failure and it is impossible to maintain or upgrade. In addition, dust in the galactic plane can confuse the IR structure. And last, infrared systems have less flight heritage, although this concept would be able to use detector technologies developed for JWST and the Wide-field Infrared Survey Explorer (WISE).



D-13: 0.5m IR Venus-like

	P/L	S/C
Dry Mass (kg)	259	663
Wet Mass (kg)		698
Power (W)	84	302

System Sizing

	Dry Mass (kg)	% of Dry Mass
Payload	259	39%
Spacecraft Bus	404	61%
ACDS	109	16%
C&DH	25	4%
Power	46	7%
Propulsion	9	1%
Structure & Mechanisms	125	19%
TT&C	20	3%
Thermal	69	10%

* Note: Passive Venus flyby is employed to position S/C in approximately a 0.6 by 0.8 AU orbit. Hydrazine used for orbit corrections during cruise-phase of the mission.

Technical Description
- Space-based survey telescope
- Infrared (6-10 μm), 1.7° x 6.8° FOV, V_{lim}= 23.6-25.4
- 0.5m aperture
- Heliocentric, Venus-like orbit (can be Venus-trailing or other elliptical orbit inside of 1 AU)
- Passively cooled

CONOPS
- Location: Heliocentric, Venus-like orbit
- Operational: 2014
- Availability: 100% in NEO detection mode
- Launch Vehicle: Delta II 2926
- Full bandpass used to maximize detection
- 10 year mission life

Rationale for Consideration
- Provide comparison with space-based Vis platforms
- Venus orbit has greater Inner Earth Orbit (IEO) object visibility

Capability
- NEO orbital parameters

Pros
- Better location to observe NEOs with Earth-like orbits
- No atmospheric absorbance in IR vs. ground-based asset
- Can conduct survey at all times (vs. night only on ground)
- Less source confusion and lower data rate than Vis
- Can look as close as ~55 degrees from Sun

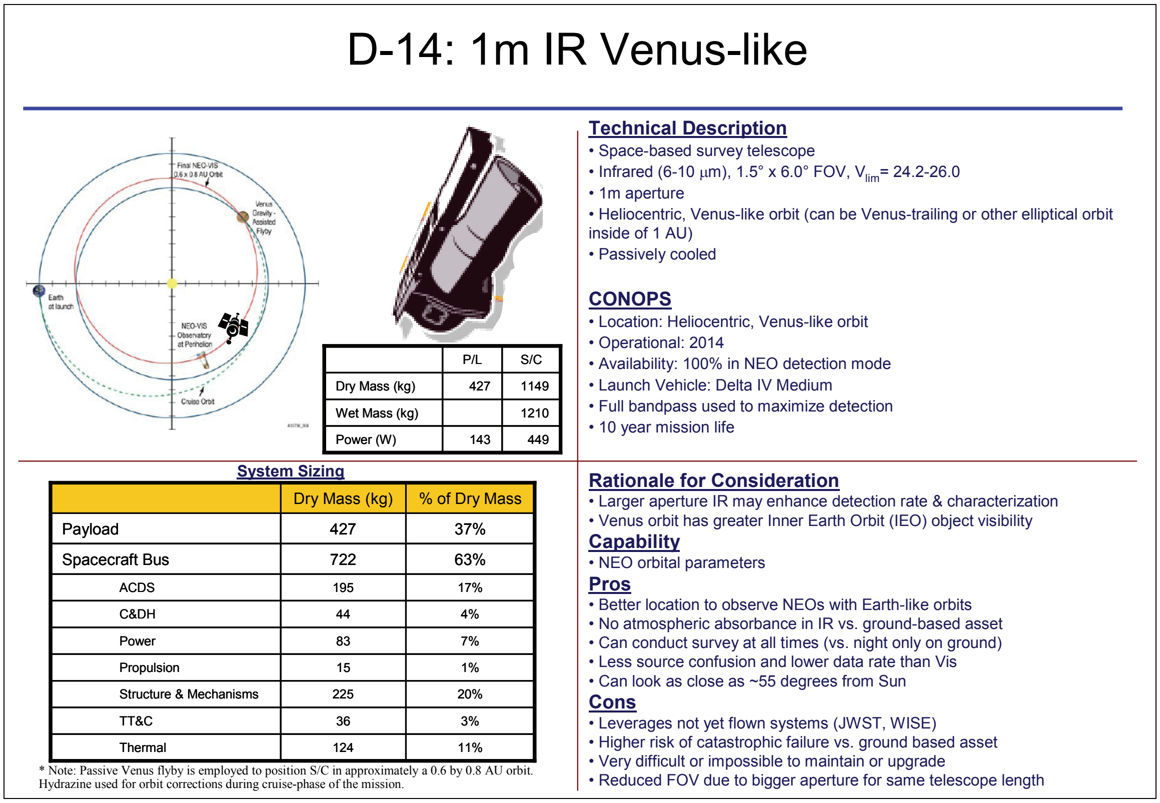
Cons
- Leverages not yet flown systems (JWST, WISE)
- Higher risk of catastrophic failure vs. ground based asset
- Very difficult or impossible to maintain or upgrade

E.1.14. 1-meter Infrared (IR) Venus-like [D-14]

Description

The 1-meter Infrared (IR) Venus-like concept is a space-based, infrared survey telescope that would scan the sky in search of NEOs. It is based on the proposed NEOCam, but would orbit the Sun in a ~0.7 AU heliocentric, Venus-like orbit. The study team included the option because PHO signatures are stronger in the IR-spectral bandpass. This concept's orbit also offers greater IEO visibility and its telescope has a larger aperture that could enhance the PHO detection rate. This detection asset will search for PHOs and can be used to calculate their orbital parameters. The design is based on other infrared, space-based telescopes.

The telescope would detect light in the infrared region between 6-10 μm. It would have a field of view of 1.5° x 6.0° and a limiting magnitude (V_{lim}) of approximately 24.2-26.0. The IR detectors are passively cooled because the spacecraft would be in a heliocentric orbit. Expected to become operational by 2014, the spacecraft would fly on a Delta IV Medium. A passive Venus flyby is employed to position the spacecraft in approximately a 0.6 by 0.8 AU orbit. Hydrazine propulsion is used only for orbital correction during the mission's cruise phase. A dedicated PHO detection asset, it uses the full bandpass to maximize detection. The spacecraft has an operational life of 10 years.



D-14: 1m IR Venus-like

	P/L	S/C
Dry Mass (kg)	427	1149
Wet Mass (kg)		1210
Power (W)	143	449

Technical Description
- Space-based survey telescope
- Infrared (6-10 μm), 1.5° x 6.0° FOV, V_{lim}= 24.2-26.0
- 1m aperture
- Heliocentric, Venus-like orbit (can be Venus-trailing or other elliptical orbit inside of 1 AU)
- Passively cooled

CONOPS
- Location: Heliocentric, Venus-like orbit
- Operational: 2014
- Availability: 100% in NEO detection mode
- Launch Vehicle: Delta IV Medium
- Full bandpass used to maximize detection
- 10 year mission life

System Sizing

	Dry Mass (kg)	% of Dry Mass
Payload	427	37%
Spacecraft Bus	722	63%
ACDS	195	17%
C&DH	44	4%
Power	83	7%
Propulsion	15	1%
Structure & Mechanisms	225	20%
TT&C	36	3%
Thermal	124	11%

* Note: Passive Venus flyby is employed to position S/C in approximately a 0.6 by 0.8 AU orbit. Hydrazine used for orbit corrections during cruise-phase of the mission.

Rationale for Consideration
- Larger aperture IR may enhance detection rate & characterization
- Venus orbit has greater Inner Earth Orbit (IEO) object visibility

Capability
- NEO orbital parameters

Pros
- Better location to observe NEOs with Earth-like orbits
- No atmospheric absorbance in IR vs. ground-based asset
- Can conduct survey at all times (vs. night only on ground)
- Less source confusion and lower data rate than Vis
- Can look as close as ~55 degrees from Sun

Cons
- Leverages not yet flown systems (JWST, WISE)
- Higher risk of catastrophic failure vs. ground based asset
- Very difficult or impossible to maintain or upgrade
- Reduced FOV due to bigger aperture for same telescope length

Qualitative Assessment

This system offers all of the same benefits of other infrared systems. In addition, its Venus-like orbit yields a greater detection rate and enables the observation of objects in Earth-like orbits. It also has the same disadvantages as other infrared space-based systems: it is difficult, if not impossible, to upgrade and maintain in the event of a failure and NASA has less experience building and flying them. There also is less historical flight heritage for infrared systems in space, although it will be able to use detector technologies developed for JWST and the Wide-field Infrared Survey Explorer (WISE).

E.2. Precision Orbit Determination Alternatives

E.2.1. Radar

Two planetary radars are capable of observing NEOs. The Goldstone radar, equipped with a 70-meter antenna and a 450 kW transmitter, is located in southern California's Mojave Desert. Because the antenna can be steered, Goldstone can observe most of the sky and follow the often-rapid motions exhibited by many NEOs. The second radar, equipped with a 305-meter aperture and a 900 kW transmitter, is located at Arecibo, Puerto Rico. Its reach is farther than Goldstone's, but because it has a fixed antenna, it can only look about 20 degrees off its zenith. As of early September 2006, planetary radars had observed 195 near-Earth asteroids and 11 comets.

Both Arecibo and Goldstone radars are heavily subscribed; only a percentage of their time is available for asteroid radar. Financial support for each system also has declined during the past several years and is inadequate for sustaining the radar capabilities. As a result, the systems have experienced difficulties mainly because of transmitter problems and difficulties maintaining personnel.

Both sites need adequate, reliable financial support to continue operations. As the current survey operates and the rate of discoveries increases, it will become increasingly clear that their limitations preclude most NEO radar reconnaissance. If radar observations of "short warning" PHOs are required, it is likely that a dedicated NEO radar observatory will be needed.

The availability of radar to observe an object over various time periods is shown in Figure 24, and the benefits of radar observations for characterization are discussed further in Reference [53].

E.3. Data Management System Alternatives

E.3.1. Scale Existing Data Management Systems [D-15]

Description

When the next-generation surveys begin, the Minor Planet Center (MPC) will need to increase its staff and modernize some of the computing resources to handle the expected increase in data, which may be up to 100 times greater than what is generated by current missions.

The MPC serves as the international clearinghouse for all worldwide asteroid, comet, and satellite astrometric and positional measurements. It is responsible for distributing astrometric observations and orbits via the Minor Planet Electronic Circulars (issued as necessary, generally once per day) and related catalogs. It specifically identifies NEOs, determines their short-arc orbits, and disseminates information about them. The MPC catalog is expected to grow to about 20,000 to 100,000 NEO records and perhaps 10 million total solar system objects after 10 years of Pan-STARRS (PS 4) operation.

The Smithsonian Astrophysical Observatory, in coordination with the International Astronomical Union (IAU), operates MPC. The MPC is located in Cambridge, MA, and has a current staff of two to three full-time equivalents (FTEs). As future detection capabilities grow 10 to 100 times the current observation rates, the staff size would likely need to increase to five or six FTEs. A one-to-two order of magnitude increase in observations will result in 200 to 10 million observations per day for minor planets and comets, and 20 to 1,000 observations per day for NEOs. The increased data flow also will require an increase in the number of objects needing follow-up.

In addition to distributing orbit and astrometric catalogs for said objects, the MPC facilitates follow-up observations of potential new NEOs. It places candidate sky-plane ephemeredes and uncertainty maps on the Web via the NEO Confirmation Page. In most cases, NEO observations are distributed to the public, free of charge, within 24 hours of receipt. The MPC also provides a variety of tools to support the NEO initiative, including sky-coverage maps, lists of known NEOs, lists of NEO discoverers, and a page that allows users to select a list of known NEOs in need of astrometric follow-up. The MPC also maintains a suite of programs to calculate the probability that any object is a new NEO based simply upon two sky-plane positions and a magnitude.

Qualitative Assessment

The MPC has a well-functioning infrastructure that is operated by the Smithsonian Astrophysical Observatory and coordinated with the IAU. As the next generation of large-scale surveys begin observing more NEOs, additional computer resources and a larger staff are necessary to support the increase in data rate. However, scaling the MPC is dependent on these detection systems producing a one-to-two order of magnitude increase in NEO observation data rate. Without this data increase it may be unnecessary to scale the MPC or similar data management systems.

E.3.2. Adopt Similar Systems [D-16]

Description

A new data-management system, or a combination of data-management systems, may have better functionality than existing NEO data systems. NEO detection programs may leverage existing systems to save money or reduce schedule and other risks. Multi-mission ground data system infrastructures currently exist to support astrophysical and geophysical data acquisition, processing, product development, and dissemination.

For example, the Infrared Processing Analysis Center (IPAC), the Multi-Mission Archive at Space Telescope, and the National Geophysical Data Center (NGDC) provide good examples. They can provide level-0 data acquisition and archival, data product development and dissemination, data fusion from multiple sources, and asset prioritization and tasking. It is important to fund and support similar services for NEO detection. This could involve developing and installing mission-unique hardware and software as required, using existing processes and data-archival services, and developing and distributing products.

Qualitative Assessment

Current NEO data-management infrastructures can be upgraded with potentially new features to improve the data-management capabilities. Better data-storage techniques, improved query functionality, and better dissemination channels are some features that can be adopted. Prioritization of services also could be a concern because of potential conflicts among users.

E.3.3. New Central Repository [D-17]

Description

Breakthroughs in telescope, detector, and computer technology allow astronomical surveys to produce terabytes of images and catalogs. [46] The U.S. National Virtual Observatory (NVO) can provide proper data management to catalog this increase in data flow, and is therefore the proposed framework for a NEO data management virtual observatory. NVO is developing new protocols and standards for data exchange and access to catalogued NEO observations, which is making it easier to use the data. The NVO has built prototypes to demonstrate the effectiveness of these new protocols and standards.

The NVO is a member of the International Virtual Observatory Alliance (IVOA), whose mission includes facilitating "*…the international coordination and collaboration* *necessary for the development and deployment of the tools, systems, and organizational structures necessary to enable the international utilization of astronomical archives as an integrated and interoperating virtual observatory.*" [47] As of January 2005, 15 different countries funded NVO projects. In the U.S., the NVO effort began in August 2001. More than 30 collaborators, principally U.S. professors with international liaisons in Europe, Japan, and Australia, support the NSF 5-year grant.

Qualitative Assessment

The NVO framework describes multi-terabyte online databases with interlinked catalogs. Query engines will become more sophisticated and the research results from the online data can potentially be as rich as those from real telescopes. New standards are being developed with the international astronomical community. The framework only is being researched and proposed; a virtual observatory has not been developed yet.

E.3.4. Backup Facilities [D-18]

Description

As the next generation of large-scale surveys begins observing NEOs, the Minor Planet Center (MPC) will need to increase staff and modernize some of the computing resources to handle a 10x to 100x increase in the observation data rate. During the interim, the NVO can be developed into a virtual observatory as the MPC is scaled to provide long-term data management. After it is fully scaled, the MPC will be the primary system and the NVO will become the backup facility.

As the MPC is being scaled to accommodate an increase in NEO observation data, the NVO framework can be implemented to manage the incoming data. The NVO is developing new protocols and standards for data exchange and access of cataloging NEO observations. The NVO will make astronomical data easier to use through the creation and adoption of standards. The NVO will build a few new protocols and standards for data exchange and access. The NVO has the main collaborators in the US with liaisons in Europe, Japan and Australia. The MPC is located in Cambridge, MA.

The MPC serves as the international clearinghouse for all asteroid, comet and satellite astrometric and positional measurements obtained worldwide. It is responsible for the dissemination of astrometric observations and orbits via the Minor Planet Electronic Circulars (issued as necessary, generally once per day) and related catalogs. It focuses specifically on identification, short-arc orbit determination, and dissemination of information pertaining to NEOs. The MPC catalog will grow to 20k-100k NEO records after 10 years of Pan-STARRS (PS 4) operation, and perhaps 10 million total objects. After the system is scaled, it will be used as the primary data-management facility. For purposes of redundancy, the NVO will become the secondary system.

Qualitative Assessment

A one-to-two order of magnitude increase in observations will result in 200 to 10 million observations/day for minor planets and comets and 20 to 1,000 observations per day for NEOs. This increase in data flow also will require an increase in the number of objects needing follow-up. The MPC will be scaled over a several years to manage this data increase. During this time, the NVO will be developed to process this data. The NVO framework is a multi-terabyte online database with interlinked catalogs. Query engines will become more sophisticated and the research results from the online data can potentially be just as rich as that from real telescopes.

This will address the near-term and long-term NEO observation data-management needs. The NVO framework is a proposed protocol and standard for data exchange and cataloging; so it is uncertain when it will be funded and become a functioning system.

Appendix F. Descriptions of Characterization Alternatives

F.1. Object Characterization Alternatives

F.1.1. Remote Characterization – Optical and Near Infrared (to 1um)

In the 1970s, astronomers began classifying asteroids into taxonomically distinct groups based on observations through three or four spectral filters. The broad groups included "C" for dark carbonaceous objects and "S" for stony (silicaceous) objects. Since then, the approach has been expanded to include several widely used systems using a progressively larger number of narrower bands or medium resolution spectro-photometry over the 0.4-um to 1-um region of the spectrum. These results will drive the follow-on observations, but taxonomy only can crudely bracket crucial parameters, such as mass, and only approximate composition. Asteroid taxonomy is covered in greater detail in Appendix Section K.4.

Spitzer Space Telescope (formerly SIRTF)

The Spitzer Space Telescope was designed to track solar system objects moving at 1"/sec (3600"/hr) and is capable of observing a large fraction of the NEO population. Spitzer provides both imaging and spectroscopic data for size and compositional analyses. When compared with ground-based surveys, Spitzer is very strong in the areas of limiting sensitivity and wavelength. Although observers will find many as-yet-undiscovered NEOs closer to the Sun than the Earth, Spitzer will not find them because of its strict Sun-avoidance constraints (Spitzer observations are only possible within 80-120º solar elongation).

Spitzer also does not automatically examine data within hours and it cannot routinely command rapid follow-up observations. Although Spitzer is not an optimal facility for NEO search, it will make major contributions in the characterization of the NEO population. It is the best available facility to provide spectroscopic and photometric studies of recently discovered objects that are too faint for detailed study with ground-based telescopes. The spectroscopic information will provide clues to an asteroid's composition, and the photometric information will derive an infrared albedo. As a result, observers will obtain a highly accurate measure of the object's size, especially compared with what an optical system could provide alone. Spitzer's imaging instruments are designed to routinely take simultaneous or near-simultaneous observations of the same region of sky at multiple wavelengths, which may lead to more robust detection of serendipitous NEO trails.

Spitzer sensitivity to these objects depends not on the integration time of the frame, but the amount of time that the object spends on each pixel. This is governed by the object's rate of motion. For a rapidly moving object, this may be only a few seconds. However, depending on the geometry with which astronomers view these objects, NEOs may NOT move rapidly. They may instead move as fast as the main belt asteroids. As a consequence, they appear near stationary for days at a time. In the latter case, reasonable integration times of 120 seconds for IRAC at 8um would allow astronomers to detect and characterize objects as small as 32 meters in diameter at a distance of 0.5 AU from Spitzer. [48]

F.1.2. Remote Characterization – Infrared

The infrared spectral region is most important for discerning an object's composition (carbonaceous, stony, or metallic), which is needed to constrain the NEO mass and to determine the most effective deflection or mitigation strategy. Figure 85 of Appendix Section K.4 demonstrates usefulness of the 1- to 2.5-micron spectral region. Therefore, coverage of the near-infrared spectral region has the highest priority. Remote infrared observations have a much greater range than radar observations, and thus afford more planning time.

Observations using modestly sized telescopes to observe NEOs at close approach and observations of newly identified PHOs shortly after their discovery are preferred. This requires access to large telescopes and a cadre of observers. In addition, for ground-based applications, polarimetry may be more effective than thermal IR observations. Table 44 details information derived from selected techniques.

Table 44. Mapping of Characterization Technique to Derived Information

Technique	Observed Parameter	Derived Information
Photometry	Light curve	Spin state, axial ratio, presence of satellites, constraint on density (cohesion?), absolute magnitude, phase curve, obliquity and shape modeling
Multi-wavelength photometry	Broad classification	First-order information: carbonaceous, stony, iron
Spectroscopy	Surface mineralogy	First-order information: density and porosity by analogy to meteorites and spacecraft data
Polarimetry (preferably at visible wavelengths but can also be done a near-infrared wavelengths)	Polarization as function of heliocentric phase angle	Polarimetric albedo: size can be estimated when used with the absolute magnitude; surface particle size and roughness information
Thermal photometry	Thermal emission	Albedo (when combined with visible photometry); thermal inertia gives estimate of the beaming parameter
Adaptive optics	Satellite detection and orbits	Mass of primary

F.1.3. Remote Characterization – Radar

As noted in section 5.10.2, radar data are capable of quickly refining orbits of some PHOs, especially for those objects with only a short optical data interval. Radial radar range measurements (i.e., round-trip light time) and radar radial velocity measurements (Doppler) can be accurate to the 8-meter and 1-mm-per-second levels, respectively, and hence have a fractional precision that is orders of magnitude better than optical position measurements.

Radar observations are capable of remotely characterizing, or constraining, a PHO's size, shape, surface roughness, and bulk density. In addition, of the 30 NEOs for which satellites were identified, 20 were found using radar techniques. The tracking of an asteroid's satellite can be used, through Kepler's third law, to determine the mass of the primary body. This mass, together with the radar-determined size (i.e., volume), can be used to determine the asteroid's bulk density. The information available from the radar characterization of a PHO is comparable to that of a spacecraft mission.

Images built from Doppler radar, which measures the frequency shift of a signal reflection to measure the speed of the target, can reconstruct the asteroid's actual shape. [49] [50] These analyses are made easier by knowing the object's rotational period and orientation, which ground-based photometric observations may help to derive.

In most modern radar observations, the transmission is circularly polarized and the ratio of the strength of two parallel receiving channel signals are used to gauge the target body's near-surface roughness at scale lengths comparable to the radar wavelengths (3.5 cm for Goldstone and 13 cm for Arecibo). The radar albedo, or reflectivity, also provides a useful constraint upon the object's characteristics, such as porosity and metal abundance. Radar imagery also may be used to determine the presence of an orbiting satellite, which can reveal the mass of the primary body.

Figure 69 and Figure 70 illustrate the ability of radar observations to characterize the shapes of asteroids and to provide constraints upon the object's surface properties. The radar observations in Figure 69 show that the main belt asteroid (216), Kleopatra, is shaped like a dog bone. Its surface is porous and loosely consolidated. Its interior may be composed of an arrangement of solid-metal fragments and loose metallic rubble. Figure courtesy of Steve Ostro, JPL. [51]

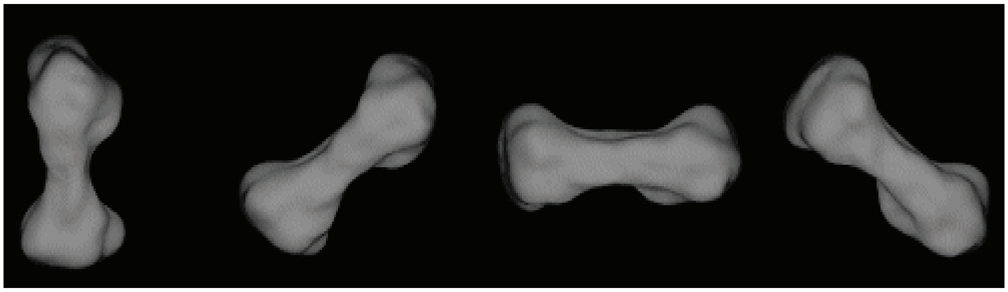


Figure 69. Radar Observations of Asteroid (216) Kleopatra

Figure 70 shows radar images of PHO (4179), Toutatis, which were made during the object's close approach to Earth on December 8, 1992. The images reveal two irregularly shaped, cratered objects about 4 and 2.5 km in average diameter. They are probably in contact with each other. The four frames shown here (from left to right) were obtained on Dec. 8, 9, 10 and 13, when Toutatis was about 4 million km from Earth. On each day, the asteroid was in a different orientation with respect to Earth. In these images, the radar illumination comes from the top of the page; so parts of each component facing toward the bottom are not seen. The large crater shown in the Dec. 9 image (upper right) is about 700 meters in diameter. *Courtesy, Steve Ostro, JPL* [52].

The availability of radar to observe an object over various time periods is shown in Figure 24. The benefits of radar observations for characterization are discussed further in Reference [53].

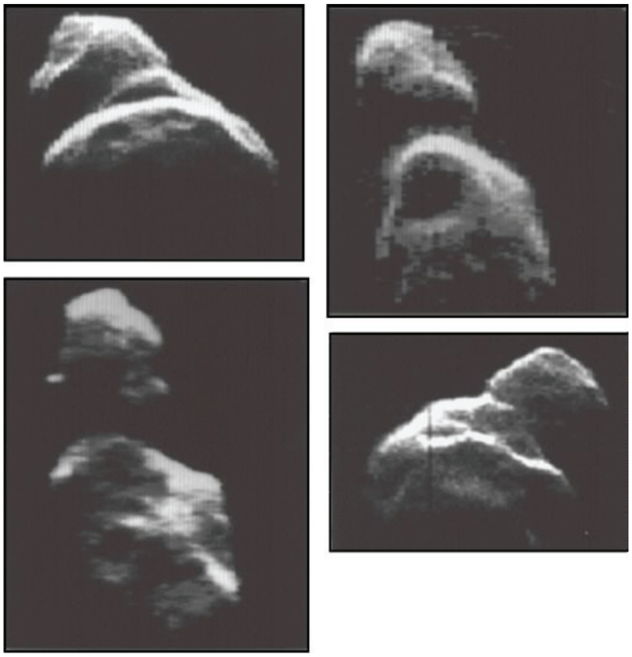


Figure 70. Radar Images of Asteroid (4179) Toutatis

F.1.4. In-Situ Characterization – Flyby

In-situ characterization missions are divided into two classes. Flyby missions, which also may include probes or impactors, are the least complex in-situ missions and may visit multiple NEOs. Orbital missions may include optional landers and surface samplers and are significantly more complex. The lower cost and complexity of flyby missions, along with their ability to visit multiple NEOs with a single launch, make them ideal for characterizing diverse objects in a population.

The most important objectives of a flyby mission would be to determine the key physical parameters of the target body. Flyby missions can provide accurate measures of size, shape, volume, albedo, general structure, rotation rate, pole location, and whether the body has any satellites. A flyby mission cannot measure the mass directly because the spacecraft is moving too quickly to measure the gravitational deflection of its trajectory by a small NEO. However, a flyby mission does provide the key parameters that are important for determining the body's mass. Once scientists know the body's volume, they only need to infer the porosity and average density to calculate the mass.

The objectives of a flyby mission can be classified into Tier-1 objectives, which are key to many deflection techniques and are readily measured by flybys. Tier-2 objectives are items that would be very helpful to understand the NEO population and may be important to know for some deflection alternatives. It may be very difficult for a flyby mission to obtain accurate measures of these Tier-2 objectives. However, the addition of an impactor to a flyby mission, similar to the Deep Impact experience, could help to achieve some of the Tier-2 objectives. These objectives are shown in Table 45.

Table 45. Possible Flyby Characterization Objectives

Tier-1 Objectives	Tier-2 Objectives (Difficult)
• Size • Shape • Volume • General Structure (rubble pile, or cohesive object) • Rotation rate and approximate axis • Albedo • Satellites?	• Mass • Density • Porosity • Detailed orbital elements (by delivering a coherent transponder to the surface) • Interior structure (by employing explosives and seismometers, or radar tomography, or other techniques for examining the interior) • Cohesiveness and strength of the NEO near surface • Composition of the NEO (both mineralogical and atomic)

There are two basic options for examining a number of NEOs with a single flyby mission. One option uses the flexibility of the trajectory to visit multiple NEOs, while the other uses a great deal of onboard propulsion. There are cost and mission objective tradeoffs involved in selecting which option to employ.

The first option is a multi-body flyby tour mission. Its orbit is similar to those of the CONTOUR mission and the Galileo and Cassini tours of Jupiter and Saturn's moon systems. The concept uses a high-energy Earth-return orbit. This mission would fly by one or two NEOs per year and then return to Earth where planners would program it for the next NEO flyby. Each of these yearly excursions forms a petal of the overall trajectory. This approach requires relatively little propulsion, as the spacecraft swings by Earth each year before it begins its next flyby.

Figure 71 shows some examples of Earth-return orbits that could employ chemical propulsion systems. The principal advantage of this type of mission is that the number of objects visited only depends on the mission's duration. This type of mission requires very little onboard propulsion and could easily fly by a large number of objects. The flyby speeds for these missions are several km/s, and therefore probably could only accomplish Tier-1 objectives without impactors. With impactors, they could get information on the targets' interior structures, thereby fulfilling a number of the Tier-2 objectives.

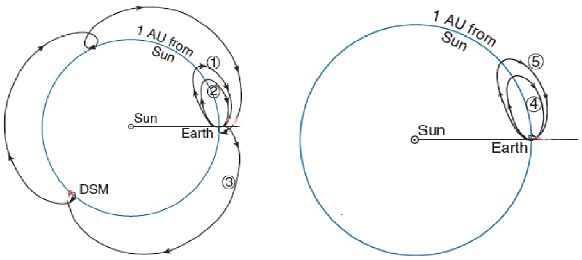


Figure 71. Examples of 1-year and multi-year Earth-return orbits

The second option for a multiple NEO flyby mission is an electric propulsion mission, either solar-electric or radioisotope-electric. While the exact amount of onboard ΔV required depends on the NEO targets chosen, most targets require at least 500 m/s to 1,500 m/s of onboard ΔV. Because of their high specific impulse (specific impulse from 600 seconds to greater than 3,000 seconds, depending on the type of electric thrusters), electric propulsion flyby missions can carry several km/s of propulsion. This should be sufficient to visit several NEOs, where the exact number depends on their orbital parameters.

The payload required for a flyby mission to accomplish its Tier-1 objectives includes imagers and spectrographs, plus some optional instruments that also could help it achieve some of the Tier-2 objectives. At least some imagers must have sufficiently high resolution to find the target body many days before their scheduled flyby. The information can help guide the spacecraft to the target, especially when the target's ephemeris is not known precisely. Other imaging assets must be able to resolve the size, shape, and detailed surface features during the high-speed flyby. This will require a tracking-mirror system for the medium-resolution camera and spectrograph. The spectrograph must have broad spectral coverage in the visible and near infrared to be able to observe the expected features of the various minerals on the NEO's surface. Additional payload elements may include a laser or radar altimeter magnetometer, neutron spectrometer, and X-ray spectrometer.

F.1.5. In-Situ Characterization – Rendezvous

While flyby missions can determine many of the NEO's physical characteristics, only a rendezvous mission with an orbital phase and possibly a lander can completely characterize a target. Flyby missions can tell a great deal about the diversity of the NEO population, but to learn more about a particular body's mass, structure, and composition, a rendezvous mission is required.

Rendezvous missions are designed to characterize a single body in great detail. The mission would get a range of characteristics about the target body, which are particularly important for selecting an appropriate deflection technique. If the mission deploys separate landers, the information they gather can reveal much about the body's interior, more so that what an orbiter alone can tell.

Rendezvous missions fulfill a wider range of Tier-1 objectives than flyby missions. Tier-1 objectives include those of a flyby mission, plus an accurate measure of the body's mass, its precise orbital motion, and a number of surface characteristics. However, a rendezvous mission requires more propulsion to arrive at the target body with zero relative velocity. This usually means that it must carry several times the onboard propulsion of a flyby mission to the same body. It also may require a trajectory that includes up to several planetary swingbys to reach the target body. See Table 46 for Tier-1 and Tier-2 rendezvous characterization objectives.

Table 46. Possible Rendezvous Characterization Objectives

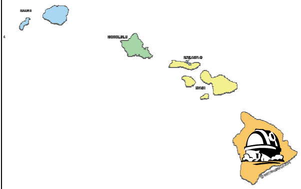
Tier-1 Objectives	Tier-2 Objectives
• Mass • Detailed orbital elements • Size and Shape • General Structure (rubble pile, or cohesive object) • Rotation rate and axis • Albedo • Scan for satellites or other bodies • Average density • Porosity • Surface structure and its variations • Surface composition	• Determine the interior structure (seismic, radio tomography, ground penetrating RADAR, etc.) • Demonstrate landing • Demonstrate anchoring to the surface with a given tensile strength • Demonstrate drilling the surface • Determine cohesiveness and strength near the surface

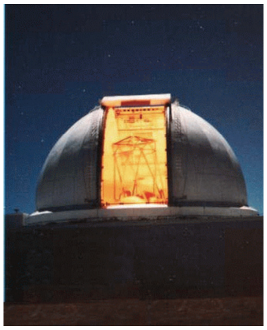
Missions with a landed component may enhance the return of information to support multiple deflection techniques. The payload of a landed component can provide more information about the body's surface composition and its interior structure. It also can experiment with landing, anchoring, and possibly drilling techniques, which could be used in a mitigation strategy. The payload for a rendezvous mission has all of the instruments of a flyby mission; however, it does not require a tracking-mirror system because there is about zero velocity between the orbiter and the NEO. In addition to the imagers, spectrographs, altimeter, and magnetometer, a landed component could have a:

- Low-power microscope to examine surface structure
- Laser-ablation mass spectrometer to study the body's molecular, atomic and isotopic composition
- Neutron spectrometer to look for hydrated minerals
- Alpha-proton-X-ray spectrometer or solar X-ray fluorescence spectrometer to examine the atomic composition of the surface
- Gamma-ray spectrometer to examine the atomic composition of the subsurface
- Plasma spectrometer provide information about its interaction with the solar wind

F.1.6. Ground-Based Characterization Concept Sheets

C-1: Shared InfraRed Telescope Facility (IRTF)





Technical Description

- Ground based telescope, alt-azimuth mount
- Infrared (0.8 - 5.5 μm), 80' x 80' FOV, V_{lim}= 22.1 – 23.9
- Monolithic, 3.0m aperture
- Current camera is not optimized for NEO characterization, a new, optimized camera could improve NEO characterization by a factor of 2

CONOPS

- Location: Mauna Kea, HI
- Operational: Currently operational
- Availability: On request, prioritized with others
- Provide follow-on observations of NEO detected by surveying telescopes upon request

System Sizing

Telescopes in System	1
Locations	1
Aperture (m)	3.0

Rationale for consideration

- Currently operational, NASA owned
- Follow-on observations of NEOs without disturbing detection effort & improved accuracy

Capability

- NEO orbital parameters, composition, size

Pros

- Much improved estimate of size, shape & albedo vs. only visible
- NEOs most detectable in IR
- Low risk of catastrophic failure, easy to maintain & upgrade vs. space asset

Cons

- Atmosphere absorbs majority of IR light, thus limited viewing of NEOs
- Limited access, observing time allocated 2x per year

C-2: Gemini

Technical Description

- Twin ground based telescopes in Northern and Southern hemispheres, alt-azimuth mount
- Visible (360-1100 nm) and Infrared (1-5.5 μm), 0.75° x 0.75° FOV, V_{lim}= 25
- Monolithic, 8.1m aperture

CONOPS

- Location: Mauna Kea, HI (North) and Cerro Pachón, Chile (South)
- Operational: Currently operational
- Availability: On request
- Provide follow-on observations of NEO detected by surveying telescopes upon request

System Sizing

Telescopes in System	2
Locations	2
Aperture (m)	8.1

Rationale for consideration

- Currently operational, multi-nation backing (including NSF)
- Follow-on observations of NEOs without disturbing detection effort & improved accuracy

Capability

- NEO orbital parameters, composition, size

Pros

- Much improved estimate of size, shape & albedo vs. only visible
- NEOs most detectable in IR
- Two 8m class telescopes at each hemisphere maximize sky access & allow parallax for orbital determination

Cons

- Atmosphere absorbs majority of IR light, thus limited viewing of NEOs

C-3: Discovery Channel Telescope (DCT)

Technical Description

- Ground based telescope, alt-azimuth mount
- Two modes: Prime Focus (2° FOV) and Ritchey-Chrétien Focus (30' FOV)
- Visible (330-1000 nm) $V_{lim}= 23$
- Monolithic, 4.2m aperture

CONOPS

- Location: Happy Jack, 40 miles SE of Flagstaff, AZ
- Operational: 2009
- Availability: On request, less limited
- Provide follow-on observations of NEO detected by surveying telescopes upon request

System Sizing

Telescopes in System	1
Locations	1
Aperture (m)	4.2

Rationale for consideration

- Development underway, partnership with Discovery Communications, Inc.
- Follow-on observations of NEOs without disturbing detection effort

Capability

- NEO orbital parameters, visible spectroscopy

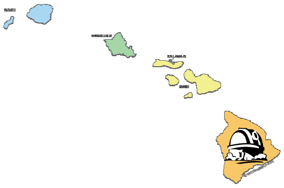
Pros

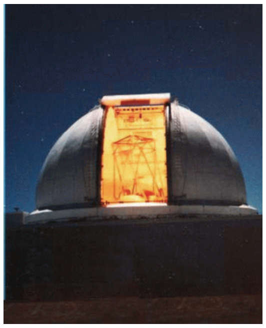
- Inexpensive follow-on of NEOs with $V_{lim} < 23$

Cons

- $V_{lim}= 23$ will not be able to provide follow up for smaller NEOs detected by an LSST or PS4-like telescope

C-7: Dedicated IRTF





Technical Description

- Ground based telescope, alt-azimuth mount
- Infrared (0.8 - 5.5 μm), 80' x 80' FOV, $V_{lim}= 22.1 – 23.9$
- Monolithic, 3.0m aperture
- Current camera is not optimized for NEO characterization, a new, optimized camera could improve NEO characterization by a factor of 2

CONOPS

- Location: Mauna Kea, HI
- Operational: Currently operational
- Availability: 100% NEO characterization mode
- Provide follow-on observations of NEO detected by surveying telescopes upon request

System Sizing

Telescopes in System	1
Locations	1
Aperture (m)	3.0

Rationale for consideration

- Optimized NEO characterization versus shared asset
- Follow-on observations of NEOs without disturbing detection effort & improved accuracy
- Dedicated, thus can quickly respond to characterizing new NEO detections

Capability

- NEO orbital parameters, composition, size

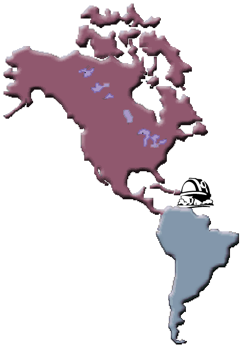
Pros

- Unlimited & rapid access, dedicated to NEO characterization
- Much improved estimate of size, shape & albedo vs. only visible
- NEOs most detectable in IR
- Low risk of catastrophic failure, easy to maintain & upgrade vs. space asset

Cons

- Atmosphere absorbs majority of IR light, thus limited viewing of NEOs

C-10: Arecibo



Technical Description

- Ground based telescope, fixed in ground
- Radar (3 – 600 cm), 305m dish
- Bowl-shaped reflector fixed in the ground, with a movable Gregorian reflector system suspended 137 meters hanging above it
- Approximately 40 kilometers of cabling supports the reflector. This prevents the Gregorian reflector system from changing shape as temperatures fluctuate and winds blow.

CONOPS

- Location: Arecibo, Puerto Rico
- Operational: Currently operational
- Availability: On request
- 13-cm wavelength (S-band) transmitter

System Sizing

Wavelength (S-band)	13-cm
Reflector diameter	304.8-m
Power (S-band)	1 MW
Surface accuracy	2 mm rms
Frequency Range	327 – 8500 MHz
Azimuth Slew Rate	0.4 deg/sec
Elevation Slew Rate	0.04 deg/sec
Zenith angle range	1.06 - 19.69 deg

Rationale for consideration

- Currently operational, backed by NSF
- Can provide high-precision characterization for NEOs and PHAs

Capability

- NEO orbital parameters, composition, mass, size, binarity, rotation , shape

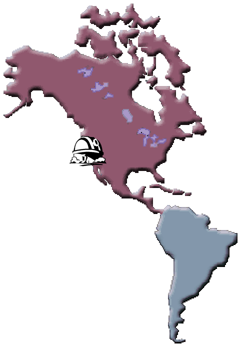
Pros

- Inexpensive follow on characterization of NEOs
- Large focusing antenna requires a few minutes of observation for collecting enough energy for analysis
- NSF supports operational, maintenance and upgrading costs

Cons

- Is limited to observations ~0.1AU or closer
- Declining financial support despite requiring receiver upgrade, small optics changes, upgrading of data acquisition system
- Small percentage of time available for asteroid radar

C-11: Goldstone



Technical Description

- Ground based telescope, steerable
- Radar (3.5 cm), 70m dish

CONOPS

- Location: Goldstone, CA
- Operational: Currently operational
- Availability: On request
- Communicates in X-band (8.6GHz) and S-band (2.3 GHz)
- Primarily uses 3.5cm wavelength (X-band) transmitter

System Sizing

Wavelength (X-band)	3.5-cm
Reflector diameter	70-m
Power (X-band)	500 kW

Rationale for consideration

- Currently operational
- Can provide high-precision characterization for NEOs and PHAs

Capability

- NEO orbital parameters, composition, mass, size, binarity, rotation , shape

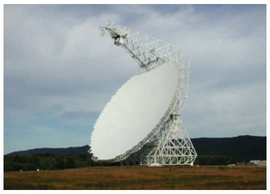
Pros

- Large focusing antenna requires a few minutes of observation for collecting enough energy for analysis
- Steerable vs. Arecibo

Cons

- Small percentage of time available for asteroid radar
- Declining financial support
- Is limited to observations ~0.1AU or closer

C-12: Bistatic 100m



Technical Description

- Two ground based telescopes, steerable
- Radar (0.9 – 3.5 cm), 100m dish
- Ka and X band
- Antennas, receivers, and transmitters will be one order of magnitude more sensitive than Arecibo
- Megawatt transmitter, each antenna's gain ~88dB
- Megawatt Transmitter: TRL 8 (Arecibo - 1 megawatt transmitter)
- Steerable 100m antenna: TRL 8 (NRAO Greenbank Telescope, West Virginia)

CONOPS

- Location: In conceptual design, no location identified
- Operational: TBD
- Availability: Dedicated (assuming funding incurred)

System Sizing

Number of Scopes	2
Wavelengths (Ka and X-band)	0.9 to 3.5-cm
Reflector diameter	100-m
Power	1 MW
Gain	88 dB

Rationale for consideration

- Would be leap forward from current radar telescopes
- Dedicated to NEOs, could compile more observations in one year than Arecibo and Goldstone can in a decade

Capability

- NEO orbital parameters, composition, mass, size, binarity, rotation , shape

Pros

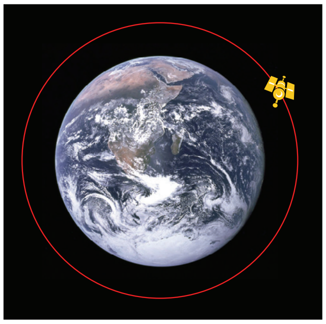
- No switching of antenna pointing between transmit and receive directions
- No interruption of data acquisition, coherent integration or orientational coverage
- Doubled data integration time
- Accessibility of arbitrarily close targets, including those within a few Earth-Moon distances (RTT < 10s)

Cons

- Very early in design process (concept stage), many unknowns
- Is limited to observations ~0.1AU or closer

F.1.7. Space-based Characterization Concept Sheets

C-13: Hubble



Technical Description

- Space based telescope, pointable
- Ultraviolet, Visible & IR (115 – 2500 nm), 28' x 28' FOV, V_{lim}=??
- Monolithic, 2.4m aperture

CONOPS

- Location: LEO, 600km altitude
- Operational: Currently operational
- Availability: On request, very limited
- Provide follow-on observations of NEO detected by surveying telescopes upon request

System Sizing

	Payload	Observatory
Dry Mass (kg)	5802	11972
Power (W)		2400

Rationale for consideration

- Currently operational
- Follow-on observations of NEOs in emergencies

Capability

- NEO orbital parameters, spectroscopy

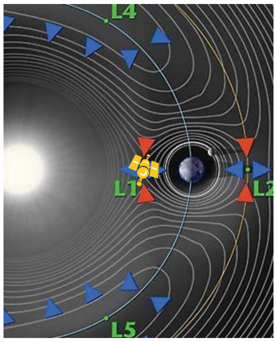
Pros

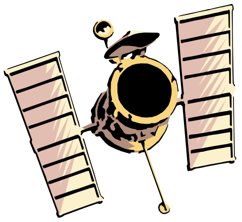
- Already launched & operational
- Above atmosphere which absorbs majority of IR light

Cons

- Limited lifetime, will not be available long term (deorbit ~2010)
- Shared asset, thus compete for telescope time

C-8: 2m Vis LEO/L1/L2 with Filter Wheel





	P/L	S/C
Dry Mass (kg)	1285	2629
Wet Mass (kg)		2629
Power (W)	367	1311

Technical Description

- Space-based dual mode (detect & characterize) telescope, pointable
- Visible, 2.81° x 2.81° FOV, V_{lim}= 23.6 in detect mode
  - FOV & V_{lim} much less in characterize mode
- 2m aperture (a little smaller than Hubble)
- Modification to solely detection system
  - Filter wheel added to provide narrow band pass for characterization

CONOPS

- Location: Earth-Sun L1 (nearly identical detection performance at LEO or L2)
- Operational: 2014 (TBR, may be affected by dual mode)
- Availability: Split between NEO detection and characterization modes
- Launch Vehicle: Atlas V 401 to L1/L2, Delta II 2920 for LEO
- 10 year mission life

System Sizing

	Dry Mass (kg)	% of Dry Mass
Payload	1285	49%
Spacecraft Bus	1344	51%
ACDS	266	10%
C&DH	74	3%
Power	225	9%
Propulsion	0	0%
Structure & Mechanisms	580	22%
TT&C	102	4%
Thermal	96	4%

Rationale for Consideration

- Add characterization capability with relatively minor modification to an asset that may be desired for detection purposes

Capability

- NEO orbital parameters, spectroscopy (if filter wheel used)

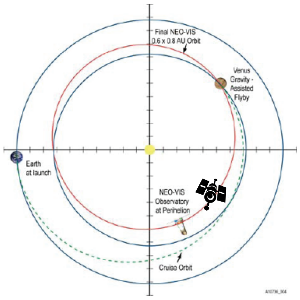
Pros

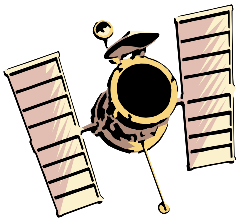
- If already in use for detection purposes, then may be cost effective design for dual (detect & characterize) purpose

Cons

- While asset in characterization mode, it would be unable to perform survey mission (will lose time which It could have been detecting NEOs)
- Will only be able to characterize NEOs with a V_{lim} much less than the telescope's V_{lim} in detect mode
- Increased moving parts & complexity vs. no filter wheel

C-9: 2m Vis Venus-like with Filter Wheel





	P/L	S/C
Dry Mass (kg)	1285	2942
Wet Mass (kg)		3095
Power (W)	367	1311

Technical Description

- Space-based dual mode (detect & characterize) telescope, pointable
- Visible, 2.81° x 2.81° FOV, V_{lim}= 23.6 in detect mode
  - FOV & V_{lim} much less in characterize mode
- 2m aperture diameter (a little smaller than Hubble Observatory)
- Modification to solely detection system
  - Filter wheel added to provide narrow band pass for characterization
- Venus-like orbit (can be Venus-trailing or other elliptical orbit inside of 1 AU)

CONOPS

- Location: Heliocentric, Venus-like orbit
- Operational: 2014 (TBR, may be affected by dual mode)
- Availability: Split between NEO detection and characterization modes
- Launch Vehicle: Delta IV Medium+ (5,4)
- Mostly autonomous spacecraft due to unique communication profile with Earth

System Sizing

	Dry Mass (kg)	% of Dry Mass
Payload	1285	44%
Spacecraft Bus	1657	56%
ACDS	266	9%
C&DH	100	3%
Power	169	6%
Propulsion	38	1%
Structure & Mechanisms	657	22%
TT&C	138	5%
Thermal	289	10%

* Note: Passive Venus flyby is employed to position S/C in approximately a 0.6 by 0.8 AU orbit. Hydrazine used for orbit corrections during cruise-phase of the mission.

Rationale for Consideration

- Add characterization capability with relatively minor modification to an asset that may be desired for detection purposes
- Venus orbit has greater Inner Earth Orbit (IEO) object visibility

Capability

- NEO orbital parameters, spectroscopy (if filter wheel used)

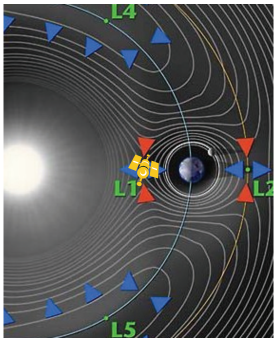
Pros

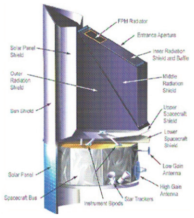
- If already in use for detection purposes, then may be cost effective design for dual (detect & characterize) purpose
- No atmospheric absorbance in IR vs. ground-based asset

Cons

- While asset in characterization mode, it would be unable to perform survey mission (will lose time which It could have been detecting NEOs)
- Will only be able to characterize NEOs with a V_{lim} much less than the telescope's V_{lim} in detect mode
- Increased moving parts & complexity vs. no filter wheel

C-16: Multiple-channel 0.5m IR L1/L2





	P/L	S/C
Dry Mass (kg)	267	608
Wet Mass (kg)		608
Power (W)	84	302

Technical Description

- Space-based dual mode (detect & characterize) telescope, pointable
- Infrared (6-10 μm), 1.7° x 6.8° FOV, V_{lim}= 23.6-25.4 in detect mode
  - FOV & V_{lim} much less in characterize mode
- Modification to solely detection system
  - Filter wheel or spectrograph added to provide narrow band pass for characterization
- 0.5m aperture
- Passively cooled

CONOPS

- Location: Earth-Sun L1 (nearly identical detection performance at L2)
- Operational: 2012 (TBR, may be affected by dual mode)
- Availability: Split between NEO detection and characterization modes
- Launch Vehicle: Delta II 2920
- 10 year mission life

System Sizing

	Dry Mass (kg)	% of Dry Mass
Payload	267	44%
Spacecraft Bus	341	56%
ACDS	109	18%
C&DH	18	3%
Power	62	10%
Propulsion	0	0%
Structure & Mechanisms	113	19%
TT&C	15	2%
Thermal	23	4%

Rationale for Consideration

- Add characterization capability with relatively minor modification to an asset that may be desired for detection purposes

Capability

- NEO orbital parameters, composition, mass, size

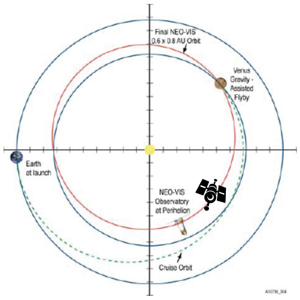
Pros

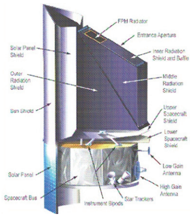
- If already in use for detection purposes, then may be cost effective design for dual (detect & characterize) purpose
- No atmospheric absorbance in IR vs. ground-based asset

Cons

- While asset in characterization mode, it would be unable to perform survey mission (will lose time which It could have been detecting NEOs)
- Will only be able to characterize NEOs with a V_{lim} much less than the telescope's V_{lim} in detect mode
- Increased moving parts & complexity vs. single channel

C-17: Multiple-channel 0.5m IR Venus-like





	P/L	S/C
Dry Mass (kg)	267	672
Wet Mass (kg)		708
Power (W)	84	302

Technical Description

- Space-based dual mode (detect & characterize) telescope, pointable
- Infrared (6-10 μm), 1.7° x 6.8° FOV, V_{lim}= 23.6-25.4 in detect mode
  - FOV & V_{lim} much less in characterize mode
- Modification to detection system
  - Filter wheel or spectrograph added to provide narrow band pass for characterization
- 0.5m aperture
- Passively cooled

CONOPS

- Location: Heliocentric, Venus-like orbit
- Operational: 2014 (TBR, may be affected by dual mode)
- Availability: Split between NEO detection and characterization modes
- Launch Vehicle: Delta II 2926
- 10 year mission life

System Sizing

	Dry Mass (kg)	% of Dry Mass
Payload	267	40%
Spacecraft Bus	406	60%
ACDS	109	16%
C&DH	25	4%
Power	46	7%
Propulsion	9	1%
Structure & Mechanisms	127	19%
TT&C	20	3%
Thermal	69	10%

* Note: Passive Venus flyby is employed to position S/C in approximately a 0.6 by 0.8 AU orbit. Hydrazine used for orbit corrections during cruise-phase of the mission.

Rationale for Consideration

- Add characterization capability with relatively minor modification to an asset that may be desired for detection purposes
- Venus orbit has greater Inner Earth Orbit (IEO) object visibility

Capability

- NEO orbital parameters, composition, mass, size

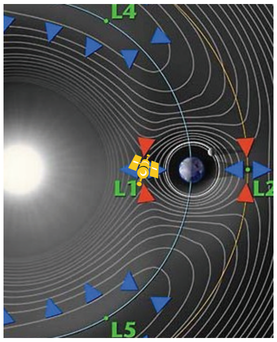
Pros

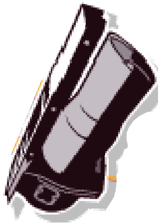
- If already in use for detection purposes, then may be cost effective design for dual (detect & characterize) purpose
- No atmospheric absorbance in IR vs. ground-based asset

Cons

- While asset in characterization mode, it would be unable to perform survey mission (will lose time which It could have been detecting NEOs)
- Will only be able to characterize NEOs with a V_{lim} much less than the telescope's V_{lim} in detect mode
- Increased moving parts & complexity vs. single channel

C-18: Multiple-channel 1m IR L1/L2





	P/L	S/C
Dry Mass (kg)	442	1051
Wet Mass (kg)		1051
Power (W)	143	449

Technical Description

- Space-based dual mode (detect & characterize) telescope, pointable
- Infrared (6-10 μm), 1.5° x 6.0° FOV, V_{lim}= 24.2-26.0 in detect mode
  - FOV & V_{lim} much less in characterize mode
- Modification to solely detection system
  - Filter wheel or spectrograph added to provide narrow band pass for characterization
- 1m aperture
- Passively cooled

CONOPS

- Location: Earth-Sun L1 (nearly identical detection performance at L2)
- Operational: 2014 (TBR, may be affected by dual mode)
- Availability: Split between NEO detection and characterization modes
- Launch Vehicle: Delta II 2925
- 10 year mission life

System Sizing

	Dry Mass (kg)	% of Dry Mass
Payload	442	42%
Spacecraft Bus	609	58%
ACDS	195	19%
C&DH	32	3%
Power	111	11%
Propulsion	0	0%
Structure & Mechanisms	203	19%
TT&C	27	3%
Thermal	41	4%

Rationale for Consideration

- Add characterization capability with relatively minor modification to an asset that may be desired for detection purposes

Capability

- NEO orbital parameters, composition, mass, size

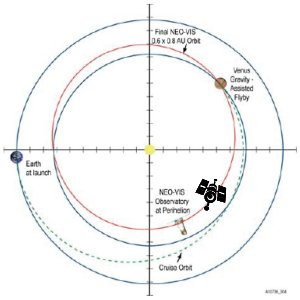
Pros

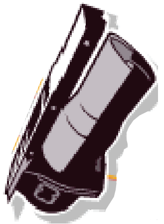
- If already in use for detection purposes, then may be cost effective design for dual (detect & characterize) purpose
- No atmospheric absorbance in IR vs. ground-based asset

Cons

- Reduced FOV due to bigger aperture for same telescope length
- While asset in characterization mode, it would be unable to perform survey mission (will lose time which It could have been detecting NEOs)
- Will only be able to characterize NEOs with a V_{lim} much less than the telescope's V_{lim} in detect mode
- Increased moving parts & complexity vs. single channel

C-19: Multiple-channel 1m IR Venus-like





	P/L	S/C
Dry Mass (kg)	442	1168
Wet Mass (kg)		1229
Power (W)	143	449

Technical Description

- Space-based dual mode (detect & characterize) telescope, pointable
- Infrared (6-10 μm), 1.5° x 6.0° FOV, V_{lim}= 24.2-26.0 in detect mode
  - FOV & V_{lim} much less in characterize mode
- Modification to detection system
  - Filter wheel or spectrograph added to provide narrow band pass for characterization
- Passively cooled
- 1m aperture

CONOPS

- Location: Heliocentric, Venus-like orbit
- Operational: 2014 (TBR, may be affected by dual mode)
- Availability: Split between NEO detection and characterization modes
- Launch Vehicle: Delta IV Medium
- 10 year mission life

System Sizing

	Dry Mass (kg)	% of Dry Mass
Payload	442	38%
Spacecraft Bus	726	62%
ACDS	195	17%
C&DH	44	4%
Power	83	7%
Propulsion	15	1%
Structure & Mechanisms	228	20%
TT&C	36	3%
Thermal	124	11%

* Note: Passive Venus flyby is employed to position S/C in approximately a 0.6 by 0.8 AU orbit. Hydrazine used for orbit corrections during cruise-phase of the mission.

Rationale for Consideration

- Add characterization capability with relatively minor modification to an asset that may be desired for detection purposes
- Venus orbit has greater Inner Earth Orbit (IEO) object visibility

Capability

- NEO orbital parameters, composition, mass, size

Pros

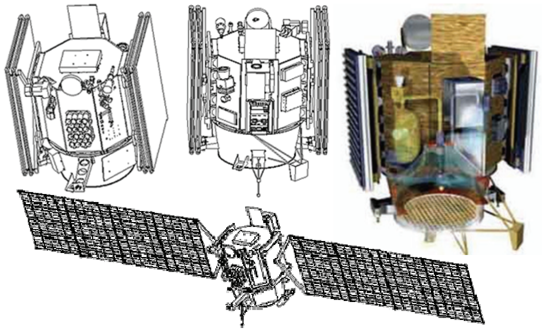
- If already in use for detection purposes, then may be cost effective design for dual (detect & characterize) purpose
- No atmospheric absorbance in IR vs. ground-based asset

Cons

- While asset in characterization mode, it would be unable to perform survey mission (will lose time which It could have been detecting NEOs)
- Will only be able to characterize NEOs with a V_{lim} much less than the telescope's V_{lim} in detect mode
- Increased moving parts & complexity vs. single channel

F.1.8. In-Situ Characterization Concept Sheets

C-21: Flyby Tour (Electric)



Technical Description

- Spacecraft with tracking mirror system, narrow and wide field-of-view imager, visible/infrared imaging spectrograph, magnetometer, laser / RADAR altimeter, gamma ray and neutron spectrometer, near infrared spectrometer, and multispectral imager
- 5 year design life
- 125m/s delta-V with 225s Isp hydrazine
- 4600m/s delta-V with 3000s Isp Xenon
- Optional STAR 37F SRM would provide up to 2467m/s delta-V

CONOPS

- Multi-body flyby tour, visiting as many NEOs as possible for characterization
- Launch vehicle: Delta II 2925 or EELV Medium

System Sizing

Payload (kg)	60
Payload Power (W)	70
Spacecraft Bus Mass (kg)	380
Spacecraft Dry Mass (kg)	440
Propellant – Hydrazine (kg)	30
Propellant – Xenon (kg)	80
Spacecraft Wet Mass (kg)	550
BOL Power (W)	2500
Optional STAR 37F SRM (kg)	1288

Rational for Consideration

- Can visit and characterize several NEOs with single mission
- Electric propulsion may allow for an increased number of NEO flybys

Capability

- Characterize general structure, size, shape, improved mass estimate, binarity, and rotation of NEOs

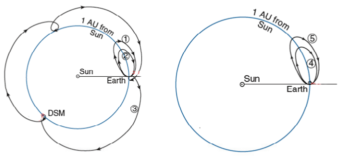
Pros

- Multiple NEOs can be targeted
- Build on heritage spacecraft (Deep Space 1)

Cons

- Complicated mission design and long flight times with electric propulsion
- Limited encounter duration vs. an orbiter

C-22: Flyby Tour (Chemical)



Orbit Options

Flyby Spacecraft

Technical Description

- Spacecraft with tracking mirror system, narrow and wide field-of-view imager, visible/infrared imaging spectrograph, magnetometer, laser / RADAR altimeter, gamma ray and neutron spectrometer, near infrared spectrometer, and multispectral imager
- 5 year design life
- 436m/s delta-V with 225s Isp
- Optional STAR 37F SRM would provide up to 2638m/s delta-V

CONOPS

- Multi-body flyby tour, visiting as many NEOs as possible for characterization
- Design and approach similar to the CONTOUR mission
- Launch vehicle: Delta II 2925 or EELV Medium

System Sizing

Payload Mass (kg)	60
Payload Power (W)	70
Spacecraft Bus Mass (kg)	330
Spacecraft Dry Mass (kg)	390
Spacecraft Wet Mass (kg)	475
BOL Power (W)	697
Optional STAR 37F SRM (kg)	1288

Rational for Consideration

- Can visit and characterize several NEOs with single mission
- Simpler mission design than electric propulsion

Capability

- Characterize general structure, size, shape, improved mass estimate, binarity, and rotation of NEOs

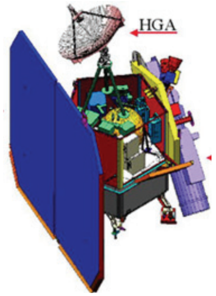
Pros

- Multiple NEOs can be targeted
- Build on heritage spacecraft (CONTOUR)
- Simpler mission design and shorter flight times than electric propulsion

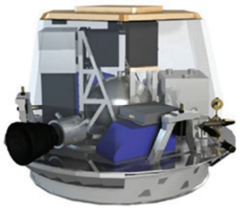
Cons

- Limited encounter duration vs. an orbiter

C-23: Flyby + Impactor



Flyby Spacecraft



Impactor

Technical Description

- Flyby –
  - Payload same as Flyby In Situ Characterization Alternative
  - 2 year design life
  - 203m/s delta-V with 225s Isp
  - Optional STAR 37F SRM would provide up to 1721m/s delta-V
- Impactor (1 used) –
  - High precision star camera (Impactor Target Sensor, ITS), and algorithms developed for DS-1, small hydrazine propulsion for attitude correction (25m/s, 1750Ns impulse)
  - Delivers 19 Gigajoules of KE (370kg at 10.2 km/s)

CONOPS

- Hit NEO with impactor and characterize debris with flyby spacecraft
- Launch vehicle: Delta II 2925 or EELV Medium

System Sizing

	Impactor	Flyby
Payload (kg)	185	377 (impactor), 60 (Instruments)
Payload Power (W)		80
Spacecraft Bus Mass (kg)	185	530
Spacecraft Dry Mass (kg)	370	967
Wet Mass (kg)	377	1060
BOL Power (W)	2.8 kW-hr for 24 hours	727
Optional STAR 37F SRM (kg)		1288

Rational for Consideration

- Can provide greater characterization than a only flyby mission
- Simpler mission design than an orbiter or flyby tour

Capability

- Characterize NEO orbital parameters, composition, improved mass estimate, size, binarity, rotation, shape, surface topography, & internal properties

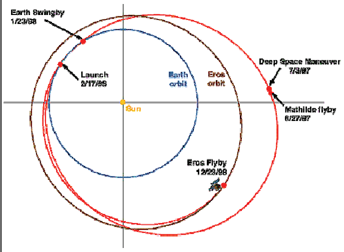
Pros

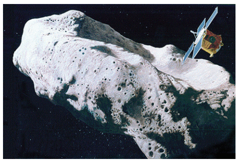
- Build on heritage spacecraft (Deep Impact)
- Additional data from impactor ejecta

Cons

- Accurate targeting from flyby spacecraft needed
- Only a single NEO can be targeted
- Impactor can only target one location on the NEO
- Limited encounter duration vs. an orbiter

C-24: Orbiter





Technical Description

- Spacecraft with tracking mirror system, narrow and wide field-of-view imager, visible/infrared imaging spectrograph, magnetometer, laser / RADAR altimeter, gamma ray and neutron spectrometer, near infrared spectrometer, and multispectral imager
- 5 year design life
- 1597m/s delta-V with 315s Isp
- Optional STAR 37F SRM would provide up to 1948m/s delta-V

CONOPS

- Characterize NEO by orbiting it
- Launch vehicle: Delta II 2925 or EELV Medium

System Sizing

Payload Mass (kg)	60
Payload Power (W)	70
Spacecraft Bus Mass (kg)	454
Spacecraft Dry Mass (kg)	514
Spacecraft Wet Mass (kg)	862
BOL Power (W)	697
Optional STAR 37F SRM (kg)	1288

Rational for Consideration

- Can provide detailed characterization of a NEO for a long period

Capability

- Characterize NEO orbital parameters, composition, mass, size, binarity, rotation, shape, and surface topography

Pros

- Build on heritage spacecraft (NEAR)
- Can directly measure NEO mass

Cons

- Only a single NEO can be targeted
- Complex mission design due to orbiting requirement
- Can only perform remote characterization vs. a lander or penetrator

C-25: Orbiter + Lander

Technical Description

- Orbiter –
    - Payload same as Orbiter In Situ Characterization Alternative
    - 5 year design life
    - 391m/s delta-V with 225s Isp
    - Optional STAR 37F SRM would provide up to 1525m/s delta-V
- Lander (3 used) –
    - Small lander deployed as black box payload from orbiter
    - Payload includes optical camera, Raman spectrometer, microscope, alpha proton x-ray detector, lidar, and penetrometer
    - 2 year design life

CONOPS

- Characterize NEO by orbiting and landing on it
- Launch vehicle: Delta II 2925 or EELV Medium
- Lander can be launched with a SRM from a small launch vehicle

System Sizing

	Lander	Orbiter
Payload Mass (kg)	10	420 (60kg + 3 landers)
Payload Power (W)	25	80
Spacecraft Bus Mass (kg)	90	653
Spacecraft Dry Mass (kg)	100	1073
Spacecraft Wet Mass (kg)	120	1281
BOL Spacecraft Power (W)	133	727
Optional STAR 37F SRM (kg)		1288

Rational for Consideration

- Can provide detailed characterization of a NEO for a long period
- Lander can provide in-situ characteristics of a NEO from its surface

Capability

- Characterize NEO orbital parameters, composition, mass, size, shape, binarity, rotation, surface topography, and sub-surface internal properties

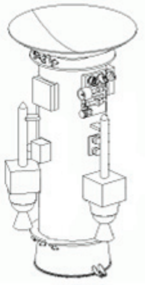
Pros

- Can directly measure NEO mass
- Multiple landers can target several locations on the NEO
- Large amount of additional data from lander

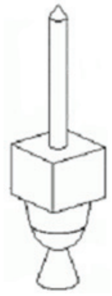
Cons

- Only a single NEO can be targeted
- Complex mission design due to orbiting requirement
- May be very complicated/impossible to land on fast rotating asteroid
- Lander may require active anchoring to counteract any moving parts

C-26: Orbiter + Penetrator



Spacecraft with
Multiple Penetrators



Single Penetrator

Technical Description

- Orbiter –
    - Payload same as Orbiter In Situ Characterization Alternative
    - 5 year design life
    - 391m/s delta-V with 225s Isp
    - Optional STAR 37F SRM would provide up to 1488m/s delta-V
- Penetrator (3 used) –
    - Miniature dart-like spacecraft with communications, command and data handling, navigation, power, thermal, and propulsion subsystems with a neutron and mass spectrometer and camera
    - 12-hour mission life

CONOPS

- Characterize NEO by orbiting and firing multiple penetrators into target
- Launch vehicle: EELV Medium

System Sizing

	Penetrator	Orbiter
Payload Mass (kg)	7	460 (60kg inst. P/L + 3 Penetrators)
Payload Power (W)		80
Spacecraft Bus Mass (kg)	51	653
Spacecraft Dry Mass (kg)	58	1113
Spacecraft Wet Mass (kg)	133	1329
BOL Spacecraft Power (W)	200 W-Hr	727
Optional STAR 37F SRM (kg)		1288

Rational for Consideration

- Can provide detailed characterization of a NEO for a long period
- Penetrator can provide in-situ characteristics of a NEO from its surface
- Penetrator design is simpler & more robust than a lander

Capability

- Characterize NEO orbital parameters, composition, mass, size, shape, binarity, rotation, surface topography, and sub-surface internal properties

Pros

- Can directly measure NEO mass
- Multiple penetrators can target several locations on the NEO
- Penetrators can be used in fast rotating asteroid

Cons

- Only a single NEO can be targeted
- Short lifetime limits amount of additional data from penetrator
- Complex mission design due to orbiting requirement

Appendix G. Description of Deflection Alternatives

G.1. Deflection Alternatives Using Impulsive Techniques

Impulsive techniques act instantaneously on the object and include kinetic impactors, which collide into the object at a high speed, and explosive techniques, which explode either on a high-velocity impact (similar to Deep Impact) or detonate during a high-velocity flyby or after they have landed on the object.

G.1.1. Conventional Explosive – Contact

A surface-level detonation of a conventional explosive potentially would add impulse to a kinetic impactor as a consequence of the ejection of near-surface material. A spacecraft on an impact trajectory with a PHO could deliver such a device and an impact fuse would detonate the explosive on contact. The mission profile and targeting would be similar to those used by a kinetic impactor.

As with a subsurface explosive, the structure and density of the asteroid is very important when trying to calculate the amount of conventional explosives needed to produce the desired change in velocity; however, a blast on the surface transfers roughly half the energy of a subsurface explosion. [34] This means the mission would have to double the amount of explosives to get the same effect. This method uses the same assumptions as the subsurface methods. Without knowing the asteroid’s inner structure, predicting the explosive’s cratering effects would be difficult.

For impact velocities of 1 km/s, an explosive may double the momentum transferred to the PHO, but research has found that for impact velocities between 2 and 3 km/s, the explosive device no longer is beneficial and might actually decrease the overall effectiveness. The gaseous products produced by the chemical detonation could prevent ejecta from leaving the surface at high velocities. [53] As a result, a simple kinetic impactor is preferred for higher-impact velocities.

Expected Performance

The team calculated the amount of chemical explosives that the Delta IV Heavy and the proposed Ares V could carry. For example, for C3 of 25 km^2/s^2, the nominal effective momentum changes for contact explosives were calculated to be about 10^6 kg-m/s and 10^7 kg-m/s, respectively.

These calculations suggest that the ΔV potential for contact chemical explosives ranges from 10 to 100 cm/s for very small PHOs (smaller than 40 meters), to 1 to 10 cm/s for small PHOs (smaller than 100 meters), to 0.1 to 1 cm/s for moderately size PHOs (smaller than 200 meters). The calculations also suggest that, with few exceptions, contact chemical explosives could not be expected to provide sufficient deflections of larger PHOs.

Characterization Required

Overall effectiveness is defined by the surface and subsurface material displaced in response to the explosion (as noted, the efficiency will be degraded as the impact velocity increases). Consequently, good information about the body's surface, internal structure, and density are very helpful for predicting the outcome. Since the device would be required to impact at a reasonably high velocity (several km a second), the spin of the PHO is not an issue, but knowing the shape and orientation of the surface at impact could be helpful because the blast wave might remove material from a sloping surface. While mission planners could design a deflection mission and spacecraft without detailed information about the target PHO, these factors should be examined further to eliminate uncertainties. It may be more effective to include several spacecraft with impact explosives in a single deflection mission.

Technology Readiness

Conventional explosives have been thoroughly tested on Earth, providing a wealth of knowledge on how different materials react to an explosion. The mechanism of action requires that the explosion remove material from near the surface at a high velocity. The effectiveness of such a technique is somewhat hypothetical and untested.

Explosive Devices — The characteristics of explosive devices are well known on Earth. Though no one has flown large explosive devices in space for some time, pyrotechnic devices have been used extensively on satellites and deep space probes. This technology area is rated as having a relatively **high level of technology readiness**.

Delivery Systems — The Deep Impact mission demonstrated a delivery system that could be used to deliver an explosive payload to a PHO. The risk level is rated as having a relatively **high level of technology readiness**.

Fusing — Fusing of conventional explosive devices is well understood, but its characteristics for high-impact velocities (on the order of 10 km/s) need to be verified. This technology area is rated as having a relatively **medium level of technology readiness**.

Overall Technology Readiness and Effectiveness

Conventional explosives on Earth are low-risk technology. Fusing, detonating, and developing shape charges are all well understood. However, these technologies have not been demonstrated or used in space, which adds an element of risk. As the impact velocity increases, the additional momentum gained by the explosive (as compared with the kinetic impact alternative) becomes a small percentage of the total momentum delivered. However, given the relatively well-developed status of conventional explosive technology, the technique is rated as having a **high overall level of technology readiness**.

Compared with other options, contact chemical explosives can provide only a moderate amount of momentum change to a PHO. However, most PHOs are relatively small. For this reason, the study judges the overall effectiveness of this approach as **medium**.

G.1.2. Conventional Explosives - Subsurface

There are two possible approaches for carrying out a subsurface explosion of conventional explosives. The first would require rendezvousing with and landing on the PHO, implanting the device, and timing the detonation to assure that the ejecta from the blast would be in the correct direction and at the optimal point in the object's orbit. [55] This option requires extensive operations near or when attached to the PHO. It also requires technologies and detailed characterization methods that currently are unavailable.

The second option involves containing the explosive inside an impacting spacecraft. The explosive would detonate some time after the spacecraft came into contact with the object's surface, allowing it to penetrate some distance into the surface. This would be similar to a "bunker-buster" aerial bomb. The approach for delivering the explosive is similar to the one used by a kinetic impactor and would not require a rendezvous. The additional weight and characterization information needed to design a reliable penetrator is comparable to what is needed to develop a similarly sized contact explosive.

This assessment does not account for any momentum transfer from ejecta caused by the detonation. As is discussed in the kinetic impact alternative, cratering can impart a significant momentum change, but is beyond the scope of this analysis. However, since the energy density of a conventional explosive is relatively small, the ability to create ejecta is expected to be small. Therefore, the overall assessment of its effectiveness is expected to be valid. The many possible surface structures, densities, and material properties may have a profound effect on mission results. These are among the uncertainties that mission planners would need to verify through testing and take into account when designing a spacecraft and mission.

Expected Performance

The team calculated the amount of chemical explosives needed to carry out "bunker-buster" approach, basing the estimate on the payload capacities of the Delta IV Heavy and the proposed Ares V. For example, for C3 of 25 km^2/s^2, the nominal effective momentum changes for contact explosives were calculated to be somewhat greater than that of the contact chemical explosives case: $3x\ 10^6$ kg-m/s and $3x\ 10^7$ kg-m/s, respectively.

These calculations suggest that the ΔV potential for subsurface chemical explosives ranges from 10 to 100 cm/s for very small PHOs (smaller than 50 meters), to 1 to 10 cm/s for small PHOs (smaller than 150 meters), to 0.1 to 1 cm/s moderate PHOs (smaller than 300 meters). The calculations also suggest that, with few exceptions, subsurface chemical explosives could not be expected to sufficiently deflect larger PHOs.

Characterization Required

The mass of the PHO and the ΔV required are the most important parameters for defining the overall deflection mission. However, density and subsurface characteristics also might help better refine a deflection campaign using this technique because it relies on the proper functioning of a subsurface device. Specific surface properties would not be required as long as the explosive device can imbed itself to the desired depth over a wide range of impact conditions and materials.

Technology Readiness

Explosive Devices — Characteristics of explosive devices are well known on Earth. Though no large explosive devices have flown in space for some time, pyrotechnic devices have been used extensively on satellites and deep space probes. This technology area is rated as having a relatively **high level of technology readiness**.

Delivery Systems/Implantation — The Deep Impact mission demonstrated a delivery system that mission planners could use to deliver an explosive payload to a PHO, but the ability to implant an explosive either by kinetic energy from the impact (high-relative velocity with no rendezvous) or by mechanical means after a soft landing (requires rendezvous) have not been verified. The complexity of this approach may be problematic. This technology area is rated as having a relatively **low level of technology readiness**.

Fusing — Fusing a conventional explosive device is well understood. However, fusing for these high relative velocities and the allowances that must be made for unknown PHO material properties must be verified. This technology area is rated as having a relatively **medium level of technology readiness**.

Overall Technology Readiness and Effectiveness

This alternative is a higher risk than its surface counterpart mainly because planners would need to understand the object's surface structure and internal composition to effectively design a mission. It is rated as having a **medium level of overall technology readiness**.

Compared with other options, subsurface chemical explosives can provide only a moderate amount of momentum change to a PHO. However, most PHOs are relatively small. For this reason, the overall effectiveness of this approach is judged to be **medium**.

G.1.3. Kinetic Impactor

A kinetic impactor mission would target a mass so that it impacts in a particular direction, similar to the approach taken with the Deep Impact mission. The objective would be to impact the impactor at a sufficiently high-impact velocity that the correct momentum is transferred to the PHO. The relative velocity at impact would be determined by the specific intercept trajectory. High-efficiency propulsion systems such as solar sails could be used to increase delivered impact mass and increase the impact velocity [56], but with a higher technology risk and much longer launch-to-deflection timeline.

Kinetic impactors greatly depend on the asteroid's structure. Generally, momentum transfer depends on the mechanics of the impact. Whether the object is solid metal or a loose pile of particles will determine the efficiency of the impact. For greatest momentum transfer, the impact should cause a large amount of cratering and expulsion of material.

For the kinetic impactor, the transfer of momentum is calculated by

$$\Delta V = \beta \frac{\left(\mathrm{m}_{\mathrm{impact}} \mathrm{u}_{\mathrm{impact}}\right)}{M_{asteroid}} \tag{2}$$

where β is the momentum multiplication constant (momentum exchange efficiency) and ΔV represents the velocity change imparted to the object. If β = 1, the collision is perfectly plastic, no ejecta is produced, and momentum is imparted directly. If the PHO is sufficiently weak and the impactor penetrates, then β<1 and the impact is less effective. If β>1, ejecta is released by the impact, and the impact is more effective. Some estimate that β could have a magnitude of 10 or more, depending on the material properties of the PHO, but a correlation of measurable asteroid characteristics and β is difficult.

The required mass is obtained as

$$m_{impact} = \frac{\Delta V_{deflection} \cdot M_{asteroid}}{v_{relative} \cdot \beta} \tag{3}$$

and the momentum transferred by the impact is

$$\Delta p = m_{impact} \cdot v_{relative} \cdot \beta \tag{4}$$

Thus, by knowing the mass of the PHO, the desired velocity increment, and the relative velocity of the impactor at impact, one can estimate the momentum imparted to the PHO and the impactor's required mass to effectively carry out the mission. β is expected to vary from 0.1 to 100 with values between 1 and 10 used for analyses in this study.

Expected Performance

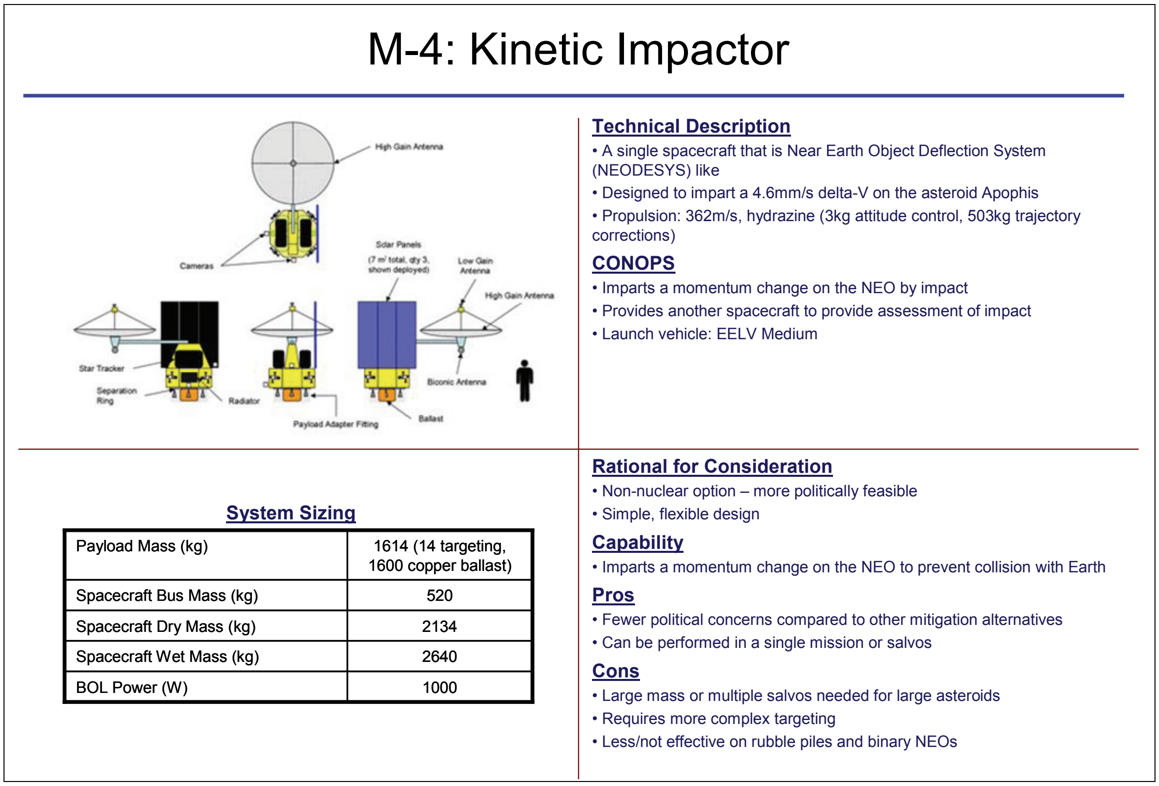
Calculations were carried out for hypothetical kinetic impactors based on various impact velocities, various values for β, and based on the payload capacities of the Delta IV Heavy and the proposed Ares V. For example, for C3 of 25 km^2/s^2, the nominal effective momentum changes for kinetic impactors were calculated to range from about 5×10^7 to 2×10^9 kg-m/s for systems launched by the Delta IV Heavy and 4×10^8 to 2×10^{10} kg-m/s for the Ares V.

These calculations suggest that kinetic impactors could be deployed to deflect moderate-to-large PHOs, perhaps even as large as a few km, if the ΔV requirement is on the order of 1 mm/s. Such small ΔV requirements are probably unusual cases, corresponding to circumstances such as keyhole encounters or cases where the deflection attempt is decades in advance of the potential collision with Earth.

More typically, the calculations for kinetic impactors suggest that they could reasonably be deployed for cases where ΔV requirements might range from 1 to 10 cm/s for moderately large PHOs (smaller than several hundred meters in size).

Characterization Required

For the kinetic impact mission, information on the PHO spin rate and shape are not required, though the location of the center of mass would be helpful. The mission and impactor can be designed using assumed size and mass estimates and assumed material properties, although definitive estimates would be helpful. The primary uncertainty related to kinetic impactors is the momentum multiplication factor, but the above approach is conservative in that it does not account for any ejecta or enhanced outgassing (as seen after the Deep Impact intercept of comet Tempel 1), which could actually provide much more effective ΔV than anticipated. As Deep Impact illustrates, a kinetic impact mission can be designed without detailed information on the target PHO, but again, a deflection mission must take into account uncertainties in the multiplication factor and other parameters.



M-4: Kinetic Impactor

Technical Description

- A single spacecraft that is Near Earth Object Deflection System (NEODESYS) like
- Designed to impart a 4.6mm/s delta-V on the asteroid Apophis
- Propulsion: 362m/s, hydrazine (3kg attitude control, 503kg trajectory corrections)

CONOPS

- Imparts a momentum change on the NEO by impact
- Provides another spacecraft to provide assessment of impact
- Launch vehicle: EELV Medium

System Sizing

Payload Mass (kg)	1614 (14 targeting, 1600 copper ballast)
Spacecraft Bus Mass (kg)	520
Spacecraft Dry Mass (kg)	2134
Spacecraft Wet Mass (kg)	2640
BOL Power (W)	1000

Rational for Consideration

- Non-nuclear option – more politically feasible
- Simple, flexible design

Capability

- Imparts a momentum change on the NEO to prevent collision with Earth

Pros

- Fewer political concerns compared to other mitigation alternatives
- Can be performed in a single mission or salvos

Cons

- Large mass or multiple salvos needed for large asteroids
- Requires more complex targeting
- Less/not effective on rubble piles and binary NEOs

Kinetic impactors do have the potential to fragment an asteroid, particularly if the asteroid has a diameter of 1-3 km. Kinetic-energy impact deflection techniques are probably viable for stronger, smaller bodies (diameter of less than 1 km) without concern for fragmentation, but planners would need to undertake a disruption analysis for asteroids a few km in diameter. For example, a kinetic impactor of sufficient size to impart a 1 cm/s ΔV to a 1-km asteroid would likely fragment the body. For targets with multiple large masses (e.g. binary objects), missions targeted at each primary mass may be required. Fragmentation is discussed further in Section 6.14.

Technology Readiness

Key technologies and systems related to kinetic impactors have been tested in space (e.g., Deep Impact), but their effectiveness for PHO deflection has not been characterized. Risks associated with critical technologies include:

Delivery Systems — Delivery systems required to deliver the impactor to the vicinity of a NEO have been demonstrated by the Deep Impact mission, which allowed no maneuvers during the last 6 minutes before impact, almost the last 4,000 km. It was still successful at hitting its target. This technology area is rated as having a relatively **high level of technology readiness**.

Targeting — The Deep Impact impactor was successfully targeted for a 10 km/s impact. [58] Some additional work may be necessary to verify this approach for smaller objects with shorter acquisition ranges and higher relative velocities. This technology area is rated as having a relatively **high level of technology readiness**.

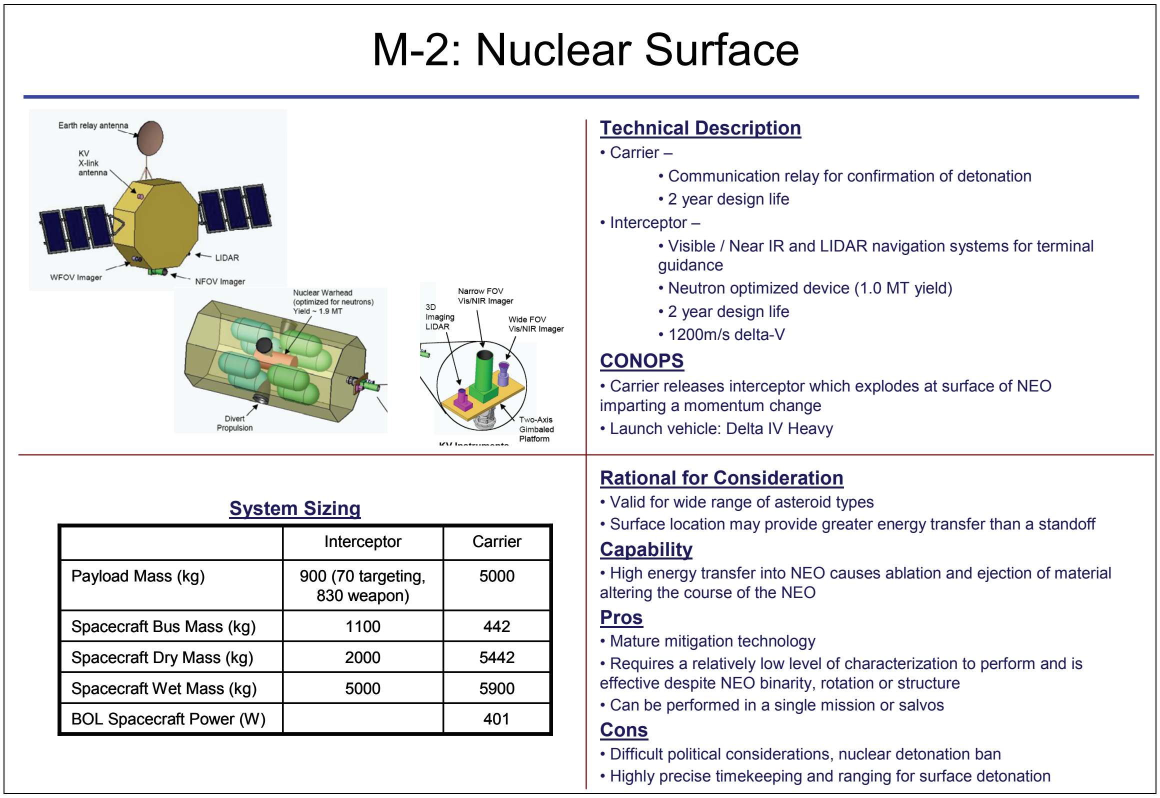
Overall Technology Readiness and Effectiveness

Because other Earth-based and space-based missions have verified many of the required technologies, **the overall technology readiness associated with this technique is judged as high**. Since it is expected to be applicable to a variety of PHOs and is highly scaleable, **its effectiveness is rated high**.

G.1.4. Nuclear Explosive – Surface Contact

The mission concept for detonating a nuclear explosive on contact with a PHO is very similar to the concept proposed for a conventional explosive. The concept is to place a nuclear explosive on an interceptor with an impact fuse. Blasting material from the PHO using the energy from the explosive would produce the momentum shift.

Differences exist between how nuclear and conventional explosives interact with a material, making nuclear explosives more efficient than their relative advantage in explosive energy. Nuclear explosives do not merely form a crater and eject material, but through radiative heating (principally from X-rays and neutrons) broadly ablate the surface of the object, transferring additional momentum.



M-2: Nuclear Surface

Technical Description

- Carrier –
  - Communication relay for confirmation of detonation
  - 2 year design life
- Interceptor –
  - Visible / Near IR and LIDAR navigation systems for terminal guidance
  - Neutron optimized device (1.0 MT yield)
  - 2 year design life
  - 1200m/s delta-V

CONOPS

- Carrier releases interceptor which explodes at surface of NEO imparting a momentum change
- Launch vehicle: Delta IV Heavy

System Sizing

	Interceptor	Carrier
Payload Mass (kg)	900 (70 targeting, 830 weapon)	5000
Spacecraft Bus Mass (kg)	1100	442
Spacecraft Dry Mass (kg)	2000	5442
Spacecraft Wet Mass (kg)	5000	5900
BOL Spacecraft Power (W)		401

Rational for Consideration

- Valid for wide range of asteroid types
- Surface location may provide greater energy transfer than a standoff

Capability

- High energy transfer into NEO causes ablation and ejection of material altering the course of the NEO

Pros

- Mature mitigation technology
- Requires a relatively low level of characterization to perform and is effective despite NEO binarity, rotation or structure
- Can be performed in a single mission or salvos

Cons

- Difficult political considerations, nuclear detonation ban
- Highly precise timekeeping and ranging for surface detonation

For a surface burst, a nuclear explosive delivers approximately 8% of its energy to the object. [59] Theoretical calculations predict that a surface burst of a nuclear explosive is roughly 3-5% as effective as that of a conventional explosive, but this shortcoming is overcome by the much higher yield per kilogram for nuclear explosives over that for conventional explosives [60]. Thus, the yield of a contact nuclear explosive required to deliver a specified impulse can be conservatively calculated by dividing the yield of the conventional explosives required by 0.03.

Expected Performance

Calculations were carried out for hypothetical contact nuclear explosives based on the payload capacities for the Delta IV Heavy and the proposed Ares V. For example, for C3 of 25 km^2/s^2, the nominal effective momentum changes for contact explosives were calculated to be about 2×10^{11} kg-m/s and 2×10^{12} kg-m/s, respectively.

These calculations suggest that the ΔV potential for contact nuclear explosives ranges from 10 to 100 cm/s for km-scale PHOs, to 0.1 to 1 cm/s for PHOs that are 10 km or larger. Surface nuclear explosives, therefore, could be expected to deflect most PHOs, given sufficient lead times (in some cases, decades to a century in advance). It is likely that, at the end of the Survey program, typical lead times for very large PHOs will probably be one or more centuries.

Characterization Required

A mission utilizing detonation of nuclear explosive on contact with a target PHO can be designed without detailed knowledge of the PHO. However, nuclear surface detonations have the potential to fracture and fragment the PHO, and some information on the composition and integrity of the PHO would be required to address this concern. For purposes of determining which characteristics are required to design the mission, it is assumed that fragmentation is not a problem, even if it does occur. Rotation rate is not required for this technique, but the orientation at impact could affect the angle of the explosion products, which might lower the efficiency in the required direction. Design of the mission should examine this possibility and include sufficient margin in the size of the explosive device, if required.

Technology Readiness

Explosive Devices — Nuclear explosives are well characterized; there is a wealth of information about the effects of nuclear weapons on materials that may be found on NEOs (e.g., sand, granite, basalt, ice, and tundra or “dirty ice”). [62] Nuclear explosives have been tested at an altitude of 400 km in space [63] and have been designed for delivery on missiles. A wide variety of designs have been tested and, while high-yield devices have been removed from the world’s nuclear-weapon stockpile, discussions with the staff at Los Alamos and Lawrence Livermore National Laboratories indicate that if specialized or high-yield explosives were needed, they could be designed and built to operate with no need for testing. This technology area is rated as having a relatively **high level of technology readiness**.

Delivery Systems — Delivery systems for these devices would be very similar to the one used in the Deep Impact mission. This technology area is rated as having a relatively **high level of technology readiness**.

Targeting and Fusing — Nuclear explosive detonation systems are well known and well characterized. A ranging system capable of providing accurate information during the final approach is required, and such systems have been demonstrated on Deep Impact and other missions. Unlike conventional explosives, a nuclear explosive does not need to come into direct contact with the surface to achieve a reasonable energy coupling. Therefore, this mission could use radar-controlled fusing, which has been tested on conventional and nuclear bombs for 60 years. The fusing and targeting technology area is rated as having a relatively **high level of technology readiness**.

Overall Technology Readiness and Effectiveness

This approach is assessed as having a **high overall level of technology readiness.** Because it could be used against any PHO, it is expected to provide a **very high level of effectiveness**.

G.1.5. Nuclear Explosive — Standoff

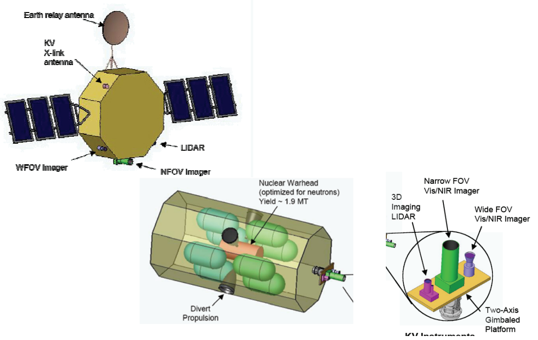
Unlike a surface explosion, a nuclear standoff detonation does not use its energy to add impulse to the asteroid, but rather to vaporize some of the asteroid's surface to produce the desired change in the NEO's velocity. [30] [64] By using a standoff detonation, the impulse absorbed will theoretically be less than the energy required to break up the asteroid, but sufficient to vaporize enough material to impart the necessary ΔV.

For this mission, the spacecraft would be designed to detonate at a specific height above the object's surface. The radiation produced by the explosion- X-rays, gamma rays, and neutrons - would bombard the surface, effectively vaporizing the surface layer. When material is vaporized and blown off an asteroid, an impulse is given to the asteroid due to conservation of momentum. Using this law and assuming the mass of the ejecta is very small compared with the mass of the asteroid, the amount of mass and average velocity of the ejecta needed to change the asteroid's velocity by a certain ΔV can be calculated as

$$\Delta V_{deflection} = \frac{m_{ejecta} v_{ejecta}}{M_{asteroid}} \qquad (5)$$

where m_{ejecta} is the mass of the ejecta, v_{ejecta} is the average velocity of the ejecta, $M_{asteroid}$ is the mass of the asteroid, and $\Delta V_{deflection}$ is the change in the asteroid's velocity. Using this relationship, one can see that by maximizing either the mass of the ejecta or its velocity, one can impart a greater momentum transfer to the asteroid.

M-1: Nuclear Standoff



System Sizing

	Interceptor	Carrier
Payload Mass (kg)	1570 (70 targeting, 1500 weapon)	5000
Spacecraft Bus Mass (kg)	1230	442
Spacecraft Dry Mass (kg)	2800	5442
Spacecraft Wet Mass (kg)	5000	5900
BOL Spacecraft Power (W)		401

Technical Description

- Carrier –
    - Communication relay for confirmation of detonation
    - 2 year design life
- Interceptor –
    - Visible / Near IR and LIDAR navigation systems for terminal guidance
    - Neutron optimized device (1.9 MT yield)
    - 2 year design life
    - 1000m/s delta-V

CONOPS

- Carrier releases interceptor which explodes within close proximity of NEO imparting a momentum change
- Launch vehicle: Delta IV Heavy

Rational for Consideration

- Valid for wide range of asteroid types
- Standoff location may provide a better geometry to deflect NEO

Capability

- High energy transfer into NEO causes ablation and ejection of material altering the course of the NEO

Pros

- Relatively mature mitigation technology
- Requires a relatively low level of characterization to perform and is effective despite NEO binarity, rotation or structure
- Can be performed in a single mission or salvos

Cons

- Difficult political considerations, nuclear detonation ban
- Precise timing required on detonation altitude required

The velocity of the gaseous ejecta is proportional to the square root of the temperature. [65] For this reason, it is better to have more mass vaporized to a relatively low temperature than little mass vaporized to a much higher pressure. To achieve this desired effect, an explosive custom made to emit mostly neutrons would be best for this scenario. Such devices have been designed and tested and are discussed in the Appendix P.

Most fusion-based explosives produce the majority of their radiation as X-rays. Although X-rays can carry more energy then neutrons, they are able to penetrate the surface to a depth of roughly 10-50 microns depending on surface structure and material. [66] Neutron radiation has the ability to penetrate to a depth on the order of 10 cm, effectively burning off more mass at a lower temperature and creating a higher-momentum transfer. Tailored neutron bombs have the ability to transfer roughly 10% of the blast energy into neutrons, which could vaporize the asteroid's surface. [69]

To transfer the highest amount of momentum to the NEO, it is important to find the detonation height above the PHO's surface. This allows the most mass to receive the most energy and to vaporize and exit with the necessary escape velocity. Reference [30] relates the momentum change, energy needed, and the optimum height of the explosion above the PHO.

Achieving the correct detonation height above the surface requires accurate measurement and fusing during the encounter. The relative velocity between the spacecraft and asteroid may range anywhere from a km per second to 10 km per second near impact. The optimum height for a standoff explosion varies widely in literature, from 6-80% of the mean asteroid diameter. For this study, the value chosen was 20 meters, or 10% of the diameter of the object. A strong correlation exists between standoff distance and effectiveness, and the standoff distance chosen (or realized due to timing errors) could affect effectiveness by one-to-two orders of magnitude.

An advantage of this technique is that it spreads the impulse over a large area of the NEO, reducing the possibility of fragmentation. Further, information on its rotation rate and other features are not required.

Expected Performance

Calculations were carried out for standoff nuclear explosives. They were based on hypothetical conventional systems and tailored neutron nuclear explosives as well as on the payload capacities of the Delta IV Heavy and the proposed Ares V. For example, for C3 of 25 km^2/s^2, the nominal effective momentum changes for tailored neutron nuclear explosives in a standoff mode were calculated to be about 10^{10} kg-m/s and 5 x 10^{10} kg-m/s, respectively.

These calculations suggest that the ΔV potential for standoff nuclear explosives ranges from 10 to 100 cm/s for PHOs up to about 1 km in size, to 0.1 to 1 cm/s for PHOs that are up to several km in size. Standoff nuclear explosives, therefore, could be expected to deflect many large PHOs, given sufficient lead times (in some cases, decades to a century in advance).

Characterization Required

Without knowledge of an asteroid's elemental composition, it is difficult to predict the effectiveness of a standoff detonation due to uncertainties in the material's vaporization. These uncertainties must be included in the mission design. Increasing the size of the explosive device probably could compensate for these uncertainties. Specific information on the size and shape of the target PHO is not required because the device is activated above the surface and the device could be sized to counter any size- or shape-related uncertainties. Similarly, the device would be sized to compensate for uncertainties in surface properties; therefore, specific information is not required.

An advantage of this technique is that it spreads the impulse over a large area of the PHO, reducing the possibility of fragmentation. Further, information on the rotation rate and other features are not required, but a single spacecraft can include an explosive device sized to deliver sufficient energy to account for these uncertainties.

Technology Readiness

This approach has fundamentally lower technology requirements than the nuclear surface contact alternative. Only the differences are discussed here.

Explosive Devices — This technology area is rated as having a relatively **high level of technology readiness**.

Targeting and Fusing — A ranging system capable of providing accurate information during final approach is required, and such systems have been demonstrated on Deep Impact and other missions. However, as noted earlier, a high-closing velocity is very challenging. This mission could use radar-controlled fusing, which has been tested on munitions for 60 years. This technology area is rated as having a relatively **high level of technology readiness**.

Overall Technology Readiness and Effectiveness

The primary issue for standoff nuclear systems relates to timing the explosion so that it occurs at the proper altitude above the PHO surface and the effectiveness of the explosion in imparting a momentum change. Nuclear explosives deliver the highest energy per unit mass to the PHO and the explosive energy can be sized to account for uncertainties. Also, the standoff devices will not create large amounts of dust or other debris that will make assessing its effectiveness difficult [70].

This approach has a **high overall level of technology readiness** and, because it could be used against any PHO, it is expected to provide **very high effectiveness**.

G.1.6. Nuclear Explosive - Subsurface

A subsurface nuclear explosive would be delivered to a PHO in a manner similar to a kinetic impactor, but the impact velocity would have to be set to the range required to achieve the desired penetration. This could require some maneuvering of the interceptor before impact. The explosive device would be detonated at the prescribed depth.

Another approach would be to rendezvous with and land on the NEO. The payload could drill a hole to the proper depth and insert the explosive device. The detonation would be timed so that the ejecta move in the direction for maximum effect. This would require a sensor system capable of determining the orientation of the PHO in space and detonating the device when the PHO is oriented correctly. Since this approach requires technologies that have not yet been designed or tested, it is not considered further here.

The effectiveness of subsurface nuclear explosives is very dependent on the internal structure of the asteroid.

Expected Performance

Subsurface nuclear explosives are expected to provide the greatest momentum change per system mass of any deflection technique considered in this analysis. Calculations were carried out for subsurface nuclear explosives. They were based on hypothetical conventional systems, tailored neutron nuclear explosives, and the payload capacities of the Delta IV Heavy and the proposed Ares V. For example, for C3 of 25 km^2/s^2, the nominal effective momentum changes for subsurface nuclear explosives were calculated to be about 5×10^{11} kg-m/s and 4×10^{12} kg-m/s.

These calculations suggest that the ΔV potential for subsurface nuclear explosives ranges from 10 to 100 cm/s for PHOs up to several km in size, to 0.1 to 1 cm/s for PHOs that are up to tens of km in size. Subsurface nuclear explosives, therefore, could be expected to deflect many large PHOs, given sufficient lead times (in some cases, decades to a century in advance).

Characterization Required

To estimate the size of the explosive required, planners would need to know the PHO's mass. They would not necessarily need to know its size, except to estimate the likelihood of fragmentation. The density is helpful for designing the penetrator. Uncertainties about the PHO's internal and external structure (e.g., if the impactor struck a steep slope and the ejecta did not move in the optimal direction) could affect the device's efficiency. Increasing the size of the explosive device could compensate for this lack of knowledge.

Technology Readiness

This approach has fundamentally higher technology requirements than the nuclear surface devices. They are discussed here.

Explosive Devices — This technology area is rated as having a relatively **high level of technology readiness**.

Delivery Systems – Although explosive penetrators are well understood in the physical environment of the Earth, less is known about how explosive penetrators will interact with PHOs in space. This technology area is rated as having a relatively **low level of technology readiness**.

Targeting and Fusing —Nuclear explosive systems are well known and well characterized; however, this case requires detonation below the PHO's surface for which there is no precedent. This technology area is rated as having a relatively **high level of technology readiness**.

Overall Technology Readiness and Effectiveness

The use of nuclear explosives below the surface of a PHO raises issues similar to those raised for conventional explosives. In addition, fragmentation of the PHO might be a real possibility, and a PHO fracture analysis would be required. Due to the challenges of detonating the nuclear explosive beneath the PHO's surface, this approach is assessed as **medium in overall technology readiness.** In addition, since it could be used against a fairly large number of PHOs, but may be more difficult to implement with the smaller PHOs, it is assessed as providing **medium overall effectiveness**.

G.2. Deflection Alternatives Utilizing Slow Push

To produce a momentum change on an asteroid, some sort of impulse, whether it is instantaneous or over time, must be imparted to the mass. In general, slow push techniques have the advantage that they impart very small amounts of force and, as a result, do not run the risk of fragmenting the PHO. However, spreading the force over a longer arc is less efficient than impulsive techniques, sometimes much less efficient. If the general orbital period of a PHO is 2.3±1.1 years [71], slow-push techniques, which act over more than a quarter of an orbital period, are expected to have large finite burn arc (gravity) losses. The momentum required for these techniques is developed from equation (18), which includes a loss for the application of force over a finite orbit arc.

G.2.1. Enhanced Yarkovsky

Russian civil engineer Ivan Osipovich Yarkovsky first predicted the Yarkovsky Effect in 1900. Yarkovsky hypothesized that the diurnal heating of a rotating body would create a force due to the escape of thermal radiation as the sunlit side rotated into darkness and cooled. As the heated surface turns away from the Sun, photons are radiated from the asteroid as it cools. Photons carry momentum off the asteroid and, due to Newton's Law, provide a pushing force. Although the force produced by the photons is extremely small, over a long period of time it can change an asteroid's orbit.

Even though this effect was theorized in 1900, it was not until 2003 that the effect was actually proven. That is when a 500-meter wide asteroid named 6489 Golevka, which astronomers had tracked since 1991, had taken a 15-km detour from its projected orbit. [72] Once proven, the Yarkovsky Effect was suggested as a deflection technique. The concept is to enhance the asteroid's radiation capabilities as a way to increase the force experienced by the asteroid, and then let the force slowly change the asteroid's orbit and reduce the threat.

Although simple in concept, implementation of this method may prove to be difficult. To enhance the effect on the asteroid, the asteroid must be covered with paint or other material. Even if done properly, the resultant force on the asteroid is extremely small and only will be able to produce enough change in momentum to successfully deflect the asteroid after years of operation. As discussed in Section 5.9, orbit perturbation may take many decades to produce a change that guarantees that an object will not strike Earth. It also may take years to measure any effects on the asteroid's orbit. Finally, the Yarkovsky Effect increases as the surface area of the asteroid increases (varies with radius squared), while mass and momentum increase as the mass (and total momentum) increases (varies with radius cubed). Therefore, larger objects are relatively more difficult than smaller objects to divert using this method.

Asteroid deflection using Yarkovsky is developed further in References [73] and [74].

Expected Performance

No calculations were performed to estimate the performance of deflection efforts that utilize the Yarkovsky Effect.

Characterization Required

The Yarkovsky Effect requires a rotating PHO. It also requires changing the PHO's surface so that the surface interacts with solar energy. Over time, the interaction will modify the object's orbit. As a result, designing a deflection mission using this technique would require information on the targeted PHO's spin rate, its mass and size, information about its surface properties (to ensure that mission planners select the correct coating material), the PHO's axis of rotation, and its rotation rate. These quantities would be required before applying the coating. Uncertainties in the rotation rate, for example, might preclude a mission using this technique.

Technology Readiness

Coating concepts — Although chalk has been suggested, it is unclear what coating types would work best in this application and how they would perform in the PHO environment. While engineers have used paint coatings to control thermal properties on spacecraft, their application to this type of mission faces many unknowns. Since no specific designs are presented, this technology area is rated as having a relatively **low level of technology readiness**.

Coating Delivery — The application of a coating on such a large scale has never been attempted before in space. The technologies necessary are largely conceptual. This technology area is rated as having a relatively **low level of technology readiness**.

Overall Technology Readiness and Effectiveness

The Yarkovsky Effect is a very small force created by sunlight acting on the surface of a NEO. Using this force for deflection would require that a method be developed to deliver a coating to the PHO's surface. This technique could be used only when the impact threat is decades or more into the future.

Neither the spacecraft used to apply the coating, or the coating itself, has been described to any level of detail. The effect of this small force will likely depend on the size and rotation rate of the PHO to which it is applied, and uncertainties in the object's size and rotation could considerably extend the required action time. **The overall technology readiness is, therefore, judged to be low**.

In general, the Yarkovsky Effect can work against small- to moderate-size objects, particularly in cases where enough time is available, where there is substantial time to generate a momentum change, and where small ΔVs are required. For this reason, **the overall effectiveness of the Yarkovsky Effect is judged to be low**.

G.2.2. Focused Solar

This concept would use a large, thin-film mirror surface to collect sunlight and focus it on a small spot on the PHO. Heating would vaporize a small amount of material and the material's departure would impart a small ΔV. The reflector spacecraft would not directly contact the PHO; rather it would stand off at a distance from the surface. As a result, its operation would not depend on the rotational motion or shape of the PHO, although rotation will decrease the efficiency of this approach.

This concept requires that the spacecraft rendezvous with the PHO and assume a station at a fixed distance from the object. At this point, the solar reflector would be erected or inflated. Energy would be reflected via a mirror on the spacecraft to a spot on the PHO's surface. The spacecraft must remain precisely positioned near the PHO for as long as the system operates.

Issues related to this technique include the effect of the vaporized material on the energy delivered to the NEO; that is, as dust and other material leave the surface, they potentially could reflect or absorb some of the energy, preventing it from reaching the surface. Potentially, this could require that the spacecraft's reflecting mirror move its focus spot, which would reduce its efficiency because new material then would have to be heated.

Expected Performance

No calculations were performed to estimate the performance of this deflection technique.

Characterization Required

The PHO's mass and surface properties are important for this technique because they define the effectiveness of the energy transfer and the amount of time required to impart a momentum change. Information about the object's rotation rate would help because it would help assure that dust and ejected material did not dissipate the incoming focused beam. No other information is required. Uncertainties in PHO properties would affect the time required to complete the deflection. This technique is unlikely to fragment the target PHO; so no information on density or other properties is required.

Technology Readiness

Large Space Structures — A large reflector system must be erected near the PHO and must maintain its shape and orientation for an extended period. Large structures of this type have not been demonstrated. **This technology area is rated as having a relatively low level of technology readiness**.

Delivery and Proximity Operations, Long Duration Autonomous Operations — This approach requires that the spacecraft be delivered to a precise location relative to the PHO and that it maintain its position for an extended period. Further, the technique requires long-term, autonomous operation of a reasonably sophisticated spacecraft. This technology has not been demonstrated. Therefore, **this technology area is rated as having a relatively medium level of technology readiness**.

Overall Technology Readiness and Effectiveness

Since this system requires a long period of operation, it will require years to assess its effectiveness in changing the target's orbit. Given that the technique requires long-term autonomous operation, it is not clear how one would overcome potentially mission-ending problems. As described earlier, this approach is notional at this point. No space missions have verified critical technologies. **The overall technology readiness for this approach is judged as low.**

However, this approach conceivably could be applied to a large percentage of PHOs. For this reason, **the overall effectiveness of the approach is judged to be medium**.

G.2.3. Gravity Tractor

The concept of a gravity tractor is to impart a momentum change using the force of gravity without coming into contact with the PHO. [75] [76] [17] [77] A gravity tractor would rendezvous with the object and hold a specific position in space adjacent to the PHO for an extended period. The mutual gravitational attraction between the PHO and the gravity tractor would slowly "pull" the asteroid to a different trajectory. Thrusters would be designed so that the exhaust from the station-keeping motors did not impinge on the PHO.

The momentum transfer of a slow push (or pull) technique depends on two important factors: the time over which the thrust is applied and the thrust itself. For this case, the thrust applied to the asteroid is simply the gravitational attraction between two bodies. Using Newton's laws of gravitation, the force applied to the bodies can be calculated as:

$$F = \frac{G\, M_{\mathrm{asteroid}}\, m_{\mathrm{tractor}}}{d^2} \tag{6}$$

where G is the gravitational constant, m_{tractor} is the mass of the tractor, and d is the distance between the two masses. This force is effectively the thrust applied to the asteroid. Inserting the thrust value into the momentum equation yields:

$$\Delta P_c = \frac{G\, M_{\mathrm{asteroid}}\, m_{\mathrm{tractor}}}{d^2} \left(\frac{t_p}{t_s}\right) \left(t_s - \frac{t_p}{2}\right) \tag{7}$$

This equation uses the very important assumption that the engines used by the gravity tractor are oriented so that the exhaust from the engines does not impede the attraction between the two bodies. The engines would be canted outward at an angle determined by the size of the bodies and the standoff distance. [77]

The geometry of the canted engines is given in Figure 72. In this case, r is the mean radius of the asteroid; d is the distance to the tractor; ϕ is the cant angle of the thrusters; m is the mass of the tractor operating with thrust T; M is the mass of the asteroid; and ρ is the mean density of the asteroid.

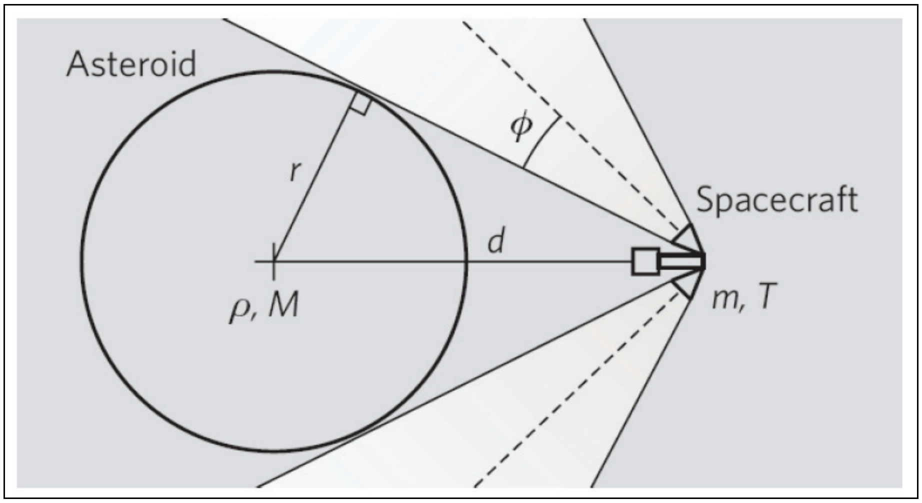


Figure 72. Geometry of the Gravity Tractor Concept

As shown, the effectiveness of the gravity tractor varies inversely with the square of the distance between the tractor and the PHO, and is therefore very sensitive to the distance chosen. While this analysis assumed a standoff distance of 1.5 times the mean asteroid radius, other studies [75] have assumed 0.5 times the radius. If the closer hover distance is feasible, the effectiveness of the gravity tractor would increase by a factor of about nine from that presented in this report.

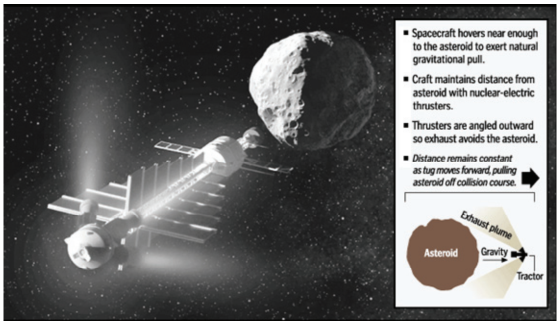
Expected Performance

Calculations were carried out for the hypothetical gravity tractor based on the payload capacities of the Delta IV Heavy and the proposed Ares V. For example, for C3 of 25 km^2/s^2, the the nominal effective momentum changes for the gravity tractor were calculated to be about 5×10^6 kg-m/s and 6×10^7 kg-m/s, respectively.

These calculations suggest that the ΔV potential for the gravity tractor is somewhat higher than for contact chemical explosives, but less than for the kinetic impactor. The calculations estimate the ΔV potential ranges from 10 to 100 cm/s for small PHOs (smaller than 90 meters), to 1 to 10 cm/s for moderately small PHOs (smaller than 200 meters), to 0.1 to 1 cm/s for moderate-size PHOs (smaller than 400-500 meters). This is sufficient to consider the gravity tractor for keyhole encounters, including Apophis's close encounter with Earth in 2029 and perhaps 2400 VD17's potential collision with Earth in 2102, provided the deflection were attempted decades before the projected impact and assuming a decade of action time (or more).

The calculations also suggest that, with few exceptions, the gravity tractor could not be expected to provide sufficient deflections for larger PHOs.

M-24: Gravity Tractor



- Spacecraft hovers near enough to the asteroid to exert natural gravitational pull.
- Craft maintains distance from asteroid with nuclear-electric thrusters.
- Thrusters are angled outward so exhaust avoids the asteroid.
- *Distance remains constant as tug moves forward, pulling asteroid off collision course.*

Technical Description

- Nuclear Electric Propulsion (NEP) based spacecraft, JIMO like
- 12 year design life
- Autonomous rendezvous and dock in orbit
- Scientific payload for NEO characterization and ranging included
- Some scaling on mass and reactor size available

CONOPS

- Imparts a momentum change on the NEO by drawing it closer using mild gravitational effects
- Assumes a 50 year lead time, applicable only for small asteroids
- Launch on two Delta IV Heavy vehicles and assembled in space

System Sizing

Payload Mass (kg)	60
Spacecraft Bus Mass (kg)	5991
Spacecraft Module Dry Mass (kg)	12810
Reactor Module Dry Mass (kg)	3177
Spacecraft Dry Mass (kg)	16047
Spacecraft Wet Mass (kg)	28117
Total Delta-V (m/s)	26000
Payload Power Thrusting (W)	3000
Payload Power Non-thrusting (W)	10000
Reactor Output (kWe)	208

Rational for Consideration

- Non-nuclear option – more politically feasible
- Viable for virtually all asteroid types

Capability

- Provides thrust and propellant capacity for gravity tractor to move NEO from colliding with Earth

Pros

- Effective on virtually all NEO types (e.g. rubble pile, binary, etc.)
- Slow deflection allows for flexible operational concepts

Cons

- Difficult political considerations, can be used to weaponize NEO
- Larger asteroids would require incrementing mass
- Large lead time required to be effective
- High complexity, cost/risk due to in space assembly
- Must maintain close station adjacent to NEO for extended period

Characterization Required

An accurate estimate of the PHO mass is critical for the gravity tractor. NASA would likely use the largest tractor mass possible, and uncertainties in the mass would be reflected in the time the tractor must operate in close proximity to the PHO. Uncertainty in mass could mean that longer deflection times than available would be required, demanding that an alternative deflection approach be used. Rotation rate and shape also are needed for defining the operational environment near the PHO, particularly if the PHO is oblate and its motion requires the tractor to back away, thereby lowering its efficiency. These two parameters also may help estimate the overall efficiency by allowing simulations to determine the net gravitational force between the two objects. Information on the surface type and material properties are not required.

Since the force exerted on the PHO is very small, this technique is unlikely to fragment the PHO. Further, if the PHO has a moon (some do), it is likely that the moon will simply continue its orbit as the tow progresses. Of course, the moon could represent a hazard to the towing spacecraft, and any maneuvers required to avoid the hazard would reduce the overall efficiency of the technique.

Technology Readiness

Control Systems — Terrestrial GEO satellites have demonstrated extended station-keeping operations, though not to the extent needed in this mission. The control systems needed do not seem to exceed the state of the art, however. This technology area is rated as having a relatively **high level of technology readiness**.

Sustained Power — Because electrical propulsion likely would be used, a stable, long-term source of power would be required. Solar photovoltaics could provide the power levels required for the gravity tractor. This technology area is rated as having a relatively **high level of technology readiness**.

Autonomous Operations — While autonomous operations have been performed during several deep space missions, none has attempted to operate so close to another body for such a long period of time. This technology area is rated as having a relatively **medium level of technology readiness**.

Overall Technology Readiness and Effectiveness

The gravity tractor requires a heavy spacecraft to rendezvous with the PHO and to fly autonomously in close proximity to the PHO for an extended period. The object's shape and rotation could affect the tractor's effectiveness to the extent that the tractor must adjust its height above the PHO as the PHO surface rotates. In addition, a small force imparted to the PHO by the tractor's stationkeeping thrusters could nullify some of the gravitational attraction.

The thruster and thruster control systems must operate while the tractor is interacting with the object and the tractor must carry a power supply capable of powering thrusters and onboard systems for extended periods. The small force imparted by the tractor would mean that a period of accurate tracking would be required before scientists could verify the technique's effectiveness.

Considering these factors, **the overall technology readiness of the gravity tractor concept is judged to be medium**. The gravity tractor is assessed to be effective in cases where a small total momentum change is required, such as for relatively small PHOs, where the time before Earth encounter is large enough to accommodate for uncertainties in the PHO mass. It also could be effective for instances involving a keyhole (see Section 5.2.3). The recent example of a well-publicized asteroid impact scenario that involves a keyhole — asteroid Apophis or 2004 MN4 — appears to be the exception rather than the general rule. [17] Keyhole scenarios with long lead times and small deflection distances have been described as "extremely rare," or far less than 1% of the total possible impacts. [16] Because the percentage of PHOs that present keyhole opportunities is unknown, the **overall effectiveness of the gravity tractor is tentatively judged to be medium**.

G.2.4. Mass Driver

A mass driver, simply stated, is a pitching machine; in other words, it mines material from the asteroid and expels it at a high velocity, producing thrust. [78] [79] [80] [81] [82] The mission would require that a spacecraft rendezvous with the object and land a vehicle on the surface. The vehicle would attach a mining device to the surface and begin ejecting the mined material over a period of time. The attachment, mining, and expulsion activities would be autonomous. The device must have a power supply capable of sustained operation on the asteroid's surface.

Expected Performance

No calculations were performed to estimate the performance of deflection efforts that use this technique.

Characterization Required

The mass of the asteroid is critical for determining the size of the mining operation and the length of time needed to achieve the desired momentum transfer. The rotation rate is another critical item. The mass driver would only work when it can expel the mass in the correct direction. The types of material the mining operation would encounter and details of the asteroid's internal structure (a hard, dense material may require different tools than would a light, porous material) also should be known.

Technology Readiness

Mass Driver — The mass driver concept is relatively simple, but the technology is currently not well defined, particularly for space operation. Rails guns developed for Earth-based applications suffer from energy storage, material fatigue, relatively low muzzle velocities, and reliability issues. This technology area is rated as having a relatively **low level of technology readiness**.

NEO Attachment and Mining — This concept requires attachment and an ongoing mining operation. Furthermore, the acceleration system must be able to dispose of the mined material. While many such concepts have been proposed, none has been built or tested. [83] This technology area is rated as having a relatively **low level of technology readiness.**

Autonomous Operations — The mass driver requires extensive, long-term autonomous operation of a complex system. Such operations have not been demonstrated. This technology area is rated as having a relatively **low level of technology readiness**.

Overall Technology Readiness and Effectiveness

The mass driver has the advantage that, once it is affixed to an asteroid's surface, it can continue to operate until the requisite ΔV has been imparted. This assumes, of course, that the system carries a suitable power supply (possibly a nuclear reactor). Problems include a reduction in efficiency because of the object's rotation, the requirement for an onboard sensor system to determine the orientation of the PHO to assure the momentum is transferred in the correct direction, the attachment system, issues with the surface materials and internal structure, the possibility that large quantities of dust may be generated and affect the solar panels (should they be used), equipment and sensors, and the long period required for operation. Accordingly, **the overall technology readiness of the mass driver technique is judged to be low**.

The mass driver may also have limited applicability. For example, it would be more difficult to attach and operate mass driver systems on small PHOs, where the gravitational attraction is smaller. Accordingly, **the overall effectiveness for the mass driver technique is judged to be medium**.

G.2.5. Pulsed Laser

A sufficiently powered ground-based laser currently does not exist. A variation of this concept would be to house the laser in a spacecraft stationed near the PHO. It would use large solar panels to capture solar energy (or draw power from a nuclear reactor) needed to drive a high-power laser. [84] The laser beam would be directed at a spot on the asteroid. Vaporization of the surface material would produce a small force on the asteroid.

An advantage of this technique is that it imparts a small force and is unlikely to fragment the body. In addition, the laser beam can be directed to multiple spots, which is important if surface dust at a particular location degrades the transfer of energy.

As recently as 1998, the U.S. Air Force unsuccessfully attempted to demonstrate the concept using space-based lasers smaller than the one required for this concept. Current estimates are that the spacecraft would weigh about 200 metric tons. [85]

Expected Performance

No calculations were performed to estimate the performance of the pulsed-laser technique.

Characterization Required

The PHO's mass and type (asteroid as compared with comet) and the time before it strikes Earth define the size of the laser required for this mission. Since the method might be more effective against icy comets than asteroids (the effectiveness might be amplified by the creation of steam), [57] information about surface material would help estimate time of operation and overall effectiveness.

Technology Readiness

Laser Technology and Surface Interactions — Development of the solar-powered, pulsed laser is in its infancy. This technology area is rated as having a relatively **low level of technology readiness**.

Long-Term Autonomous Operations — As with other deflection concepts requiring extended periods of autonomous operation, such a capability has not been demonstrated. This technology area is rated as having a relatively **medium level of technology readiness**.

Sustained Power — Solar panels or nuclear power might power a laser system. If solar photovoltaics were used, this technology area has a relatively **high level of technology readiness**.

Overall Development Risk and Effectiveness

This concept requires substantial technology development and systems integration. **The concept's overall technology readiness is judged to be low**.

However, this approach could conceivably be applied to a large percentage of PHOs. **For this reason, the overall effectiveness of the approach is judged to be medium**.

G.2.6. Space Tug

Slow push techniques maintain better control over the asteroid as they apply a change in velocity. The asteroid tug is a vehicle that would dock with a PHO and push the object in the desired direction.

In this case, characterization is very important. In particular, the asteroid's center of mass defines a line along which the thrust vector must be applied to avoid adding rotational acceleration and reducing the system's overall efficiency. And if the asteroid is rotating, the period when the thrust can be applied in the desired direction will be reduced, minimizing the technique's efficiency, as seen in Figure 73. As illustrated, the thrust acts only when the orientation of the tug assures the thrust will impart momentum in the correct direction.

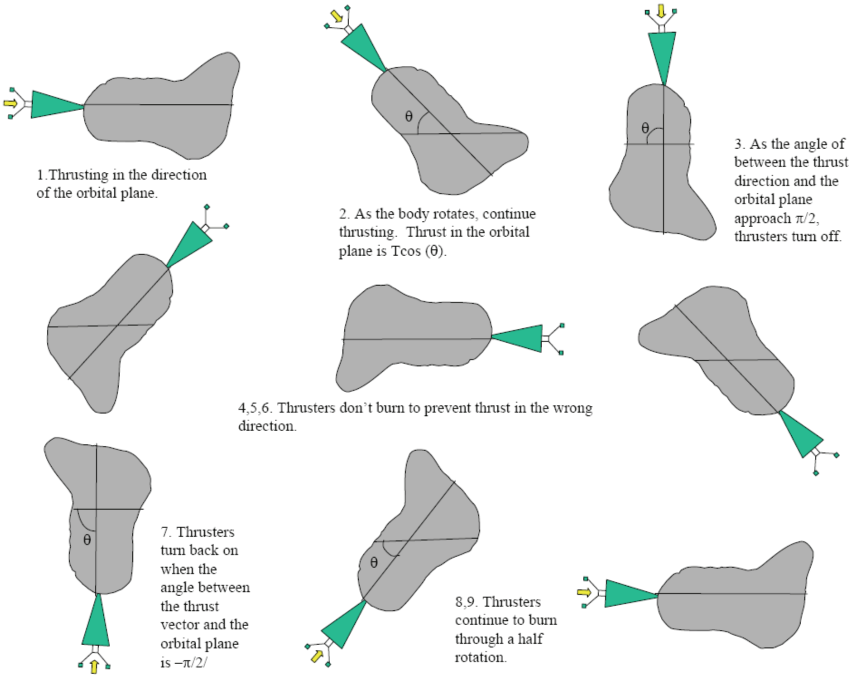


Figure 73. Illustration of Space Tug acting on a PHO

For example, assuming the worst possible scenario where the angle between the axis of rotation and the orbital plane is 90 degrees, and using the momentum equation derived from Izzo's distance equation [86]:

$$\Delta P = T(\frac{t_p}{t_s})(t_s - \frac{t_p}{2}) \qquad (8)$$

Where:

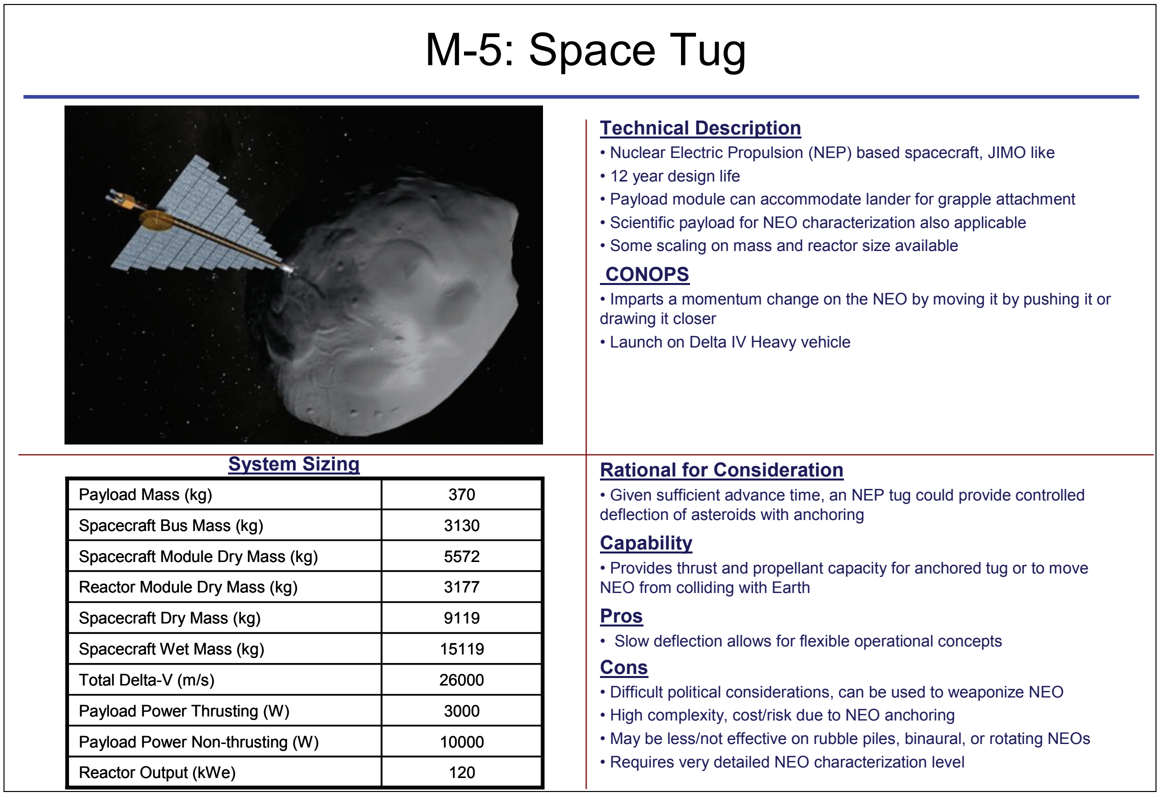
T is the thrust of the propulsion system, t_p is the pushing time and t_s is the time before impact, an equation for a rotating asteroid can be found. If the thrusters fire for half of the rotation along the orbital plane, the thrust efficiency can be calculated by:

$$\beta = \frac{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \mathrm{T}\cos\theta \,\mathrm{d}\theta}{\mathrm{T}(2\pi)} = \frac{1}{\pi} \tag{9}$$

Propulsion options for these systems include purely chemical systems (not generally feasible because of the large quantities of propellant and oxidizer that must be transported to the NEO), nuclear thermal propulsion (more efficient with lower propellant requirements, but not tested in space), and lower-thrust, electric-propulsion systems. Two of these systems were used for this analysis: the NSTAR solar-electric system using three and six thrusters and the NEXIS nuclear-electric system using five and 10 thrusters.

The NSTAR thrusters are rated to produce 91 mN of thrust per thruster [87]. Placing a combination of thrusters on the vehicle could increase the thrust level. The NEXIS thrusters use electricity from a nuclear reactor to produce more thrust, roughly 473 mN per thruster. [88] Using many thrusters, the asteroid tug could produce more thrust and, as a result, more change in momentum. Using these values for the propulsion systems, the calculation seen in Equation (9) can be used to find the change in momentum. However, if the body is rotating, the thrust efficiency becomes a factor and the equation becomes:

$$\Delta \mathrm{P}_{\mathrm{rot}} = \frac{\mathrm{T}}{\pi}\left(\frac{\mathrm{t_p}}{\mathrm{t_s}}\right)\left(\mathrm{t_s} - \frac{\mathrm{t_p}}{2}\right) \tag{10}$$



M-5: Space Tug

Technical Description
- Nuclear Electric Propulsion (NEP) based spacecraft, JIMO like
- 12 year design life
- Payload module can accommodate lander for grapple attachment
- Scientific payload for NEO characterization also applicable
- Some scaling on mass and reactor size available

CONOPS
- Imparts a momentum change on the NEO by moving it by pushing it or drawing it closer
- Launch on Delta IV Heavy vehicle

System Sizing

Payload Mass (kg)	370
Spacecraft Bus Mass (kg)	3130
Spacecraft Module Dry Mass (kg)	5572
Reactor Module Dry Mass (kg)	3177
Spacecraft Dry Mass (kg)	9119
Spacecraft Wet Mass (kg)	15119
Total Delta-V (m/s)	26000
Payload Power Thrusting (W)	3000
Payload Power Non-thrusting (W)	10000
Reactor Output (kWe)	120

Rational for Consideration
- Given sufficient advance time, an NEP tug could provide controlled deflection of asteroids with anchoring

Capability
- Provides thrust and propellant capacity for anchored tug or to move NEO from colliding with Earth

Pros
- Slow deflection allows for flexible operational concepts

Cons
- Difficult political considerations, can be used to weaponize NEO
- High complexity, cost/risk due to NEO anchoring
- May be less/not effective on rubble piles, binaural, or rotating NEOs
- Requires very detailed NEO characterization level

Expected Performance

Calculations were carried out on the space tug. The team based the calculations on payload capacities of the Delta IV Heavy and the proposed Ares V. The team also looked at various rotational rates of potentially hazardous objects. To deflect non-rotating PHOs, for example, C3 of 25 km^2/s^2, the nominal effective momentum changes for the space tug, were calculated to be about 4 x 10^7 kg-m/s and 6 x 10^8 kg-m/s, respectively.

These calculations suggest that the ΔV potential of the space tug is somewhat greater than that of the gravity tractor, and in the range that might be accomplished using various kinetic impactors. For non-rotating PHOs, the space tug could be expected to provide ΔVs ranging from 10 to 100 cm/s for moderately small PHOs (smaller than 200 meters), to 0.1 to 1 cm/s for moderately large PHOs (smaller than about 900 meters), given sufficient lead times (in some cases, decades to a century in advance). The calculations also suggest that, with few exceptions, the space tug could not sufficiently deflect larger PHOs.

Characterization Required

The space tug's effectiveness greatly depends on the asteroid's characteristics. It is very important for mission designers to know the target object's mass and rate of rotation so that they can better define the action time and propulsive capabilities. They also should know surface characteristics since the device must attach to the surface. Orientation of the axis of rotation also is important because the tug can function only when oriented in the proper direction. The shape and location of the center of mass will affect the design and determine the overall effectiveness of the docking mechanisms and thrusting systems.

Technology Readiness

Attachment Systems —- The docking mechanism is simply a concept. It has not been built, let alone proven in space. This technology area is rated as having a relatively **low level of technology readiness**.

Long-Term Autonomous Operations — No one has verified the ability to operate major components of a space tug system for extended periods. This technology area is rated as a relatively **medium level of technology readiness**.

Sustained Power — Power systems used in electric thrusters have flown and operated in space for long periods, but applying this technology to PHO deflection might require pulsed operation, particularly if the PHO is rotating. This would add complexity to an already-unproven and untested operational scenario. In addition, a nuclear thermal reactor propulsion system might be worth considering for this application because these systems could potentially provide very high thrust levels, which would sharply reduce mission time. This technology area is rated as having a relatively **medium level of technology readiness**.

Overall Technology Readiness and Effectiveness

Small thrusters, while very efficient, are required to operate for extended periods. In many cases, the power delivered over time will be reduced by the rotation of the PHO. Furthermore, the line of action of the thrust must be through the center of gravity to avoid an unwanted rotational component to the energy delivered. Should the tug fail, a back-up deflection system must be developed and launched. More important, it must work. Once the tug has been developed, it may prove to be a very effective alternative for moving PHOs, but given its current state of development, **its overall technology readiness is judged as low.**

Despite this, the tug could in principle be used to deflect a high percentage of PHOs. For this reason, **its overall effectiveness is judged to be medium**.

Appendix H. Analysis Methodologies

H.1. Analysis of Alternatives Methodology

The analysis team started with selected concepts from the study working groups. The concepts were a subset of the overall concepts explored by the working groups. They were selected to address advanced space- and ground-based systems, systems that exist today, and those planned for the future. The analysis team, in coordination with the working groups, suggested additional concepts for evaluation to fully explore the trade space. The working groups endorsed all concepts that the analysis team evaluated as part of the Analysis of Alternatives (AoA).

Initially, trade trees were constructed and concepts were grouped. Duplication was removed. In areas where the concepts could be grouped by similarity, one example was selected to represent the group.

The analysis team then performed a first-order mass and power sizing on each concept, including spacecraft bus and instrument(s). The team also developed operational concepts and mission timelines. Details for existing and planned ground-based telescopes and radars were gathered and used to further define the concepts. System sizing tools, based on data from actual ground- and space-based systems, were developed to parametrically determine the mass and power of each space-based concept.

The concept definition process included a review by the NASA working groups to ensure that concepts were correctly interpreted and that assumptions used in developing the concept design detail were consistent with the intent of the NASA working groups.

In parallel, the analysis team developed the figure of merit (FOM) methodology to evaluate each of the concepts. This methodology included the approach; modeling and tools to determine life-cycle costs, nominal development time, mission risks; and qualitative and quantitative performance metrics for the detection, characterization, and deflection systems.

Additional studies to explore issues associated with characterization and deflection missions were conducted. These provided additional contextual information on the overall feasibility of executing these missions, particularly in terms of required ΔV, launch capabilities, and launch and arrival timing. The analysis team also examined the precision tracking problem. It assessed the quality of orbit-determination capabilities for representative PHOs.

Each concept was evaluated against cost, development time, development risk, mission risk, and the relevant performance FOMs. Concepts were then combined into architectures, and the overall funding profiles were developed for these architectures. The architectures selected consisted of sets of assets that would be used to support survey, characterization, and deflection programs. They represented a range in costs and capabilities.

Evaluation results of the individual concepts, program architectures, and end-to-end architectures were compiled. The performance of potential survey systems and tracking capabilities were integrated into the results. This was done to develop cost-benefit and overall effectiveness assessments. Analysis team results, including the detailed descriptions of the concepts, figure of merit methodology, and results were documented and integrated into the final study report.

H.2. Survey Performance Analysis

H.2.1. Performance Simulations

Performance simulations for a number of candidate ground-based and space-based PHO detection systems were conducted at JPL by Steve Chesley and Paul Chodas. The detection capabilities of the systems were tested using a set of 1000 test PHOs from the Bottke et al. population. [4] The positions of each PHO on the plane-of-sky of each detector system were simulated daily from the assumed operational start date of the system through the year 2030. The PHO was a candidate for detection on a given day by a given system if it fell within the search region for that system for that day, and if it was sufficiently bright to be detected. To study the dependence of magnitude on object size, each PHO was replicated into 25 different size bins, from 32 meters to 10 km in size, and the magnitude predicted for each assumed size. One component of the magnitude calculation was the geometry, the distances of the object from the Earth and Sun and the phase angle, but another important component was the assumption used for the object's albedo (reflectivity).

The PHO population was divided into two equal groups – one with a darker albedo of 7% and the other with a brighter 23% albedo. This bimodal albedo distribution is thought to be representative of the actual PHO population. Another correction applied to the magnitude calculation was due to an object's motion during the sensor integration time, producing a small trail on the detector rather than a single spot of light. The predicted magnitude was corrected for these so-called trailing losses by using a reduction proportional to the square root of the trail length. Also, for ground-based systems, an air mass correction was made to account for the loss in sensitivity as the detector looks through the increasingly large air mass when looking away from the zenith.

Each simulated PHO was considered to be *detected* if it fell within the region covered by a simulated sky scan, and if it was brighter than the system's limiting magnitude. The object was not considered to be *discovered* until it had been detected on two separate nights within a one week period and then a third time within 40 days. Simulations are carried out under the assumption that all survey alternatives will do their own follow up observations as part of their operational cadences due to the large aperture needed to detect the fainter PHOs.

Additionally, a magnitude correction was calculated for solar phase angle. Spacecraft in Venus like orbits preferentially view the PHOs near perihelion and full phase. Ground-based systems see PHOs and IEOs in particular at large phase angles which significantly reduced their apparent magnitude. Consequently, the same IEO would appear 1-2 magnitudes brighter as seen from a Venus-like orbit compared to a ground-based telescope.

Simulation of Ground-Based Systems

The ground-based detection systems were simulated by following a monthly pattern. For a period of time around each new moon, the system's search region was assumed to be completely scanned three to four times. The limits of the search region varied slightly from system to system. In addition, in all but one case, the search region was limited by specifying two limiting air-masses, one to be used within 10 degrees of the ecliptic, and the other to be used away from the ecliptic. Typically, these limits were set at 2.5 and 2.0 air masses, respectively, corresponding to elevation limits of about 23.5 and 30 degrees, respectively.

The time required to complete a full scan of the search region also varied from system to system, depending on such system parameters as the exposure time, field of view, and percentage of time allocated to PHO observations (i.e., whether the system was shared with non-PHO observations or was operated in a 100% dedicated mode). This cycle time varied from 4 to 6 days. No attempt to avoid the galactic plane was made. To account for losses due to poor weather and moonlight, only a portion of the available nights each month were assumed productive. For the shared systems, only 12 to 15 nights per month were assumed productive for PHO searches, while for the dedicated systems, 18 to 20 nights were assumed productive.

Large Aperture Synoptic Survey Telescope (LSST) - Two versions of the LSST were simulated, a shared system and a dedicated system. In shared mode the telescope would not be dedicated to PHO observations, with only 75% of the observing time assumed available for PHO observations, and the telescope would operate at a somewhat reduced sensitivity to obtain color data. In this mode, the limiting magnitude would be 24.8 and the search region would be more restricted (the off-ecliptic air-mass limit was set to 1.5, corresponding to an elevation of 42 degrees), and only 3 scan cycles were assumed to be available each month with each cycle requiring 5 days.

To simulate the Dedicated LSST, the limiting magnitude was increased to 25.4, the search region was increased by increasing the off-ecliptic air mass limit to 2.0 air masses (elevation of 30 deg), and the number of scan cycles was increased to 4 per month. The assumed operational start dates for the shared and Dedicated LSST are 2014 and 2016 respectively.

PanSTARRS 4 telescope array (PS4) – For PS4, four collocated 1.8 meter aperture telescopes provide a 7 degree field of view, and it is assumed that a planned active seeing correction system will be capable of observing down to an air mass of 2.0 (2.5 near the ecliptic plane). Two versions of PS4 were simulated: shared and dedicated each with an assumed limiting magnitude of 24.0. When operated as a shared asset, only 30% of the time would be available for PHO observations, and it would not be possible to scan the entire available sky. To simulate this mode, the search region was reduced to a large box around the opposition point and two smaller boxes around the two quadrature points. The scan cycle was assumed to require 4 days, with 3 scan cycles fit into each lunation.

To simulate a dedicated PS4 system, the search region was expanded to the entire sky down to an air mass limit of 2.0 (elevation of 30 deg), along with the usual near-ecliptic limit of 2.5 air masses. In this mode, the scan cycle would lengthen to 6 days. The assumed operational start dates for the shared and dedicated PS4 systems are 2010 and 2013 respectively.

PS8 - The PS8 system consists of two geographically collocated PS4 systems. The two telescopes were assumed to operate in conjunction with one another, so that a fainter limiting magnitude of 24.4 could be attained with the same exposure times as used by PS4.

PS16 - The PS16 system was simulated by replicating two PS8 systems, one each in the northern and southern hemispheres. Each operated independently so the limiting magnitude was the same as the PS8 system (24.4). Both the PS8 and PS16 systems are assumed to begin operations in 2014.

Simulation of Space-Based Systems

Both visible and near infrared wavelength space-based systems were considered, located either at the first Lagrange point, L1 (323,000 km sunward from Earth on a line between the Sun and Earth), or in a Venus-like orbit about the Sun. Each space-based system was assumed to follow a daily 23-hour duty cycle; with the remaining hour being used to transmit the day's data to an Earth based receiving station. No attempt to avoid the galactic plane was made. The operational start dates for the space-based systems are 2013 for the 0.5 m IR telescope at L1 and 2014 for all other space-based IR and visual telescopes, except for the 2.0m visual system in LEO or at L1.

Visible Space-Based System - A 2 meter aperture telescope, located at L1 or in a Venus-like orbit, was considered.

Infrared (IR) Space-Based System - Because of the greater reflected solar flux in the IR band pass, smaller apertures were used, and apertures of both 0.5 and 1.0 meters were simulated. The zodiacal light background confusion was considered separately for the IR systems at both the L1 and Venus orbit locations.

H.2.2. Survey Performance Simulation Verification

To verify the current JPL detection performance simulations, several test cases were run against similar cases carried out in 2003 for the SDT report [2] using independent software (i.e., FROSST) provided by the MIT's Lincoln Laboratory. For these verification runs, a single albedo of 14% was assumed and for the cases that are of the highest interest, the differences between the JPL and Lincoln Lab simulation results were within 2%of one another, thus verifying the current simulation software. Results may be considered valid to within 2-5% of expected results.

H.3. Deflection Analysis Methodology

H.3.1. The Asteroid Deflection Formula

The momentum change required to deflect a PHO can be estimated based on an analysis discussed in Reference [86]. The quantities discussed in this analysis are shown in Figure 74. This analysis approximates PHO deflection performance by assuming that the given deflection produces a relatively small perturbation in the PHO orbit characteristics. This assumption was evaluated in Reference [89] using the JPL PHO database [71] and found to agree with accurate numerical simulations of deflections. In this formulation, the minimum distance by which the PHO would miss the earth is given by:

$$d_{\min} = \frac{3\,a\,\gamma\,v_e}{\mu}\int_0^{t_p}(t_s - t)\,\overrightarrow{v_n}\cdot\vec{A}\,dt \tag{11}$$

Where:

a is the target object orbit semimajor axis
γ is a non-dimensional parameter that describes the encounter geometry
v_e is the Earth's velocity at encounter
t_s is the time before impact when the deflection is started
t_p is the time to complete the deflection
μ is the gravitational constant of the Sun
v_n is a vector representing the unperturbed velocity of the PHO
A is the action (acceleration) applied to the PHO

The quantity, γ, is determined from the following equations:

$$\gamma = \sqrt{v_n^2\varphi^2 + (1+v_e)^2 - 2v_n\varphi(1+\varphi v_e)\cos\alpha} \tag{12}$$

$$\varphi = \frac{v_n\cos\alpha - v_e}{v_n^2 + v_e^2 - 2v_n v_e\cos\alpha} \tag{13}$$

The encounter geometry between the PHO and the Earth is illustrated in Figure 74. The quantity γ becomes small when the relative velocity between the PHO and Earth is large and the angle α is small.

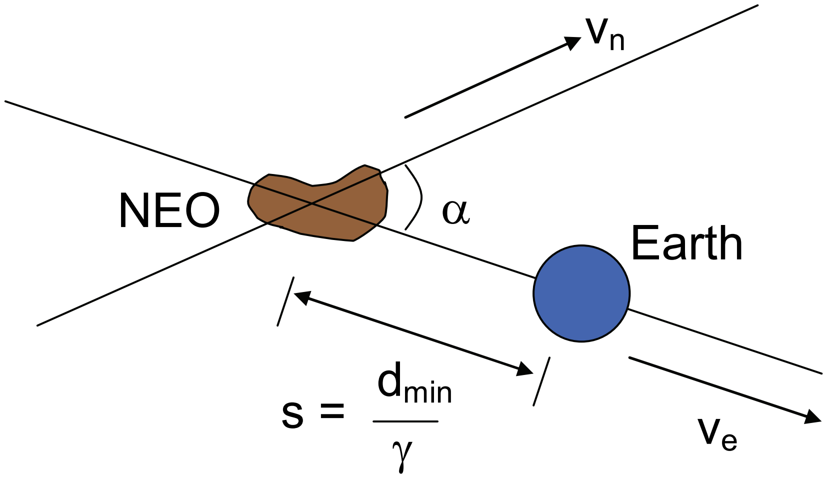


Figure 74. PHO/Earth Encounter Geometry

When a PHO deflection is carried out impulsively, either through kinetic energy impact or explosive energy transfer, equation (1) may be simplified to the following form for low eccentricity orbits.

$$d_{\min} = C_n \frac{\Delta p t_s}{m_n} \tag{14}$$

$$\Delta p = m_n \Delta v \tag{15}$$

H.3.2. Effective Momentum Change

The miss distance equation for slow push methods is calculated as

$$\mathrm{d}_{\min} = \frac{3\, \mathrm{a}\, \gamma\, \mathrm{v}_{\mathrm{e}}}{\mu} \int_0^{\mathrm{t_p}} (\mathrm{t_s} - \mathrm{t})\, \vec{\mathrm{v}} \cdot \frac{\overrightarrow{\mathrm{T(t)}}}{\mathrm{M_n}}\, \mathrm{dt} \tag{16}$$

Where:

T(t) is the thrust vector as a function of time
M_n is the mass of the asteroid

Assuming that the thrust is directed optimally along the unperturbed velocity vector, thrust is constant, and the eccentricity of the orbit is small; the integral can be solved to produce:

$$\mathrm{d}_{\min} = C_{\mathrm{n}} \frac{\mathrm{Tt_p}\left(1 - \frac{t_p}{2t_s}\right) t_s}{m_n} \tag{17}$$

To compare impulsive and slow push deflection concepts that are started at the same time relative to the Earth impact date, the action which creates an equivalent minimum miss distance, $d_{\min}$ is evaluated. With all other quantities being equal, the effective momentum change imparted by a slow push deflection technique is:

$$\Delta p_{eff} = Tt_p\left(1 - \frac{t_p}{2t_s}\right) \tag{18}$$

This equation shows that while the effective momentum change grows with action time, the momentum effect diminishes as the action time becomes significant with respect to the time to impact.

H.4. Technology Readiness Assessment of Deflection Alternatives

Table 47 summarizes the readiness of the primary technology areas that apply to impulsive techniques. Table 48 summarizes the readiness of the primary technology areas that apply to the slow push techniques. The rationale for these ratings is described in greater detail in Appendix G.

Table 47. Readiness for Technology Areas for Impulsive Techniques

	Subsystem Technology Readiness			Overall
Conventional Explosive (contact)	🟩 Explosive Devices	🟩 Delivery Systems Targeting	🟨 Fusing	🟩 **High**
Conventional Explosive (subsurface)	🟩 Explosive Devices	🟥 Delivery Systems Implantation	🟨 Fusing	🟨 **Medium**
Kinetic Impact	▨	🟩 Delivery Systems Targeting	▨	🟩 **High**
Nuclear Explosive (contact)	🟩 Explosive Devices	🟩 Delivery Systems Targeting	🟩 Fusing	🟩 **High**
Nuclear Explosive (standoff)	🟩 Explosive Devices	🟩 Delivery Systems Targeting	🟩 Fusing	🟩 **High**
Nuclear Explosive (subsurface)	🟩 Explosive Devices	🟥 Delivery Systems Implantation	🟩 Fusing	🟨 **Medium**
Nuclear Explosive (surface delayed)	🟩 Explosive Devices	🟨 Delivery Systems Attachment	🟩 Fusing	🟨 **Medium**

Table 48. Readiness for Technology Areas for for Slow Push Techniques

	Critical Technology Areas			Overall
Enhanced Yarkovsky	🟥 Coating concepts	🟥 Coating delivery	▨	🟥 **Low**
Focused Solar	🟥 Large Space Structures	🟨 Delivery and Proximity Operations	▨	🟥 **Low**
Gravity Tractor	🟩 Control Systems	🟩 Sustained Power	🟨 Autonomous Operations	🟨 **Medium**
Mass Driver	🟥 Mass Driver	🟥 Attachments & Mining	🟥 Autonomous Operations	🟥 **Low**
Pulsed Laser	🟥 Laser and Surface	🟨 Sustained Power	🟨 Long Term Operations	🟥 **Low**
Space Tug	🟨 Sustained Power	🟥 Attachment Systems	🟨 Autonomous Operations	🟥 **Low**

Appendix I. Additional Survey Performance Results

Figure 89 through Figure 93 display the percentage of completeness for each year ending in 90% completeness. The following performance architectures are shown as examples:

- Figure 75. Buildup of Baseline – Existing + Shared PS4 + Shared LSST
- Figure 76. Buildup of Baseline + Dedicated PS8
- Figure 77. Buildup of Baseline + Dedicated LSST
- Figure 78. Buildup of Baseline + 0.5m IR @ L1
- Figure 79. Buildup of Baseline + 0.5m IR @ Venus

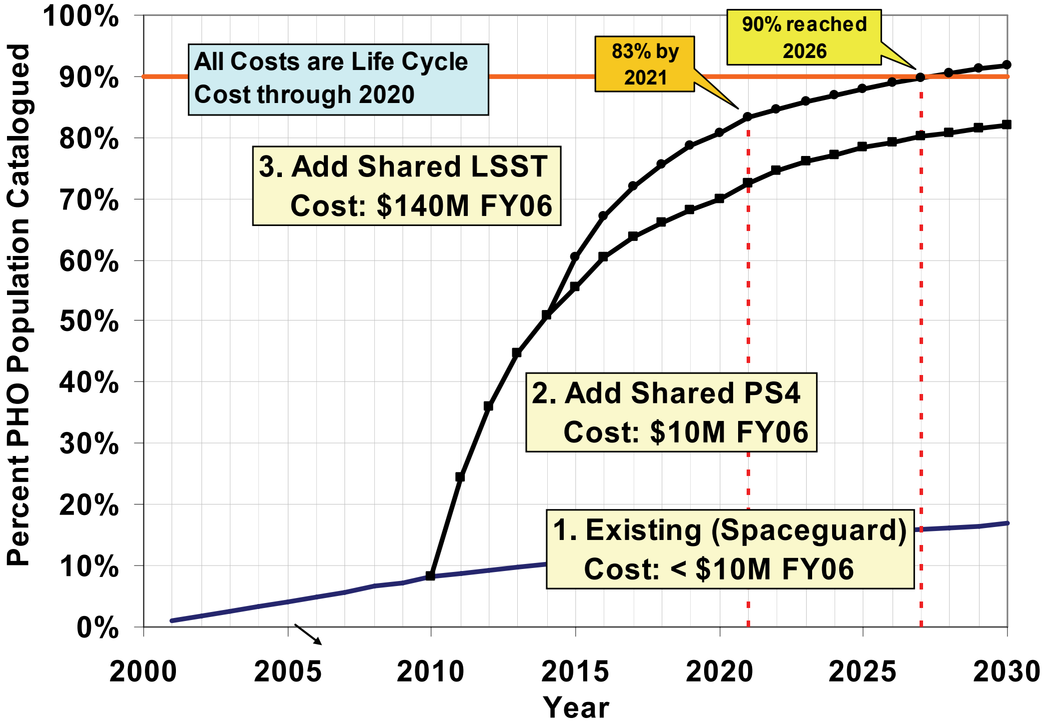


Figure 75. Buildup of Baseline – Existing + Shared PS4 + Shared LSST

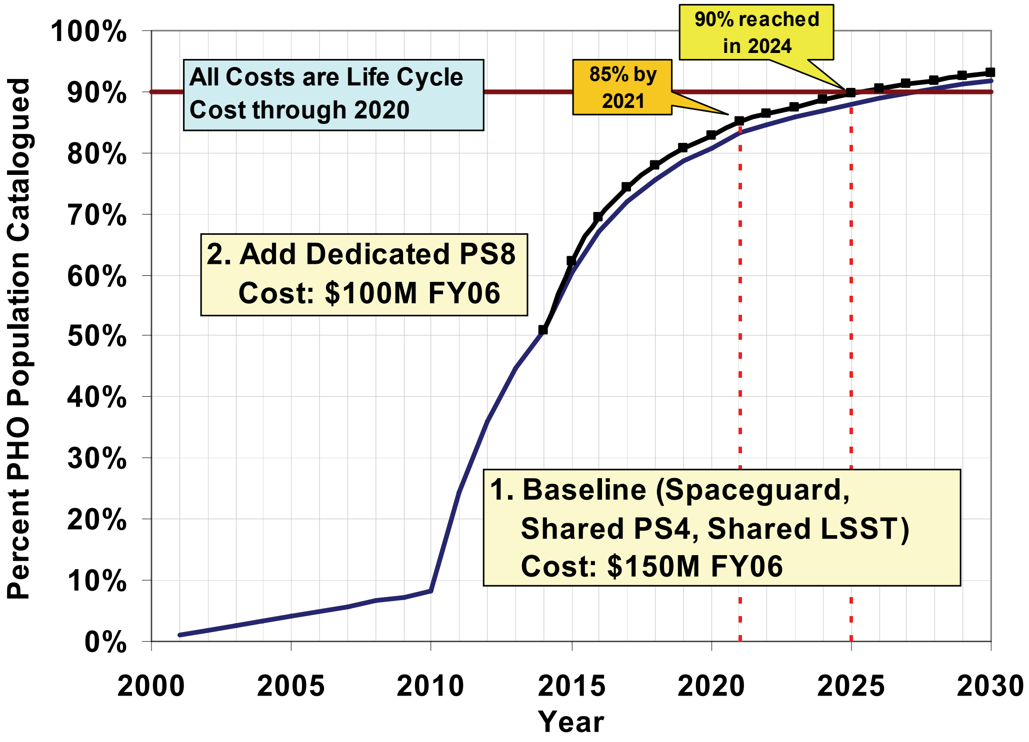


Figure 76. Buildup of Baseline + Dedicated PS8

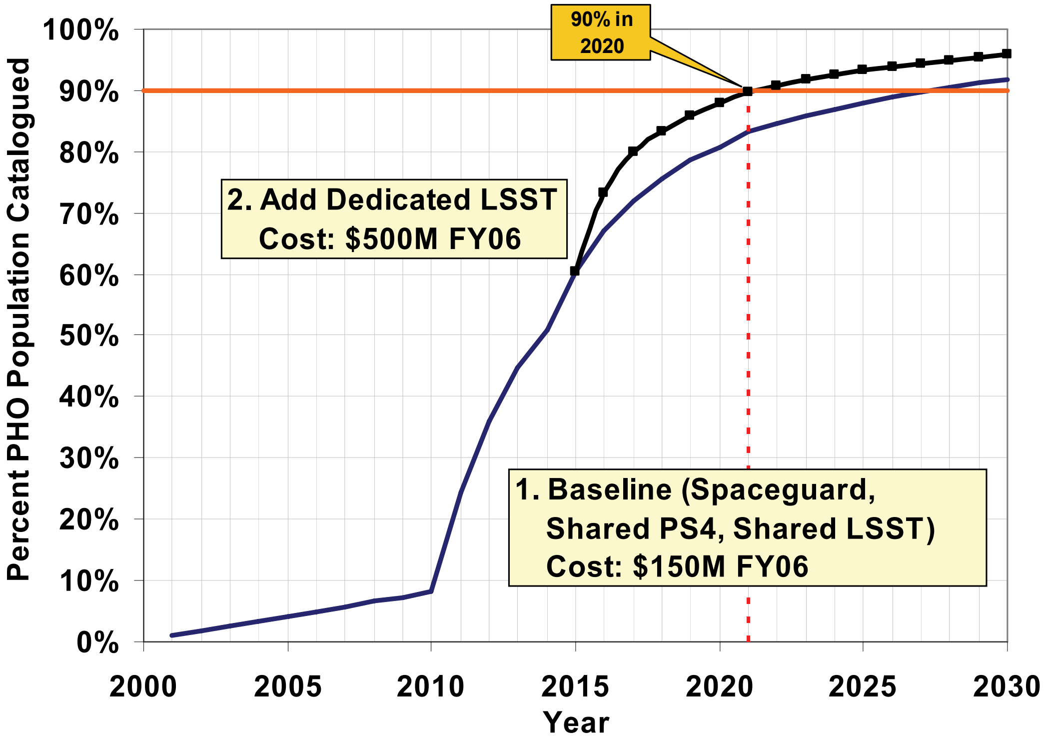


Figure 77. Buildup of Baseline + Dedicated LSST

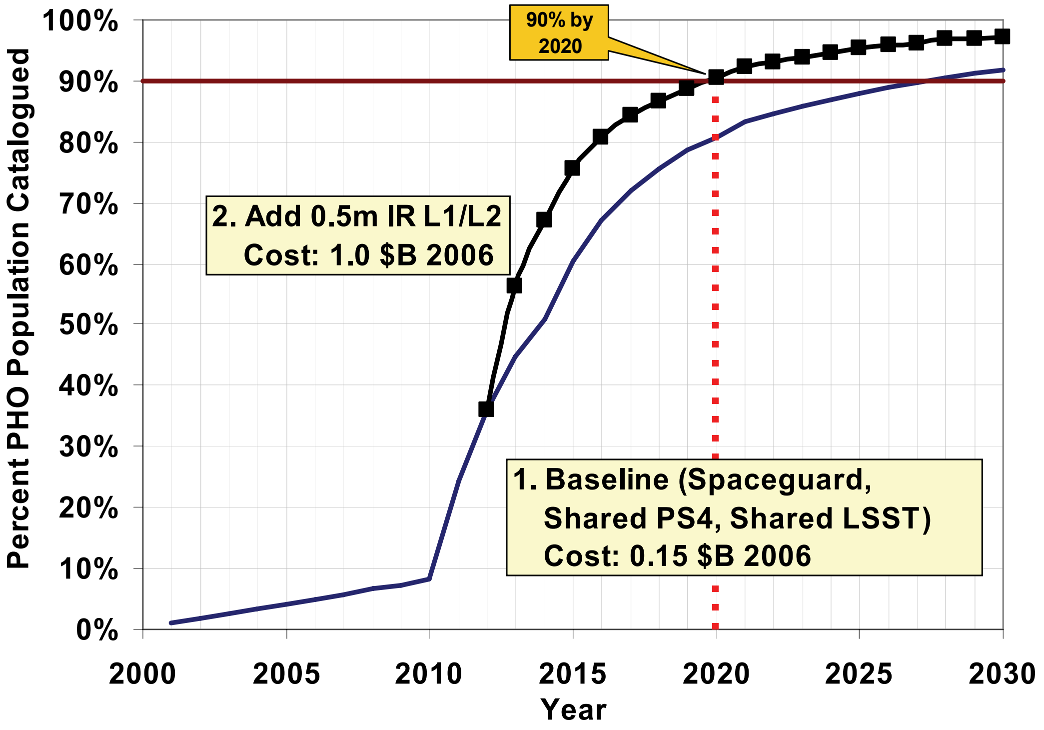


Figure 78. Buildup of Baseline + 0.5m IR @ L1

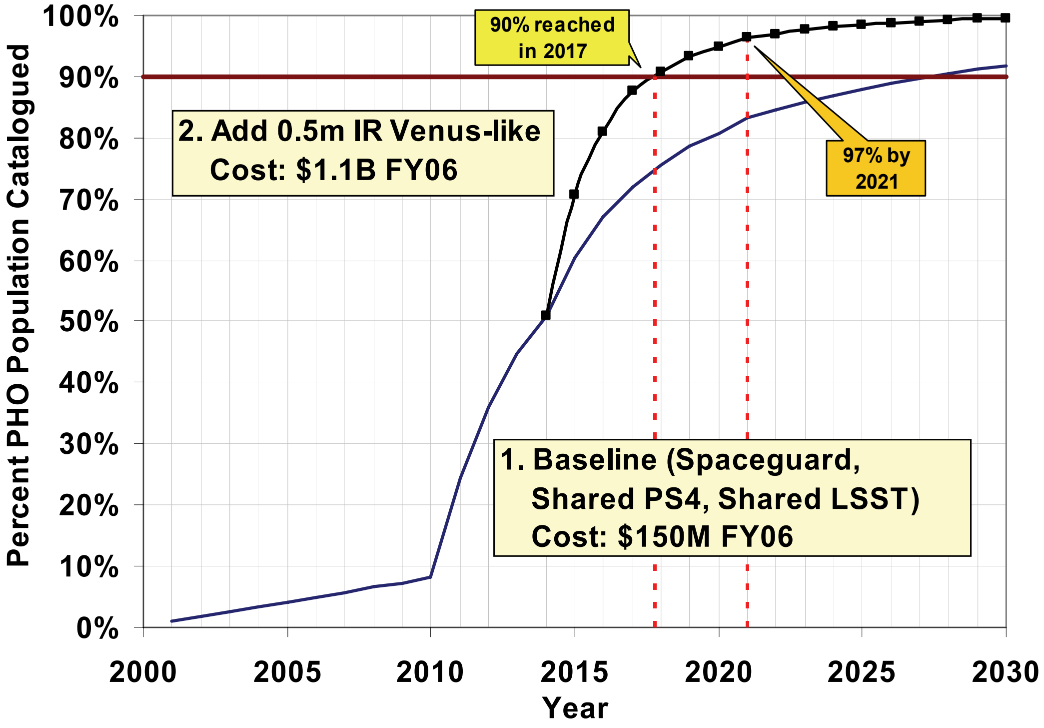


Figure 79. Buildup of Baseline + 0.5m IR @ Venus

Appendix J. Current Assets and Activities

J.1. International Activities

J.1.1. United Nations

In its 1999 UNISPACE III conference, the standing United Nation's Committee on the Peaceful Uses of Outer Space (UNCOPUOS), recommended that NEOs be a topic of future consideration. Since then, the UNCOPUOS Scientific and Technical Subcommittee (STSC) has included NEO on its agenda and has established an Action Team of interested member states to make recommendations to the STSC and the full Committee.

The STSC currently is involved in a 3-year work plan (2005-2007) that essentially allows member states to report on national NEO activities and facilitates presentations at the STSC by interested international organizations and non-governmental organizations (NGOs). To date, no specific proposals have been made by UNCOPUOS member states, but various NGOs have made proposals during presentations to UNCOPUOS.

In 2007, the STSC Action Team may recommend that a standing STSC Working Group be established to address a full slate of NEO issues, including threat deflection and international decision making. The U.S. is an active participant in UNCOPUOS and the STSC.

J.1.2. European Space Agency (ESA)

In July 2004, ESA established and international panel, the Near-Earth Object Mission Advisory Panel (NEOMAP), to recommend next steps in the area of NEO investigation and research. NEOMAP produced a set of recommendations for observatory and rendezvous missions from an international context.

Flowing from NEOMAP, ESA has established the Don Quijote mission as one of its top space science missions. Don Quijote is an asteroid deflection precursor mission designed to assess and validate technology that might be used to deflect a NEO. It will consist of two separate spacecraft, launched on separate interplanetary trajectories. The orbiter (Sancho) will arrive at the target asteroid first to assess, measure, and monitor. The impactor (Hidalgo) will arrive later to hit the asteroid. Sancho will monitor the result. The 7-year mission will launch no earlier than 2011. All major ESA members, including Italy, France, and Germany, will have a role in Don Quijote.

J.1.3. Italy – Italian Space Agency (ASI)

The Italian scientific community participates in the observation campaigns mounted by other countries. For example, the Italian Space Agency (ASI) is participating in the NASA Dawn Discovery mission. It is providing a visible-infrared mapping spectrometer. ASI also is participating in ESA's Rosetta mission, which was launched in 2004. It will fly by two asteroids in 2008 and 2010 en route to an encounter with comet 67P/Churyumov-Gerasimenko in 2014. Italy will be a prime participant in the ESA Don

Quijote mission. Italy also is currently engaged in discussions with the French Space Agency (CNES) on a potential future bilateral NEO space mission.

Italy is very active in the detection, tracking, and characterization of NEOs, primarily through its NEO Dynamic Site (NEODys), which is similar to JPL's Sentry system. Fundamentally, NEODyS is a database of NEO information; however, the system's distinguishing feature is that each near-Earth asteroid has its own "home page." The site offers sections devoted to the object's orbit, observations, and close encounters.

NEODyS provides interactive ephemeris services to the observer in both tabular and graphical forms. The graphical ephemeris depicts the uncertainty region on the celestial sphere, including nonlinear effects, which can be of paramount importance in the recovery of lost or nearly lost objects. With the database query service, one may search for all asteroids demonstrating some desired orbital characteristic. This makes it easy, for example, to find all he asteroids that are large enough to be hazardous, yet are effectively lost.

The database is automatically updated daily, as new observations are released from the Minor Planet Center. All data files needed to reproduce the NEODyS results are freely available.

J.1.4. Japan - Japan's Aerospace Exploration Agency (JAXA)

Japan's Aerospace Exploration Agency (JAXA) is currently involved in a major NEO research mission, called Hayabusa. The mission included the 2003 launch of a spacecraft to rendezvous with the asteroid, Itokawa, and the subsequent rendezvous and observation campaign in the fall of 2005. Observations will occur from as close as 3 km. The spacecraft's return, including the samples it gathered, was planned for 2007, but due to an anomaly in the spacecraft's propulsion system, JAXA is working on an alternative plan to return the spacecraft in 2010. NASA and DLR are participating with JAXA in the Hayabusa mission. NASA is participating in the Hayabusa mission in these areas:

- Heat shield development at Ames
- Tracking including data receiving at DSN stations
- Ground observations of Itokawa for ephemeris and shape information, including radar observations

J.1.5. Germany - German Aerospace Center (DLR)

DLR activities include use of ground-based and space-borne astronomical telescopes (primarily NASA assets) for observations, theoretical investigations, and data reduction and analysis. DLR is interpreting data from NASA's Deep Impact mission and from JAXA's Hayabusa mission. DLR also participates in the European Fireball Network, a network of all-sky cameras that record and track information on NEOs.

DLR also has proposed establishing the German Spaceguard Center, which would serve a similar function as JPL's Near-Earth Object Program Office and the United Kingdom's Near-Earth Object Information Centre.

J.1.6. Canada

Defense Research and Development Canada (DRDC) and the Canadian Space Agency (CSA) are collaborating to place a microsatellite in low-Earth orbit to perform optical detection and tracking of both IEOs and Earth-orbiting satellites and debris (i.e., "Resident Space Objects," RSOs).

In 2009, Canada plans to launch the NEO Surveillance Satellite (NEOSSat), a spacecraft equipped with a 15-cm, visible-imaging sensor. The tracking mission will conduct repeated surveys, with the aim of finding more than 50% of all IEOs whose diameters exceed more than 1 km.

J.1.7. United Kingdom (UK)

The British National Space Centre (BNSC) coordinates and monitors NEO activities and serves as the policy lead for all NEO-related matters. Two national centers provide information on NEOs. Within the NEO research community, the Spaceguard Centre coordinates the national Comet & Asteroid Information Network and liaises with Spaceguard organizations in 17 different countries. The Near-Earth Object Information Centre provides public outreach and information to the general population. The UK is a strong advocate of NEO activities within the European Space Agency and has taken a lead role within UNCOPUOS in this area. The UK heads UNCOPUOS Action Team #14, which is studying NEO-related issues. While it is taking a strong role with respect to NEO policy issues, the UK government's actual direct funding of NEO research is relatively modest, with most UK research efforts taking place in the academic sector.

J.2. United States Activities

J.2.1. NASA

Prior to the NASA Authorization Act of 2005, NASA's responsibilities included:

1. Solicit and select all science investigations, ground-based and space-based, for the detection and scientific exploration of NEOs;
2. Coordinate with other agencies and organizations, including international agencies and organizations, and
3. Assess the evolving understanding of NEOs, which will result from the search and characterization effort to guide strategic planning and mission selection.

After several years of studies attempting to define the threat posed by NEOs and the capabilities necessary to more comprehensively detect a sizable portion of the population, NASA in 1998 adopted the goals of the Shoemaker Spaceguard Survey and committed to "*…find and catalog 90% of Near-Earth Objects larger than one km in the next ten years.*" This became NASA's Near-Earth Objects Observation (NEOO) Program, for which funding was identified within the Planetary Astronomy Research and Analysis Program to pay teams of asteroid astronomers to search near-Earth space for these potentially hazardous objects. Since that time, funding for the NEOO program has leveled out to slightly more than $4 million per year, which funds activities of the NEO Program Office and five NEO search teams.

J.2.2. Jet Propulsion Laboratory (JPL) NEO Program Office

As part of the NEO Observation Program, NASA established an NEO Program Office at JPL with the following responsibilities:

1. Coordinate ground-based observations to complete the survey of NEOs and obtain accurate orbital elements for newly detected NEOs based on the best available data.
2. Facilitate communication both within the observing community and between the community and the public about any PHOs that are discovered as a result of the expanded observational program. The office also responds to public inquiries.
3. Establish, update, and maintain a catalog of NEOs, together with an estimate of the quality of the orbital elements accessible to the scientific community and the public.
4. Develop and support a strategy and plan for the scientific exploration of NEOs, including their discovery, recovery, ephemeredes, characterization, in-situ investigation, and resource potential.
5. Support NASA HQ in coordinating with other government agencies, foreign governments, and international organizations on all NEO issues.

On a daily basis, the Minor Planet Center makes available NEO astrometric data to JPL's NEO Program Office and to a parallel, but independent orbit computational center in Pisa, Italy (with a mirror site in Valladolid, Spain). At JPL, 340,000 bodies in a searchable Small Bodies Database are maintained for the international community.

JPL's Horizons on-line system is an interactive ephemeris generation site that automatically generates about 3,000 products per day to the international science community (http://horizons.jpl.nasa.gov). Within the JPL SENTRY system (http://neo.jpl.nasa.gov/risk/), risk analyses are automatically run on those objects that have a potential for Earth impact. They usually consist of newly discovered objects for which orbital information is unknown. These objects are prioritized in the SENTRY system, according to the quality of their orbital data and their potential to closely approach Earth's orbit.

The JPL system automatically updates the orbits of about 40 NEOs per day and close-approach tables are generated and posted on the Web (http://neo.jpl.nasa.gov/cgi-bin/neo_ca). Approximately five risk analyses are run each day. Each run provides 10,000 multiple solutions out to 2105. A parallel process in Pisa, Italy, and significantly non-zero Earth impact cases are manually checked between JPL and Pisa before the risk-analysis data are posted on the respective Web sites. Since its inception in 2002, about 400 objects have appeared on the SENTRY risk page. For recently discovered objects of unusual interest, the MPC, JPL, and Pisa will often alert observers that additional future or precovery data are needed.

J.2.3. Harvard/Smithsonian Minor Planet Center

The Smithsonian Astrophysical Observatory, in coordination with the International Astronomical Union (IAU) through a Memorandum of Agreement (MOA), operates the Minor Planet Center (MPC). Given its association with IAU, it has an international charter. Since 1978, the MPC has served as the international clearinghouse for all asteroid, comet, and satellite astrometric and positional measurements obtained worldwide.

The MPC processes and organizes data, identifies objects, computes orbits, assigns tentative names, and disseminates information on a daily basis. For objects of special interest, the center solicits follow-up observations and requests archival data searches. The MPC is responsible for distributing astrometric observations and orbits via the Minor Planet Electronic Circulars (issued as necessary, generally at least once per day) and related catalogues.

In addition to distributing complete orbit and astrometric catalogs for all small bodies in the solar system, the MPC facilitates follow-up observations of new potential NEOs by placing candidate sky-plane ephemeredes and uncertainty maps on the Web via The NEO Confirmation Page. The MPC focuses specifically on identification, short-arc orbit determination, and dissemination of information pertaining to NEOs. In most cases, NEO observations are distributed to the public, free of charge, within 24 hours of receipt. The MPC also provides a variety of tools to support the NEO initiative, including sky-coverage maps, lists of known NEOs, lists of NEO discoverers, and a page that allows users to select a list of known NEOs in need of astrometric follow-up. The MPC also maintains a suite of programs to calculate the probability that any object is a new NEO based simply upon two sky-plane positions and a magnitude. [93]

Primary MPC funding in 2003 was $130,000 a year from NASA, despite the Agency's increased spending on NEO surveys. Other income from subscriptions and donations is insufficient to cover the 80- to 100-hour workweeks currently staffed by director Brian Marsden, associate director Gareth Williams, and a few graduate students. Marsden, now 69, and Williams are critical assets to the current NEO discovery and cataloguing efforts.

MPC is having difficulties keeping up with the volume of data it receives now. A new survey that will generate up to 100 times more data and the same need for follow-up observations will likely overwhelm the organization under its current structure.

J.2.4. Spaceguard Survey Assets and Capabilities

The NASA NEOO program has leveled out to slightly more than $4 million per year. The money funds five NEO search teams, who operate nine separate, one-meter-class survey telescopes across the southwestern U.S., Hawaii, and Australia. These five teams are listed below:

Spacewatch, operated by the University of Arizona Lunar and Planetary Laboratory, provides two telescopes on Kitt Peak, AZ, http://spacewatch.lpl.arizona.edu/.

Near-Earth Asteroid Tracker (NEAT), operated by JPL, operates detection cameras on a U.S. Air Force telescope on Maui, Hawaii, and on a telescope at Palomar, CA, http://neat.jpl.nasa.gov/.

Lincoln Near-Earth Asteroid Research (LINEAR) is operated by MIT/LL under a U.S. Air Force contract funded by NASA. Two telescopes operate near Socorro, NM, http://www.ll.mit.edu/LINEAR/.

Lowell Observatory Near-Earth Object Search (LONEOS) is obviously operated by the Lowell Observatory near Flagstaff, Arizona, http://asteroid.lowell.edu/asteroid/loneos/loneos.html.

Catalina Sky Survey, operated by a separate team also at the University of Arizona Lunar and Planetary Laboratory, operates two telescopes on Mt. Lemmon, Arizona, and one at Siding Spring, Australia, its only Southern Hemisphere asset, http://www.lpl.arizona.edu/css/.

Planetary Radar Systems - Arecibo and Goldstone

Two planetary radars are capable of observing near-Earth objects. Radar data are extremely powerful in reducing orbital uncertainties, as discussed earlier in this report. In addition to gathering data on NEOs, both facilities carry out radar investigations of planets in the inner solar system and small bodies that orbit as far as the main asteroid belt.

The Goldstone radar is located in southern California’s Mojave Desert. It uses the 70-meter antenna of NASA’s Deep Space Network (DSN14), which is currently equipped with a 450-kW transmitter. It can receive on this dish or other nearby DSN antennae. Because it is steerable, the antenna can reach most of the sky and can follow the often-rapid apparent motions of NEOs.

The second radar is located at Arecibo, Puerto Rico. It is owned and managed by the National Science Foundation (NSF) and operated by Cornell University under a cooperative agreement with NSF. It is equipped with a 305-meter aperture and a 900-kW transmitter. Its reach is farther than that of Goldstone, but because it has a fixed antenna, it can only look about 20° off its zenith position.

As of early September 2006, 195 near-Earth asteroids and 11 comets were observed with the planetary radars.

J.2.5. Current Cataloguing and Data Management Infrastructure

To catalog a newly discovered NEO, enough observations must be obtained to determine its orbital path about the Sun. Currently, most new objects are detected by one or more of the five NASA-funded search projects, operating up to nine different ground-based telescopes. See 0. The sunlight reflected from almost all new NEOs is so dim that astronomers can search for them only on the darkest nights of the month, usually for about two weeks when moonlight does not obscure their light, and, of course, only on nights when the sky is relatively clear.

To determine whether the detected point of light is not just another star but a small object moving in the solar system, multiple images must be collected of the same area of sky. Enough time must pass between observations to allow the relatively near object to move against the background of stationary stars. Currently, at least three images, sometimes five, are taken each night of the same area of sky, separated by about 30 minutes on average. A computer-automated image processor then compares the images. A NEO will appear as a point of light moving a few arc seconds across the rectified, sequentially ordered images. This is considered a detection.

Observation data, in the form of right ascension and declination position angles, can then be taken on the detected moving object. Astronomers can compare the object's positions to the known positions of the background stars. This observational process is called "astrometrics." With a good star catalog, astronomers can take precise observations with errors of less than one-half an arc second. All the search projects collect multiple observations of the objects each observable night.

The projects forward these data to the Minor Planet Center, where they are either correlated with already-known objects or determined to be previously unknown objects. For these new objects, an initial rough orbit can be determined. Most detections are objects in the main asteroid belt beyond the orbit of Mars, but a handful each night are determined to be NEOs. The MPC publishes the predicted orbital positions, called "ephemeredes," for new NEOs on its NEO Confirmation Page as a way to solicit and collect additional observations, often done by talented amateur astronomers. Additional observations must be collected within a few nights to sufficiently determine the new object's orbit, or "secure" it, so that it can be tracked into the future. If the object is tracked on at least 3 nights over a span of 40 days, it can be cataloged as a new "discovery."

If the orbit of a newly detected NEO is predicted to come within 0.05 AU (about 5 million miles) of Earth's orbital path, it is a possible new PHO and the MPC will send an alert to the NEO Program Office at JPL and to the NEODys operated by the University of Pisa, Italy (now with a backup site at the University of Valladolid, Spain). If the newly determined orbit shows there is a possibility of an Earth impact at some point in the future, the MPC also will send an alert of a new "PHO of Interest."

Observatories and amateurs, who attempt to collect follow-up observations, receive these alerts and often send what data they collect to the MPC. The MPC updates the ephemeredes, and if a possible Earth impact still exists, more observations are directly solicited from observers who have a good chance of being able to observe the object.

Meanwhile, all of the MPC data are automatically sent to JPL and the University of Pisa. JPL and NEODys perform separate precision orbit determinations and calculate the potential of Earth impact. If observations are obtained confirming the hazardous impact orbit, then the organizations pass along the information up the management chain at NASA until it reaches the Administrator.

If, at any time, astronomers determine that an object no longer poses a threat, MPC's routine object processing capability catalogues the orbital information.

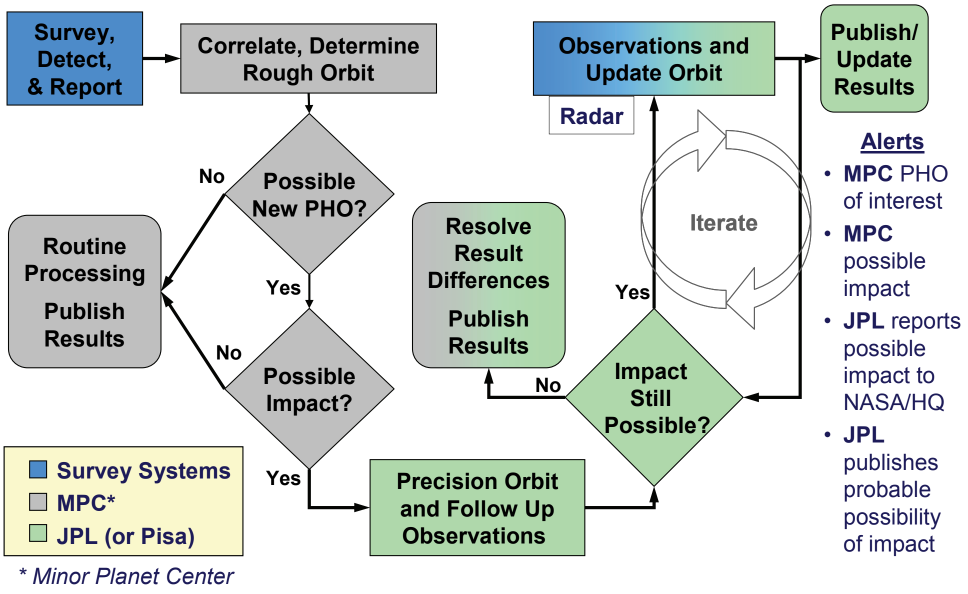


Figure 80. Data Flow for Spaceguard Survey

Four different types of infrastructure keep this system running: search projects detect new objects; observatories — some of which are run by amateurs — collect follow-up observations; JPL and Pisa precisely determine orbits and potential impacts; and the MPC collects and archives all data. The MPC maintains an archive of all observations received, including those that have never been correlated with a cataloged object in hopes that someday they will – perhaps providing a critical extension to an orbital arc. MPC also maintains an archive of all orbital parameters ever calculated on known objects.

The MPC is currently the only non-redundant part of the data analysis and storage system that catalogs and tracks NEOs. Additionally, if the search is expanded to smaller NEOs, the day-to-day work that the MPC needs to perform will increase as new, more capable, observing platforms become available. It is expected that the data throughput will increase at least tenfold, and possibly as much as a hundredfold. The MPC will need to substantially update its hardware and software.

It also is possible that the work done at the MPC and at JPL could be done elsewhere. It might be consolidated into one central data management center for NEOs. Potential sites include a few of the NASA centers, or major universities or science institutes involved in small-body planetary science.

NASA’s Planetary Data System (PDS) is a distributed archive of solar system data prepared in a standard format for use primarily by astronomers, mission planners, educators, and students. NASA’s Office of Space Science Exploration of the Solar System Division sponsors PDS to ensure the long-term use of data, to stimulate research, to facilitate data access, and to support correlative data analysis.

The Small Bodies Node (SBN) is a distributed node, which specializes in data concerning asteroids, comets, and interplanetary dust. Its archives consist of data from NASA missions, astronomical observations, and laboratory measurements, organized into a structure and format suitable for archival and retrospective research by the scientific community. The node data collection and verification activities are spread among several institutions specializing in particular bodies (comets, asteroids, or dust), while the main archives and user services are collected in a single place.

The Comet Subnode is located at the University of Maryland, College Park, MD. In addition to maintaining the combined archives of the SBN and supporting a Web site, this group collects, formats, verifies, and consults on datasets concerned with comet observations. It also supports active comet missions and observing campaigns.

The Asteroid/Dust Subnode is located at the Planetary Science Institute in Tucson, Arizona. The subnode collects, formats, verifies, and reviews ground-based and mission data pertaining to asteroids, trans-neptunians, small planetary satellites, and interplanetary dust.

Further information is available at http://pdssbn.astro.umd.edu/.

Appendix K. Object Characteristics Useful for Mitigation

The physical properties of NEOs are extremely diverse, creating an added challenge to mitigation planning. Upon discovery, a NEO is an unresolved point of light whose motion reveals its orbit. Basic measurements of colors and albedos are needed for at least a preliminary assessment of composition and size. Sizes of currently known Earth-intersecting objects range from 10 meters to 9 km.

Additional measurements can reveal whether a NEO may be single or binary (or more), with components orbiting one another or joined to a single mass by gravity or mechanical means. About 15% are expected to be multiple-body orbiting systems by commonly accepted estimates; however, some estimates are as high as more than 50%. [102] [103]

NEO interiors are likely highly fractured or porous, with little or no tensile strength. The likelihood of having some tensile strength is greatest for bodies below about 180 meters in diameter. Most NEOs (estimated 85%) likely originated in the main asteroid belt and up to 15% may have originated as comets that now appear inactive.

The diversity of asteroid and comet compositions, as well as the diversity of meteorites, suggests NEOs are made of a wide range of materials. Current results for meteorite correlations suggest that NEO compositions range from low-density rocky material to high-density nickel-iron. Spin rates are typically a few hours, but can be orders of magnitude greater or smaller.

At the smallest scales, NEO surfaces are thought to be boulders strewn with some regolith that is generally coarser than the regolith found on the Moon. Impacts generate seismic shaking, which force the fine dust to settle into smooth “ponds.” Seismic shaking also may erase small craters and fill in cracks or fractures that might be present at the surface. [104]

A more detailed discussion of some of the asteroid characteristics important for evaluating deflection alternatives follows.

K.1. Mass of Potentially Hazardous Asteroids

The mass of the PHO is the most important quantity necessary to mitigate the threat because the mass affects the basic design and sizing of the impactor, explosive, or slow push payload, and therefore the mass that must be launched from Earth. The mass is the product of the NEO’s volume and density. Because NEO reflectivity can vary from about 2% to 50%, simply measuring brightness and assuming reflectivity will result in a diameter estimate with a factor-of-two uncertainty. This leads to a factor-of-eight uncertainty in the volume. Asteroid densities are believed to vary from about 2- to 7-g/cm^3. Adopting a mean density introduces another factor-of-two uncertainty into the mass. Thus, the total uncertainty in the momentum and impact energy, due to the individual uncertainties in the diameter and density, can be as large as a factor of 16 if only NEO detection-related means are employed.

The taxonomic class of an asteroid can be determined from visual photometry. This constrains the mineralogy of the object and reduces the uncertainty in the density estimate. Size estimates based on visual photometry and infrared radiometry are accurate within 10%. These observations reduce the total mass uncertainty to about 50%. [106]

K.2. Orbits of Hazardous Asteroids

A very large percentage (more than 99.9%) of PHO detections are expected to be asteroids. In conjunction with mass, the orbit of a threatening object is the most important information for designing a deflection alternative. This section discusses the statistical distribution of asteroid orbits, derived from the JPL potentially hazardous asteroid (PHA) database [71], a set that is assumed to be representative of all PHAs 140 meters and larger. While the complexity of orbital mechanics makes it difficult to generalize the orbit transfer energy (ΔV) and the time required for a set as diverse as this, studying three parameters provides some insight into the difficulty of reaching potential threats before they reach the Earth.

K.2.1. Potentially Hazardous Objects Orbit Periods

Orbital period measures the time an object takes to travel around the Sun — the longer the orbital period, the farther the mean distance from the Sun. That means it will take the object longer to rendezvous or intercept. Figure 81 illustrates the statistical distribution of PHA orbital periods. [71]

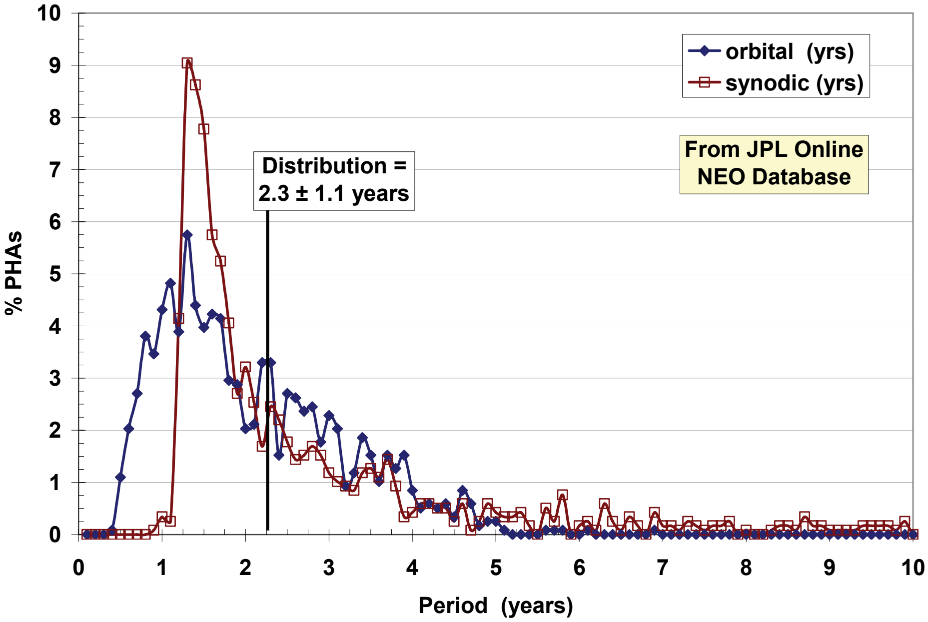


Figure 81. Statistical Distribution of PHA Orbit Periods

K.2.2. Orbit Inclination

The angle between the object's orbit and the plane of Earth's orbit determines orbit inclination. If the angle is large, more energy is required to travel to the object. Figure 81 illustrates the statistical distribution of PHA orbit inclinations. [71]

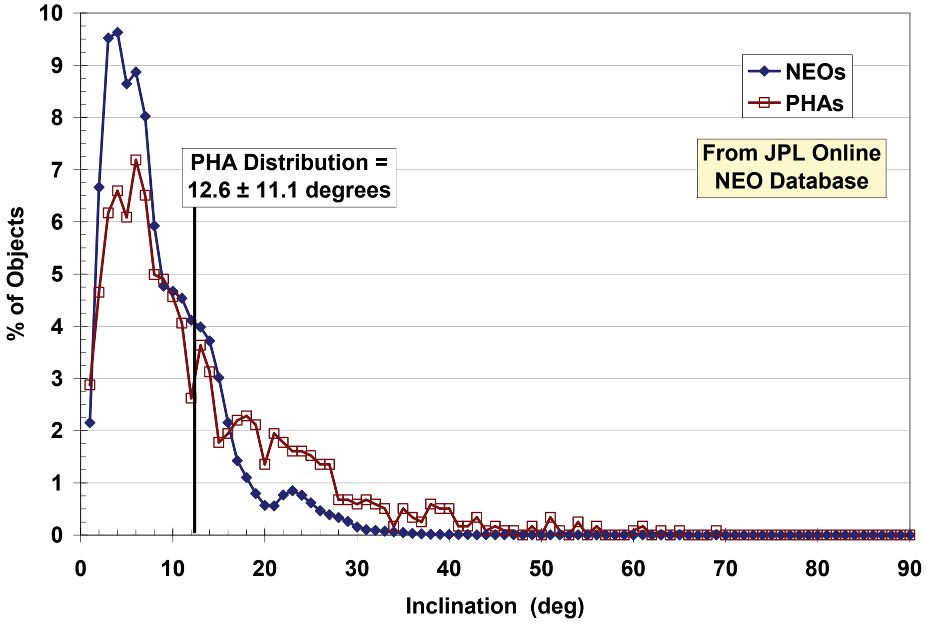


Figure 82. Statistical Distribution of PHA Orbit Inclinations

K.2.3. <u>Potentially Hazardous Objects Orbit Eccentricities</u>

Figure 81 illustrates the statistical distribution of PHA orbit eccentricities.

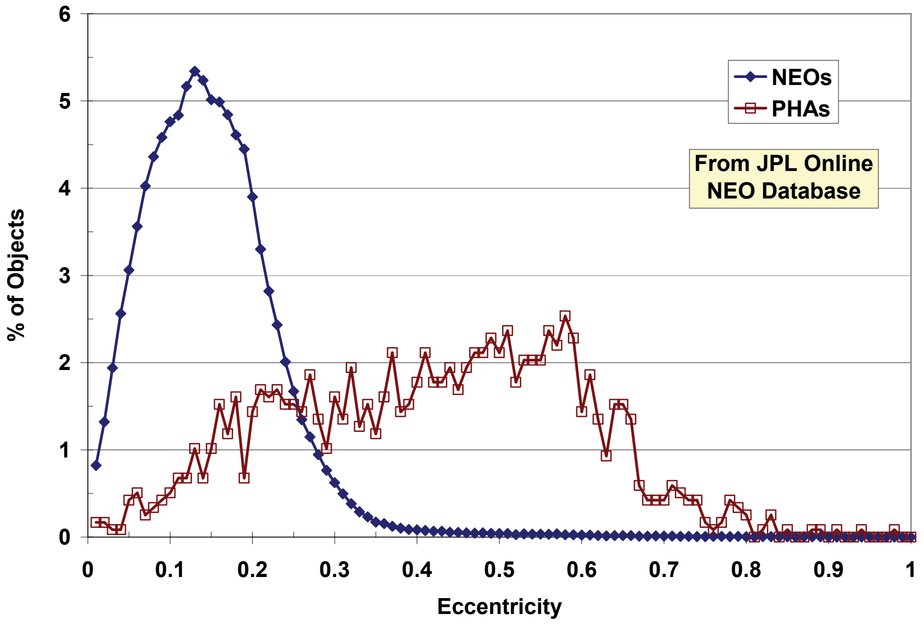


Figure 83. Statistical Distribution of PHA Orbit Eccentricities

Orbit eccentricity is measured between 0 and 1 and represents how circular an orbit is. For an eccentricity of 0, an object stays equidistant from the Sun and travels in a circle. Objects with increasing eccentricity travel in increasingly more elliptical orbits. These objects travel much faster near the Sun than when they are farther away, and this variation can affect the required orbit transfer ΔV and impact velocities and intercept angles. Note that PHA eccentricities vary more than those of NEOs. [71]

K.3. Density of Potentially Hazardous Asteroids

The density of the NEO provides additional information on the internal structure of the object and helps to define whether the object is "either a porous or volatile-rich rock, or a solid rock." [57] This property also might help determine the response of the PHO to the mitigation attempt. For example, a solid body is more likely to withstand a high-velocity impact by a kinetic impactor or a blast of a nuclear explosive than a porous body. Also, as was evidenced by the Deep Impact mission [105], volatiles within a body could add significantly to the effectiveness of some techniques. They may increase the efficiency of the momentum transfer of the ejecta.

Some impulsive techniques may also fragment a PHO, a concern from the perspectives that: 1) It would be more difficult to design back-up techniques to deal with several large fragments; 2) Fragments could be a greater threat to Earth than the single object [109]; and 3) The fragmentation event could create a debris cloud, making verification of the effectiveness difficult. Reference [104] notes that the size of the asteroid is important in estimating the likelihood of fragmentation. This reference estimates that asteroids larger than 1 km in diameter are the weakest from this perspective.

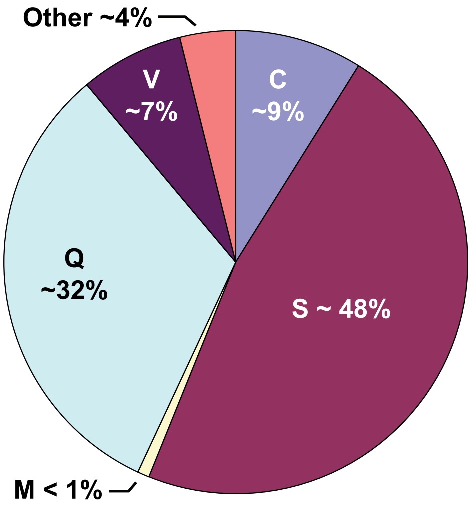


Figure 84. Approximate Distribution of Asteroid Types

Figure 84 shows current estimates for the distribution of the asteroid types described in Table 49. [101] Note that the density estimates for asteroids can vary by a factor of about four due to material composition (grain density), with additional uncertainty in mass due to porosity. The table illustrates the most commonly made associations between taxonomic classes and meteorites when other detailed information is unavailable. The reference stresses that taxonomy is not composition and that this table and figure represent only a preliminary estimate, again in the absence of more detailed information.

Table 49. Generalization of Taxonomic Classes and Densities

Taxonomic Class	Generally Inferred Meteorite Association[1]	Meteorite Densitites[2]
C	Carbonaceous chondrites	2.2-3.7
S	Diverse: Primitive achondrites ordinary chondrites differentiated olivine/ pyroxene / metal assemblages	2 – 5 ?
M	Iron or Stony Meteorites	7 - 8
Q	Ordinary chondrites	3.5 – 3.9
V	Basaltic achondrites	3.1 – 3.8

[1] Caveat emptor. Subject to ambiguities

[2] These are grain densities (g cm^{-3}) assuming zero porosity

If interception of a threatening PHO occurs very close to Earth, disruption of the objects into small fragments may be a more desirable outcome than no action at all. However, the cloud of small fragments would impart the same amount of energy as the original object to Earth and the atmosphere, and as Reference [110] notes, such a cloud could cause "extreme damage" to orbiting satellites and the climate.

K.4. Taxonomic Classes and Asteroid Types

The composition of asteroids shown in Table 49 is drawn from recovered meteorites, providing an indirect link between spectral class, taxonomic class, and meteorite data. Since these classes do not describe the porosity, number of diverse bodies, elasticity, surface structure, or ratio of constituent materials, they are only of moderate use for deflection alternatives that require more information than mass and orbit.

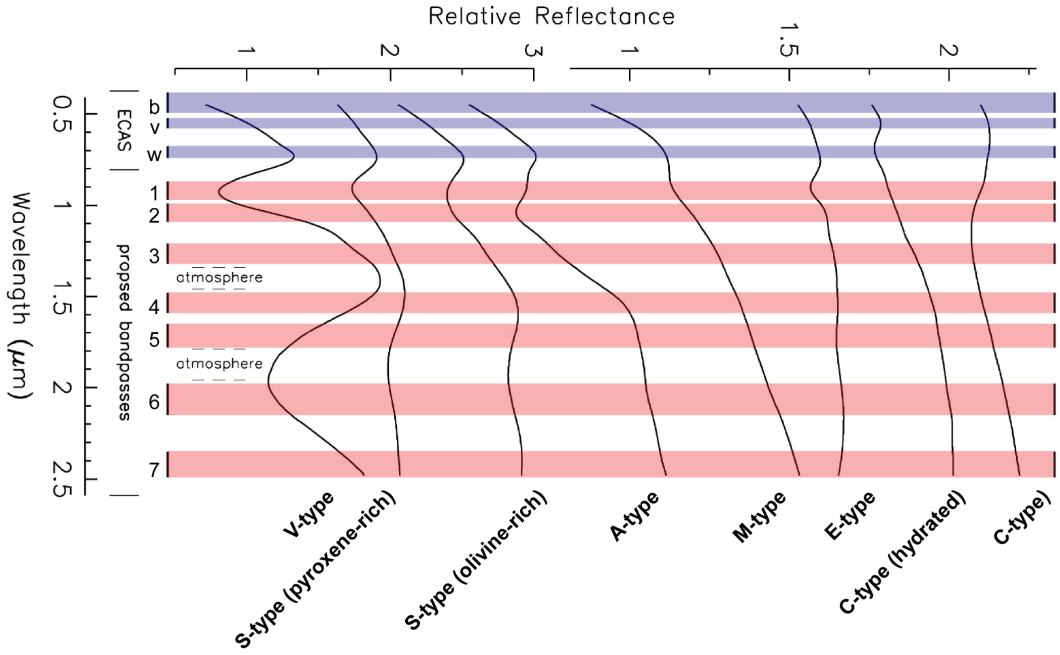


Figure 85. Infrared Signatures of Asteroid Types

It is possible that a different taxonomy from those used by scientists may prove useful for developing deflection alternatives, but such a new structure is not suggested here. Instead, it is assumed that the scientific asteroid types are representative of the types of information useful for differentiating mitigation approaches.

Infrared measurements may distinguish asteroid types by using the signatures seen in and correlating those to meteoroid samples. They are shown in Figure 85.

K.5. Porosity and Efficient Transfer of Momentum

Figure 86 shows that the momentum transferred per unit mass of the impactor can vary three orders of magnitude depending on the porosity of the targeted PHO. The ejecta efficiency in the chart is related to the impact efficiency coefficient (β), developed in the discussion of the kinetic impact alternative. [29]

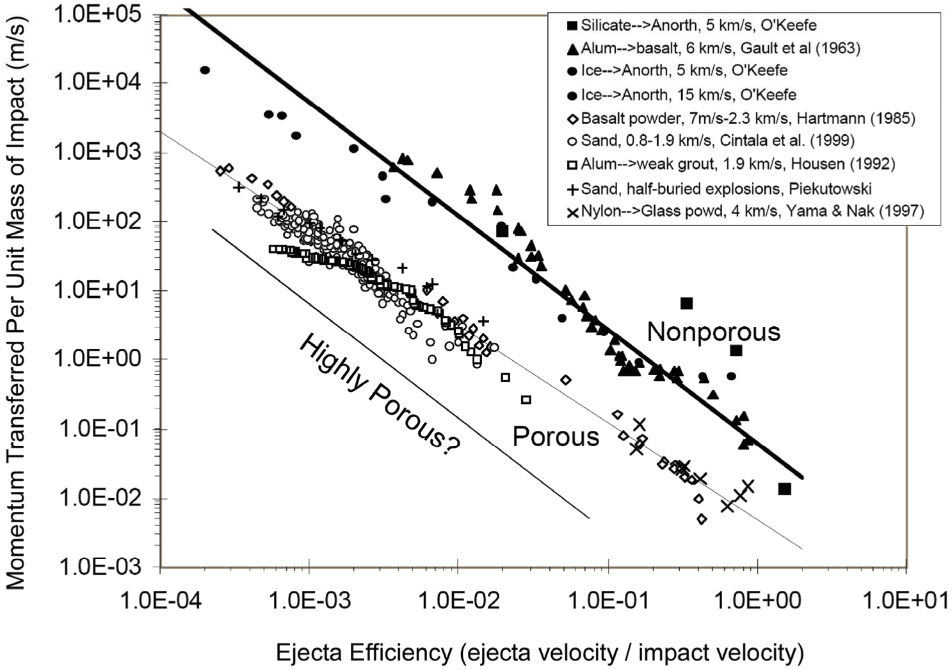


Figure 86. Momentum Exchange Efficiency Depends on Porosity

K.6. Rotation Rates of Near-Earth Asteroids

Rotation rate also may be important for some deflection techniques, primarily those that require a soft landing, thrusting for long periods, or long-term operation in very close proximity to the PHO. In addition, the rotation rate may help estimate the likelihood that the object is a binary or a rubble pile. For impulsive techniques, a high spin rate may make it difficult to target a favorable location for imparting momentum change.

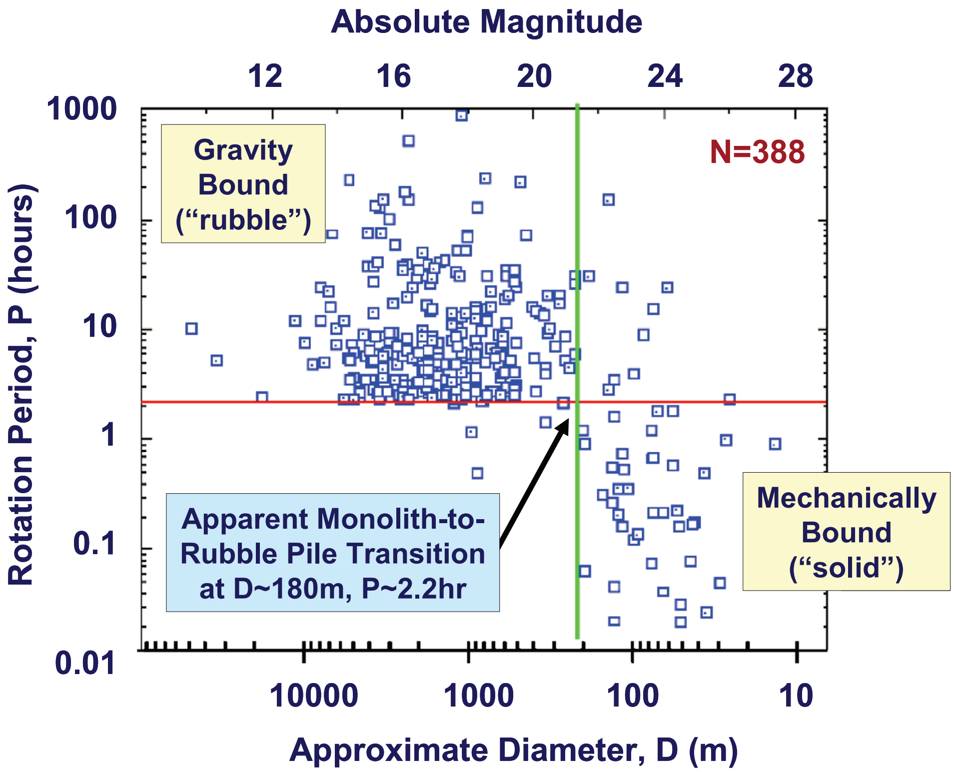


Figure 87. Rotation Rates as compared with Diameter - Fast Rotation Barrier

Figure 87, developed from Reference [107], shows the distribution of 388 observed objects according to rotation rates and diameter. This figure shows two thresholds that separate asteroids into small mechanically bound "solid" objects and larger gravitationally bound "rubble piles."

If representative of the general population of asteroids of this size, Figure 87 shows that a large percentage of asteroids 180 meters and smaller have rotation rates of **under 2 hours**. Due to the power law relationship between the number of NEOs and diameter, there are expected to be 100 times more 140-meter objects than those with diameters of 1 km. If proven, this assertion indicates that any of the deflection alternatives that require maintaining contact with the target object will operate in a very dynamic and changing environment. Operations, such as communications, power generation, and maintaining thrust direction, will be very challenging, if not infeasible for some alternatives.

On almost all asteroids smaller than about 180 meters, the spin rate is so high that a surface package would not remain bound except at the poles. The asteroid can still be a rubble pile, due to simple frictional effects, but will be rotating so fast (period faster than a couple of hours) that a landed package would simply drift into orbit unless somehow tethered. Thus, landing surface packages on a PHO up to about 200 meters in diameter requires that the rotation rate be well characterized and that it be slower than a critical rate, defined as:

$$\omega_{crit} = (GM/r)^{0.5} \tag{14}$$

where r is the radius and M is the asteroid's mass. Asteroids larger than about 1 km almost all rotate slower than this rate, so simple surface anchoring is possible.

One of the benefits of a fast rotation is that it makes the objects potentially easier to disrupt. A relatively small cratering charge on the equator of a rapidly rotating asteroid might send a lot of mass to escape velocity because all it has to do is shake the material loose, not accelerate it. This has not been studied in any detail. But if a powerful seismic event (blast event) shakes the rubble loose, then dynamical friction instead of static friction applies, and the asteroid will go into a landslide-type reconfiguration of mass. Whatever is moving faster than escape velocity (e.g. the equatorial regions) might be permanently lost.

Appendix L. Launch Capability for Characterization and Mitigation

L.1. Launch Capability (C3) of Current and Planned Launch Systems

The critical parameter needed to match launch capability with the ability to intercept (less so for rendezvous) an asteroid with a certain payload by a certain time (flight time) is the C3. It is equal to twice the specific (per unit mass) orbital energy, and has units of km^2/s^2.

Figure 88 shows the launch C3, as compared with payload capability for a number of past and current launch systems. Note how quickly payload decreases as launch C3 requirements increase. Deflection options for impulsive techniques have generally been sized at C3 = 25 km^2/s^2.

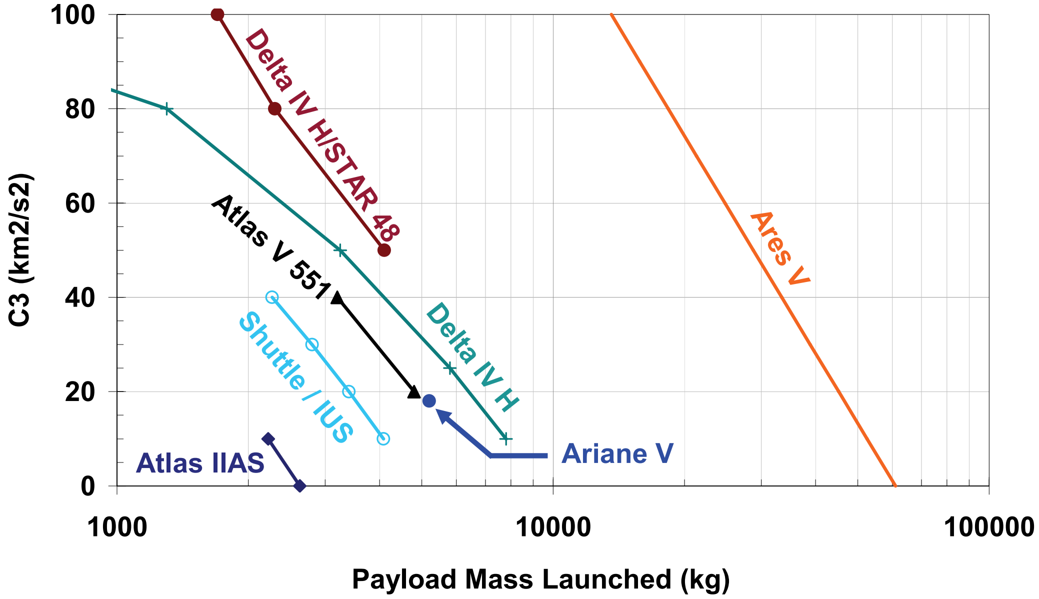


Figure 88. C3 of Current and Planned Launch Vehicles

L.2. Launch Capability Required

To ascertain both feasible mission designs as well as warning-to-deflection timelines, one needs to determine the minimum launch C3 and transit time required to travel to a PHA of interest. The C3 computation was performed for two scenarios.

1. The first sets the launch date and allows the asteroid to vary in its orbit. This might represent a mission scenario where the spacecraft is required to the leave the Earth by a fixed date. This might be the case for precursor characterization missions or deflections of an imminent threat.
2. The second scenario allows both the launch date and the arrival date to vary. This might represent a precursor mission that would characterize a PHA well in advance of its projected time of closest approach with the Earth. For this type of

precursor mission, there would be more flexibility in the launch and arrival dates and the mission could wait until a more favorable relative geometry was achieved.

For each of these, the minimum launch C3 was computed for three conditions: the C3 required to launch the spacecraft onto an intercept course with the PHA without regard to the arrival conditions; rendezvous with the PHA (minimization of the sum of the launch and arrival speed C3); and minimization of the arrival speed without concern for the launch C3. Since the goal was to produce a statistical summary of the C3 requirements, the minimum C3 for each PHA was found over the search space. In addition, a cumulative histogram was generated to show what percentage of the PHA population could be reached for each of the scenarios as a function of C3.

L.3. Launch Energy (C3) for Varied and Fixed Launch or Arrival Dates

The results of the Apophis case for a fixed launch date are shown in Figure 11 for the launch-to-intercept condition. The spikes in the plot reflect the times when the Lambert solution switched from going the “long way around” the transfer orbit to Apophis to the “short way” and back. For each PHA, data such as Figure 89 would be produced and the minimum launch C3 would be saved. The launch-to-intercept, rendezvous, and minimum arrival speed C3 would not necessarily be the same, as different transfer trajectories could produce different optimal launch C3.

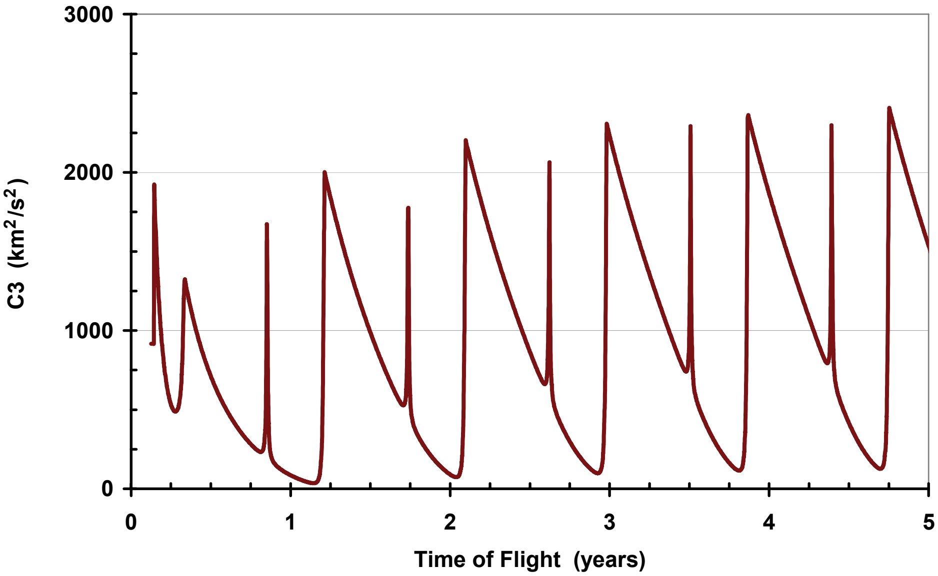


Figure 89. Required launch C3 for Apophis for a Fixed Launch Date

Figure 90 and Figure 91 both show the percentage of the PHAs reachable for a given launch C3. In Figure 90 the launch date is fixed to intercept the PHA within 5 years. The C3 values computed for the population are relatively high. For example, the Ares V lunar cargo launch vehicle has a planned capability of launching a payload of 55,000 kg to a C3 of 25 km^2/s^2. This indicates it could only intercept about 40% of the PHAs should the launch date be a constraint on the mission (i.e., a short warning situation). For rendezvous cases such as required by slow push techniques, 27% would be reachable.

In Figure 91, both the launch date and the arrival date at the PHA vary to permit an optimal transfer. Much lower transfer velocities are possible if transit time is less of a factor.

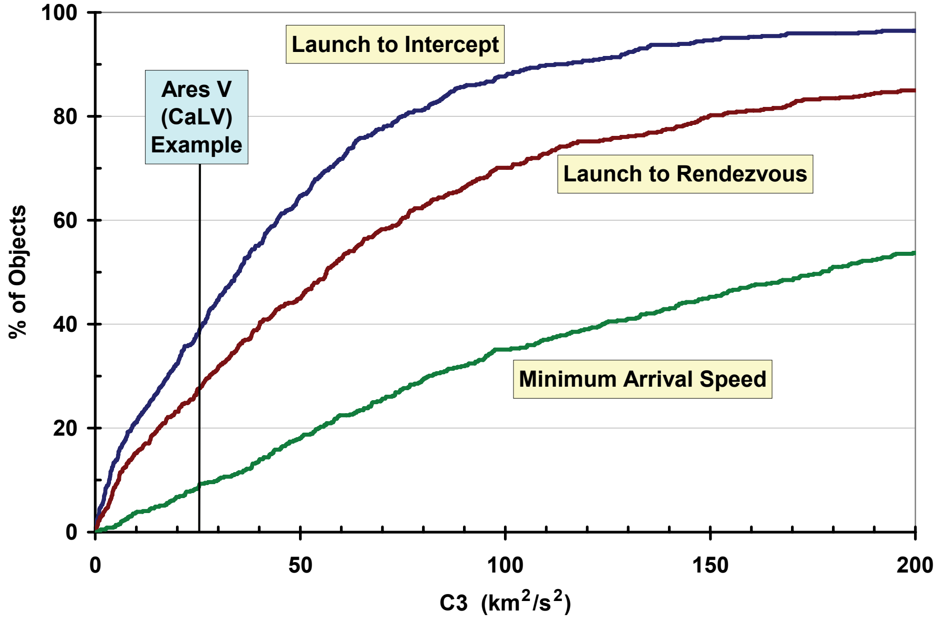


Figure 90. Launch C3 for Fixed Launch Date

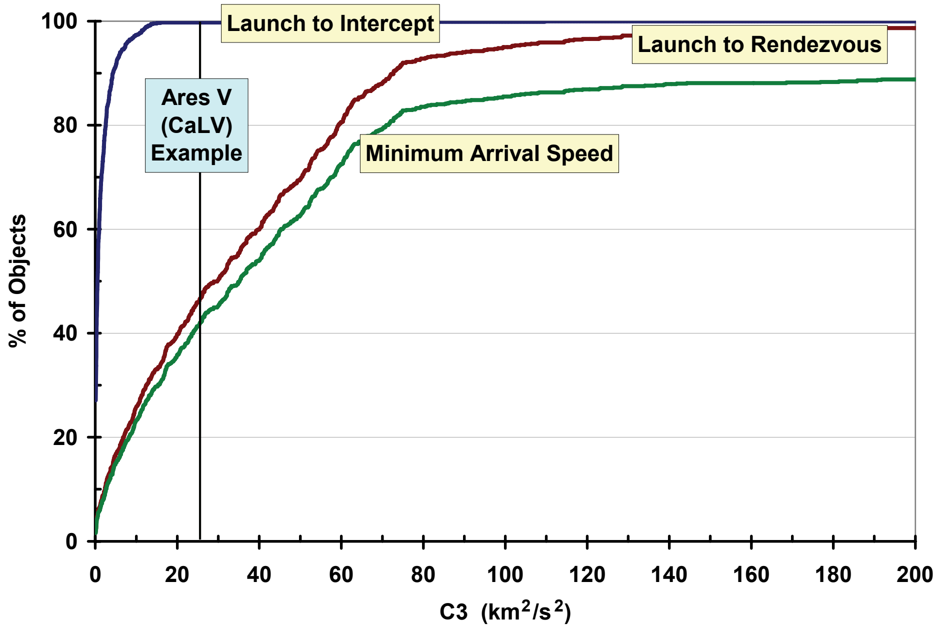


Figure 91. Launch C3 Launch and/or Arrival Dates Vary

An additional solution was examined wherein an angular constraint of 15º was placed upon the approach angle to the PHA. This constraint would represent the end-point requirement for a kinetic impactor that needed to either push or slow the PHA by directing its force as close as possible to the PHA's pre-existing velocity vector.

Figure 92 shows the result for the launch-to-intercept condition with and without the angular constraint for a fixed launch date. For the Ares V, imposing a 15º constraint reduces the PHAs that could be reached from about 40% to about 25%. For rendezvous, the percentage of reachable PHAs would drop from 27% to 18%. If other constraints on the mission are added, such as line-of-sight communications between the spacecraft and the Earth during mission critical events, the impact on the C3 requirements could be even more pronounced. Figure 93 shows that many more potential threats are reachable if launch and/or arrival dates are allowed to vary.

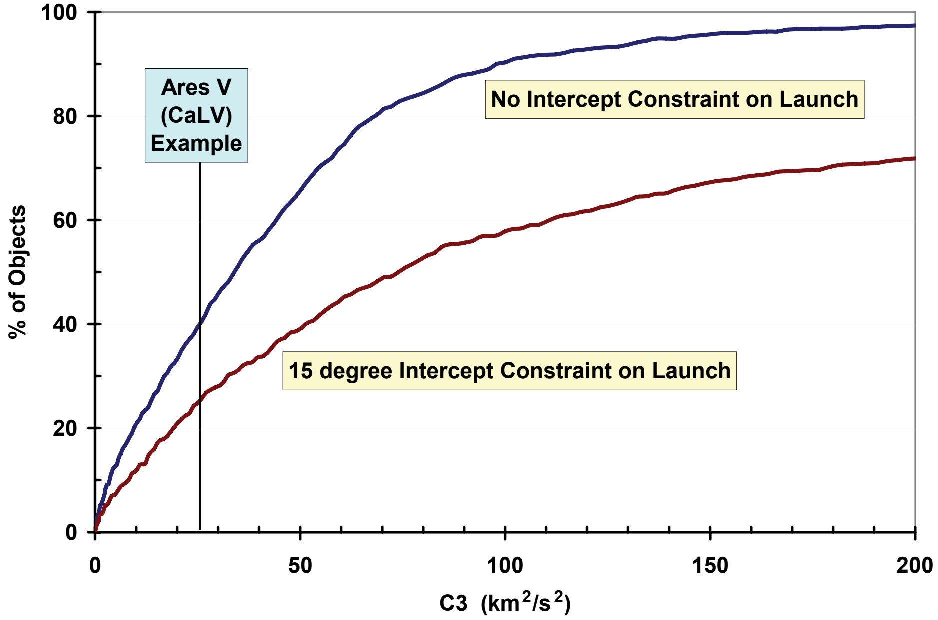


Figure 92. Realistic Intercept Constraints – Fixed Launch Date

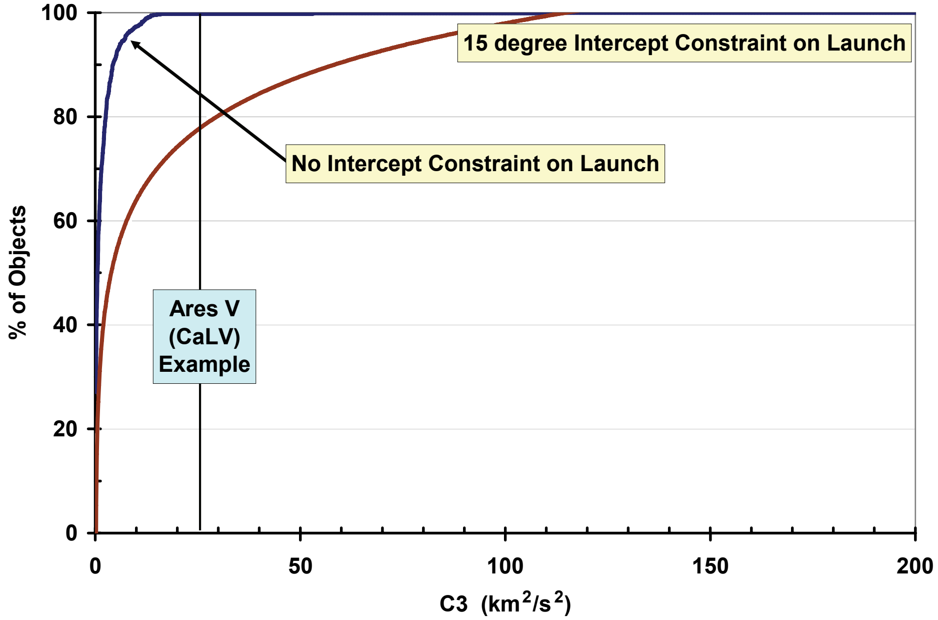


Figure 93. Realistic Intercept Constraints – Variable Launch/Arrival Date

Similar results as those shown in Figure 90 and Figure 92 are generated (within 10-15% of ΔV for a given C3) if the arrival time is fixed but the launch date is allowed to vary.

As many NASA missions have shown, swing-by trajectories using the Earth or other celestial bodies may reduce transfer ΔV in some circumstances. Swing-by trajectories also are launch-date dependent and are likely not applicable to short-warning launches, but would be studied for the preponderance of threats that will have long warning durations. Since flyby trajectories are case dependent and analysis intensive, they were considered outside the scope of this study, except to note their value in producing minimum ΔV transfers.

L.4. Launch Capability Required to Intercept Comets

The launch capability required to intercept comets is discussed in the context of the scenario described in Section 6.13.6.

L.5. Launch Capability Summary and Conclusions

The conclusions of this section are manifold. C3 requirements are large (compared with current and planned launch capability) for characterization or mitigation missions when launch or arrival time is unconstrained and a favorable geometry between the Earth and the PHO cannot be attained. For realistic launch constraints, fewer than 25% of potential threats can be reached with the planned capabilities of the Ares V.

For characterization missions without a time constraint, or deflection missions with sufficiently long warning, C3 values are lower and within current and expected launch capabilities. Since the synodic periods of the majority of PHAs is on the order of a few years, warning times of several decades will allow for selection of favorable geometries and thus avoid the worst case crisis situation.

Appendix M. Additional Cost Results

The following sections display the results of developing the life-cycle cost (LCC) figure of merit (FOM). The sections include the LCC for the individual concepts, followed by combinations of concepts that collectively form an architecture.

M.1. Detection and Tracking Survey Element Costs

Table 50 displays a further breakout of the space-based survey systems in FY06$M. Figure 94 shows a breakout of development, launch, and operations costs through 2020.

Table 50. Space-Based Survey Systems Life-cycle cost Breakout

Concept Aperture Band Orbit	D-8A 2.0 m Visible LEO	D-8B 2.0 m Visible L1/L2	D-9 1.0 m Visible Venus	D-10 2.0 m Visible Venus	D-11 0.5 m IR L1/L2	D-12 1.0 m IR L1/L2	D-13 0.5 m IR Venus	D-14 1.0 m IR Venus
PM/SE/MA	$ 102	$ 102	$ 91	$ 117	$ 37	$ 57	$ 41	$ 63
Flight System	$ 476	$ 476	$ 507	$ 582	$ 170	$ 279	$ 200	$ 318
Payload	$ 274	$ 274	$ 161	$ 276	$ 100	$ 140	$ 101	$ 140
Pre-launch GDS	$ 112	$ 112	$ 100	$ 128	$ 40	$ 62	$ 45	$ 68
Development Reserve	$ 394	$ 395	$ 298	$ 406	$ 87	$ 133	$ 88	$ 147
Total Development	$ 1,357	$ 1,358	$ 1,157	$ 1,508	$ 434	$ 671	$ 474	$ 736
Launch Vehicle	$ 95	$ 132	$ 132	$ 159	$ 95	$ 107	$ 107	$ 132
MO&DA + Reserve	$ 329	$ 329	$ 330	$ 328	$ 341	$ 336	$ 340	$ 335
Total Mission Cost	$ 1,781	$ 1,819	$ 1,619	$ 1,995	$ 870	$ 1,114	$ 921	$ 1,204

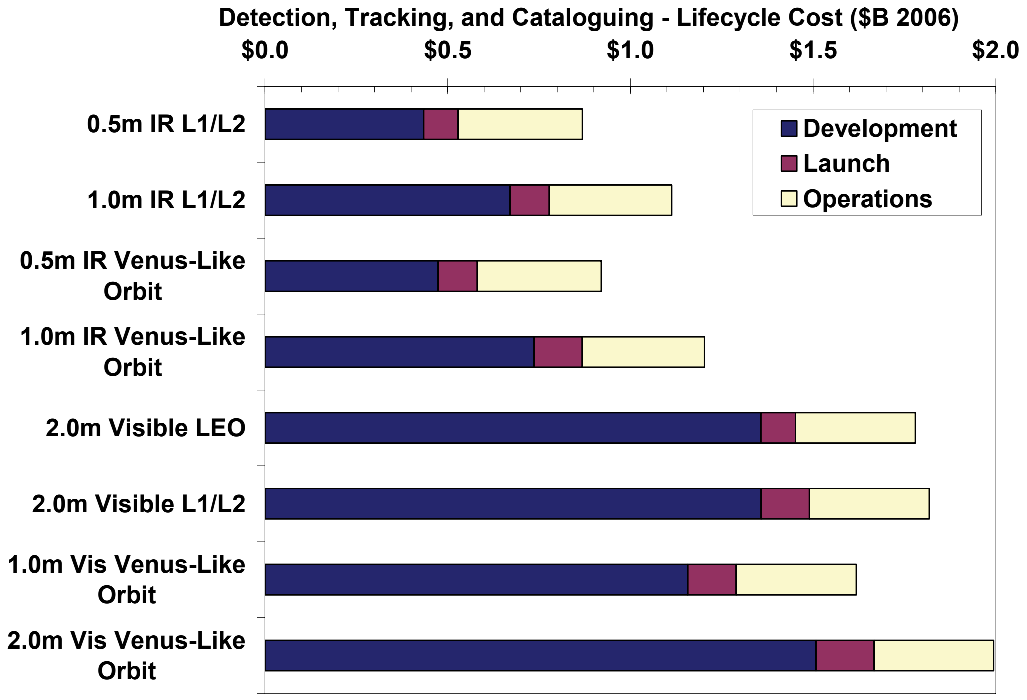


Figure 94. Breakout of Search Element Costs

M.2. Characterization Element Results Costs

Figure 95 displays the LCC through 2020 in FY06$B for the characterization concepts and Figure 96 breaks out the costs for the space-based systems.

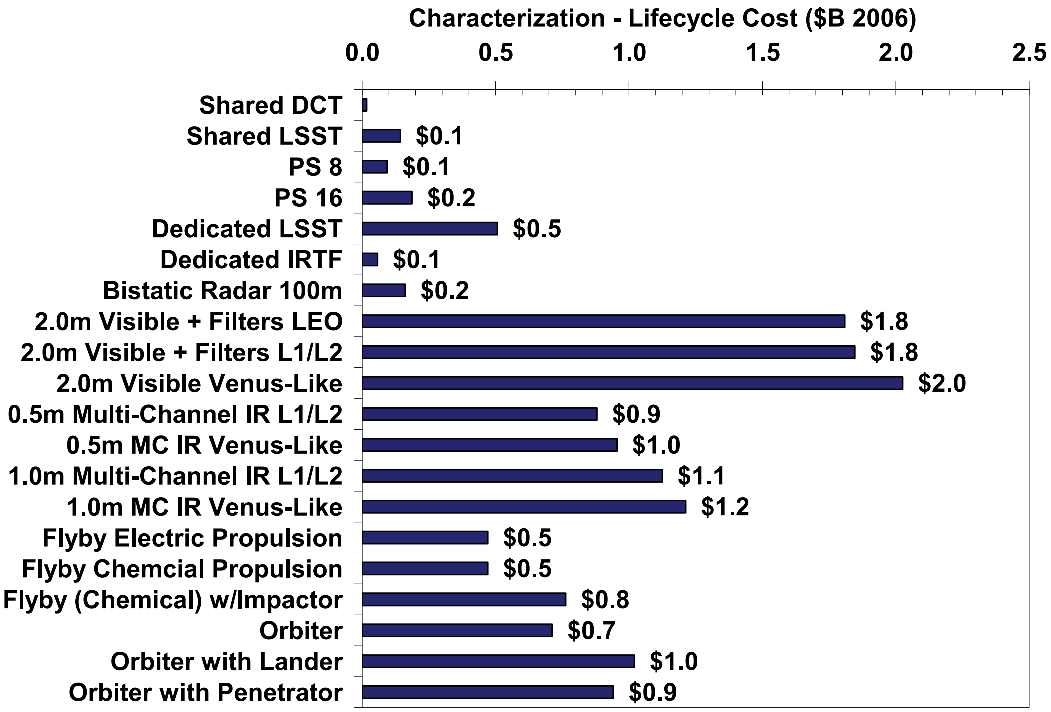


Figure 95. Characterization Alternatives Life-cycle cost Results

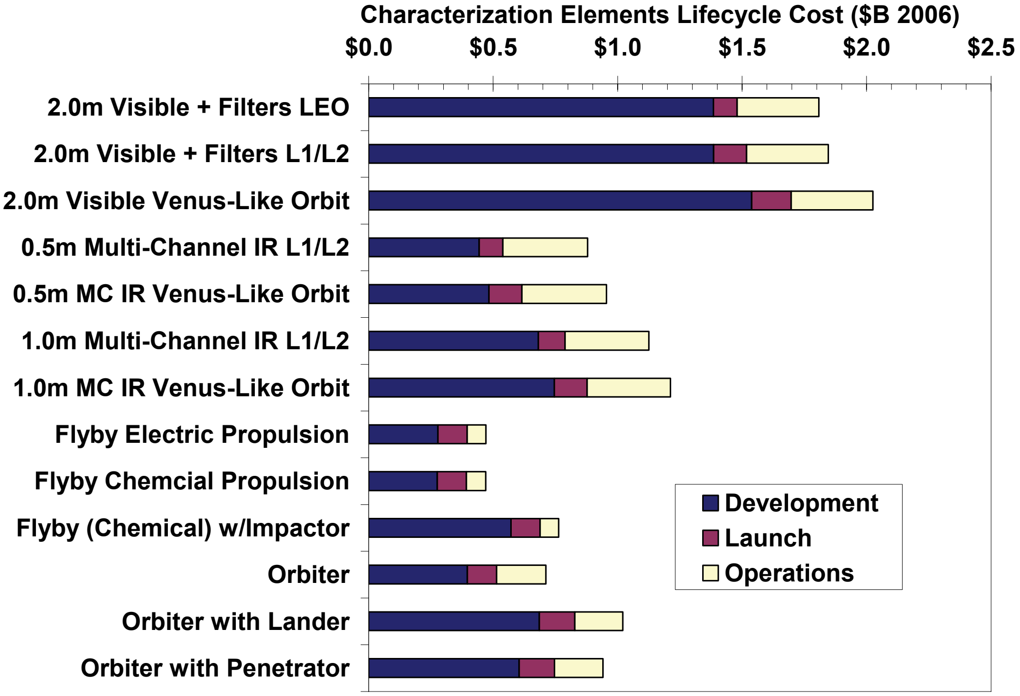


Figure 96. Breakout of Space-based Characterization Element Costs

Table 51 displays a further breakout of the space-based remote sensing Characterization systems in FY06$M

Table 51. Space-Based Remote Characterization Systems LCC Breakout

Concept Aperture Band Orbit	C-8A 2.0 m Visible FW LEO	C-8B 2.0 m Visible FW L1/L2	C-09 2.0 m Visible FW Venus	C-16 0.5 m IR MC L1/L2	C-17 0.5 m IR MC Venus	C-18 1.0 m IR MC L1/L2	C-19 1.0 m IR MC Venus
PM/SE/MA	$ 109	$ 109	$ 118	$ 40	$ 43	$ 59	$ 64
Flight System	$ 519	$ 519	$ 584	$ 188	$ 213	$ 291	$ 322
Payload	$ 277	$ 277	$ 277	$ 102	$ 102	$ 142	$ 143
Pre-launch GDS	$ 119	$ 119	$ 128	$ 43	$ 47	$ 65	$ 69
Development Reserve	$ 362	$ 363	$ 307	$ 72	$ 77	$ 125	$ 147
Total Development	$ 1,386	$ 1,386	$ 1,413	$ 444	$ 483	$ 682	$ 746
Launch Vehicle	$ 95	$ 132	$ 159	$ 95	$ 132	$ 107	$ 132
MO&DA + Reserve	$ 329	$ 329	$ 330	$ 342	$ 341	$ 337	$ 335
Total Mission Cost	$ 1,809	$ 1,847	$ 1,902	$ 880	$ 956	$ 1,126	$ 1,213

Table 52 shows a summary of space-based in-situ characterization system costs.

Table 52. Space-Based In-Situ Characterization Systems LCC Breakout

Concept Approach Descirption	C-21 Flyby Electric	C-22 Flyby Chemical	C-23 Flyby Impactor	C-24 Orbiter Only	C-25 Orbiter Lander	C-26 Orbiter Penetrator
PM/SE/MA	$ 23	$ 24	$ 47	$ 32	$ 57	$ 51
Flight System	$ 87	$ 92	$ 267	$ 157	$ 290	$ 257
Payload	$ 88	$ 88	$ 89	$ 89	$ 144	$ 128
Pre-launch GDS	$ 19	$ 19	$ 38	$ 26	$ 47	$ 41
Development Reserve	$ 54	$ 45	$ 120	$ 87	$ 135	$ 116
Total Development	$ 272	$ 268	$ 561	$ 392	$ 674	$ 593
Launch Vehicle	$ 117	$ 117	$ 117	$ 117	$ 142	$ 142
MO&DA + Reserve	$ 75	$ 78	$ 74	$ 198	$ 193	$ 194
Total Mission Cost	$ 464	$ 463	$ 752	$ 706	$ 1,009	$ 930

M.3. Detailed Deflection Element Cost Results

Table 53 contains a breakout of deflection system elements included in the life-cycle costs. These estimates include nominal costs for an appropriately sized Delta launch vehicle; the costs for Ares V at higher flight rates have not been determined.

Table 53. Deflection Systems Life-Cycle Cost Breakout

Concept Description	M-1 Nuclear Standoff	M-2 Nuclear Surface	M-3A Conventional Surface	M-3B Conventional Surface-Delay	M-4 Kinetic Impactor	M-5 Space Tug	M-7 Gravity Tractor
PM/SE/MA	$ 169	$ 162	$ 161	$ 161	$ 66	$ 486	$ 568
Flight System	$ 1,166	$ 1,115	$ 1,105	$ 1,105	$ 421	$ 3,320	$ 3,979
Payload	$ 50	$ 50	$ 50	$ 50	$ 51	$ 174	$ 111
Pre-launch GDS	$ 192	$ 184	$ 182	$ 182	$ 74	$ 551	$ 645
Development Reserve	$ 531	$ 487	$ 507	$ 507	$ 134	$ 1,294	$ 1,769
Total Development	$ 2,108	$ 1,998	$ 2,006	$ 2,006	$ 747	$ 5,825	$ 7,073
Launch Vehicle	$ 233	$ 233	$ 220	$ 220	$ 132	$ 233	$ 233
MO&DA + Reserve	$ 112	$ 112	$ 112	$ 112	$ 113	$ 559	$ 557
Total Mission Cost	$ 2,452	$ 2,342	$ 2,337	$ 2,337	$ 992	$ 6,616	$ 7,862

M.4. Characterization Architecture Cost Results

The figures in the section display the annual funding requirements in RY$M for each of the following characterization architectures:

Option	Descriptions
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
Option 6	O1 + O2 + O3 + 8 Orbiter Missions
Option 7	O1 + O2 + O3 + Orbiter Mission at Fixed P(I) Threshold

Table 54 shows the buildup of average life-cycle cost for each characterization capability option.

Table 54. Life-cycle costs of Characterization Capability Options

	Nominal Development Time (Parallel Developments)	Lifecycle Cost (Through 2020)
Architecture	Months	$B 2006
Option 1: Use Existing Assets + Detection and Tracking Systems		
Existing Optical + Shared DCT + Shared LSST	72	$ 0.7
Existing Radars + Shared DCT + Shared LSST	67	$ 0.2
Option 1 Average	**70**	**$ 0.5**
Option 2: Dedicated Ground Systems		
Existing Radars + Shared DCT + Shared LSST + Dedicated PS8	73	$ 0.3
Existing Radars + Shared DCT + Shared LSST + Dedicated PS16	73	$ 0.4
Existing Radars + Shared DCT + Shared LSST + Dedicated LSST	80	$ 0.7
Existing Radars + Shared DCT + Shared LSST + Dedicated IRTF	66	$ 0.3
Existing Radars + Shared DCT + Shared LSST + Dedicated Bistatic Radar	99	$ 0.4
Option 2 Average	**78**	**$ 0.4**
Option 3: Option 1 + Dedicated Space-Based Remote Sensing		
Existing Radars + Shared DCT + Shared LSST + 2m Vis LEO w/Filters	86	$ 2.0
Existing Radars + Shared DCT + Shared LSST + 2m Vis L1/L2 w/Filters	86	$ 2.1
Existing Radars + Shared DCT + Shared LSST + 2m Vis Venus-Like Heliocentric Orbit w/Filters	88	$ 2.3
Existing Radars + Shared DCT + Shared LSST + 0.5m Multi-Channel IR L1/L2	65	$ 1.1
Existing Radars + Shared DCT + Shared LSST + 0.5m Multi-Channel IR Venus-Like Heliocentric Orbit	63	$ 1.2
Existing Radars + Shared DCT + Shared LSST + 1.0m Multi-Channel IR L1/L2	72	$ 1.4
Existing Radars + Shared DCT + Shared LSST + 1.0m Multi-Channel IR Venus-Like Heliocentric Orbit	71	$ 1.4
Option 3 Average	**76**	**$ 1.6**
Option 4: Option 1+ Option 2+ Option 3 + 2 Flyby Missions		
Existing Radars + Shared DCT + Shared LSST Dedicated IRTF + 2 SEP Flyby Missions	67	$ 2.0
Existing Radars + Shared DCT + Shared LSST Dedicated IRTF + 2 Flyby Missions	67	$ 2.0
Option 4 Average	67	**$ 2.0**
Option 5: Option 1 + Option 2 + Option 3 + 8 Orbiter/Flyby Missions		
Existing Radars + Shared DCT + Shared LSST + Dedicated IRTF + 0.5m Multi-Channel IR + 8 Orbiters	67	$ 5.2
Existing Radars + Shared DCT + Shared LSST + Dedicated IRTF + 0.5m Multi-Channel IR + 8 Flybys	67	$ 3.7
Existing Radars + Shared DCT + Shared LSST + Dedicated IRTF + 0.5m Multi-Channel IR + 8 Flybys/Impactors	69	$ 4.9
Option 5 Average	**68**	**$ 4.6**
Option 6: Option 1 + Option 2 + Option 3 + 8 Orbiter/Lander Missions		
Existing Radars + Shared DCT + Shared LSST + Dedicated IRTF + 0.5m Multi-Channel IR + 8 Orbiter/Landers	68	$ 6.4
Existing Radars + Shared DCT + Shared LSST + Dedicated IRTF + 0.5m Multi-Channel IR + 8 Orbiter/Penetrator	69	$ 6.1
Option 6 Average	**69**	**$ 6.3**

Appendix N. Roles of Advanced Systems and Technologies

N.1. Detection, Tracking, Cataloguing, Characterization Systems

N.1.1. Advanced Follow-up Systems and Technologies

Radar measurements are useful for rapidly improving the accuracy of orbital information particularly during a close approach to Earth. Radar also can determine other PHO characteristics, including shape. Arecibo and Goldstone are limited to 0.3 AU for tracking and 0.1 AU for characterization. Radar signal strength decreases proportionally to the distance to the target (R) to the fourth power for radar signals ($\propto R^4$), making it very difficult to significantly extend the signal reach beyond what current systems can provide. Furthermore, increasing power beyond current levels will not significantly increase performance due the Earth's atmosphere. It is unlikely that a more capable radar will developed, and no technologies have been identified to improve effective radar ranging.

On the contrary, proposed telescopes with extremely large apertures will significantly affect both characterization and tracking accuracy. Based on the increase in aperture, the amount of light reaching a detector will increase by orders of magnitude. The increase in flux will allow more detailed spectroscopic measurements using smaller bandpasses. Some of the largest projects are predicting that with adaptive optics they will be diffraction limited and have resolution on the order of hundreds of micro-arc seconds, offering improved positional accuracy with every observation. In addition, recent advances have created ever-larger detectors that have a wide dynamic range, smaller pixels, large well depths, low dark current, low noise, fast readout, and very high quantum efficiency. These technologies will lead to improvements in follow-up and characterization systems.

Currently, several operational or nearly complete 8-meter or larger telescopes are coming on line, as shown in Table 55. Designed for astronomical imaging and/or spectroscopy, they, therefore, have small fields of view.

Table 55. Planned or Existing Large Observatories

Observatory	Effective Aperture	Location(s)
Gemini	8.1 m	Mauna Kea, Hawaii Cerro Pachon, Chile
Very Large Telescope	8.2 m	Cerro Paranal, Chile
Subaru	8.3 m	Mauna Kea, Hawaii
Hobby-Eberly	9.2 m	Mount Fowlkes, Texas
South African Large Telescope	9.8 m	Sutherland, South Africa
Keck	10.0 m	Mauna Kea, Hawaii
Large Binocular Telescope	11.8 m	Mount Graham, Arizona

Two approaches currently are available for obtaining a larger aperture: using a large number of small segments or combining the light from several telescopes. A number of telescopes with effective apertures significantly larger than 8 meters are under construction or in a significant design stage, and some of these are shown in Table 56. None of these systems is designed to have a wide field of view required by a survey mission, but they will likely add considerably to the ability to follow-up and characterize newly discovered objects.

Table 56. Proposed Very Large Observatories

Observatory	Effective Aperture	Location(s)
Gran Telescope Canarias	10.4 m	La Palma, Canary Islands
Keck Interferometer	14.6 m	Mauna Kea, Hawaii
Very Large Telescope	16.4 m	Cerro Paranal, Chile
Giant Magellan Telescope	21.4 m	Chile?

Even as these proposed telescopes are progressing, astronomers are planning the next class of ground-based telescopes, collectively considered Extremely Large Telescopes. They are listed in Table 57. Their funding and planning remain in flux due to the many technical challenges that they must be overcome.

Table 57. Postulated Extremely Large Observatories

Proposed Observatory	Effective Aperture	Proposed Location
Atacama Telescope Project	25 m	Cerro Chajnantor, Chile
Thirty Meter Telescope	30 m	To be determined
Maximum Aperture Telescope	30-50 m	To be determined
Euro50	50 m	La Palma, Canary Islands
Overwhelmingly Large Telescope	100 m	To be determined

The Atacama Telescope Project is intended to observe very long wavelengths, ranging from 100 microns into the sub-millimeter. Longer wavelengths should lead to improved characterization of asteroid composition and structure. The Thirty Meter Telescope project resulted from the merger of several 30-meter class projects each of which had run into technical or funding issues.

Using an infrared bandpass for the follow-up and characterization of PHOs is desirable. PHOs tend to have low albedo and will radiate in the infrared; there are twice as many solar photons available in that band as contrasted with the visible. In addition, solar phase angle dominates the apparent visible brightness of solar system objects, but plays little part in the infrared.

In summary, the ability to follow-up observations of asteroids to more accurately determine position, composition, existence of companions, rotation, and of asteroids using optical and infrared means can be expected to greatly increase over the foreseeable future.

N.1.2. Advanced Survey Systems and Technologies

Increasing the rate of detection of PHOs required for surveys relies primarily on two variables: the amount of light reaching the detector (telescope aperture) and observation geometry. Therefore, few technologies make a significant difference in NEO surveys other than increasing the amount of light available by increasing size of the aperture.

The size of near infrared detectors has progressed from 58 x 62 pixels to 2048 x 2048 pixels in a little over a decade; optical detectors are commercially available in much larger sizes, over 10k x 10k. An area of very active research today is to continue increasing the spatial extent of detectors with an immediate industry goal of creating a monolithic IR detector of 4096 x 4096 pixels. One of the greatest challenges is maintaining high uniformity across such a large area. These larger detectors will lead to more capable space-based systems, but at increased cost and spacecraft complexity. While the sensors on planned systems such as the James Webb Space Telescope may meet some of the sensitivity requirements for PHO detection, these systems are generally ill-suited to survey operations which need to cover larger areas of sky.

Future technology may allow for cheaper and more reliable space missions but will not fundamentally change the need to view from different angles for a PHO survey. Aside from the other benefit of circumventing atmospheric absorption, the difficulty, cost, and risk of space missions, particularly of launching very large optics and radiation damage to detectors leaves little room for growth barring a breakthrough in launch vehicles or deployable mirrors. The size of the Hubble Space Telescope (2.4 m), which itself is not suitable to survey or follow-up operations, appears to be at the practical limit for space-based optical systems.

Beyond the current 8-meter class of ground-based telescopes, proposed systems are not expected to have a large field of view, except the LSST. The steady increase in telescope aperture does not generally correspond to an increase in étendue, which is the limiting factor in optical system throughput. Therefore, the field of view for these extremely large telescopes will not increase appreciably from that of typical astronomical observatories without overcoming difficult optical design challenges. To avoid untenable growth in the size of the telescope enclosures; very fast optical systems are required leading to formidable difficulties keeping stray light off of the massive optical elements. This, in turn, requires short integration when observing in visible light, which partially negates the gain in aperture and leads to a reduction in telescope performance.

In parallel with ground state of the art, there are a number of large aperture (3.5 – 6 meters) space-based astronomical IR telescopes which are either on-orbit or will be by the close of the decade: Spitzer, Space Infrared Telescope for Cosmology and Astrophysics (SPICA), the Single Aperture Far-Infrared Observatory (SAFIR), and the James Webb Space Telescope (JWST). These telescopes share several key aspects in common: they will operate far from the Earth, either near L2 or in an Earth-trailing orbit; they are actively cooled, some to as low as 5.5 K to observe nearly the entire infrared spectrum, and have narrow fields of view. As detailed in another section of this study, detection rate of asteroids can be greatly increased if significantly different viewing geometries are available, e.g. a detector located in a Venus-like orbit. Future technology will likely allow for cheaper and more reliable space missions but will not fundamentally change the need to view from different angles for a NEO survey. Aside from the other benefit of circumventing atmospheric absorption, the difficulty, cost, and risk of space missions, particularly of launching very large optics and radiation damage to detectors leaves little room for growth barring a breakthrough in launch vehicles or deployable mirrors.

Cooling requirements have been relaxed somewhat for optical detectors but cooling of infrared detectors and optics remains necessary so that the instrument does not create its own warm photons that would mask the desired incoming light. Factors that directly affect the temperature at which a detector must be cooled are the composition of the detector (material and doping), the bias, and the cutoff wavelength; longer wavelengths require greater cooling. For instance, undoped silicon-based detectors have a bandpass of roughly 0.4 – 1.1 microns and can be operated at temperatures from 140º to 300º Kelvin. As the operating temperature is increased, the red response suffers and the dark current increases exponentially, resulting in noisier frames. Doped silicon, particularly the impurity-band conductor arsenic-doped silicon, can reach wavelengths of 26 microns but must be cooled to 10 K. If cooling were not an issue, this would be an example of a highly appropriate detector for a survey mission as it can be fabricated into fairly large arrays.

Material	Typical Bandpass (μm)	Operating Temperature (ºK)
Si	0.35 – 1.1	140 – 300
Doped Si	< 26	10
Ge	1.1 – 2.3	140 – 300
Doped Ge	< 25	25
InGaAs	1.1 – 1.7	77 – 140
InSb	2.2 – 5.5	65 – 77
HgCdTe	5.5 – 12	20 – 300

In the optical, quantum efficiency can be greater than 80% over much of the visible spectrum and into the near infrared; strictly in the infrared, HgCdTe chips routinely achieve 60% efficiency over a wider bandpass. Quantum efficiency is a function of wavelength and may drop off significantly before reaching either end of the bandpass depending on detector doping and fabrication. Since the quantum efficiency is generally so high, particularly in the optical, the only practical method of achieving lower threshold flux is to increase aperture. These improvements are not expected to lead to revolutionary survey system capabilities, but are part of the evolution of optical sensor technologies.

Two areas where infrared detector research is actively conducted are bolometers and quantum-well infrared photodetectors (QWIPS). These are unlikely to provide additional capabilities to survey or follow-up systems. Bolometers have a few advantages. They can be run at fairly warm temperatures, can be fabricated into fairly large detectors, and have very long cutoff wavelengths that extend to the microwave. However, little solar energy is reflected back at these long wavelengths. Their poor sensitivity exacerbates this. QWIPS has appeared to be a promising detector technology for the infrared, as the bandpass is fairly tunable during fabrication. The resulting bandpass is usually quite narrow and the detector sensitivity is roughly two orders of magnitude less than silicon, for instance.

In summary, advanced technologies are not expected to increase sensitivity over the currently planned 8-meter ground systems, and no planned systems larger than 8 meters are expected to be capable of a field of view useful for next-generation surveys. While space-based systems of the size proposed in this study appear feasible, these systems are approaching the practical limit of aperture size and, therefore, survey performance.

N.2. In-Situ Mitigation

N.2.1. Technologies

As discussed in recent NASA reports, advanced technologies may substantially increase the number of alternatives available for asteroid or comet deflection. [26] [27] A summary of these advanced technologies follows.

- High-thrust, high-specific impulse propulsion systems (such as plasma or nuclear) would deliver orbit modification systems to target NEOs and may provide the necessary efficiency to enable or significantly improve additional deflection alternatives.
- Multi-megawatt to gigawatt-class electrical power systems are required for many advanced propulsion and laser applications.
- Advanced thermal management systems are critical to reject large amounts of waste heat developed during the operation of many advanced deflection systems.
- Reliable, high-power pulsed laser ablation systems with adaptive laser optics, precision beam width focusing, and closed-loop control system would provide continuous orbit modification capability. Systems also could be potentially used as an active ranging system for precision orbit determination.
- Advanced autonomous or semi-autonomous rendezvous and station-keeping capability that engage the NEO at close distances are also necessary for many advanced concepts. In addition, formation-flying capability and precise attitude control may be needed for interferometry using orbiting detectors.
- Development of neutron or X-ray nuclear explosives may be considerably more effective than conventional devices. They can shed the crust of some types of asteroids, thereby providing additional efficiency in the transfer of explosive energy to PHO momentum.
- Lightweight materials for solar sails and inflatable structures might enable high-power systems, space tug alternatives, or allow hazardous objects to be “wrapped” in order to change thermal and electrical forces on the objects.

N.2.2. Suggested Studies

This analysis of the deflection alternatives suggests several areas where additional research and technology verification may be warranted to enhance the ability to mitigate a possible threat. Key issues raised in this study could be resolved through the following additional studies:

- *Understand the timing and key decisions that must be made during the evaluation of a potential threat.* As noted in this chapter, if a credible threat is identified in the next decade or two (while a precision orbit catalog is developed), it is likely that a decision to proceed will be based on imperfect information. If this transient problem is a concern, studies of the critical steps in the decision-making process would provide a decision tree to be followed in response to a credible threat. Perhaps a "war games" simulation would provide some useful insights.

- *Study intercept-trajectory design further.* As noted in some of the scenarios developed in this study, finding intercept trajectories that are within an available launch capability and actually intercepting the object can be a significant challenge for missions with short warning times. Studies should be conducted to define the set of threat conditions where trajectory options are currently available and suggest alternatives for those that are not.
- *Understand the prevalence, characteristics, and hazard of companion bodies.* It is known that NEOs can have companion bodies or moons, and it is possible that these bodies could be of sufficient size that they also threaten Earth. Studies are recommended to characterize the orbits of companion bodies.

Appendix O. Potential Synergy of Survey Systems with DoD

A classified report examining the possibility of using NEO survey systems for Department of Defense (DoD) applications and applying DoD assets or data to the NEO survey mission was prepared for this study. However, all of the fundamental findings of this effort are unclassified and are presented in this unclassified appendix.

While certain planned assets might, in principle, be able to contribute to the NEO detection problem, they could never perform this mission by themselves. In addition, the extensive NEO detection simulations carried out by JPL in recent months, with particular emphasis on Potentially Hazardous Asteroids (PHA), has clearly demonstrated that the incremental benefit would be small of almost all existing/planned assets identifying 90% of the 140-meter PHAs by 2020.

One of the most important findings of the NASA 2006 NEO Survey Study is that a key asset (such as an LSST-class telescope) trumps all others, except another key asset with a different bandpass and/or geometrical perspective — hence, the powerful synergy that is found between an LSST-class, optical ground-based telescope, and a space-based IR sensor at the L1 point, or the even more powerful synergy between a space-based optical sensor at Venus' orbit with a space-based IR one at either the L1 point or in a Venus orbit. No currently planned DoD sensor assets analyzed can provide much serendipitous support to key assets such as those.

In the following sections, the potential utility and known or expected disadvantages of existing or planned assets are discussed.

O.1. Contributions of DoD Systems to PHO Survey

O.1.1. System A

This geographically distributed set of ground-based optical telescopes has been for many years one of the mainstays of the Space Surveillance Network for the detection and tracking of deep space targets. With its recent upgrade to advanced CCD cameras, it is now producing more tracks per day than ever before. However, because of limited aperture sizes, and the Concept of Operations (CONOPS) of their standard surveillance mode, these sensors are unable to approach the limiting magnitude required for the PHA detection problem. Comparably sized optical telescopes with CCD cameras currently being used for asteroid detection, such as those of the Catalina Sky Survey and Project Spacewatch, have much better limiting magnitudes after several minutes of integration time per single look. It would not be possible to significantly improve upon this limit of System A.

O.1.2. System B

The primary mission and resultant CONPOS of System B preclude it from reaching the required limiting magnitude. In addition, its extremely fast optical design means that its limiting magnitude would be degraded by night-sky brightness even at longer integration times. An analysis of comparable systems has shown that copies of this asset, with a different optical design and a different CONOPS, might possibly contribute to the PHO detection problem, although not with sufficient performance to meet the congressionally mandated 2020 deadline. This contribution would at best be similar to systems such as sharing PS4 or LSST.

O.1.3. System C

This system has been the pathfinder for space-based surveillance systems. However, with its small aperture it could not contribute in any meaningful way to the PHO detection problem

O.1.4. System D

This sensor is designed to replace System C and act as a second pathfinder for space-based surveillance. However, despite its larger aperture and more advanced CCD focal planes, it could still only have a moderate PHO detection capability. Further, it is a single satellite system with a primary mission duty cycle that would preclude secondary tasking for NEO detection, other than purely serendipitous ones at rather bright limiting magnitudes. Duplicates of the space segment (with a new ground segment) are encompassed by other analyses in this report.

O.1.5. System E

This concept may be a future, multiple-satellite constellation of sensors, each at least as capable as that of System D. The multiple satellites in the constellation might alleviate the asset availability issue. Furthermore, there is the possibility of a future technology upgrade from Si CCDs, with a bandpass of 0.35 - 1.1 μm, to InGaAs detectors, with an increased bandpass of 0.4 to 2 μm, thereby doubling the number of reflected solar photons available to the sensor. Nevertheless, these systems ultimately will still be aperture-, and thus, stare-time limited. Longer integration times place severe drift and jitter demand on the spacecraft and, along with the requirement for multiple looks, also on the duty cycle of the sensor constellation. These space systems could potentially be modified for the purpose of detection PHOs, but are not very capable in their current configurations for this task.

In general, these space sensor systems would have to interleave PHO tasking with their standard mission planning. New search patterns and algorithms also would be required, along with appropriate data pathways. While it is possible that an integrated system could be developed, it is difficult to predict if the global benefit would warrant the demonstrated difficulty of working across classification and national mission boundaries.

O.1.6. System F

This concept shares many of the attributes of System E, but it is unlikely that its sensors will actually be as capable in terms of limiting magnitude.

O.1.7. Summary

In summary, all current and planned sensor assets studied have technological or operational limitations that will constrain their ability to contribute significantly to the

NEO search mission. This is even more so when such assets are compared with a ground-based LSST-class telescope or a space-based system.

O.2. Possible Contributions of NEO Survey Systems to Other Missions

A fully government-owned and operated LSST-class system would be able to contribute to other missions, although it would have concept of operations issues if a NEO search were its primary mission. Pan-STARRS1 (PS1) may have to deal with exactly this problem. However, the LSST design is not ideal for synoptic space surveillance (slew rate will be low and the telescope is too large). System B is a better design for synoptic space surveillance of deep space targets than LSST. An LSST could do targeted space surveillance (and SOI) for deep space. This would slow down the NEO search rate, however, and extend the 90% Survey completion schedule.

It is very likely that none of the space-based concepts for NEO search can contribute at all to other missions — most are simply stationed too far from the Earth (L1 or Venus orbit). A large-aperture LEO optical asset might be ideal for these other missions, but is sub-optimal for the search for PHOs. Follow-up assets for NEOs have their own unique requirements, and generally do not lend themselves to other missions, except perhaps Space Object Identification (SOI). For example, given a large-aperture, ground-based IR telescope at high-altitude, the ability to share such an asset between NEO follow-up observations and SOI missions could work, although prioritization may be an issue.

In summary, no asset proposed for this study meets any significant fraction of the DoD requirements when concept of operations and duty cycle are considered.

O.3. Sharing of Archived Data

In general, the DoD systems studied do not archive data sufficiently long enough to support activities such as precovery. Systems A and C may archive more data than others, but neither of these meets sensitivity requirements for precovery. In addition, assets planned for the near future will have the same data archiving limitations. Precovery is most effective in astronomy applications tailored for NEO surveys; that is, when large field of view photographic plates are used. As both the Survey program systems and future DoD systems are fielded, opportunities for sharing data between missions will be explored further. If opportunities for cooperation or collaboration are identified, these will be pursued as they are now, but advanced planning to facilitate these interactions may not be warranted.

Appendix P. Potential Synergies of Deflection with Exploration

One approach to developing technologies and capabilities required for deflection is to develop and use deflection-related technologies as part of exploration missions. Techniques and hardware required for robotic systems and resource utilization on the Moon or landing large payloads on Mars, for example, relate directly to those needed for subsurface explosives, mass drivers, or a space tug. Developing confidence in the ability to utilize these common technologies reliably will lower the risk of using them for deflection missions.

Table 58 shows that a number of capabilities, including space transportation, rendezvous, autonomous systems, and highly robust solutions, are needed for many PHO characterization and deflection systems. They overlap with technologies required to explore the solar system. Other technologies, such as nuclear and conventional explosives and precision intercept, do not. Therefore, the Deep Impact missions and other opportunities might be used to develop confidence in these techniques. Large energy sources also appear to be a common need, and the availability of reliable sources of power would facilitate the evolution of slow push deflection approaches.

Given the relatively poor performance of the slow push techniques, it does not appear that they provide a conclusive rationale for developing nuclear or other high specific impulse propulsion technologies. However, if these technologies were developed for Exploration or science, their use could be re-evaluated in the context of their demonstrated performance.

There may be options for system-level demonstrations of the Crew Exploration Vehicle (CEV), Ares I (crew launch vehicle), Lunar Surface Access Module (LSAM), and/or Ares V (lunar cargo launch vehicle) to contribute to PHO deflection demonstrations. For example, in 2012 and 2013 several uncrewed launches of the Ares I will be conducted with the CEV's Crew and Service Modules. These systems have considerable mass, precision rendezvous and docking capability, as well as considerable performance margin when the Service Module is fully loaded. A similar system launched at a passing PHO could provide a significant deflection demonstration.

In addition, while the Ares V's Earth Departure Stage does not have rendezvous capability, it does have sufficient performance to launch a large demonstration vehicle for many of the deflection alternatives. It is possible that the demonstration of parts of the lunar system could be directed toward an asteroid deflection to improve the reliability of lunar system elements.

Table 58. Characterization and Deflection Technology Needs Compared with Exploration

<table>
<tr><th rowspan="2">Technologies required</th><th rowspan="2">Space transportation & rendezvous *</th><th rowspan="2">Soft landing</th><th rowspan="2">Precision landing</th><th rowspan="2">Anchoring</th><th rowspan="2">Highly autonomous **</th><th rowspan="2">Highly robust ***</th><th colspan="2">Large energy source</th><th rowspan="2">High accuracy tracking</th><th rowspan="2">Low G mining</th></tr>
<tr><th>Large Solar collectors</th><th>Nuclear</th></tr>
<tr><td>**NEO Characterization**</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Optical mapping</td><td>X</td><td></td><td></td><td></td><td>X</td><td>X</td><td colspan="2">X</td><td></td><td></td></tr>
<tr><td>Gravity/volatile mapping</td><td>X</td><td></td><td></td><td></td><td>X</td><td>X</td><td colspan="2">X</td><td></td><td></td></tr>
<tr><td>Local surveying</td><td>X</td><td></td><td></td><td></td><td>X</td><td>X</td><td colspan="2">X</td><td></td><td></td></tr>
<tr><td>Sample collection/analysis</td><td>X</td><td>X</td><td></td><td>X</td><td>X</td><td>X</td><td colspan="2">X</td><td></td><td>X</td></tr>
<tr><td>**NEO Mitigation**</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Standoff Nuclear Explosive</td><td>X</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Nuclear Surface Detonation</td><td>X</td><td></td><td>X</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Kinetic Impactor</td><td>X</td><td></td><td>X</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Conventional Explosive (Surface Detonation)</td><td>X</td><td></td><td>X</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Gravity Tractor</td><td>X</td><td></td><td></td><td></td><td>X</td><td>X</td><td></td><td>X</td><td></td><td></td></tr>
<tr><td>Asteroid Tugboat</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td colspan="2">X</td><td></td><td></td></tr>
<tr><td>Laser</td><td></td><td></td><td></td><td></td><td>X</td><td>X</td><td colspan="2">X</td><td>X</td><td></td></tr>
<tr><td>Focused Solar</td><td>X</td><td></td><td></td><td></td><td>X</td><td>X</td><td>X</td><td></td><td>X</td><td></td></tr>
<tr><td>Embedded Nuclear Explosive</td><td>X</td><td></td><td>X</td><td></td><td></td><td></td><td></td><td></td><td></td><td>X</td></tr>
<tr><td>Standoff Conventional Explosive</td><td>X</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Embedded Conventional Explosive</td><td>X</td><td></td><td>X</td><td></td><td></td><td></td><td></td><td></td><td></td><td>X</td></tr>
<tr><td>Mass Driver</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td>X</td><td></td><td>X</td><td></td><td>X</td></tr>
<tr><td>Enhanced Yarkovsky Effect</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>**Exploration**</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Robotic</td><td>X</td><td>X</td><td></td><td></td><td>X</td><td>X</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Manned sorties to moon</td><td>X</td><td>X</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Manned sorties to Mars</td><td>X</td><td>X</td><td></td><td></td><td></td><td>X</td><td colspan="2">X</td><td></td><td></td></tr>
<tr><td>Surface operations</td><td>X</td><td>X</td><td></td><td>X</td><td>X</td><td>X</td><td colspan="2">X</td><td></td><td>X</td></tr>
</table>

* Beyond earth orbit

** A certain amount of autonomy is expected for all options, highly autonomous refers to those options which have a need for long term, remote operations.

*** A certain amount of robustness is expected for all options, highly robust refers to those options which have a need for long term, remote operations.

Appendix Q. Potential Synergies of Deflection with the DoD

Q.1. Overview

The U.S. Air Academy SPACECAST 2020 report, which was published in 1994, discusses the surveillance of objects that could potentially impact the Earth and examines ways to counter threats through various deflection techniques. This Air Force report takes the position that asteroids are potential threats that the DoD should evaluate and prepare to defend against. The report also discusses benefits of a DoD role in an international effort and provides some specific recommendations.

However, unless significant funding is allocated to developing and testing asteroid deflection technique(s), any future asteroid deflection campaign will be a “come as you are” affair. It will involve whatever assets and infrastructure are available at the time, probably on a global scale.

Q.2. Launch Systems

Launch requirements for specific asteroid deflection approaches are described in the body of this report. In general, the minimum launch requirements for asteroid deflection include large-lift capacity (6000 kg or more into high-energy, interplanetary trajectories), multiple interceptor launches during infrequent and very short windows of opportunities (a few weeks at most), and long transit times (up to many years) prior to an autonomous terminal guidance phase to collide or rendezvous with the target asteroid.

The Delta 4 Heavy is the largest launcher available in the U.S. and is operated primarily for the U.S. Air Force. NASA plans call for the development of a heavy-lift expendable launch vehicle for Moon and Mars exploration. Expected to be available by 2020, the vehicle may use RS-68 engines similar to those on the Delta 4 Heavy.

With several years of warning, the Delta 4 may be able to launch a nuclear explosive that could deflect a percentage of the potentially threatening objects, with sizes ranging up to several hundred meters in diameter. But the Delta 4 cannot be surge launched in rapid succession during short windows, which this report suggests to assure launch success and redundant intercept attempts. Also, the Delta 4 has only one launch site, which is subject to weather delays.

Until a more capable (larger and higher surge flight rate) is available, an asteroid deflection campaign will require using the heaviest launch vehicles available from many nations to ensure overall success.

Although the DoD’s evolving launch requirements call for eventually developing a capability to responsively launch tactical payloads in rapid succession, these systems will not provide the heavy-lift capability required for asteroid deflection. Recent studies have not been able to find a stronger linkage than currently exists between DoD requirements for small “launch on need” capabilities, DoD and NASA requirements for “commercial” launch Earth orbit on schedule services, NASA’s requirement for infrequent “launch on schedule” interplanetary missions, and a capability to support a possible asteroid deflection (many rapid very heavy interplanetary launches once every 5,000 years on average).

In 1996, The Aerospace Corporation analyzed a wide range of futuristic space applications (civil, military, and commercial) and their launch requirements to see if dramatic cost reductions might be possible if missions emerged. As part of this study Aerospace developed a Space Transportation Economic Index (STEI) — a numerical scoring method to compare the feasibility of each futuristic application's spacelift requirements with current spacelift capabilities and cost.

The index considers weight to orbit, flight rate, required launch cost (for economic feasibility of the mission), and manned as compared with unmanned reliability as variables in the evaluation, and included many types of commercial, civil, and military missions. An STEI score of 1.0 is typical of today's commercial and military programs. Potential space applications with higher STEI scores require significant reduction in launch costs to be economically feasible.

Asteroid deflection (a launch application not considered in the original Aerospace study) has among the highest STEI scores recorded. Therefore, it is very unlikely that any future military, civil, or commercial application will emerge to justify the development and sustainment of a heavy-lift launch fleet with a surge launch capability that could be available for an asteroid deflection campaign.

Launch services are, indeed, likely to be "come as you are" situations.

Q.3. Deflection Campaign Operations

Currently, no government agency or international organization has overall responsibility for deflecting asteroids to avert the threat of an impending collision, although NASA's charter includes the goal of protecting Earth. Coordinating and de-conflicting deflection attempts by different countries will be required. Mission planning and execution procedures among missions will need to be established, probably by international agreement under United Nations auspices. Oversight by a U.S. military agency would likely not be acceptable to the world community, particularly if nuclear technologies were required, as is likely.

If an asteroid threatened the Earth, it can be assumed that the U.S. government would suspend many of the treaty and ITAR constraints that currently discourage international cooperation. Such constraints would place severe limits on international cooperation.

Q.4. Guidance Technology

During the terminal guidance phase, the interceptor must autonomously guide itself toward the desired aim point on the surface of the asteroid at very high closing velocities. Rendezvous, on the other hand, occurs at very low closing relative velocity and is not technically as difficult as interception, provided there is sufficient fuel and maneuver authority to continuously correct guidance errors until it lands or achieves orbit.

A unique aspect of the asteroid intercept problem is that the extended target may have an unknown, irregular shape. For missile defense interceptors, a relatively smaller target remains essentially a point image right up until impact, simplifying the guidance problem significantly. The asteroid's image will balloon in size on an optical tracking system's focal plane during the terminal phase. The expanding edge could confuse methods developed for defense applications to the point that they think that the object has additional relative motion. DoD experience with homing guidance against large extended targets is limited and the asteroid impact problem would likely require different techniques.

Additionally, radar and laser ranging can become ambiguous due to the size and terrain of an asteroid. This can affect terminal guidance and warhead fusing. The DoD has considerable experience with bomb fusing, but not at the high closing velocities seen in asteroid deflection.

For kinetic and surface explosive deflection techniques, the desired aim point is through the object's center of gravity. The center of gravity may be difficult to determine if the shape is irregular and made of multiple large masses. Characterization missions might be able to determine the shape of the object, but the exact attitude of the object at the time of impact also must be known to determine the exact aim point. Again, DoD experience with this sort of targeting problem is limited or non-existent, as targets are generally well characterized.

The time delays and high closing velocity during terminal intercept maneuvers preclude man-in-the-loop commanding of an asteroid interceptor, as with TV-guided bombs. Many of the rendezvous and "slow push" operations will need to be autonomous due to communication time delays or the lack of communication altogether if the deflection system is out of Earth's line of sight.

The DoD has considerable experience with "fire and forget" cruise missiles, but flight times for these systems are only a few hours, not the years required for transit time or the months of "slow push" operations. NASA experience with interplanetary trajectories is likely more applicable to this problem than DoD's.

Since significant research and development and testing of sensor suites and guidance systems suitable for hitting the center of gravity of an extended, irregularly shaped asteroid target will be required, there is little synergy with DoD terminal guidance requirements and technologies.

Q.5. Industrial Base

Currently, all sectors of the space industry (military, civil and commercial) are struggling. The worldwide launch rate has been stagnant or declining for the last several years. In addition, fiber optics, the end of the Cold War, emergence of terrorist threats, and lack of enthusiastic support for human spaceflight make some less bullish on the future growth of space applications. The overall situation is pressuring the commercial and civil space sectors to consolidate and eliminate capabilities. Consequently, military space acquisition officials are concerned about the future health of the industrial base needed to support proposed advanced military programs.

In light of these prospects, will adequate technologies and sufficient production and launch infrastructure exist in the future to support an asteroid deflection campaign?

As called for in the SPACECAST 2020 report, DoD cooperation with agencies planning for an asteroid deflection should be encouraged. The challenge is to translate public and congressional concerns about the potential threat of an asteroid hitting the Earth into a reinvigoration of the military and civil industrial base to meet such threats. This could be done while avoiding the security and international issues that a cooperative effort may create. Even in the event of an identified threat, the issues related to the classification of some potentially relevant technologies may make DoD participation difficult, particularly if the asteroid strike is not likely to affect the U.S. (which is likely for local or regional impact scenarios).

The need to work with the international space community, as NASA does with the International Space Station, poses a severe constraint on DoD's involvement in the asteroid deflection and technology development effort. Military space officials are always mindful that foreign governments may want to develop their own military space capabilities and see ventures with the U.S. as a way to gain access to U.S. technology.

Q.6. Conclusion

The DoD would obviously play important roles in any asteroid deflection campaign, especially if nuclear explosives are called for. But many aspects of asteroid deflection (surge heavy-lift launch, high-speed terminal guidance against large extended objects, autonomous operations over several years, international cooperation, and information sharing) have little or no synergy with DoD's current or future requirements for space systems.

Appendix R. Role of Nuclear Explosives Technology

As part of this study, a representative of the National Nuclear Safety Administration (NNSA) prepared a classified report on the role of nuclear technologies for the deflection of PHOs. An unclassified summary of this report appears in this appendix.

R.1. Nuclear Explosive Design

The principal assumption made about nuclear explosives is that their approximate yield-to-weight ratio in the range of tens of kilotons to tens of megatons is well known. It is further assumed that these devices are sufficiently well known and that they either exist or could be made available within 12 to 18 months.

Within limits these assumptions are true. The process to construct nuclear explosives in the range of yields that have been tested and stockpiled by the U.S. is well known. It is probably safe to assume that the same holds true of Russia. There are some points that must be taken into consideration, however. They are described in detail in the classified report:

- Current designs for nuclear explosives were not intended for use in deep space. It is unknown and unlikely that one could take a stockpile weapon and use it for PHO mitigation without any modification. However, nuclear explosives have been tested in space and there are no known impediments to their use for PHO deflection. The roles of DoD and DoE and the regulatory requirements are not clear in the event such an event became necessary.
- While no nuclear testing would be needed to qualify a physics package for space applications, the necessary electromechanical components (arming, fusing, and firing) might need some modification and in-space qualification.
- The U.S. no longer stockpiles multi-megaton warheads. If there were a need for a very high-yield device, there is ample design and test information to construct such a device given sufficient lead-time (12-18 months).
- Enhanced Radiation Systems (nuclear explosives designed for generating a large fraction of energy in the form of neutrons, for example) have been designed and tested by the U.S. Explosives of this type for NEO deflection and mitigation could be produced without requiring testing.
- Specific designs can and would be designed for optimal launch and potential re-entry safety. This includes using the most advanced available technologies to ensure that the device could not be used as a weapon if lost.