Finding Hazardous Asteroids Using Infrared and Visible Wavelength Telescopes

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Committee on Near Earth Object Observations in the Infrared and Visible Wavelengths

Space Studies Board

Division on Engineering and Physical Sciences

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Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

Lance A.M. Benner, Jet Propulsion Laboratory, California Institute of Technology,
William F. Bottke, Southwest Research Institute,
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Yanga Fernandez, University of Central Florida,
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Zeljko Ivezic, University of Washington,
Harold Reitsema, Independent Consultant,
Irwin I. Shapiro, NAS,[1] Harvard-Smithsonian Center for Astrophysics,
Grant H. Stokes, NAE,[2] MIT Lincoln Laboratory,
George W. Sutton, NAE, Analysis and Applications, Inc., and
Faith Vilas, Planetary Science Institute.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Steven J. Battel, NAE, Battel Engineering, Inc. He was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content of the report rests entirely with the authoring committee and the National Academies.

[1] Member, National Academy of Sciences.
[2] Member, National Academy of Engineering.

Preface

In summer 2018, NASA's Chief Scientist asked the National Academies of Sciences, Engineering, and Medicine to establish a study to address the issue of the relative advantages and disadvantages of infrared and visible observations of near Earth objects (NEOs). NASA has had a NEO observation program for nearly two decades using ground-based telescopes to search the night sky for NEOs that are large enough to cause major damage if they impact Earth. Since 2005, NASA has been guided in its search by the requirements of the George E. Brown, Jr. Near-Earth Object Survey Act. In recent years, NASA has used a space-based telescope to aid in its NEO search and has studied the possibility of using a dedicated space-based telescope to continue this work. This report of the Committee on Near Earth Object Observations in the Infrared and Visible Wavelengths addresses the space-based telescope subject while acknowledging that there are many larger issues associated with detecting, tracking, and characterizing NEOs.

Contents

Summary

In December 2018, an asteroid detonated in the upper atmosphere over the Bering Sea (western Pacific Ocean) with the explosive force of nearly 200 kilotons, or 10 times that of the Hiroshima bomb. This event, which was detected by various sensors and spotted by a Japanese weather satellite, demonstrates that Earth is frequently hit by objects, some of which could cause significant damage if they hit a populated area, as happened almost 6 years earlier over the Russian city of Chelyabinsk. Currently, NASA funds a network of ground-based telescopes and a single, soon-to-expire space-based asset to detect and track large asteroids that could cause major damage if they struck Earth. In 2018, NASA asked the National Academies of Sciences, Engineering, and Medicine to establish the ad hoc Committee on Near Earth Object Observations in the Infrared and Visible Wavelengths to investigate and make recommendations about a space-based telescope's capabilities, focusing on the following tasks:

- Explore the relative advantages and disadvantages of infrared (IR) and visible observations of near Earth objects (NEOs).
- Review and describe the techniques that could be used to obtain NEO sizes from an infrared spectrum and delineate the associated errors in determining the size.
- Evaluate the strengths and weaknesses of these techniques and recommend the most valid techniques that give reproducible results with quantifiable errors.

THE GEORGE E. BROWN ACT AND NEO DETECTION, TRACKING, AND CHARACTERIZATION

Currently, NASA's efforts to detect and track NEOs are guided by the 2005 George E. Brown, Jr. Near Earth Object Survey Act,[1] which requires NASA to "detect, track, catalogue, and characterize the physical characteristics of near Earth objects equal to or greater than 140 meters in diameter in order to assess the threat of such near Earth objects to Earth. It shall be the goal of the Survey program to achieve 90 percent completion of its near Earth object catalogue (based on statistically predicted populations of near Earth objects) within 15 years after the date of enactment of this Act."

NASA has not accomplished this goal and cannot accomplish it with currently available assets by December 31, 2020.[2] Although Congress has charged NASA with NEO detection and threat characterization, it has failed to provide specific funding to enable NASA to adequately pursue this task.

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[1] Technically, this language was included in the 2005 NASA Authorization Act, which states: "This section may be cited as the 'George E. Brown, Jr. Near-Earth Object Survey Act.'" The committee uses the terms "George E. Brown" and "George E. Brown Act" throughout this report. The goals established by the George E. Brown Act were primarily derived from NASA, "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," August 22, 2003, https://www.nasa.gov/sites/default/files/atoms/files/pdco-neoreport030825.pdf

[2] A 2017 report indicated that it would take 9-25 years to complete the survey, depending on search methods (and equipment) that was employed. This places the earliest date for completing the survey in the later 2020s (G.H. Stokes et al., 2017, *Report of the Near-Earth Object Science Definition Team: Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs*, NASA Science Mission Directorate, p. iv).

The George E. Brown Act was based on findings of a 2003 NASA science definition team study of NEOs. A follow-on 2017 NEO science definition team report also used the act as a baseline (e.g., the focus on 140-meter diameter NEOs and a 90 percent completion rate). Any effort to develop a survey of NEOs must have goals to compare to, and most studies and proposals for NEO searches since the act have used its goals as the baseline.

In addition to detecting NEOs and determining their orbits, it is necessary to estimate their mass to quantify their destructive potential. An NEO's diameter is the most readily available indicator of its mass, a value that can be improved when a density estimate is available. This is the rationale for the 140-meter-diameter requirement included in the act—finding 90 percent of that population or larger would eliminate 90 percent of the remaining hazard from NEOs (at the time of the publication of the Stokes et al. (2003) report).[3] In the 14 years since the passage of the George E. Brown Act, there have been several studies that have reiterated the validity of the 140-meter-diameter requirement and indicated that even smaller size asteroids can pose a significant threat. The asteroid that exploded over Chelyabinsk, for example, is estimated to have been approximately 20 meters in diameter. It damaged more than 7,000 buildings and injured approximately 1,600 people. In comparison, Arizona's Meteor Crater, which is approximately 50,000 years old, is believed to have been created by a significantly denser (nickel/iron) object approximately 50 meters in diameter (see Figure S.1). Asteroids smaller than 140 meters in diameter are much more numerous than those larger than this size. Although they are far more difficult to detect and track, many of them are still detected in the search for larger asteroids. Although asteroids smaller than the size established in the George E. Brown Act pose a hazard, it is not currently practical to implement systems capable of detecting and tracking a significant proportion of them, and the committee concluded that the requirements established in the George E. Brown Act remain valid.

Recommendation: Objects smaller than 140 meters in diameter can pose a local damage threat. When they are detected, their orbits and physical properties should be determined, and the objects should be monitored insofar as possible.

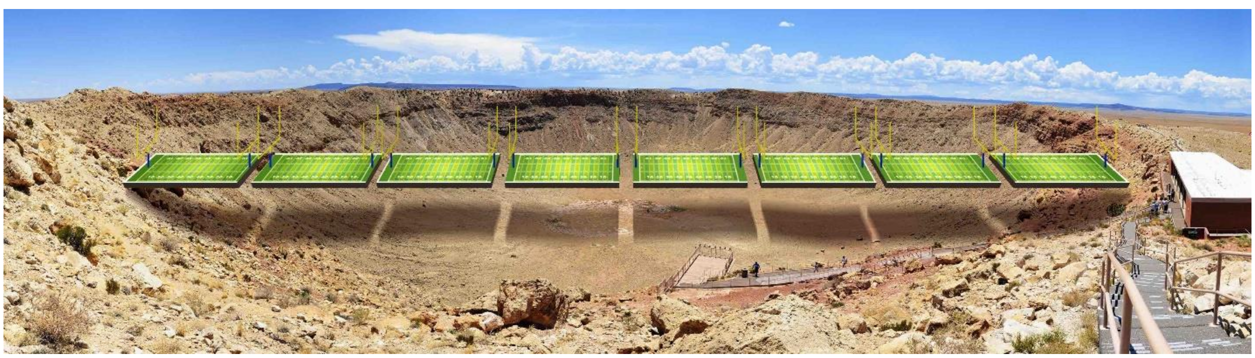

FIGURE S.1 An illustration showing Arizona's Meteor Crater with football fields superimposed to provide a sense of scale. This crater was created approximately 50,000 years ago by a nickel-iron asteroid estimated to have been 50 meters in diameter.

The committee concluded that the accuracies of determining NEO diameters derived from thermal-infrared measurements and simple modeling usually far exceed those based on measurements of visible brightness alone. For this reason, thermal-infrared detection and tracking of asteroids, which can be accomplished only by a space-based platform (due to the properties of Earth's atmosphere, which block infrared wavelengths), is highly valuable. A thermal-infrared search program that can detect NEOs, determine their orbits, and measure NEO sizes to 25 percent typical uncertainty or better is preferable to separate search and characterization programs. To gain the same information about an NEO's size with ground observations would require both a search program and a separate characterization program.

[3] The risk of impact by long period comets (LPCs) is much lower than the risk of impact by NEOs.

Characterization—that is, determining the physical properties of NEOs—is critical for a full understanding of impact hazard. Characterization observations include radar as well as photometry and spectroscopy in the visible and near infrared. Although planetary defense missions are not science driven, significant scientific input is essential to optimally design a planetary defense task.

SPACE-BASED NEO DETECTION AND TRACKING

After hearing from representatives of different organizations, including persons who had sought to develop alternative proposals for both ground- and space-based NEO detection systems, the committee concluded that a space-based thermal-infrared telescope designed for discovering NEOs is the most effective option for meeting the George E. Brown Act completeness and size requirements in a timely fashion (i.e., approximately 10 years) (see Figure S.2). The most important justification for a shorter timespan is that mitigation by deflection requires early detection.

A thermal-infrared discovery survey will provide an immediate measure of asteroid diameters—and hence a mass estimate—even without a measurement of the asteroids' optical brightness. An optical discovery survey is not able to provide this diameter measurement/mass estimate with the same accuracy within a similar timeframe, as it depends upon thermal-infrared follow-up observations. Furthermore, the availability of an observation asset capable of obtaining this thermal-infrared follow-up is not guaranteed (ground-based observations are strongly limited in wavelength range and sensitivity, while future space-based infrared observatories like the James Webb Space Telescope are not able to perform quick-turnaround observations or nearby NEOs). Hence, only a space-based thermal-infrared survey is capable of meeting the requirement of obtaining a diameter/mass estimation. A major advantage of an infrared space-based system is its ability to provide the diameter shortly after detection, as soon as orbital parameters are available. Visible light and near-infrared measurements are severely compromised for size determination, whereas even relatively simple analyses of mid-infrared measurements can return accurate sizes for NEOs. Visible, ground-based surveys are also compromised by the day-night cycle and weather, as compared to space-based surveys. As a result, a space-based infrared survey is better able to detect and characterize the NEO population to meet the requirements of the George E. Brown Act goal. A detailed study of a mid-infrared mission has concluded that the proposed system can reach the George E. Brown Act goal more quickly than currently considered alternatives.[4] (See Appendix C for a summary table of advantages and disadvantages of ground and space based options for infrared and visible observations of NEOs.)

The committee found that in-space infrared telescopes

- Are more effective at detecting NEOs than visible wavelength in-space telescopes,
- Provide diameter information that visible wavelength telescopes cannot provide, and
- Do not cost significantly more than in-space visible wavelength telescopes (a primary driver of space telescope cost is aperture).

Although ground-based visible telescopes can be significantly less expensive than space telescopes, currently existing and building visible ground-based telescopes (such as the Large Synoptic Survey Telescope [LSST]) cannot accomplish the goals of the George E. Brown Act. The committee heard from experts on LSST that in 10 years LSST would be 50-60 percent complete for NEOs with an absolute magnitude (H) of less than 22. When combined with other search efforts, this would be approximately 77 percent.[5]

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[4] G.H. Stokes, et al., 2017, *Report of the Near-Earth Object Science Definition Team: Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs*, NASA Science Mission Directorate, p. 187.

[5] "LSST's Projected NEO Discovery Performance," Steve Chesley & Peter Vereš, Briefing to NAS Committee on Near Earth Object Observations in the Infrared and Visible Wavelengths, Irvine, California, February 25, 2019.

Recommendation: If the completeness and size requirements given in the George E. Brown, Jr. Near-Earth Object Survey Act are to be accomplished in a timely fashion (i.e., approximately 10 years), NASA should fund a dedicated space-based infrared survey telescope. Early detection is important to enable deflection of a dangerous asteroid. The design parameters, such as wavelength bands, field of view, and cadence, should be optimized to maximize near Earth object detection efficiency for the relevant size range and the acquisition of reliable diameters.

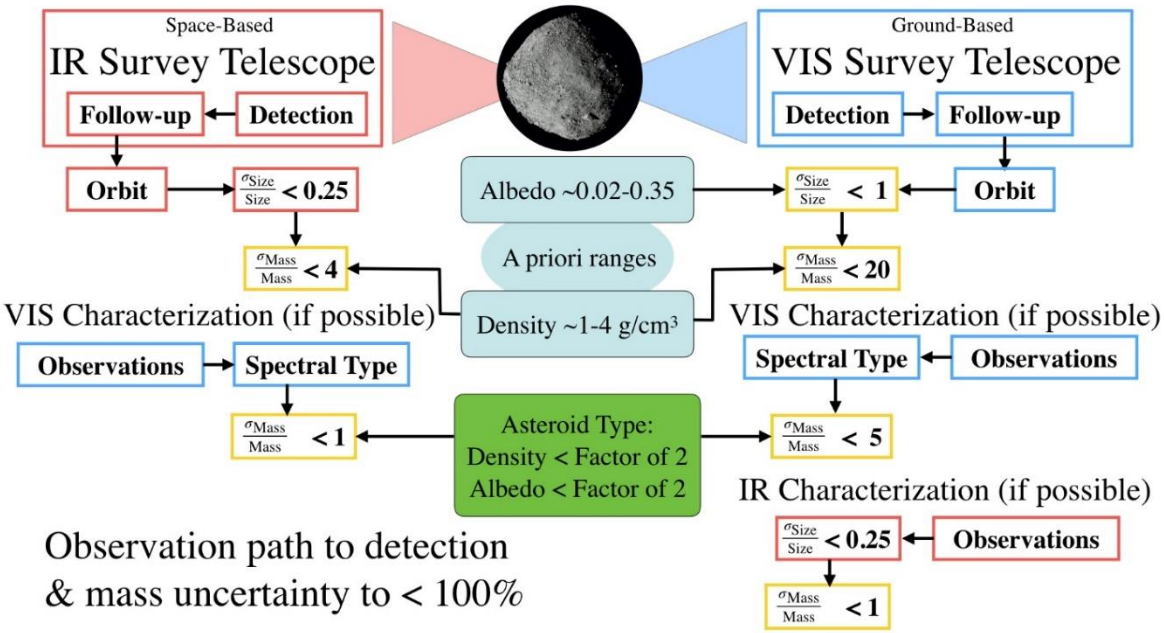

FIGURE S.2 Necessary sequence of observations from asteroid discovery to a mass determination accurate to ~100 percent. *Left*: An asteroid detected with a space-based infrared observatory will immediately have a mass uncertainty to within a factor of 4. If follow-up observations determine its spectral type, the mass uncertainty reduces to a factor of 1. *Right*: An asteroid detected with a ground-based visible observatory has an initial mass uncertainty to within a factor of 40. If follow-up observations determine its spectral type, the mass uncertainty reduces to a factor of 10, and infrared observations reduce this uncertainty by up to a further factor of 10. Uncertainty estimates are approximate and based on assumed ranges in albedo and density. The light blue box shows a priori uncertainties in density and albedo from the overall population. The green box shows the expected improvement in these parameters if the asteroid type can be determined using follow-up spectroscopy observations.

For more than a decade, NASA has provided technology development funding for a space-based, passively cooled, thermal-infrared telescope designated NEOCam, but has not pursued this project to full-scale development. The committee heard from representatives from NEOCam. The committee also heard from a representative from NASA Goddard Space Flight Center who had proposed alternative space-based telescope proposals and a representative from the Jet Propulsion Laboratory who is proposing a small satellite (SmallSat) telescope constellation. Proposed alternatives include visible wavelength ground- and space-based telescopes and SmallSat constellations. The committee concluded that, at the moment, none of these alternatives is competitive with a thermal-infrared space telescope in terms of detection capabilities or cost.

To date, opportunities for a space-based NEO survey telescope have been primarily available via the Discovery program. However, *Vision and Voyages for Planetary Science in the Decade 2013-2022* (the 2011 planetary science decadal survey), a report that prioritizes the planetary science program and exerts great influence on the selection of Discovery mission proposals, explicitly does not address "issues relating to the hazards posed by near Earth objects and approaches to hazard mitigation."[6] As a result, there is a bias against selection of planetary defense-focused missions in this program or any other program without an explicit planetary defense component.

Recommendation: Missions meeting high-priority planetary defense objectives should not be required to compete against missions meeting high-priority science objectives.

CURRENT NASA NEO SURVEY EFFORTS

NASA currently funds several ground-based telescopes for NEO detection, including the Catalina Sky Survey, Pan-STARRS, among others. It also funds the space-based NEOWISE spacecraft, which will likely not operate much longer (possibly less than 1 year). No existing ground- or space-based platform can satisfy the size and completeness requirements of the George E. Brown Act goals in the foreseeable future. A new, dedicated survey mission is required to achieve the George E. Brown Act goals.

The LSST, which is expected to enter into operation in 2023, has—in addition to a number of astrophysics missions—the mission to detect solar system objects and NEOs at a higher rate than current ground-based telescopes. However, LSST will not achieve the George E. Brown Act goals even after a decade. Even a dedicated LSST optimized for NEO detection would not achieve the George E. Brown Act goals for several decades. The committee heard from representatives of LSST about its capabilities for NEO detection and concluded that, even though it cannot meet the completeness goal at the appropriate time, it would be useful for NASA to fund work to discover NEOs in the LSST archive as a complement to other methods.

Observation by ground-based systems equipped with specific instrumentation is necessary for subsequent characterization of NEOs after discovery.

Recommendation: If NASA develops a space-based infrared near Earth object (NEO) survey telescope, it should also continue to fund both short- and long-term ground-based observations to refine the orbits and physical properties of NEOs to assess the risk they might pose to Earth, and to achieve the George E. Brown, Jr. Near-Earth Object Survey Act goals.

ARCHIVAL RESEARCH AND CATALOGUING NEOS

Archival research can and has played an important role in detecting and characterizing NEOs. Archiving all data and images to support future improved thermal modeling, searching for serendipitous "precovery" observations (i.e., NEOs that were imaged but not noted at the time, but are located when data is later reviewed), and other types of studies not considered during the survey mission are critical to detecting and characterizing NEOs. The current system for archiving NEO data is not optimized for accessing data and analyzing data in an automated fashion. As new systems become operational, such as LSST and a space-based infrared telescope, this will become a more pressing issue.

Recommendation: All observational data, both ground- and space-based, obtained under NASA funding supporting the George E. Brown, Jr. Near-Earth Object Survey Act, should be archived in a publicly available database as soon as practicable after it is obtained. NASA should continue to support the utilization of such data and provide resources to extract near

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[6] NRC (National Research Council), 2011, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, Washington, DC: The National Academies Press, p. S-2.

Earth object detections from legacy databases and those archived in future surveys and their associated follow-up programs.

There is currently no consistent NASA policy on archiving NEO survey data, especially images. Access to archived data is important for future threat evaluation and research by the general science and planetary defense community.

ORGANIZATION OF THIS REPORT

This report is divided into seven chapters. Chapter 1 provides an introduction and background, including an explanation of the recent policy history for planetary defense. Chapter 2 discusses the challenges of conducting planetary defense in terms of estimating key parameters for NEOs. Chapter 3 discusses current and near-term observation systems, which are primarily ground-based telescopes funded by NASA. Chapter 4 explains the advantages of space-based platforms and addresses infrared versus visual space-based telescopes in terms of capability and costs. Chapter 5 discusses techniques to obtain NEO sizes, a key factor in determining their mass and therefore their destructive potential if they impact Earth (and one of the components of the George E. Brown Act requirements for NEO survey and detection). Chapter 6 addresses the importance of archiving the large amounts of data generated by NEO survey systems. Last, Chapter 7 discusses some other relevant objects that are not part of the George E. Brown Act survey criteria, but that are nevertheless important for understanding the overall impact threat.

1

Introduction and Background

Large asteroid impacts have scarred our planet in the past and will likely do so again in the future. The consequences can sometimes be deadly. There is strong scientific evidence and consensus that the impact of asteroids and comets, or near Earth objects (NEOs),[1] played a major role in the mass extinctions documented in Earth's fossil record. For example, during the Cretaceous-Paleogene (K-Pg formerly K-T) event 66 million years ago, an asteroid with a diameter currently estimated as 12-14 kilometers impacted what is now the Yucatan Peninsula and resulted in long-duration global climate change that famously caused, or contributed to, the extinction not only of the dinosaurs but also of more than 75 percent of all nonavian life on Earth. [2] Such devastating impacts are fortunately rare, but our highly interconnected modern society may be vulnerable to much smaller impacts. It is estimated that if Earth were struck by an approximately 1-kilometer-diameter NEO, the impact could trigger earthquakes, tsunamis, and other secondary effects—such as climate change sufficient to cause global crop failures for several years[3,4]—that extend far beyond the immediate impact area.

As of January 2019, the number of known asteroids of all sizes that pass within 0.05 astronomical units of the Earth's orbit was 19,560.[5] Of these, 897 are estimated to be larger than 1 kilometer in diameter. The frequency of NEO impacts rises in inverse proportion to their sizes (see Table 1.1), meaning that large NEO impacts such as the one that generated the K-T event (~15 kilometers diameter) are few and far between, occurring at most once every 100 million years.[6] In comparison, the average time between impacts of 1-kilometer objects is around 1 million years (see Table 1.1),[7] and the greatest number of asteroids are small enough to burn up in the atmosphere, going completely undetected and

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[1] A near Earth object (NEO) is an asteroid or a comet that has an orbit that brings it within 1.3 astronomical units (AU), approximately 125 million miles, of the Sun. They may also be referred to as either a near Earth asteroid (NEA) or an Earth approaching comet (EAC), as appropriate.

[2] A.S.P. Rae, Collins G. S., Poelchau M., Riller U., Davison T. M., Grieve R. A. F., Osinski G. R., Morgan J. V., and IODP-ICDP Expedition Scientists, 2019, Stress-Strain Evolution During Peak-Ring Formation: A Case Study of the Chicxulub Impact Structure, *Journal of Geophysical Research: Planets* 5:33-22.

[3] O.B. Toon, K. Zahnle, D. Morrison, R.P. Turco, and C. Covey, 1997, Environmental perturbations caused by the impacts of asteroids and comets, *Review of Geophysics* 35(1):41-78.

[4] O.B. Toon, C. Bardeen, and R. Garcia, 2016, Designing global climate and atmospheric chemistry simulations for 1 and 10 km diameter asteroid impacts using the properties of eject from the K-Pg impact, *Atmospheric Chemistry and Physics* 16:13185-13212. See also: National Research Council, 2010, *Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies*, Washington, DC: The National Academies Press.

[5] Center for Near Earth Object Studies, 2019, *NEA Stats*, JPL, https://cneos.jpl.nasa.gov/.

[6] For comparison, at the smallest sizes, recently released U.S. Department of Defense (DoD) data show that between 1994 and 2013, 556 bolide events were observed in the atmosphere; these correspond to asteroids ranging from 1 m to 20 m in size entering Earth's atmosphere. National Science and Technology Council, 2018, *National Near-Earth Object Preparedness Strategy and Action Plan: A Report by the Interagency Working Group for Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects*, p. 2.

[7] National Research Council 2010, *Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies*, Washington, DC: The National Academies Press, https://doi.org/10.17226/12842.

doing no damage. However, there are many asteroids between these sizes that are able to cause damage—sometimes significant damage—and have impact frequencies on the time scales of human civilization. For example, objects approximately 25-30 meters in diameter can cause a fireball, airburst, shockwave, and minor damage. An object approximately 50 meters in diameter could cause local damage comparable to that of a large thermonuclear weapon. Objects 140 meters in diameter can cause destruction on a regional or national scale. Objects 300-500 meters in diameter can cause continental-scale destruction.

TABLE 1.1 The Likely Consequences of an Asteroid Impact as a Function of Asteroid Size

Characteristic Diameter of Impacting Object	Approximate Average Impact Interval (years)	Estimated Number of Objects	Energy Released (megatons TNT)	Estimated Damage or Comparable Event
25-30 m	80-180	2.6-5.5 million	2	Fireball, airburst, shockwave, minor damage
50 m	1,500	>~310,000	10	Local damage comparable to that of largest existing thermonuclear weapon
140 m	20,000	~24,000	~500	Destruction on regional/ national scale
300-500 m	≥64,000-130,000	3,500-7200	≤10,000	Destruction on continental scale
1 km	520,000	~900	80,000	Global effects, many millions dead
10 km	120 million	4	80 million	Complete extinction of the human species

NOTE: It is important to note that (1) size is not the only determinant of damage—other determinants are composition (which may affect how much of the NEO survives its travel through the atmosphere and hits the ground) and velocity; (2) the probabilities (version of column 2) cannot be converted to impact intervals in years. A probability of 1 in 100,000 cannot be viewed as an impact every 100,000 years. In other words, just because there has not been a 300- to 500-meter impact in 100,000 years does not mean that Earth is "due for one." Neither is it the case that it is not. The numbers of objects listed are cumulative, meaning number of objects in that size and larger.
SOURCE: See Harris and D'Abramo (2015).

For example, a NEO of diameter about 25 meters is expected to impact Earth about once every one or two centuries.[8] According to current estimates, there are almost 10 million NEOs larger than 20 meters, and many are extremely difficult to detect prior to entering Earth's atmosphere.[9] An asteroid impact from a 20-meter-diameter object can have severe and costly effects. In early 2013, the air above the city of Chelyabinsk, Russia, was struck by a fireball and sound wave blast from a small asteroid about 20 meters (about the length of a bowling alley) wide that exploded approximately 25 kilometers above the town. The blast produced 20-30 times more energy than that released by the first atomic bombs (about 15 kilotons). There were more than 1,600 people injured by broken glass and approximately $30 million in

[8] P. Brown, R.E. Spalding, D.O. ReVelle, E. Tagliaferri, and S.P. Worden, 2002, The flux of small near-Earth objects colliding with the Earth,. *Nature* 420:294-296.

[9] National Science and Technology Council, 2018, *National Near-Earth Object Preparedness Strategy and Action Plan: A Report by the Interagency Working Group for Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects*, p. 3.

property damages from the blast.[10] Had the object had a steeper entry angle, the consequences would have been even more severe.

In 1908, an object approximately 40-60 meters in size (the height of the Statue of Liberty) exploded over Tunguska, Russia, with the equivalent of 5-10 megatons of TNT (hundreds of times greater than the first atomic bombs and comparable to the most powerful hydrogen bombs), leveling more than 2,000 square kilometers of forest (10 times the area of Washington, D.C.). If a similar event occurred over a major metropolitan area, it could cause millions of casualties (see Figure 1.1). NASA estimates that there are more than 300,000 objects larger than 40 meters that could pose an impact hazard. Many would be very challenging to detect more than a few days in advance.[11]

NEOs larger than 140 meters (about the height of the Washington Monument) have the potential to inflict severe damage to entire regions. Such objects would strike Earth with a minimum energy of over 60 megatons of TNT, which is greater than the most powerful nuclear device ever tested. Although NASA is confident that it has discovered and catalogued nearly all NEOs large enough to cause damage on a global scale (objects greater than 10 kilometers in diameter) and those capable of causing global effects (objects greater than 1 kilometer in diameter) and has determined that they are not on collision courses with Earth,[12] after almost two decades of search, NASA and its partners have catalogued only about one-third of the estimated 24,000 NEOs that are at least 140 meters in diameter.[13]

Permission Pending

FIGURE 1.1 Tunguska damage area compared with major U.S. cities. SOURCE: Courtesy of the Schiller Institute, https://schillerinstitute.com/our-campaign/sde/.

[10] O.P. Popova, et al., 2013, Chelyabinsk Airburst, Damage Assessment, Meteorite Recovery, and Characterization, *Science* 342(6162): 1069-1073.

[11] National Science and Technology Council, 2018, *National Near-Earth Object Preparedness Strategy and Action Plan: A Report by the Interagency Working Group for Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects*, p. 3.

[12] Although they are not asteroids, there is still some chance that large comets from the outer solar system could appear and impact Earth with warning times as short as a few months.

[13] National Science and Technology Council, 2018, *National Near-Earth Object Preparedness Strategy and Action Plan: A Report by the Interagency Working Group for Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects*, p. 4.

IMPACTS AND THE TSUNAMI THREAT

While the effects of impacts on land are reasonably well understood, there has been extensive uncertainty about impacts in the ocean. Early analyses suggested that tsunamis raised by even small impacts into the ocean would carry enormous amounts of energy and thus devastate coastal cities, greatly magnifying the hazard anticipated from small asteroid impacts. Later and more detailed analyses, including an older report by the Naval Research Laboratory, however, found that the impact waves would largely break near the impact itself or on continental shelves, dissipating the impact energy in turbulence and thus not substantially magnifying the hazard. At the present time, impact-generated tsunamis are not considered a serious global hazard, although they may create flooding near the impact site and should be considered in civil defense schemes.[14]

CHARACTERIZING ASTEROIDS

Asteroids emit no visible light of their own; their visible brightness depends on the amount of sunlight reflected/scattered from their surfaces. For a given location relative to the Sun and the observer, larger asteroids and those with lighter, more reflective, surfaces appear brighter. The brightness of an asteroid can therefore provide information on its size. Astronomers quantify the brightness of an object in the sky with a quantity called magnitude. Historically, the Greek astronomer Hipparchus categorized stars into six magnitude classes, 1 through 6. The brightest stars in the sky (e.g., Sirius, the brightest star visible from Earth) were assigned magnitude 1, the next brightest group magnitude 2, and so on, with the faintest stars visible to the human eye assigned magnitude 6. Somewhat paradoxically, the fainter a star is, the larger is its magnitude on this scale. In the nineteenth century, this system was placed on a more mathematical basis by defining a difference of five magnitudes as being exactly equal to 100. A consequence of this was that magnitudes were no longer restricted to positive integers and some stars' magnitudes were changed. Thus, following this change, Sirius is magnitude −1.46. Powerful telescopes extend this scale down to magnitudes as large (as faint) as 28.

Unlike stars, however, asteroids are sometimes brighter and sometimes fainter, depending on how close they are to Earth at the time of observation. For these objects, a brightness scale called absolute magnitude, denoted by the capital letter H, has been developed. The absolute magnitude H is defined as the magnitude the asteroid would appear to have at visible wavelengths if it were located 1 astronomical unit (AU; 1 AU is approximately 150,000,000 km) distant from both Earth and the Sun, and observed in a direction exactly opposite to the Sun, so that it is fully illuminated like the full moon (this is a hypothetical configuration, which is impossible to achieve when observing from Earth). Asteroids are never actually observed under these conditions, and so corrections must be made for their actual distance from both Earth and the Sun and their solar phase angle (i.e., the Sun-asteroid-observer angle) to obtain their absolute magnitude from the magnitude actually observed.

In addition to the phase correction, the absolute magnitude of an asteroid with a given diameter also depends on the fraction of the sunlight it reflects at visible wavelengths. This fraction is called the albedo, with the symbol pv, and for known asteroids it varies between extremes of about 1 and 50 percent, with a

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[14] G.S. Collins, H.J. Melosh, and R.A. Marcus, 2005, Earth Impact Effects Program: A Web-based computer program for calculating the regional environmental consequences of a meteoroid impact on Earth, *Meteoritics and Planetary Science* 40:817-840, http://doi.org/10.1111/j.1945-5100.2005.tb00157.x; J.G. Hills, I.V. Nemchinov, S.P. Popov, and A. V. Teterev, 1994, "Tsunami Generation by Small Asteroid Impacts," in *Hazards from Comets and Asteroids*, edited by T. Gehrels (Tucson: University of Arizona Press), pp. 779-789; W.G. van Dorn and B. Le Mehaute, 1968, *Handbook of Explosion-Generated Water Waves*, Rep. TC-130 (Pasadena, Calif.: Tetra Tech); K. Wünnemann, G.S. Collins, and R. Weiss, 2010, Impact of a cosmic body into Earth's ocean and the generation of large tsunami waves: Insight from numerical modeling, *Reviews of Geophysics* 48(4):RG4006, http://doi.org/10.1029/2009RG000308.

typical range being between 2 and 35 percent.. If the albedo is unknown, which is usually the case upon first discovery, it is common to assume a mean value of about 15 percent.

The absolute magnitude of an asteroid is related to its size because the amount of light reflected is proportional to its area, which in turn is proportional to the square of the diameter. In order to derive a diameter from H, an albedo must be known or a default value used; if the latter, the resulting diameter is uncertain, as discussed in detail elsewhere in this report. The George E. Brown, Jr. Near Earth Object Survey Act's minimum size of 140 meters corresponds to an absolute magnitude of 22 for an albedo of 14 percent (a reasonable limiting faintness for telescopes envisaged in 2005) and an albedo of 15 percent. Accurate diameters, however, are very difficult to obtain from visible observations, because true albedos are not easily determined, whereas infrared observations give far more accurate estimates of diameters, as explained later in this report.

THE NATION'S RESPONSE TO THE NEO IMPACT THREAT

Like other natural disasters (e.g., tsunamis) and space weather events (e.g., solar storms), NEO impacts can be deadly to life and property. However, unlike most other natural disasters, NEO movements and impacts are predictable many years in advance and may be preventable if the impacting object is known, hence the requirement to search for them. Even if the impact were beyond U.S. territory, its environmental, economic, and geopolitical consequences would be detrimental to the United States. The U.S. government has therefore directed action in planetary defense—identifying and, if possible, preventing the hazard of NEO impacts.

Congressional interest in the subject started when Congress directed NASA to initiate a "Spaceguard Survey" to search for NEOs in the late 1990s and also officially established a NEO survey program. In 1998, Congress directed NASA to discover at least 90 percent of 1-kilometer-diameter or larger NEOs within 10 years; NASA met this mandate by the end of 2010, according to the best statistical models of the overall population.

The George E. Brown Act, included in NASA's fiscal year 2005 Authorization Act, amended the National Air and Space Act of 1958 to declare that "the general welfare and security of the United States require that the unique competence of the Administration be directed to detecting, tracking, cataloguing, and characterizing near-Earth asteroids and comets in order to provide warning and mitigation of the potential hazard of such near-Earth objects to Earth."[15] Section 321 of the act provides the following specific guidance:

> 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 in order to assess the threat of such near-Earth objects to the Earth. It shall be the goal of the Survey program to achieve 90 percent completion 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.[16]

[15] NASA Reauthorization Act of 2005, P.L. 109-155, 119 Stat. 2923, December 30, 2005.
[16] NASA Reauthorization Act of 2005, P.L. 109-155, 119 Stat. 2922, December 30, 2005.

Box 1.1

National Near-Earth Object Preparedness Strategy and Action Plan

Goal 1: Enhance NEO Detection, Tracking, and Characterization Capabilities.

NASA will lead the development of a roadmap for improving national capabilities for NEO detection, tracking, and characterization. Supporting actions will reduce current levels of uncertainty and aid in more accurate modeling and more effective decision-making.

1.1. "Identify opportunities in existing and planned telescope programs to improve detection and tracking by enhancing the volume and quality of current data streams, including from optical, infrared, and radar facilities.
1.2. Identify technology and data processing capabilities and opportunities in existing and new telescope programs to enhance characterization of NEO composition and dynamical and physical properties.
1.3. Use the roadmaps developed in Actions 1.1 and 1.2 to inform investments in telescope programs and technology improvements to improve completeness and speed of NEO detection, tracking, and characterization.
1.4. Establish and exercise a process for rapid characterization of a potentially hazardous NEO."

While NASA created the Planetary Defense Coordination Office (PDCO) in January 2016 to serve as a planetary defense coordination and communications node for the federal government and to achieve the George E. Brown Act objective to detect, track, and catalogue at least 90 percent of NEOs equal to or greater than 140 meters in size by 2020, this target will not be met, given the inadequate resources dedicated to the task since 2005.

Finding: The George E. Brown Act requires NASA to "detect, track, catalogue, and characterize the physical characteristics of near-Earth objects equal to or greater than 140 meters in diameter in order to assess the threat of such near-Earth objects to Earth. It shall be the goal of the Survey program to achieve 90 percent completion of its near-Earth object catalogue (based on statistically predicted populations of near-Earth objects) within 15 years after the date of enactment of this Act." NASA has not accomplished this goal and cannot accomplish it with currently available assets by December 31, 2020.

Subsequent federal policies and directives have revisited this theme without specific thresholds or funding to carry out the goals stated in the George E. Brown Act. The 2010 National Space Policy of the United States underscored the general mandate, specifically directing the NASA Administrator to "pursue capabilities, in cooperation with other departments, agencies, and commercial partners, to detect, track, catalogue, and characterize near-Earth objects to reduce the risk of harm to humans from an unexpected impact on our planet and to identify potentially resource-rich planetary objects."[17] Most recently, in 2018, the government released a National NEO Preparedness Strategy and Action Plan.[18] The very first goal of the strategy is to "Enhance NEO Detection, Tracking, and Characterization Capabilities" (Figure 1.2).

[17] Executive Office of the President, 2010, Presidential Policy Directive 4: National Space Policy of the United States of America, p. 12.

[18] National Science and Technology Council, 2018, *National Near-Earth Object Preparedness Strategy and Action Plan: A Report by the Interagency Working Group for Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects*, p. 1.

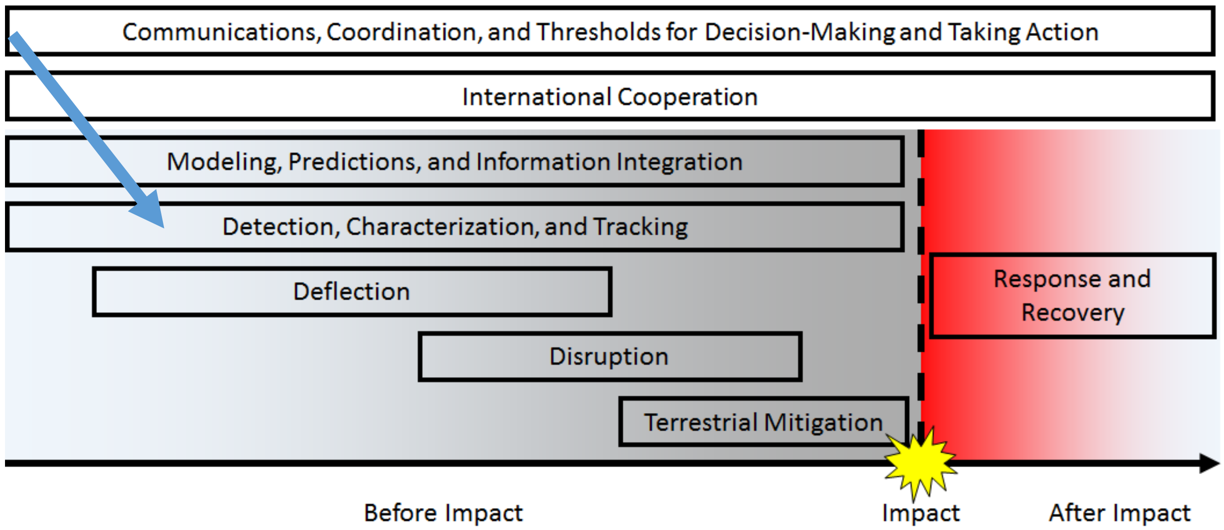

FIGURE 1.2 Illustrative timeline of the phases of operations in a near Earth object (NEO) preparedness strategy. SOURCE: Executive Office of the President, 2010, Presidential Policy Directive 4: National Space Policy of the United States of America, p. 5, https://www.whitehouse.gov/wp-content/uploads/2018/06/National-Near-Earth-Object-Preparedness-Strategy-and-Action-Plan-23-pages-1MB.pdf.

Box 1.1 lists the action items that are expected to address this goal. The actions do not select any particular solutions—such as a space-based infrared telescope—but simply lay out the process. Although Congress added "warning and mitigation of potential hazards of NEOs" as the seventh of seven policy and purposes of NASA in 2010, and although "detect[ing] asteroids, understand[ing] their composition, predict[ing] their paths, and provid[ing] timely and accurate communications about potentially hazardous objects" is part of NASA's strategic objective, these activities have remained under the umbrella of the Science Mission Directorate's planetary science division, leaving NEO detection to compete with planetary science research for funding. In many ways, NEO detection, tracking, and characterization is primarily an operational mission rather than one that pushes the frontier of science, though it does that as well.[19]

Finding: Congress has charged NASA with NEO detection and threat characterization, and NASA has created a PDCO to pursue these congressionally mandated activities; however, these operational activities have had to compete with scientific missions for funding.

As the Chelyabinsk and Bering Sea fireballs demonstrate, objects smaller than 140 meters in diameter frequently reach Earth. And the Chelyabinsk event demonstrates that some of them can be dangerous. Although it is difficult, they can occasionally be detected.

Recommendation: Objects smaller than 140 meters in diameter can pose a local damage threat. When they are detected, their orbits and physical properties should be determined, and the objects should be monitored insofar as possible.

[19] See Title 51 US Code, http://uscode.house.gov/view.xhtml?path=/prelim@title51/subtitle2/chapter201&edition=prelim); NASA's strategic plan 2018, https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/nasa_2018_strategic_plan_0.pdf; 2020 budget request, https://www.nasa.gov/sites/default/files/atoms/files/fy_2020_congressional_justification.pdf.

2

The Components of Planetary Defense

The difficulty in appreciating the hazard due to asteroid impacts is that the likelihood of a large asteroid strike in any given year, or even over a human lifetime, is very small. However, the consequence of such a strike is very large, amounting to an existential risk to humanity depending on the size of the near Earth object (NEO). The difference between the asteroid hazard, however, and most other deadly natural events, such as hurricanes and earthquakes, is that asteroid strikes can be both more devastating and also potentially predictable and preventable. Prediction and prevention, however, require knowledge of the asteroid population. Discovery and characterization observations—those that first identify potential NEOs and determine their nature—are made with telescopes either on the ground or in space *with radar facilities providing additional positional and characterization measurements*. This chapter discusses the data needed to detect, track, and characterize NEOs.

In comparison to the planets, asteroids are small and dim. They shine by reflected light from the Sun and by thermal radiation from their warm surfaces. Therefore, the ability to detect an asteroid depends on how much light it reflects, how warm it is, and the wavelength region in which the detection is being made. In visible wavelengths, the brightness depends on the asteroid's size as well as on the intrinsic reflecting ability (albedo) of its surface (most asteroids are very dark, reflecting only 10 percent or less of the sunlight that falls on them), and the phase at which it is observed. Most small asteroids are sufficiently faint that they cannot be seen from Earth unless they make a close approach and are then picked up as moving points of light against the background sky by a sufficiently sensitive instrument. Once a newly detected asteroid moves away from Earth, it quickly becomes dimmer and eventually undetectable until it makes another close pass, perhaps as many as several years or even decades later.

In addition to initially detecting a NEO, there are other variables needed to determine the possibility of an asteroid impact and its potential severity. One of the most important among them is the NEO's orbit, which determines if it is likely to intersect the orbit of Earth. This information, in turn, helps estimate not only whether there will be an impact but also the timeline of impact, the warning time, and the velocity at which the impact occurs. In addition to orbit, crucial for determination of the impact velocity, location, and time, there are other physical characteristics, such as mass and density, that determine the energy, and therefore the severity, of a NEO's impact. The final important component of NEO detection strategy is the length of time it would take to achieve the George E. Brown, Jr. Near Earth Object Survey Act's goals.

ORBIT AND VELOCITY

While a NEO's discovery observation can typically be used to derive an approximate orbit, follow-up observations are required to refine this solution and enable the prediction of the NEO's position in the future. Such observations may be made both during the asteroid's first appearance as well as during reobservation on a subsequent close-pass by Earth, which may occur many years, even decades, later. It also may involve "precovery" data, which are archival images in which an object was not found at the time the images were taken but is identified in them at a later time with the help of subsequent observations. NEO discovery surveys benefit from dedicated follow-up observations to improve the objects' orbits and to provide information on their physical properties.

Astrometric observations measure the course of an asteroid across the sky in order to refine its orbit. Without astrometric observations, the positional uncertainties from insufficiently constrained orbits will quickly grow, impeding future targeted observations and the accurate assessment of impact probabilities. The quality of astrometric observations is dependent on the ability to pinpoint the position of an asteroid, the uncertainties of the asteroid images, the number of stars with well-known positions on each frame, and other factors. In practice, a given system will optimize some of these factors at the possible expense of others. However, observations over a long time span (or "arc") usually allow for the rejection of poor-quality astrometric measurements and allow high-quality orbits to be determined. While current and future optical surveys (e.g., Catalina Sky Survey, Pan-STARRS, Large Synoptic Survey Telescope [LSST]) provide astrometric follow-up for some serendipitously observed asteroids soon after discovery, targeted observations of select objects (e.g., objects showing nonnegligible impact probabilities) will be necessary before their positional uncertainties grow too large or the objects become too faint (however, Targeted follow-up is pointless for objects with very large uncertainties). Well-timed and short, single-apparition observations are sufficient to improve orbits in most cases. If initial orbits are recognized as being problematic, they will have to be followed-up during the discovery apparition or risk being lost. In cases where they are lost, they will have to await rediscovery (or be located in a pre-discovery image) at which point they will be linked with the discovery observations and a much-improved orbit determined. LSST will have to perform its own follow-up because the NEOs it discovers will be too faint and too many for the existing follow-up assets. The plan is that LSST will return to the same region of the sky every few nights to ensure that each discovered object receives sufficient follow-up.

Knowing the orbit allows an impact time to be determined if an impact is to occur. Knowing the orbit of an object allows that object's velocity to be calculated for any point in the orbit. This is part of the motivation for asteroid searches in the first place—to determine whether an object has an orbit that intersects Earth's orbit (and is thus a threat) or not, and to allow the impact velocity to be calculated if it does. For discussions of the NEO population as a whole, an average or typical velocity is usually adopted to represent the destructive power of a hypothetical impactor.

MASS

The severity of an asteroid impact is a function of its incoming energy, which is directly proportional to its mass. Small impactors are affected sufficiently by atmospheric drag that they fall at a relatively slow terminal velocity of a few hundred kilometers per hour—a potential problem for anything that happens to be at the spot where they land, but not an issue for broader areas. Larger, more massive objects are less affected and strike the ground at tens of thousands of kilometers per hour, fast enough to create a shock that more closely mimics an explosion than a rock dropped from a rooftop. The impact energy associated with an asteroid impact can be calculated from the asteroid's mass and velocity. As a result, these are the two most important drivers for planetary defense studies.

Direct measurements of mass are more difficult to make than those of possible impact speed. In those cases where NEOs have satellites, the system mass can be determined remotely by determining the orbit of the NEO satellite. In some cases, mass can be inferred by making very precise positional measurements and measuring discrepancies between those positions and predicted positions due to the effects of nongravitational, mass-dependent forces (like the "Yarkovsky force"). In the general case, however, NEO masses can only be directly measured during spacecraft visits, which are rare.

Due to the need for mass estimates in general cases, indirect methods for estimating masses have been developed, using measurements or estimates of the NEO volumes and densities. Although there are additional uncertainties for NEOs with highly irregular shapes, in the general case, NEOs are usually treated as spheres. Because the volume of a sphere can be easily calculated from its radius or diameter, these are used as proxies for volume. For historical reasons, "size" usually refers to the diameter of a

NEO rather than its radius. The language of the George E. Brown Act, which established NASA's mandate to find asteroids of a certain size, is motivated by the use of asteroid diameters as a proxy of their destructive power.

While accurate diameter measurements—serving as a proxy for mass in combination with inferred bulk densities—have the highest importance for planetary defense purposes, additional physical properties can be constrained with a range of observational methods, improving the former estimate. Depending on the method, useful information may be obtained with relatively few observations or could require repeated observations over the course of many years. Focusing intensive efforts on the truly threatening objects, out of the roughly 30,000 NEOs, will benefit from an estimate of the diameter and mass in the initial detection, particularly if the facility needed for this estimate is of limited lifetime.

> **Finding:** In addition to detecting NEOs and determining their orbits, it is necessary to estimate their masses to quantify their destructive potential. An NEO's diameter is the most readily available indicator of its mass.

NEOs are too small to appear as more than point sources in telescopic data. In favorable cases, radar can be used to obtain a direct measurement of asteroid size. In the great majority of cases, however, the size of an asteroid must be calculated from its brightness and its distance, with the latter determined from its orbit. The population of NEOs has a wide variation in how reflective their surfaces are, which leads to uncertainty in this size-measurement technique. However, the uncertainties are much smaller when the measurements are done using emitted infrared light rather than reflected visible light (the reason for this improved accuracy is that albedo has only a weak effect on the emitted thermal flux). This difference underpins some of the reasoning for preferring infrared systems for asteroid surveying. (See Chapter 5 for further information.)

> **Finding:** The accuracies of asteroid diameters derived from thermal-infrared measurements and simple modeling usually far exceed those based on the measured visible brightness alone.

DENSITY AND OTHER CHARACTERISTICS

The cause of the largest uncertainty in impactor destructive power in the general case, which cannot be easily reduced from remote data, is the uncertainty in object density. Considering the total range of possible densities (~1 to 8 g/cm^3—see below) this factor of ~8 in possible densities translates to a factor of ~8 uncertainty in mass for NEOs with no data from which to constrain their densities. If some compositional information is present or rare compositions are excluded, there is still roughly a factor of 2 uncertainty in mass, which corresponds to a factor of 2 in impact energy. As a result, this factor of 2 in impact energy is used as the acceptable level of uncertainty in other measurements. The velocity and orbit uncertainties are easily dismissed as too small to contribute significantly to the overall uncertainties.

In order to have the size uncertainty be less important than the density uncertainty for likely impactors in terms of determining the mass of an object in the general case, the volume uncertainty must be less than a factor of 2. Given the well-known relationship between size and volume, given the established shape, that means the size uncertainty must be less than the cube root of 2, or roughly 1.26. This means that a ~25 percent uncertainty in size must be achieved by the NEO characterization systems considered here.

> **Finding:** A search program that can measure NEO sizes to 25 percent uncertainty or better with the same observations used to discover them and obtain their orbits is preferable to separate search and characterization programs, unless separate systems can complete the survey more quickly or cost effectively than a single program that does both.

Meteorite data can be used to make density estimates. Meteorite densities are dependent on composition, with a porous carbonaceous chondrite having a density as low as 1 g/cm^3 and a solid rock of the most common composition ("ordinary chondrite") having a density of 3.0 to 3.5 g/cm^3. Other important compositions have densities from 2,000 to 7,500 kg/m^3 when they are solid chunks, although less than 4 percent of meteorites are high-density irons (density 7,500 kg/m^3). Kilometer-size asteroids are expected to rarely if ever be solid chunks, however, and they can have 30-50 percent void space in their volume, bringing down the overall density. Density measurements of asteroids have a weighted average value of 2.62±1.23 g/cm^3, also suggesting that most asteroid densities fall in a relatively small range.[1] However, neither measure may be completely apt; meteorite densities are biased toward higher-density objects that can better survive atmospheric entry, and the available asteroid densities are generally for objects much larger than the NEOs of interest here. Nevertheless, both suggest that extreme values for asteroid density are rare.

If no other information is available, the factor of ~8 in density between solid iron and porous carbonaceous chondrite can be reduced only by making probabilistic arguments, such as those in the preceding paragraph. If compositional information is available from reflectance spectroscopy, the probable density range can be narrowed significantly. If albedo information is available, the likely density range can be similarly narrowed, although with somewhat less certainty.

There are several types of characterization observations that can be made. *Photometric observations* of asteroids measure the amount of solar light that is reflected by their surfaces. Quantifying their brightness over time and along their orbits over many apparitions constrains their surface albedos when combined with diameter measurements from thermal infrared observations, as well as their shapes and rotational properties. The derived albedo can be used to infer the targets' composition and hence their bulk densities. In order to measure accurate asteroid albedos, repeated measurements over many apparitions along their orbits are required. The measurement of asteroid shapes and rotational properties through brightness variations due to their irregular shapes and rotations also requires a large amount of highly accurate photometric observations over many apparitions. Both properties, combined with accurate thermal-infrared observations, can significantly improve the physical characterization of asteroids and are able to improve bulk density estimates. Accurate photometry can be obtained for a small number of large and bright asteroids with easily accessible small telescopes (~1 meter aperture), but fainter asteroids require larger facilities. Often, the absolute magnitude of an NEO (H) is determined using data optimized for finding its position, and can have uncertainties of 30 percent or more. In addition, the brightness of an object changes as viewing angle changes, captured in a parameter called G. With concerted effort, improved values of H and G can be determined for NEOs, which in turn improve estimates of size.

Spectroscopic observations in visible and near-infrared light measure the amount of solar light that is reflected by the surface of the asteroid as a function of wavelength. The observed reflectance spectrum provides a spectral classification of an asteroid. Spectral classes have been linked to meteorite analogs, enabling fairly accurate inference of the bulk density and albedo. Quantitative spectral analysis can also retrieve information on surface particle size and mineralogy. For the majority of asteroids, such observations require large telescopes (>4 meter aperture) and long observations, except when they are very close to Earth. Single apparition observations are sufficient to put constraints on spectral classifications.

Spectrophotometry-photometric observations using different broadband filters provides a simple means to roughly constrain an asteroid's spectral classification.[2] While enabling a less-detailed taxonomic

[1] B. Carry, 2012, Density of asteroids, *Planetary and Space Science* 73:98-118.

[2] Z. Ivezić and 31 coauthors, 2001, Solar System Objects Observed in the Sloan Digital Sky Survey Commissioning Data, *Astronomical Journal* 122:2749-2784, doi:10.1086/323452; M. Jurić and 15 coauthors, 2002, Comparison of Positions and Magnitudes of Asteroids Observed in the Sloan Digital Sky Survey with Those Predicted for Known Asteroids, *Astronomical Journal* 124:1776-1787, doi:10.1086/341950; B. Zellner, Tholen, D.J., and Tedesco, E.F., 1985, The Eight-Color Asteroid Survey: Results for 589 Minor Planets, *Icarus* 61:355-416, doi:10.1016/0019-1035(85)90133-2.

classification than spectroscopy, spectrophotometry enables the characterization of fainter, and hence smaller, asteroids with generally smaller telescopes. Single apparition observations are sufficient to put constraints on spectral classifications.

Polarization measurements of the Sun's visible and near-infrared light reflected by the surface of asteroids directly provide the albedo and thus, via the albedo, a rough constraint on the density. They are also indicative of spectral classification and provide additional information on surface properties like particle sizes and mineralogy. Polarimetric observations require well-timed multi-apparition observations and medium-size telescopes (>2 meter aperture) in order to provide useful information. Hence, only a small sample of asteroids can be investigated using this method.

Radar observations provide an opportunity to obtain highly accurate astrometric data and shape and rotational information for a small sample of asteroids that come close enough to Earth to be observed with this technique. While this limitation prevents its broader use for asteroid characterization in a large-scale survey, it can be used to understand the range of properties in the overall asteroid population by characterizing individual objects. *Radar has been used to make measurements of a representative sample of NEOs down to an H magnitude of 28.* High-precision, single-apparition radar data are extremely useful, and multi-apparition data, where available, are able to improve bulk density estimates through precise astrometric measurements that enable orbit migration due to non-gravitational effects.[3] Observations of binary NEOs directly yield bulk densities.[3]

Finding: Characterization—that is, determining the physical properties of NEOs such as their diameters and densities—is critical for a full understanding of the impact hazard. Characterization observations can include radar and visible-infrared photometry and spectroscopy. Most often, not all are available.

OTHER FACTORS: TIME SCALE, COMPLEMENTARITY, AND COST

The timescale over which measurements will be made is considered in the context of the George E. Brown Act that includes a timeframe for discovery of NEOs >140 meters. It is apparent that the timeframe specified in the act cannot be completed by 2020, yet an infrared platform operating in conjunction with ground-based visible light telescopes both current and under construction will allow the completeness goal to be met in a timeframe constrained by physics, and development time needed to employ the technology that will achieve the completeness goal stated in the congressional mandate.

Another factor, although one that is not straightforward to quantify, is the "complementarity" of a new system to existing systems. A survey system with capabilities unmatched by existing systems, whether in observable areas of the sky, detection limits, with observing biases that are minimal or at least different from existing systems, and so on, is preferred to one that simply supersedes an existing system but still leaves portions of the survey space uncovered.

The discussion is focused on L1 as it is currently considered a very feasible location for a survey telescope. While it is true that locations at different heliocentric longitudes offer other advantages, it might be more challenging to maintain operations due to limited bandwidth and other aspects. L1 offers a good compromise. The overlap in search volume with ground-based surveys should be very limited as is shown in Figure 4.1: While ground-based surveys tend to focus on opposition observations, thermal-infrared space-based telescopes typically aim at quadrature to maintain cooling of the spacecraft.

Last, the cost of a system is another factor that can be used in assessments, but only in conjunction with other metrics. For instance, in general, a low-cost system that would take several decades to complete the survey would not be preferable to a hypothetical higher-cost system that could complete it faster—assuming reasonable costs; the committee is not claiming that cost is unimportant, only that taking many decades to conduct a survey in order to save costs could have deleterious effects, including

[3] D.J. Scheeres et al., 2019, The dynamic geophysical environment of (101955) Bennu based on OSIRIS-REx measurements, *Nature Astronomy* 3:352-361.

cancelation and the inability to recruit talent to undertake a project with no clear end point. On the other hand, small investments in existing or planned astrophysical assets could allow them to contribute meaningfully, if incrementally, to completing the survey even if they do not play a large role. The scope of this study does not allow for new costing models to be developed. The committee therefore has had to rely on what public information does exist as well as indirect information where available.

THE ROLE OF SCIENCE IN NEO SURVEYS

Because understanding of asteroids is still evolving, and because the properties of asteroids are essential for gauging the destructive potential of any impact, as well as evaluating the effectiveness of any proposed deflection method, it is necessary to incorporate scientific input into the development of survey techniques and technologies.

Finding: While planetary defense missions are not science driven, significant scientific input is essential to optimally design the planetary defense task.

The most successful campaign to protect Earth from the consequences of a large impact will involve strong contributions both from scientific study of the solar system and engineering approaches to asteroid discovery and deflection. Pure science will inevitably profit from a robust asteroid detection and defense program, while the proper design of deflection strategies must be informed by the latest scientific discoveries about the nature of asteroids and comets. A good example of how this synergy between pure and applied science might work is the Double Asteroid Redirect Test mission, which is a NASA-funded mission to change the orbit of an asteroidal satellite in space, demonstrating a possible mitigation technique.

3

Current and Near-Term NEO Observation Systems

When sunlight hits an asteroid's surface, it both reflects photons and absorbs them to emit their energy in the infrared. Astronomers use telescopes to amplify the light in the night sky combined with sensors designed to detect signals at wavelengths carrying pertinent information about the target under study. This chapter describes the systems for near Earth object (NEO) detection and characterization and explains the value of searching for NEOs while simultaneously characterizing them using a space-based platform.

NEO OBSERVATION ASSETS: PAST, PRESENT, AND NEAR FUTURE

In the past 23 years, the search for NEOs has been dominated by ground-based, visible-wavelength telescope systems. These systems are described briefly below.

- *Lincoln Near-Earth Asteroid Research (LINEAR) program.*[1,2,3] The Massachusetts Institute of Technology (MIT) Lincoln Laboratory LINEAR asteroid search program began in 1998. Between 1998 and 2013, the program used two 1-meter, ground-based, visible-wavelength telescopes located near Socorro, New Mexico, to detect asteroids. In 2013, the program transitioned to using the Space Surveillance Telescope (SST) at White Sands Missile Range, New Mexico. The program has since continued as a joint operation between MIT Lincoln Laboratory, NASA, and the U.S. Air Force. In 2017, ownership of SST was transferred to the Air Force. The telescope is currently undergoing relocation to Western Australia, where it is expected to resume operations—possibly including the search for NEOs—in the early 2020s.
- *Near-Earth Asteroid Tracking (NEAT) program.*[4,5,6] The NEAT program, operated between December 1995 and April 2007, was a collaboration between NASA, the Jet Propulsion Laboratory (JPL), and the Air Force. The monthly automatic search program used three 1-meter aperture, ground-based, visible-wavelength telescopes (two located in Hawaii and one at Palomar Observatory in southern California).

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[1] Massachusetts Institute of Technology Lincoln Laboratory, 2019, *On The Watch for Potentially Hazardous Asteroids,* https://www.ll.mit.edu/impact/watch-potentially-hazardous-asteroids.

[2] Massachusetts Institute of Technology Lincoln Laboratory, 2019, *Space Surveillance Telescope,* https://www.ll.mit.edu/r-d/projects/space-surveillance-telescope.

[3] See https://apps.dtic.mil/dtic/tr/fulltext/u2/1001992.pdf.

[4] S.H. Pravdo et al., 1999, The Near-Earth Asteroid Tracking (NEAT) Program: An Automated System for Telescope Control, Wide-Field Imaging, and Object Detection, *The Astronomical Journal* 117:1616-1633.

[5] Ibid.

[6] T. Morgan, 2019, *Near Earth Asteroid Tracking V1.0*, NASA, urn:nasa:pds:context_pds3:data_set:data_set.ear-a-i1063-3-neat-v1.0.

- *Spacewatch.*[7] Spacewatch is the small object—including NEOs—observing program of the University of Arizona's Lunar and Planetary Laboratory. The program began in 1980 and since 1998 has focused on follow-up astrometry of targets, focusing on the orbits of those objects that may present a hazard to Earth. Observations are made using two ground-based, visible-wavelength telescopes with 0.9-meter and 1.8-meter apertures located at Kitt Peak National Observatory in Arizona.
- *Lowell Observatory Near-Earth Object Search (LONEOS).*[8,9,10] LONEOS was an NEO-detection program run by Lowell Observatory between July 1998 and February 2008. The project used a 0.6-meter-aperture, ground-based, visible-wavelength telescope located at Anderson Mesa near Flagstaff, Arizona, to conduct the survey with observations happening on average 200 nights per year.
- *Catalina Sky Survey (CSS).*[11] CSS, founded in 1998 and operated by the University of Arizona's Lunar and Planetary Laboratory, is an ongoing program to detect and track NEOSs with diameters larger than about 140 meters in order to assist completion of the George E. Brown Act requirements. CSS utilizes ground-based, visible-wavelength telescopes with apertures of 0.7, 1.0, and 1.5 meters located in Arizona, two for discovery and two for follow up.
- *Panoramic Survey Telescope and Rapid Response System (Pan-STARRS).*[12,13] Pan-STARRS is a fully operational astronomical imaging system designed and run by the Institute for Astronomy, University of Hawaii. The system has been in operation since 2010 and uses two 1.8-meter ground-based, visible-wavelength telescopes on Maui, Hawaii (see Figure 3.1). Pan-STARRS 2 only began operations in 2018.
- *Asteroid Terrestrial-Impact Last Alert System (ATLAS).*[14] The ATLAS system, developed by the University of Hawaii, was funded in 2013 and began detecting asteroids in 2015. The system is composed of two 0.5-meter ground-based, visible-wavelength telescopes located in Hawaii 100 miles apart. The survey views the whole sky several times each night.
- *Zwicky Transient Facility* at Palomar. This telescope is serendipitously finding a modest number of asteroids, despite not being funded for that purpose by NASA.[15]

There have been far fewer space-based NEO surveys, including the following:

- *NEOWISE.*[16] NEOWISE, funded by NASA's Planetary Science Division, leverages the Wide-Field Infrared Survey Explorer (WISE) space-based, infrared telescope, which ended its primary mission in 2010. NEOWISE operated from September 2010 until February 2011. Observations were halted until December 2013, when the telescope was reactivated; observations continue to the present as the NEOWISE Reactivation Survey (see Figure 3.2). The survey's lifetime is

[7] T. Bowell and B. Koehn, 2008, *The Lowell Observatory Near-Earth-Object Search*, https://asteroid.lowell.edu/asteroid/loneos/loneos.html.

[8] T. Bowell and B. Koehn, 2004, *About LONEOS*, https://asteroid.lowell.edu/asteroid/loneos/loneos1.html.

[9] T. Bowell and B. Koehn, 2000, *Searching for Near-Earth-Objec*ts, https://asteroid.lowell.edu/asteroid/loneos/loneos2.html.

[10] T. Bowell and B. Koehn, 2008, *LONEOS Asteroid Observations*, https://asteroid.lowell.edu/asteroid/loneos/public_obs.html.

[11] Arizona Board of Regents on behalf of the University of Arizona, 2019, *About CSS,* https://catalina.lpl.arizona.edu/.

[12] See http://pswww.ifa.hawaii.edu/pswww/.

[13] University of Hawaii, 2019, *The Pan-STARRS1 data archive home page*, https://panstarrs.stsci.edu/.

[14] University of Hawaii ATLAS Project, 2019, *Asteroid Terrestrial-Impact Last Alert System (ATLAS)*, http://atlas.fallingstar.com/home.php.

[15] NASA also funded NEA searches with the Dark Energy Camera on the 4-meter Blanco Telescope in Chile between 2014-2016.

[16] California Institute of Technology, 2019, *The NEOWISE Project*, https://neowise.ipac.caltech.edu/.

governed by the spacecraft's evolving orbit, and predictions of when the survey will cease to provide useful data are uncertain.

Over time, NEO surveys have used larger telescopes that have more sensitive detectors and observe larger regions of the night sky. As a result, the rate of NEO discoveries over the past 20 years has risen steadily, to the point where more than 2,000 NEOs were discovered in 2017 alone—two orders of magnitude more annual discoveries than in 1995. The impact of adding new, complementary telescopic search programs can be seen in the increase of the number of new NEOs discovered as systems have come online over time (see Figure 3.3).

CSS and Pan-STARRS are both extending the number of discoveries and finding smaller objects. Figure 3.4 shows the impact of the CSS and Pan-STARRs surveys contributing to the discovery rate of objects >140 meters.

As shown in Figure 3.5, current NEO survey systems will not satisfy the George E. Brown Act goals regardless of how long they operate.

Permission Pending

FIGURE 3.1 The PanSTARRS-1 telescope atop Haleakala on Maui, Hawaii. There are two PanSTARRS telescopes operational.

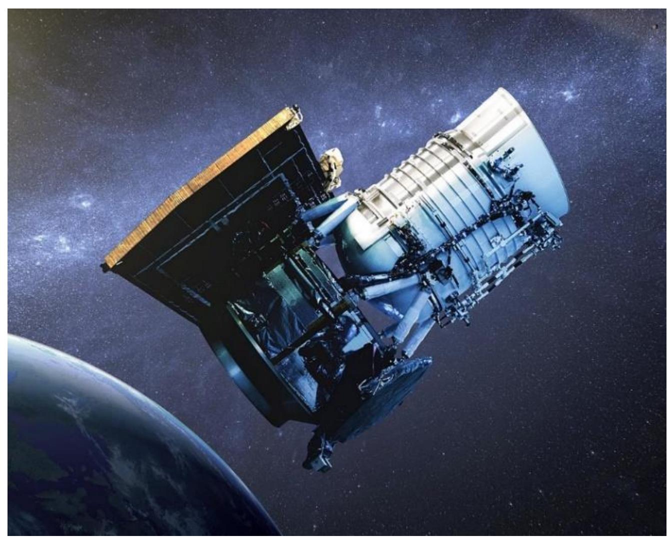

FIGURE 3.2 Artist concept of the Wide-Field Infrared Explorer spacecraft that is currently conducting the NEOWISE asteroid survey mission. SOURCE: Courtesy of NASA/JPL-Caltech.

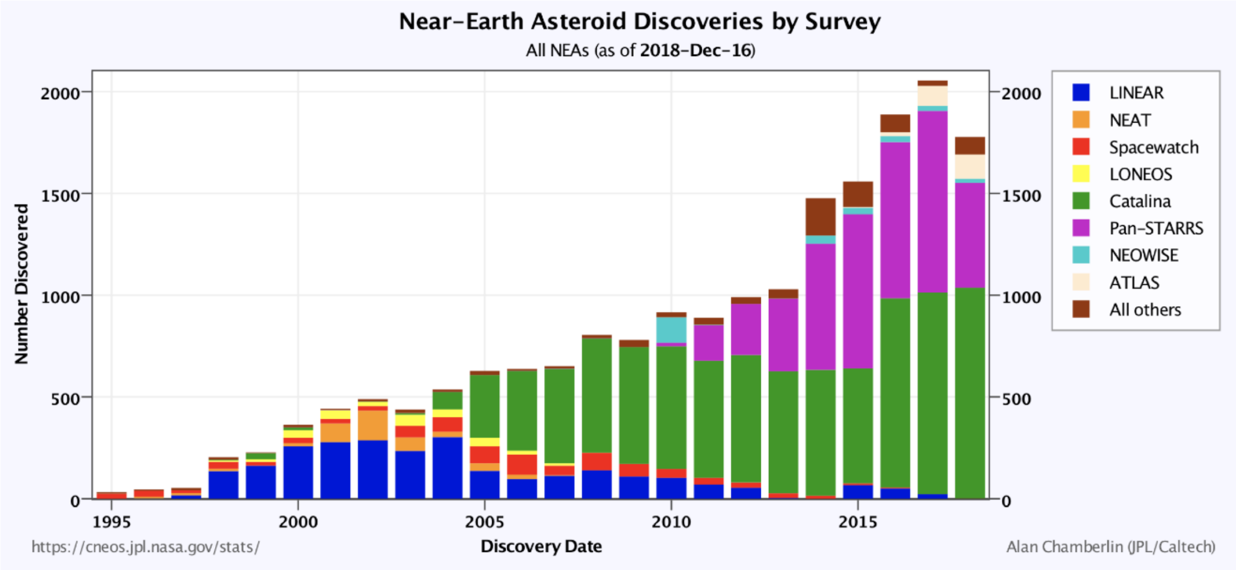

FIGURE 3.3 Number of near Earth objects (NEOs) discovered from 1995 to December 16, 2018. In 2011, the then-existing NEO survey systems achieved the Spaceguard goal of finding more than 90 percent of NEOs larger than 1 kilometer. NOTE: Information about achieving the Spaceguard goal is from Mainzer et al. (2011); Tricarico (2017); and Science Definition Team Report (2017, sec. 9.1.) SOURCE: Center for Near Earth Object Studies, "Discovery Statistics: By Survey (all)," https://cneos.jpl.nasa.gov/stats/site_all.html, accessed December 16, 2018; courtesy of NASA/JPL/Caltech.

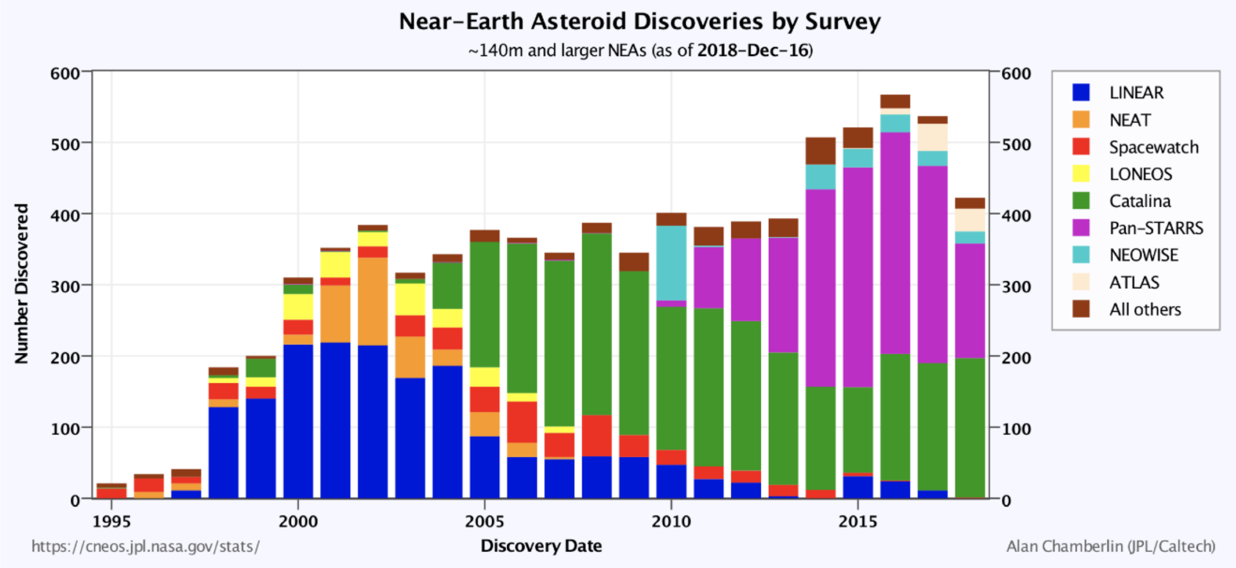

FIGURE 3.4 Near Earth objects 140 meters and larger, discoveries made by various surveys since 1995 as of December 16, 2018. The most recent drop in discoveries was largely due to poor weather over Hawaii, which reduced discoveries made by PanSTARRS. SOURCE: Center for Near Earth Object Studies, "Discovery Statistics: By Survey (140 m)," https://cneos.jpl.nasa.gov/stats/site_140.html, accessed December 16, 2018; courtesy of NASA/JPL/Caltech.

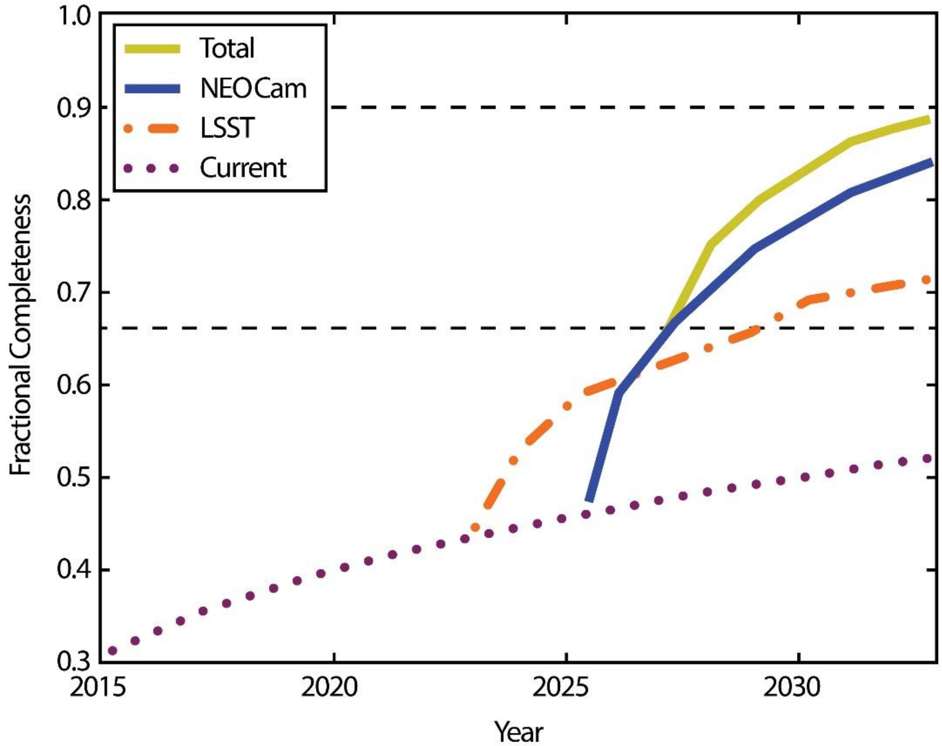

FIGURE 3.5 Estimate of near Earth object (NEO) survey completeness (D > 140 m) for current (circa 2019), LSST, and proposed NEOCam surveys, plus all survey assets combined. The dates the LSST and NEOCam become operational are the current estimates. Provided these do not change, relative to one another, by more than a couple of years, the curves shown here are still representative of the expected performance to within a few percent. Note that the curve labeled "Total" is not simply the sum of the other survey curves, because it takes into account the circumstance that different surveys will often discover the same object. The "LSST" and "Current" curves are adopted from Vereš and Chesley (2017), and the NEOCam curve is obtained from Mainzer (2016) but repositioned to 2026 start date. NOTE: See P. Vereš and S.R. Chesley, 2017, High-fidelity Simulations of the Near-Earth Object Search Performance of the Large Synoptic Survey Telescope, *Astronomical Journal* 154:12, Fig. 19; A. Mainzer, 2016, "NEOCAM: Near Earth Object Camera: A Comprehensive Survey of the Solar System," presentation at the 14th Meeting of the NASA Small Bodies Assessment Group, January 27-29, https://www.lpi.usra.edu/sbag/meetings/jan2016/presentations/Mainzer.pdf.

PROJECTIONS FOR LSST

Ground-based telescopes continue to add to our inventory of NEOs, as seen by the steep slopes of the cumulative numbers of NEOs discovered larger than 140 meters in Figure 3.5. This trend will continue into the future, particularly as new ground-based telescopes come online.

Of particular importance to the ground-based NEO search, the Large Synoptic Survey Telescope (LSST)[17] is scheduled to come online in 2023. Located in Chile, it will conduct a 10-year baseline survey using an 8.4-meter mirror (see Figure 3.6). One of LSST's four science goals is to observe the solar system. The other three goals are astrophysical: understanding dark matter, exploring the changing sky,

[17] National Science Foundation, 2019, *Mirror, Mirror on the Mountain – LSST Primary/Tertiary Mirror (M1M3) Arrives on Cerro Pachón*, https://www.lsst.org/news/mirror-mirror-mountain.

and tracking motions of stars in the Milky Way galaxy. The planned operations will find many more NEOs, but the accuracy of the diameter measurements is not as good as that determined by infrared observations and will not reach the completeness requirements of the George E. Brown Act. LSST's contributions to NEO survey goals have been modeled, yielding the following results:

- If the contributions of NEO search efforts from their inception in the early 1990s to the present are included, the LSST will result in a NEO catalogue for objects with an absolute brightness, or H value, of less than 22, which is 75 percent complete by the end of its 10-year baseline survey. (As mentioned later in this report, diameter estimates from visible observations at the LSST will have very large uncertainties due to the unknown albedo of a given object.)
- The astrometric accuracy of the positions obtained by the LSST will be on the order of 50 milli-arcseconds (mas) due to use of the Gaia star catalogue and the large number of catalogue stars per image frame.[18] These measurements result in accurate orbital calculations for the detected NEOs.

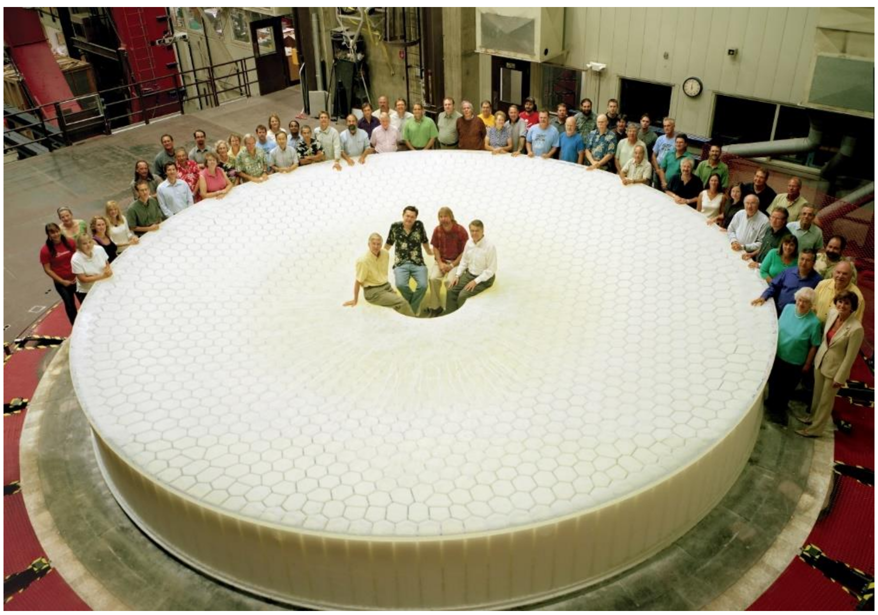

FIGURE 3.6 The mirror for the Large Synoptic Survey Telescope early in production. SOURCE: Howard Lester/LSST Project/NSF/AURA.

At the same time that LSST will contribute to the NEO search and discovery, photometric measurements obtained by the telescope can be used to infer diameter estimates that have larger uncertainties than those derived from infrared measurements. LSST diameter estimates are derived from the absolute magnitude (H) from visible photometry and an assumed geometric albedo.[19] Unfortunately, catalogue H values are notoriously unreliable (see, for example, Pravec et al. (2012)[20]) with errors of up to 0.5 mag or more, depending on the brightness of the object. This problem will probably worsen as smaller (fainter) objects are discovered in future surveys, with a consequent increase in the uncertainty of diameters derived from visual observations. It should be noted that H values are not required for the derivation of diameters from thermal-infrared observations and cannot be provided by the latter. As

[18] A milli-arcsecond (mas) is one-thousandth of an arc-second, and equals 1/3600th of a degree. It is an angular unit of measure used to describe the apparent size of an object in space as viewed from a telescope either on the ground or in space.

[19] The relationship between size, geometric albedo (pv), and absolute visual brightness (H) is: $D = 10^{-H/5} \times 1329/\sqrt{pv}$ km.

[20] Pravec et al., 2012, *Icarus* 221:365-387.

previously noted, the extreme range for visual albedos is 0.01 to 0.5, whereas the more typical visual geometric albedo (p_V) values are between ~0.02 and ~0.35 for well-observed NEOs in the size range greater than ~1 kilometer, and this albedo distribution is assumed to be the same for small NEOs. Under these assumptions, a random NEO LSST discovery with H = 22 will have a diameter between 90 and 375 m. Assuming full multi-color photometry is available, these limits can be reduced to a size range of about 140 to 240 m. Surveys at visual wavelengths are biased against discovering low-albedo objects. A LSST survey starts to become significantly incomplete fainter than H = 21 (Jones et al. 2017); it is likely that many of the missing H = 22 NEOs in visual surveys will have albedos closer to 0.02 than to 0.35. LSST can detect objects fainter than H = 22, but only a fraction of these low-albedo NEOs will be discovered at higher values of H (fainter). Their relatively high infrared fluxes favor detection with an infrared telescope, which is also the preferred method to provide accurate diameters. In this regard, ground- and space-based telescopes are synergistic.

The committee heard from experts on LSST who informed the committee that LSST would be 50-60 percent complete on H < 22 NEOs in 10 years. When combined with other search efforts, this would be approximately 77 percent. The committee was also informed that even a second dedicated LSST would not achieve the George E. Brown Act goals, and the committee determined that any additional LSST-class telescope would take up to a decade or more to make operational.[21]

Finding: No existing ground- or space-based platform can satisfy the size and completeness requirements of the George E. Brown Act goals in the foreseeable future.

Finding: It might be possible to build a ground-based telescope that could satisfy the completeness requirement of the George E. Brown Act if operated for a very long time (i.e., many decades). However, such a telescope would not meet the goals for size measurements. A new, dedicated, space-based infrared survey mission is required to achieve the George E. Brown Act goals.

Finding: The LSST will find many NEOs, despite the fact that this is only one of the telescope's four goals. However, it will not achieve the George E. Brown Act goals. Even an LSST dedicated to finding NEOs would not achieve the George E. Brown Act goals alone, or even in combination with other current ground-based assets.

Discovery observations provide positions for determining orbits and estimates of either diameter (for thermal infrared systems) or absolute magnitudes (H, for visual systems). Additional observations for physical characterization—for example, to determine composition and estimate density—must be obtained by nonsurvey assets. This is because, in general, survey telescopes do not have the required instrumentation and, even if they did, characterization observations would reduce the time spent surveying, and thus reduce the discovery rate. The same is true of follow-up astrometric observations; survey time and space-based instruments should not be spent on obtaining necessary astrometric data for objects that can be observed from the ground and accomplish the same goals.

Finding: Despite the limitations of ground-based telescopes for detection of NEOs, observation by ground-based systems is necessary for subsequent characterization of NEOs after discovery.

Recommendation: If NASA develops a space-based infrared near Earth object (NEO) survey telescope, it should also continue to fund both short- and long-term ground-based observations to refine the orbits and physical properties of NEOs to assess the risk they might pose to Earth, and to achieve the goals of the George E. Brown, Jr. Near-Earth Object Survey Act.

[21] "LSST's Projected NEO Discovery Performance," Steve Chesley & Peter Vereš, Briefing to NAS Committee on Near Earth Object Observations in the Infrared and Visible Wavelengths, Irvine, California, February 25, 2019.

This chapter has identified the current state as well as some of the limitations of ground-based visual NEO surveys. Chapter 4 addresses space-based platforms for NEO surveys.

4

The Advantages of Space-Based Infrared Platforms

A space-based system dedicated to near Earth object (NEO) survey detection, initial orbit determination, and estimation of diameters is necessary to reach 90 percent completeness of the inventory of NEOs larger than 140 meters and to assess the potential impact hazard to Earth. Although ground-based surveys provide larger apertures and greater light collection, space-based infrared surveys

- Can search efficiently the region interior to the orbit of Earth, where some NEOs orbit (see Figure 4.1);
- Provide more time for searching compared to observing from the ground, which is reduced by daylight and by sky brightness due to the Moon and by bad terrestrial weather; and
- Do not contend with the effects of Earth's atmosphere, which include scattered light and atmospheric absorption—both of which reduce the flux measured from a NEO on the ground, and atmospheric emission, which can blind a telescope to a NEO in the infrared.

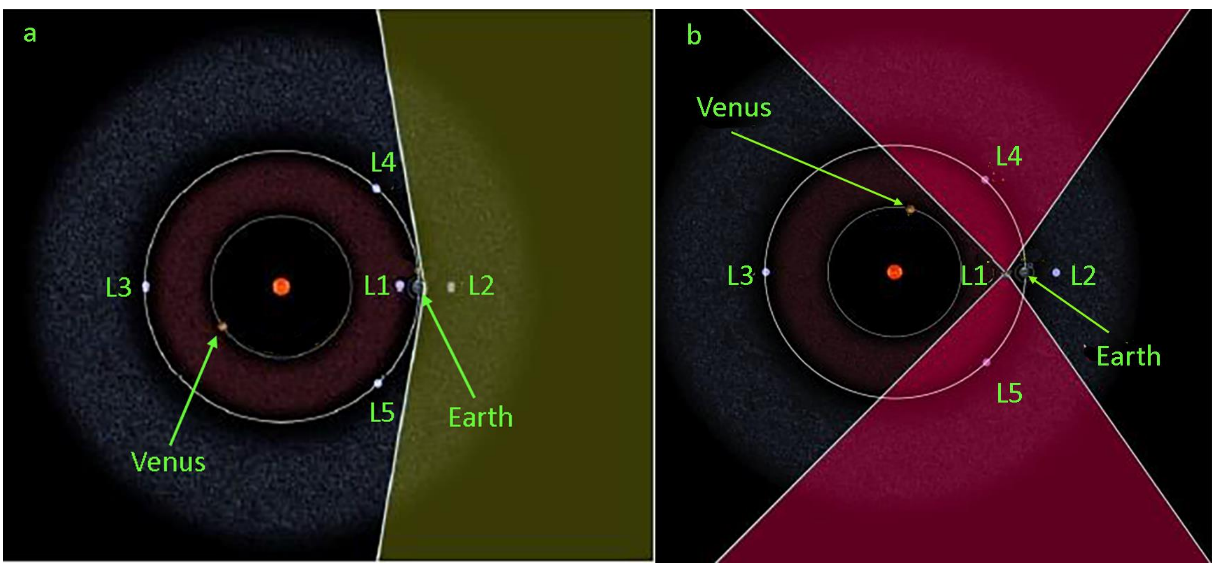

FIGURE 4.1 Schematic looking down on the solar system with the Sun in its center and the orbits of Venus and Earth portrayed. Lagrangian points L1 through L5 are labeled; these are regions of gravitational stability with respect to the Sun and Earth. Approximate NEO search regions are indicated schematically. Panel a shows the region accessible from the ground (olive shading) and how observations toward the Sun are restricted by the horizon and the effects of the atmosphere close to it. Panel b is for a space-based telescope at L1. With Earth out of the way, it can have better access to the region inside Earth's orbit, as shown by the regions shaded in magenta. SOURCE: G.H. Stokes et al., 2017, *Report of the Near-Earth Object Science Definition Team: Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs*, NASA Science Mission Directorate, https://cneos.jpl.nasa.gov/doc/2017_neo_sdt_final_e-version.pdf, p. 101.

Space telescopes operating at low temperature provide unique capabilities for detection of NEOs in the mid-infrared. Since NEOs are at a similar distance from the Sun and Earth, they are at similar temperatures. Thus, ground-based mid-infrared telescopes must pull the signal from a NEO out of the far larger (by a factor of up to a million) foreground emission by the telescope and atmosphere. The spectacular sensitivity of cooled infrared telescopes in space has been demonstrated by a series of very productive space astronomy missions such as Infrared Astronomical Satellite (IRAS), Infrared Space Observatory (ISO), Spitzer Space Telescope, Akari (previously known as ASTRO-F or IRIS-InfraRed Imaging Surveyor), and Wide-Field Infrared Survey Explorer (WISE).

Furthermore, the information obtained in the visual and infrared wavelength regimes is different. Infrared observations are better suited to estimating asteroid diameters with the least uncertainty. Due to the enormous numbers of NEOs that a space-based infrared survey will discover, use of a relatively simple first-cut model for size determination will be essential. Even relatively simple analyses of mid-infrared measurements can return reasonable estimates for NEOs, whereas visible light and near-infrared measurements are severely compromised for size determination. More accurate estimation of sizes using the Near Earth Asteroid Thermal Model (NEATM) is discussed in the Chapter 6.

Given a typical reflected light level of only about 15 percent, a substantial majority of the energy emerges in the mid-infrared, making the objects easier to detect there. The combination of all these factors results in an infrared space telescope potentially achieving the George E. Brown, Jr. Near-Earth Object Survey Act goal faster than other feasible approaches (see Figure 4.2).

With regard to the fact that a space-based, infrared survey has advantages over a visible-alone survey, visible surveys have a bias against discovering small low-albedo NEOs regardless of the limiting magnitude, suggesting there may be a population of undiscovered small low-albedo NEOs. Infrared surveys have a bias against discovering small high-albedo NEOs, although this bias is smaller than the bias of visible surveys.

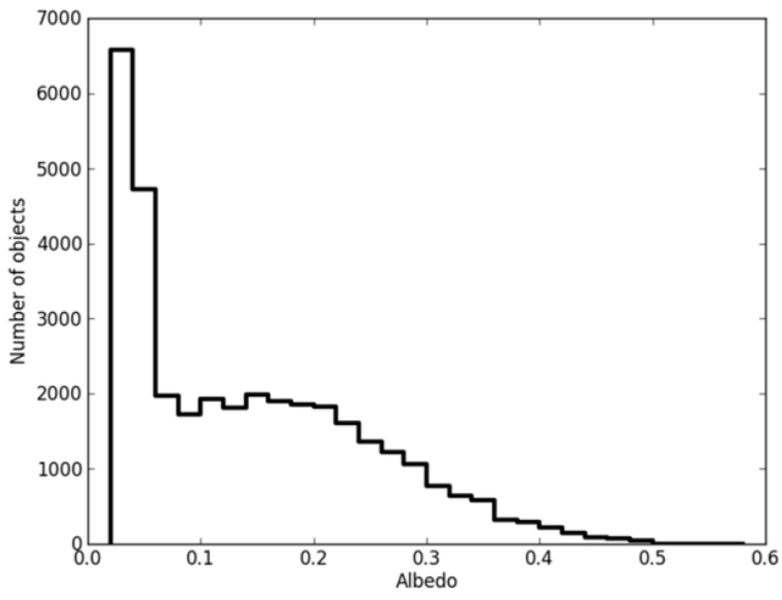

FIGURE 4.2 The albedo distribution for objects with a diameter greater than 100 m, used in the 2017 *Report of the Near-Earth Object Science Definition Team* synthetic population. The albedo distribution is assumed constant across diameter space. SOURCE: G.H. Stokes et al., 2017, *Report of the Near-Earth Object Science Definition Team: Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs*, NASA Science Mission Directorate, https://cneos.jpl.nasa.gov/doc/2017_neo_sdt_final_e-version.pdf, p. 23.

Visible and near-infrared measurements are preferred for obtaining measurements of orbits over extended time and for determining the surface properties of an asteroid through multicolor photometry and spectroscopy. More advanced modeling of the NEO size and other properties can be based on the combination of visible and mid-infrared measurements (see Figure 4.3). The committee notes that while space-based surveys, unlike their ground-based counterparts, are not limited to observing the night-time sky and are able to discover relatively faint objects, they have the disadvantage that in general ground-based telescopes will be unable to provide short-term follow-up observations to secure orbits. Therefore, an effective space-based survey will have to be designed with a scanning cadence that maximizes the probability that detected objects are observed multiple times at intervals that allow accurate orbits to be established.

A space-based telescope operating in the thermal infrared is the approach best capable of giving sufficiently accurate diameters to meet the intent of the George E. Brown Act (see Figure 4.4). This telescope would need to be ~50 centimeters or larger in aperture.[1] For example, a number of much smaller infrared telescopes would not have the sensitivity or the resolution to reach to the necessary diameter level and to determine accurate orbits.

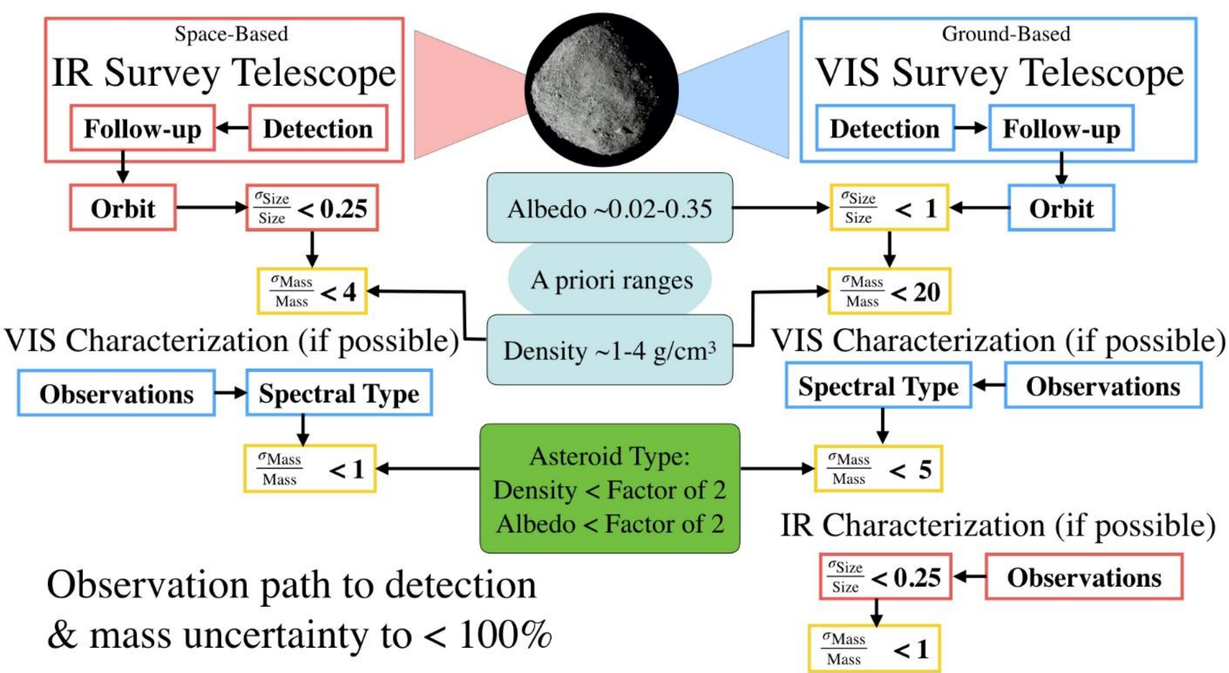

FIGURE 4.3 Necessary sequence of observations from asteroid discovery to a mass estimate accurate to ~100 percent. *Left*: An asteroid detected with a space-based infrared observatory will immediately have a mass uncertainty to within a factor of 4. If follow-up observations determine its spectral type, the mass uncertainty reduces to a factor of 1. *Right*: An asteroid detected with a ground-based visible observatory has an initial mass uncertainty to within a factor of 40. If follow-up observations determine its spectral type, the mass uncertainty reduces to a factor of 10, and infrared observations reduce this uncertainty by up to a factor of 10. Uncertainty estimates are approximate and based on assumed ranges in albedo and density. The light blue box shows a priori uncertainties in density and albedo from the overall population.

[1] G.H. Stokes, et al., 2017, *Report of the Near-Earth Object Science Definition Team: Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs*, NASA Science Mission Directorate, “Warning Efficiency: L1 Systems”, p. 138.

The green box shows the expected improvement in these parameters if the asteroid type can be determined using follow-up spectroscopy observations.

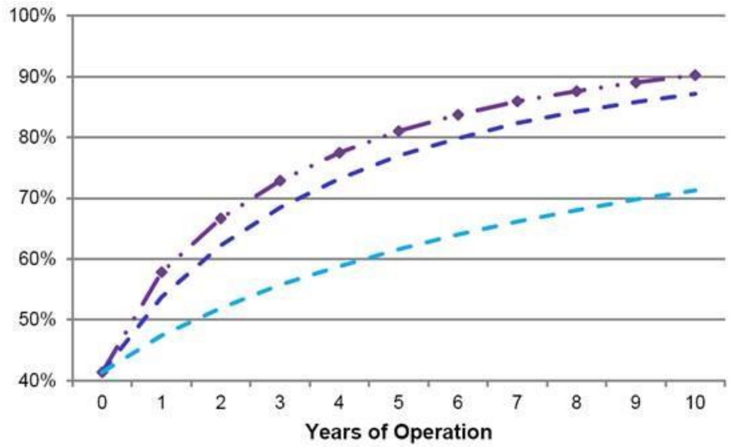

FIGURE 4.4 Comparison of completion rates for a space-based 0.5-meter infrared telescope at L1 (middle line), a space-based 0.5-meter visual wavelength telescope at L1 (bottom line), and the total of both operating together. This indicates that a 0.5-meter infrared telescope in space is superior to a visual wavelength in space, especially when considering that their costs are comparable. The 2017 Science Definition Team binned completeness rates for 126- to 158-meter-diameter near Earth objects, which is equivalent to what George E. Brown, Jr. Near-Earth Object Survey Act requires. SOURCE: G.H. Stokes et al., 2017, *Report of the Near-Earth Object Science Definition Team: Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs*, NASA Science Mission Directorate, https://cneos.jpl.nasa.gov/doc/2017_neo_sdt_final_e-version.pdf, p. 101.

SPACE-BASED VISUAL WAVELENGTH TELESCOPES

A team of scientists and engineers at NASA Goddard Space Flight Center (GSFC) studied multiple NEO survey system designs at both visual and infrared wavelengths. While the discovery rate of NEOs increases with time using existing ground-based assets, the 90 percent completeness by 2020 specified in the George E. Brown Act will not be met, extrapolating current discovery rates of ground-based telescopes. This point was repeatedly made by numerous reports and those reporting to this committee.

Space-based visual wavelength systems presented to the committee were explored for low-cost and high reliability, examining different telescope apertures as well as launch ridesharing and piggy backing on existing space-borne platforms such as the International Space Station (ISS). All space-based systems, especially ones designed specifically for detection of NEOs, have space-based platform advantages including the following:

- Near full-time operations;
- Access to large sky coverage;
- Scanning flexibility optimized for NEO discoveries;
- Ability to observe above Earth’s atmosphere, enhancing signal and reducing noise.

Visual wavelength space-based systems take longer to reach a high completion rate than space-based infrared telescopes and have inherent biases that cannot be overcome in either ground-based or space-borne platforms. This bias includes the inability to differentiate between large dark objects and small bright ones, a limitation of all visual wavelength telescopes whether ground- or space-based. This limitation is the result of large uncertainties in diameter estimates because of the compounding H-magnitude uncertainty, and the uncertainty inherent in assuming an albedo to estimate diameter.

GSFC's telescope performance tool allows survey simulations with the following variables:

- Detectors and their performance;
- Telescope pointing as a function of sky background related to zodiacal light and Earth and moon shine;
- NEO orbital populations of both size frequency and orbital distributions;
- Telescope pointing and field of view;
- Search results as a function of discovery criteria.

Among the visual wavelength systems looked at by GSFC's engineers and scientists are the following:

- 1.5 m telescope platform in geostationary, equatorial orbit;
  - High sensitivity
  - Mature technologies
  - Low risk
  - Fast development
- 0.5 m and 0.8 m large field of view, low-cost platform attached to the ISS;
- 1.0 m survey telescope co-manifested with various launch vehicles and locations in space;
- 4-0.4 m telescopes, two visual wavelength, two infrared, co-manifest with various launch vehicles to different locations in space (LEO, GEO, L2).

Michael Shao of the Jet Propulsion Laboratory presented a concept of a constellation of five micro satellites (20- to 30-cm-aperture telescopes) for NEO search and survey featuring synthetic tracking to optimize detections. Large-sky coverage would be achieved by the multiple, small-aperture telescopes and automated analysis of moving targets' signal. This approach is very interesting and has promise for NEO detection and survey, although the large format detectors are in development, software is being tested and improved and has not yet been demonstrated in space. Calculations of time to completion of 90 percent of 140-m NEOs is close to 20 years—twice that of an infrared, space-based platform.

The committee concluded that none of the visual wavelength-alone platforms matched the predicted performance of infrared, space-based platforms. Yet the combination of ground-based visual wavelength and infrared space-based platforms reached the desired completion rate in the shortest time period.

The committee, after hearing from scientists and engineers who considered visual wavelength space-based platforms, found no contradiction to numerous previous reports that concluded that an infrared space-based platform dedicated to the survey of NEOs will reach a completeness level of 90 percent for 140-meter-diameter objects sooner than any visual wavelength platform on Earth or in space. The physics of the interaction of sunlight with asteroid surfaces responds such that measurements of emitted radiation in the infrared spectral region can find NEO's more efficiently than any visual wavelength space-based system operating alone. Additionally, the estimated diameters derived from infrared measurements have lower uncertainty when combined with visual wavelength measurements. Thus the two spectral wavelengths regions complement each other in the detection, cataloging, and diameter estimates of NEOs.[2]

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[2] At the committee's first meeting in mid-December 2019, professor Richard P. Binzel of MIT, a planetary scientist who has made significant contributions to the study of asteroids and Kuiper Belt objects across five decades, commented on the committee's statement of task, point by point. Previous reports written by experts from both government and private sectors on the subject of NEO surveys include search simulations, analyses of technical

COST OF SPACE TELESCOPES

The cost of space-based telescopes can be estimated roughly as parameterized by Stahl and Henrichs (2016).[3] Their formulation shows a strong dependence on aperture and only weak dependences on operating temperature and wavelength. This behavior is confirmed by detailed costing of a range of space-based telescopes in the Near-Earth Object Science Definition Team (SDT) report (2017).[4] They estimated that a 0.5-meter-aperture visible telescope in either low Earth orbit or geosynchronous orbit would cost about $480 million, while one at the L1 or L2 Lagrangian point would be about $120 million more. The numbers for a 1-meter telescope were about $700 million, or $850 million at L1 or L2.

The 2017 SDT report estimates the cost of constructing a dedicated 8-meter, ground-based visible-light telescope as about one-seventh the cost of a 0.5-meter telescope in space.[5] The collecting area of the ground-based telescope would be 250 times that of the space-based version. This comparison dramatizes the ability of the ground to provide important capabilities by telescope size. Of course, ground-based telescopes have operating limitations that space-based telescopes do not, such as the inability to operate during the day, before sunrise or immediately after sunset, and in poor weather.

Operation at L1 or L2 is strongly favored for an infrared telescope; the 2017 SDT study found that an infrared telescope in the L1 or L2 orbit requires a cost increase of just a few percent over the same-size visible telescope in the same orbit and provides better NEO detection and characterization.[6] The SDT study provided a cost estimate that agreed well with the independent, detailed cost modeling for NEOCam (see the following section).

The committee draws two conclusions. First, it is reasonable to compare performance in the two spectral regions for telescopes of the same size; the costs for both rise so steeply with increasing aperture that only a modest increase in size of a visible light telescope would make it match the cost of an infrared one. Second, since an infrared telescope in space significantly outperforms an in-space visible wavelength telescope, from a cost/benefit analysis it is unnecessary to consider space-borne visible telescopes in depth. The advantage for the visible region comes from operating on the ground where very large telescopes are feasible.

TEST OF FEASIBILITY OF A SPACE-BASED INFRARED TELESCOPE

In addition to a detailed cost estimate, the Near-Earth Object Camera (NEOCam) provides a test of the detailed mission design and technical risk of a dedicated NEO-detecting telescope. NEOCam is a proposed mid-infrared space-based telescope that would scan the solar system to detect and track NEOs. It would use a passively cooled mid-infrared telescope with a 0.5-meter-diameter mirror and would operate at the Sun-Earth L1 point. NEOCam has received NASA funding for risk reduction and for mission concept development. All the relevant technologies are at a technology readiness level (TRL) of 5 or higher. According to the NEOCam project, if launched, the spacecraft would be able to detect

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approaches and their costs, as well as preparedness and mitigation strategies that were solicited by NASA. Some of these reports were carried out under the auspices of the Space Studies Board of the National Academies of Sciences, Engineering, and Medicine. The list of reports numbers more than 18 in the past 11 years and can be found at https://www.nasa.gov/planetarydefense/supporting_documents and at links from this site. Those reports assessing the technical aspects of NEO search, cataloguing, and characterization conclude that the most comprehensive approach toward meeting the task at hand is to employ space-based infrared surveys that both discover and estimate diameters upon discovery.

[3] H.P. Stahl and T. Henrichs, 2016, Multivariable parametric cost model for space and ground telescopes, *Proceedings of the Society of Photo-Optical Instrumentation Engineers 9911, Modeling, Systems Engineering, and Project Management for Astronomy VI*, 99110L.

[4] G.H. Stokes, et al., 2017, *Report of the Near-Earth Object Science Definition Team: Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs*, NASA Science Mission Directorate, p. 157.

[5] Ibid., p. 150.

[6] Ibid., p. 158

approximately 80 to 87 percent of the >140-meter-diameter NEOs within 5 years.[7] In an extended 10-year mission, NEOCam would meet the George E. Brown Act goal.

The committee notes that NEOCam is primarily a planetary defense mission that has been forced to compete within NASA's Discovery program against other proposals that have primarily scientific objectives. This has placed NEOCam and similar planetary defense-related missions at a competitive disadvantage.

CONCLUSION

Visible, ground-based surveys are compromised by the day-night cycle and weather, as compared to space-based surveys. A major advantage of an infrared space-based system is its ability to provide a more reliable diameter shortly after detection, as soon as orbital parameters are available. Visible light and near-infrared measurements are severely compromised for size determination, whereas even relatively simple analyses of mid-infrared measurements can return accurate sizes for NEOs. As a result, a space-based infrared survey is better able to detect and characterize the NEO population to meet the requirements of the George E. Brown Act goal. A detailed study of a mid-infrared mission has concluded that the proposed system can reach the George E. Brown Act goal more quickly than currently considered alternatives.

Finding: A space-based mid-infrared telescope designed for discovering NEOs and operating in conjunction with currently existing and anticipated ground-based, visible telescopes is the most effective option for meeting the George E. Brown Act completeness and size determination requirements in a timely fashion.

The cost of a ground-based capability designed to meet the George E. Brown goal in a timely fashion is substantial. In addition, there is a range of possible costs and capabilities from the ground. The NEO SDT report (2017) quantifies the benefits relative to a space-borne infrared telescope, and they appear to scale roughly with cost.

Recommendation: If the completeness and size requirements given in the George E. Brown, Jr. Near-Earth Object Survey Act are to be accomplished in a timely fashion (i.e., approximately 10 years), NASA should fund a dedicated space-based infrared survey telescope. Early detection is important to enable deflection of a dangerous asteroid. The design parameters, such as wavelength bands, field of view, and cadence, should be optimized to maximize near Earth object detection efficiency for the relevant size range and the acquisition of reliable diameters.

Finding: Past space-based survey mission proposals such as NEOCam have been required to compete within scientific programs for selection. This has put them at a competitive disadvantage because of fundamental differences in their objectives.

Recommendation: Missions meeting high-priority planetary defense objectives should not be required to compete against missions meeting high-priority science objectives.

This could be addressed by having a separate Planetary Defense mission line with an announcement of opportunity that is focused on planetary defense needs, something that is currently under discussion within NASA. Observations in the thermal infrared can provide far more accurate asteroid sizes than observations in the visible region, provided the illumination and observing geometries and rotation of the asteroid are taken into account.

[7] Mainzer, A., 2006, NEOCam: The Near-Earth Object Camera, *Bulletin of the American Astronomical Society*, 38, p. 568, http://adsabs.harvard.edu/abs/2006DPS....38.4509M.

Chapter 5 provides a quantitative discussion of the methods and relative accuracies of asteroid size determinations.

5

Techniques to Obtain NEO Sizes

If the albedo of an object is known, then the visible brightness of the object can provide an estimate of size. The main drawback of this method is the lack of knowledge of the physical properties of a newly discovered asteroid. While the orbit, and therefore distances from the Sun and Earth, at any time may already be well known, observational data on surface properties, such as albedo, have to await follow-up visible-infrared photometry and spectroscopy observations, which are more demanding in terms of target brightness and telescope time and may not be feasible until a later apparition—that is, many months or years after discovery (see Chapter 2). The 2010 National Space Policy of the United States specifically directed the NASA Administrator to “pursue capabilities, in cooperation with other departments, agencies, and commercial partners, to detect, track, catalog, and characterize near Earth objects (NEOs) to reduce the risk of harm to humans from an unexpected impact on our planet.” The most important *physical* parameter from the harm point of view is the size, which is the first thing the public would want to know, should a seriously hazardous object be detected in a survey. Accurate diameter measurements have the highest importance for planetary defense purposes and should therefore be made as soon as possible.

Visible reflectance spectra can provide taxonomic classification, which can be used to infer approximate albedo intervals for many asteroids. Some classes of asteroids, however, have relatively flat, featureless spectra, making taxonomic classification difficult without high-quality spectra.

Most solar radiation incident on an asteroid is absorbed, thereby heating it up and giving rise to the emission of thermal radiation in the mid-infrared region of the spectrum. The amount of solar energy incident on a surface element of an asteroid can be determined given knowledge of its orbit and the Sun’s radiation output. A simple model of the temperature distribution around the asteroid’s surface, which is normally assumed to be spherical, then suffices to enable a reliable prediction of the thermal-infrared brightness of the object as measured at an infrared telescope. In practice, an iterative procedure is used to match the model prediction to the measured brightness, resulting in a best-fit value of the diameter. A very simple asteroid thermal model might be a spherical black body, which absorbs all radiation incident on it and has a constant equilibrium temperature around its surface. In practice, however, surface elements facing the Sun will be warmer than those on the night side of the object, and a telescope might be observing a side that is only partially illuminated by the Sun. In addition to the illumination and observing geometries, the rotation of the asteroid and its surface properties, such as cratering or roughness and whether the surface is dusty and porous (i.e., has low thermal inertia) or rocky (high thermal inertia), influence the thermal emission observed at the telescope. A significant number of small asteroids are either contact binaries or are highly irregular in shape. Averaging three to four thermal infrared measurements over a time span of approximately 1 month or more should provide adequate sampling over view angles to allow accurate size estimation in these cases, with a simple spherical model in many cases. Furthermore, repeated thermal-infrared measurements will reveal objects with large infrared lightcurve amplitudes, indicative of elongated and irregular shapes, of interest for further investigation.

THE DEVELOPMENT OF ASTEROID THERMAL MODELING

A slowly spinning asteroid with low thermal inertia will have a prominent peak in surface temperature, and therefore thermal emission, on the side facing the Sun (Figure 5.1). This situation is well described by the Standard Thermal Model (STM), which was successfully used to determine the sizes of main-belt asteroids and a few NEOs—for example, using ground-based telescopes such as the Infrared Telescope Facility (IRTF) and the orbiting Infrared Astronomical Satellite (IRAS) telescope.

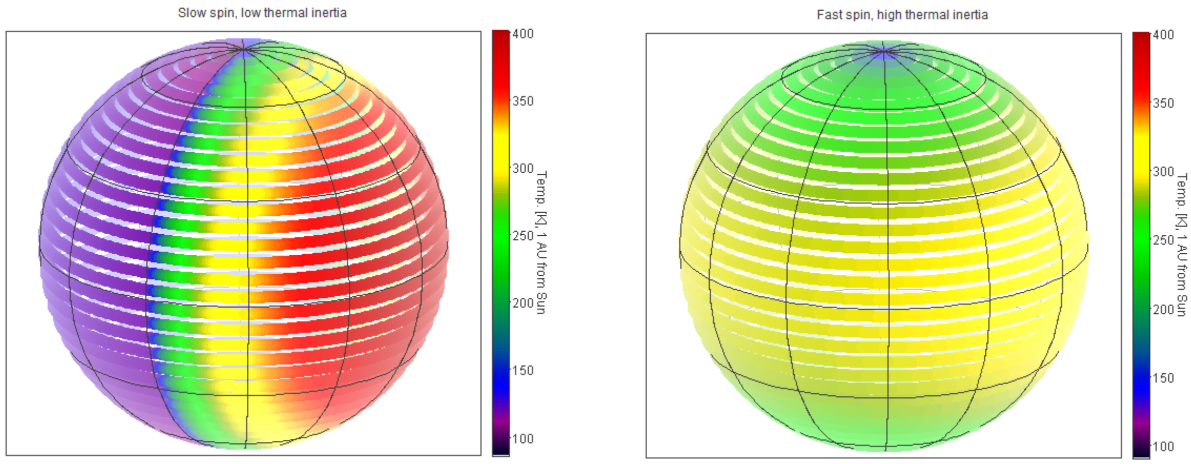

FIGURE 5.1 Temperature distributions similar to those of the Standard Thermal Model (STM) (*left*) and the Fast Rotating Model (FRM) (*right*). Solar radiation is incident from the right. SOURCE: A.W. Harris, German Aerospace Center's Institute of Planetary Research.

The sizes of a significant number of asteroids, especially NEOs, derived using the STM were inconsistent with results derived using other techniques—for example, radar. In certain cases, the inconsistencies could be resolved by means of an alternative simple model, called the Fast Rotating Model (FRM; also referred to as the isothermal latitude model), which describes the surface temperature distribution in the case of fast rotation and high thermal inertia.

A significant advantage of the STM and FRM is that they require observations in only one thermal-infrared wavelength band, typically in the range 5 to 20 μm. A very significant disadvantage is that, in the case of a newly discovered asteroid with unknown physical properties, there is no way of knowing which of the two alternative models should be applied. Selection of the wrong one can give rise to very large errors.

Over the past few decades, as more information on the physical properties of asteroids has been gathered, it has become clear that most objects have thermal properties somewhere between the extremes represented by the two simple models mentioned above. The rapid increase in computing power in recent years now allows detailed thermophysical models to be applied to observational data to provide very accurate sizes and reliable estimates of thermal inertia and surface roughness. Such models represent the current state of the art in the analysis of infrared and optical data of asteroids but require large amounts of observational data taken over wide ranges of observational geometry, and accurate information on the shape of the object in question. In the case of NEOs, such comprehensive data sets are normally built up over periods of years, using optical, infrared, and radar telescopes, during several apparitions of an object, and are currently available for just a few hundred asteroids. While thermophysical modeling is a powerful and relatively accurate method, it cannot be applied reliably until the requisite amount of relevant data has been acquired.

For the estimation of sizes and albedos in the absence of information on physical properties, another option exists, the Near Earth Asteroid Thermal Model (NEATM), which represents a compromise between the STM and FRM and removes the problem of not knowing which of the two alternatives to apply.

THE NEAR EARTH ASTEROID THERMAL MODEL

NEATM uses spherical geometry and is based on the STM, but with two important improvements. First, the NEATM incorporates a fitting parameter, normally called η, which in effect modifies the surface temperature distribution to allow the model thermal radiation to be fit more accurately to that observed at the telescope. Second, the observing geometry (Sun-asteroid-observer) is taken account of explicitly so that the radiation flux calculated from the model represents that part of the surface facing the telescope, which may be a combination of day- and night-side fractions of the asteroid. While the NEATM is still a relatively simple model based on spherical geometry, it has been used extensively by many groups since its publication, and its accuracy is well documented in the literature.[1]

There are two ways of applying the NEATM, depending on the availability of thermal-infrared measurements in more than one band. If measurements in at least two well-separated thermal-infrared bands are available, then the model radiation fluxes can be fit to the observed fluxes by varying the asteroid size and the η parameter (Figure 5.2). The resulting best-fit value of η may contain useful bonus information on the thermal properties of the asteroid, such as thermal inertia. As shown in Appendix B, evidence from comparisons of NEATM results with results based on other techniques reported in the literature such as detailed thermophysical modeling and radar observations indicate that the NEATM often provides diameters accurate to ±10 percent or better. NEATM is generally significantly more accurate than the STM or FRM.

If measurements in only one thermal-infrared band are available, then some assumption about the appropriate η value may be made. It has been shown from Near Earth Object Wide-Field Infrared Survey Explorer (NEOWISE) results, among others, that η depends on the observing geometry, increasing as the solar phase angle of the asteroid (i.e., the Sun-asteroid-observer angle) increases. In a number of studies, an appropriate value of η has been estimated on the basis of the phase angle at the time of the observations. While the accuracies of resulting diameters cannot match those of the fitted-η method described above, this technique may still give diameters to an accuracy of around ±20 percent (see Appendix B).

An overview of the results described in Appendix B is provided in Table 5.1.

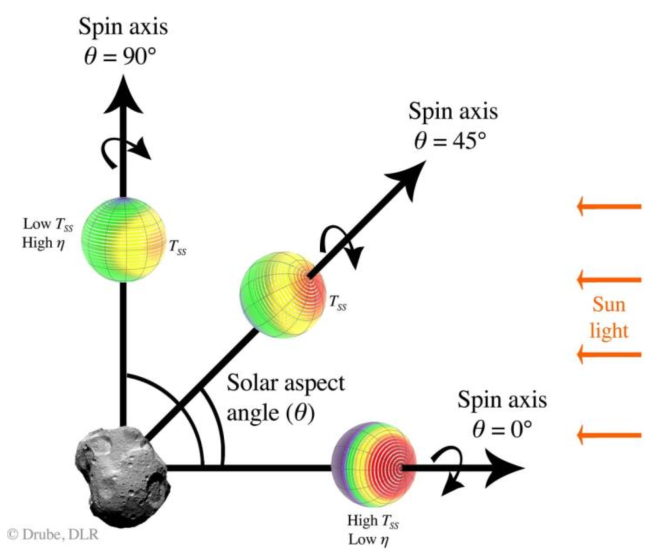

FIGURE 5.2 An asteroid's surface temperature distribution is governed by the rotation rate, the thermal inertia, surface roughness, and the solar aspect angle, θ. The solar aspect angle is the angle between the spin vector of the asteroid and the solar direction (90 degrees minus subsolar latitude). In the Near Earth Asteroid Thermal Model (NEATM), given measurements of an asteroid's thermal emission in two or more infrared spectral bands, the surface temperature distribution is modified by varying the model parameter η to obtain the best fit of the model thermal fluxes to those measured at the telescope. T_{SS} = subsolar temperature. SOURCE: A.W. Harris and L. Drube, 2016, Thermal Tomography of Asteroid Surface Structure, *Astrophysical Journal* 832:127, reproduced by permission of the AAS.

[1] A.W. Harris, 1998. A thermal model for near-Earth asteroids, *Icarus* 131(2):291-301.

TABLE 5.1 Representative Error Estimates in Asteroid Diameter Determinations

Method	Maximum Diameter Error	Typical Error[a]
Visible observations,[b] assuming albedo, pv, = 15% taking extreme range 0.01 < pv < 0.5	-80% +100%	
Visible observations[b] assuming albedo, pv = 0.15 taking typical range 0.02 < pv < 0.35	−30%, +100%	−70%, +75%
IR/STM		
$\alpha = 20°$	−25%	−10%
$\alpha = 50°$	−25%	−10%
IR/FRM		
$\alpha = 20°$	+45%	+30%
$\alpha = 50°$	+25%	+10%
IR/NEATM, fixed $\eta = f(\alpha)$, one purely thermal band	±40%	±20%
IR/NEATM, fitted η, ≥ two thermal bands		
$\alpha = 20°$	+5%	<5%
$\alpha = 50°$	+15%	+5%

[a] Values for thermal models[c] assume typical NEO thermal inertia[d] = 200 $Jm^{-2}s^{-0.5}K^{-1}$.
[b] Diameters derived from visible photometry depend on measurements of the absolute visible brightness, H, of an object. Published values of H have typical errors of ~±0.3 magnitudes, which are included in the diameter error estimates given in the first two rows of the table.
[c] For the IR/NEATM fixed-η mode, Harris et al. (2011) concluded that the RMS diameter uncertainty from Warm Spitzer observations is ±20%, based on a comparison with published NEO "ground-truth" results. In contrast, the estimated errors for the STM, FRM, and NEATM in fitted-η mode should be treated as best-case uncertainties. In the case of the FRM and NEATM, the error estimates are broadly consistent with the results of Mommert et al. (2018), which are based on a completely different and more comprehensive study.
[d] Error estimates given here are based on current knowledge of the NEO population. Errors in diameter determinations for unusual objects with physical properties outside of the observed normal ranges may be greater than the values given here. Values of H can be improved with follow-up ground-based observations although the faintness of most of the NEOs discovered in the next-generation surveys, and the need for multiple observations over at least 10° or so of solar phase angle, means this will be possible for only a subset of the most hazardous NEOs.

REFLECTED SOLAR RADIATION

Use of the NEATM in fitted-η mode requires measurements in two or more infrared bands in which reflected solar radiation is insignificant (wavelengths longer than about 4.5 μm for NEOs) or can be calculated and subtracted from the measured total fluxes. Corrections for the reflected component in wavelength bands below 5 μm often result in thermal flux values with relatively large uncertainties.[2] To optimize the accuracy of diameter determinations, the wavelength bands of filters should be chosen so as to minimize contamination by reflected solar radiation (Figure 5.3). For a typical NEO at 1 AU from the Sun, the reflected solar component is insignificant in filter bands beyond about 4.5 μm. The relative amount of reflected solar radiation increases with increasing albedo and heliocentric distance.

[2] See, for example, N. Myhrvold, 2018, Asteroid thermal modeling in the presence of reflected sunlight, *Icarus* 303:91-113.

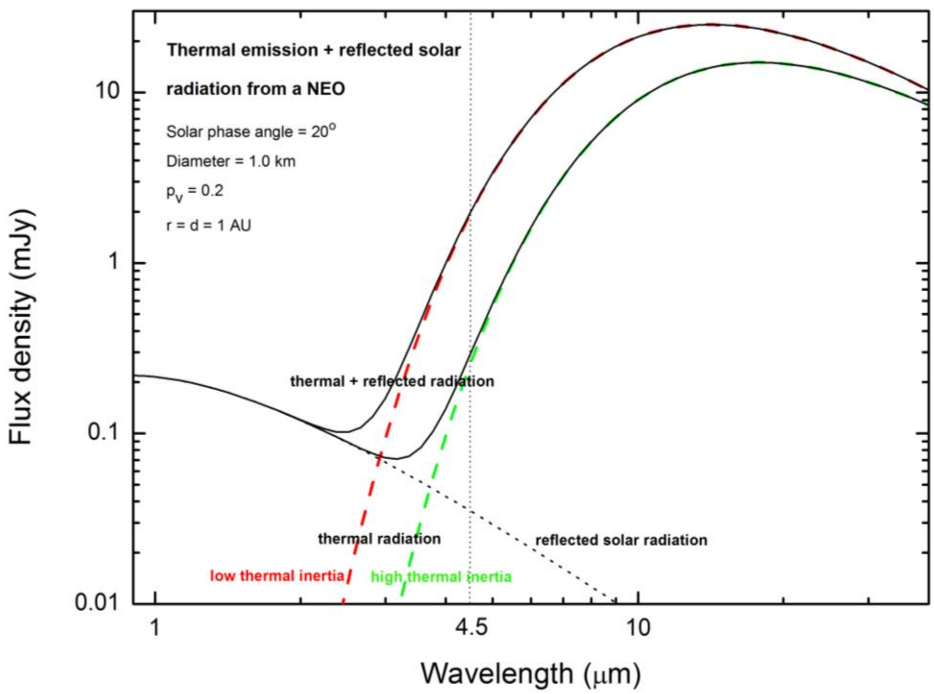

FIGURE 5.3 The measured infrared radiation from an asteroid is a combination of thermally emitted radiation and reflected solar radiation. Given typical physical properties and observing geometry, the reflected component of a near Earth object's (NEO's) measured radiation is negligible compared to its thermal emission at wavelengths longer than ~4.5 μm. The red and green curves represent thermal emission from a NEO with thermal inertia at the extreme low and high ends, respectively, of the known range of NEO thermal inertia values. SOURCE: A.W. Harris, German Aerospace Center's Institute of Planetary Research.

REMARKS ON ACCURACY

Apart from the infrared NEATM fixed-η case, the errors listed in Table 5.1 are based on modeling and do not account for real-world effects such as observational errors and irregular shapes, which must be included in a realistic overall error analysis. More irregularly-shaped NEOs may be found as improved surveys probe the smaller-size range of the NEO population (diameters of less than 150 meters). They may discover a greater proportion of small monolithic collisional fragments compared to more regularly shaped rubble piles found among the larger objects. Irregular shapes give rise to rotationally induced light curves with larger amplitudes in both reflected and emitted radiation, which may lead to increased errors in derived sizes, depending on how the light curves are sampled by the observations. In practice, the associated error can be minimized by taking measurements at several phases of the light curve, which is often done in thermal-infrared observations of asteroids. For example, the Wide-Field Infrared Survey Explorer (WISE) cryogenic survey made an average of 10 detections of a typical asteroid or comet spaced over ~36 hours. Furthermore, several thermal-infrared measurements made over a number of weeks, thus sampling different aspect and phase angles, may be averaged to provide good size estimates with a simple spherical model even in the case of a contact binary or other highly irregular shape.

Finding: To optimize the accuracy of diameter determinations a space-based infrared survey would have at least two filter bands at wavelengths longer than about 4 μm to minimize contamination by reflected solar radiation.

Modified versions of the NEATM (e.g., the Night Emission Stimulated Thermal Model)[3] and the FRM (e.g., the Generalized FRM)[4] have been proposed, which may perform better than the conventional NEATM for populations of NEOs with certain physical properties. Unfortunately, the physical properties of NEOs, especially small ones, are not well known. While these models have not been thoroughly tested in the way NEATM has been by many workers over many years, physical characterization of NEOs expedited by means of coordinated ground-based optical and radar observations, in addition to infrared measurements, would enable the applicability, scope, and accuracy of alternative modeling approaches to be tested. The well-documented archiving of all types of NEO observational data, enabling easy and flexible retrieval, is also important to allow new observations to be linked to existing data.

Thus, improved knowledge of the distribution of NEO physical properties will lead to improved models, which can be applied to existing and future infrared data sets to increase the accuracy of derived parameters, such as size. Furthermore, in the course of time, as more observational data become available for an object, thermophysical modeling based on an accurate shape model can significantly improve the initial results obtained from simpler models.

A number of groups are currently analyzing WISE data, in combination with other observations, to enhance the NEOWISE results published to date.

CONCLUSION

Studies (see Appendix B) indicate that an absolute size accuracy of ±10 percent or better is often achievable with current well-tested analysis procedures, given flux measurements in two or more thermal-infrared wavebands—that is, beyond about 4.5 μm. However, due to real-world effects, such as observational errors and irregular shapes, realistic expectations should allow for root-mean-square errors of ±20 percent. If flux measurements contain significant reflected solar radiation (i.e., at wavelengths below about 4.5 μm), the accuracies of derived sizes may be reduced.

[3] S.D. Wolters and S.F. Green, 2009, Investigation of systematic bias in radiometric diameter determination of near-Earth asteroids: the night emission simulated thermal model (NESTM), *Monthly Notices of the Royal Astronomical Society* 400(1):204-218.

[4] N. Myhrvold, 2016, Comparing NEO search telescopes, *Publications of the Astronomical Society of the Pacific* 128:045004.

6

The Role of Archival Data

Although the committee was not directly charged with considering archival aspects, it deemed this matter highly relevant and crucial for the success of any near Earth object (NEO) survey mission. The committee was also concerned that new ground- and space-based systems may collect such large volumes of data that they could overwhelm the archives and the systems used to access them.

Observations made both from the ground and from space retain value long after they are obtained because they are valuable in providing orbit improvement and characterization information. Hence, the proper archiving and hosting of any NEO survey data is crucial for the survey's success and its legacy value. NEO survey data include image data, source and object catalogues, as well as calibration products that are necessary to fully understand the performance of the survey system.

Image archives of the sky obtained at visual and infrared wavelengths are valuable because they may contain previously unrecognized detections of NEOs discovered by the space-based survey. Positions obtained from archived images often enable a significant improvement in the accuracy of an object's orbit after its initial discovery. For example, discovery observations of the ~500-meter-diameter, potentially hazardous, asteroid Apophis indicated a potential impact in 2029. However, shortly after the recognition of its potentially hazardous nature, archived observations taken 3 months prior to its discovery were used to better calculate its orbit and rule out the possibility of an impact. Access to such "precovery data" requires both archival and public access to these data.

Finding a precovery image is not simply a matter of finding images that should have been found originally, but rather of being able to search an image to lower signal-to-noise ratio. This is made possible because if it is known that an object is within, perhaps, 10 resolution elements of a given position, then a signal-to-noise ratio of 3, or even less, is adequate to identify an object compared with the original search having to identify the object at a signal-to-noise ratio of approximately 5 among 109 resolution elements. In addition, when searching for a precovery image, one knows the direction and rate of motion of the object and so can perform a moving co-add, which significantly increases the signal-to-noise ratio. Finally, newer, more accurate star catalogs (e.g., Gaia), enable old positions to be re-measured to higher accuracy than at the time they were taken.

Catalogue data, including photometric source catalogues that tabulate brightness measurements taken over time, represent a higher-level product that is generated from the image data. The publication of such catalogues enables, for instance, the derivation of absolute magnitudes, which crucially support the data provided by a mid-infrared survey system by enabling the estimation of albedos and improving diameter estimates based on thermal models.

Typically, researchers put a focus on the archiving aspect, which includes the storage and backup of data. However, recent technological developments enabled the real-time browsing and search through archival image and catalogue data (e.g., the Spitzer Heritage Archive[1]), and the Solar System Object

[1] California Institute of Technology, 2018, *Spitzer Heritage Archive,* https://sha.ipac.caltech.edu/applications/Spitzer/SHA/.

Image Search Tool by the Canadian Astronomy Data Centre[2]). Such tools have been proven immensely useful in the identification of precovery data as well as additional serendipitous observations to further constrain the physical and orbital properties of asteroids.

Finding: Effective archiving will facilitate improved knowledge of the distribution of NEO physical properties, leading to more appropriate model parameters and increased accuracy of derived properties, such as size.

Finding: Research using archival data can play and has played an important role in future threat evaluation and NEO science by the general research and planetary defense community. Archiving all data and images to support future improved thermal modeling, searching for serendipitous precovery observations, and other types of studies not considered during the survey mission is critical to detecting and characterizing NEOs.

Currently, archiving of NEO-related data is mainly accomplished through three available services in the United States: the NASA Planetary Data System (PDS),[3] the International Astronomical Union Minor Planet Center (MPC),[4] and the NASA Infrared Science Archive (IRSA).[5] PDS is NASA's main hub for data archival of planetary data and mainly consists of isolated archive files; the MPC is the official clearing house for solar system objects and provides large databases of small-body observations and orbital properties; IRSA includes image and catalogue data from the Spitzer and Wide-Field Infrared Survey Explorer (WISE) space telescopes.

The modus operandi for accessing data from these services varies significantly and often impedes the use of the data that is stored. Common issues are that data are isolated and cannot be queried in a meaningful way. For instance, archive files from the PDS and MPC have to be downloaded and information has to be extracted and combined locally. While IRSA provides a state-of-the art user interface, NEO flux data from the Near Earth Object Wide-Field Infrared Survey Explorer (NEOWISE) have to be extracted from source tables, involving highly time-consuming queries using other services.

Furthermore, most current asteroid survey programs report only astrometry and, in some cases, photometry for some select observations to the MPC, making it hard to use the existing data for further characterization efforts. The publication of additional data products would be invaluable for the physical and orbital characterization of asteroids and hence relevant to this study. To the knowledge of this committee, there is currently no uniform NASA policy in place to track whether or how NEO survey data have to be archived.

Finding: The current system for archiving NEO data is not optimized for accessing data and analyzing data in an automated fashion, and there is no consistent NASA policy on archiving NEO survey data.

The committee heard from experts on data archiving and was reassured that storage capacity for data will not be a problem in the future, given regular and reasonable upgrades to storage systems. However, storage alone is insufficient. In order to leverage the legacy value of NEO survey missions, it is mandatory that all data products generated by the survey are properly archived and made public in a

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[2] Canadian Astronomy Data Centre, 2019, *Solar System Object Image Search*, http://www.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/ssois/.

[3] University of Maryland, 2019, *NASA Planetary Data System: Small Bodies Node*, https://pds-smallbodies.astro.umd.edu/.

[4] Harvard & Smithsonian Center for Astrophysics and NASA, *The International Astronomical Union Minor Planet Center*, https://minorplanetcenter.net.

[5] California Institute of Technology, *NASA/IPAC Infrared Science Archive*, https://irsa.ipac.caltech.edu/frontpage/.

timely manner. The publication of such data enables not only the generation of higher-level data products that are relevant to threat evaluation, but also an independent verification of the results through the scientific community. Support for such efforts should continue to be provided by NASA, as is currently being done through the Near Earth Objects Observation (NEOO) program elements of Research Opportunities in Earth and Space Sciences (ROSES). Furthermore, it is mandatory for NASA to continue support for ground-based astrometric and photometric follow-up observations to improve orbital elements and provide additional characterization information.

Recommendation: All observational data, both ground- and space-based, obtained under NASA funding supporting the George E. Brown, Jr. Near Earth Object Survey Act, should be archived in a publicly available database as soon as practicable after it is obtained. NASA should continue to support the utilization of such data and provide resources to extract near Earth object detections from legacy databases and those archived in future surveys and their associated follow-up programs.

7

Impact Hazards Not Explicitly Considered by the George E. Brown, Jr. Act

Near Earth objects (NEOs) are not the only objects in space that can potentially impact Earth. As understanding of the solar system has advanced and more telescopic observations have been made, scientists have identified other objects that could pose an impact hazard and are also of scientific interest. These are summarized in this chapter for the sake of completeness.

JUPITER-FAMILY AND LONG-PERIOD COMETS

It is possible for comets from the outer solar system to cross Earth's orbit.

- *Jupiter-family comets (JFCs)*. Referred to as short-period comets with orbital periods less than 20 years—they are a source region for bodies that evolve to become NEOs.
- *Long-period comets (LPCs).* Take more than 200 years to orbit the Sun. They originate from the Kuiper belt. LPCs can be NEOs.
- *Isotropic comets*, which encompass LPCs and Halley-type comets (HTCs), generally have periods greater than 20 years and have an arbitrary boundary in orbital period at 200 years. All of these comets originate in the Oort Cloud.

The contribution of multiple NEO source regions is shown in Figure 7.1. Most NEOs come from the inner and central main belts; few come from the outer main belt or JFCs. For LPC and HTC populations, the goal should be to know the number-flux density of such comets (i.e., the number of comets per unit time per size bin) through near-Earth space, because the absolute number is huge and it is extremely difficult to identify them all individually, because the vast majority are too distant.

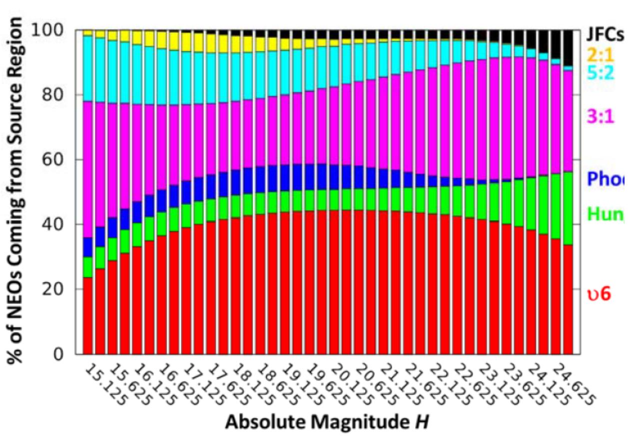

FIGURE 7.1 The main near Earth asteroid source regions are two asteroid groups (Hungaria and Phocaea), four main-belt escape routes (via the ν_6 secular resonance; 3:1, 5:2, and 2:1 mean-motion resonances with Jupiter), and the Jupiter-family comets (JFCs). SOURCE: G.H. Stokes et al., 2017, *Report of the Near-Earth Object Science Definition Team: Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs*, NASA Science Mission Directorate, https://cneos.jpl.nasa.gov/doc/2017_neo_sdt_final_e-version.pdf, p. 11.

OBJECTS WITH DIAMETERS LESS THAN 140 METERS

The George E. Brown, Jr. Near Earth Object Survey Act specified 140 meters as the lower limit for the NEO survey requirements in the 2005 NASA Authorization Act. Objects smaller than 140 meters are being found and catalogued in existing visible surveys. Although the completeness level of these surveys is low, it is important to discover and catalogue these objects. The 2013 Chelyabinsk fireball and the December 2018 fireball that exploded over the western Pacific Ocean had energies of 440 and nearly 200 kilotons, respectively. The Chelyabinsky fireball resulted in major damage to buildings. Both meteoroids were estimated to be significantly smaller than 140 meters in diameter (see Figure 7.2).

INTERSTELLAR OBJECTS

Interstellar objects, of which only one has been discovered in the history of astronomy, can be treated as part of the LPC population and are a miniscule fraction thereof.

- The probability of an impact by an LPC is only 1 percent that of a NEO impact.[1]
- The energy of an Earth impact would be high, because velocity at Earth orbit would be high, and energy is proportional to square of velocity and is calculated at ~30 percent larger than a typical NEO impact.

Definitions of these types of NEOs are included in this report for the sake of completeness and to explain why they should be considered within the context of the George E. Brown Act requirement, although they are not a driver in meeting the requirement.

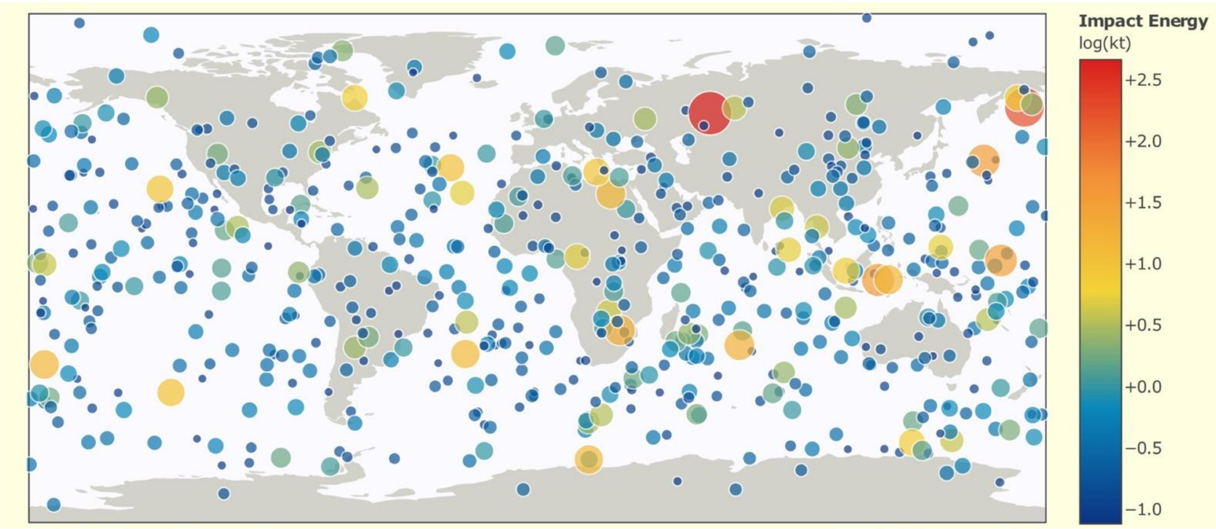

FIGURE 7.2 Fireballs reported by U.S. government sensors between April 15, 1988, and March 15, 2019. The 2013 Chelyabinsk fireball is visible at upper center right, and the December 2018 Bering Sea event is at upper right. These objects were all well below 140 meters in diameter. SOURCE: NASA Jet Propulsion Laboratory, Center for Near Earth Object Studies, "Fireballs Reported by U.S. Government Sensors," https://cneos.jpl.nasa.gov/fireballs, accessed March 15, 2019; courtesy NASA/JPL-Caltech.

[1] G.H. Stokes, et al., 2017, *Report of the Near-Earth Object Science Definition Team: Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs*, NASA Science Mission Directorate.

Appendixes

A

Letter of Request

National Aeronautics and Space Administration
Headquarters
Washington, DC 20546-0001

July 31, 2018

Reply to Attn of: Office of the Chief Scientist

Dr. Fiona Harrison
Chair, Space Studies Board
National Academies of Sciences, Engineering, and Medicine
500 5th Street NW
Washington DC, 20001

Dear Dr. Fiona Harrison,

NASA's 2005 authorization legislation directed the Agency to find 90% of all near-Earth objects (NEO) 140 meters or larger by the end of 2020 —a total population most recently estimated to be about 25,000. It is now well known that a significant fraction of NEO's have small albedos in the visible spectrum (primarily reflected light) and are bright in the infrared (IR) portion of the spectrum since the IR signature also contains the heat radiated by the asteroid. In the 2010 NAS report *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies* that committee found that "detections of potentially hazardous NEOs by an infrared telescope (one sensitive to infrared light) will result in a more accurate size-frequency distribution for these objects." NASA chartered a team of experts in late 2015 to update estimates of what's out there, what's yet to be found, and assess the technology available to us today for detection. The science definition team stated that sufficient developments in infrared technology have occurred with the potential to significantly advance our ability to find and determine the size of near-Earth objects.

Statement of Task: The National Academies of Sciences, Engineering and Medicine will establish an ad-hoc committee to investigate the following and make recommendations:

• Explore the relative advantages and disadvantages of IR and visible observations of NEOs.

• Review and describe the techniques that could be used to obtain NEO sizes from an infrared spectrum and delineate the associated errors.

• Evaluate the strength and weaknesses of these techniques and recommend the most valid techniques that give reproducible results with quantifiable errors.

In order for NASA to be able to use the results of this study, NASA would like to receive the Academy's findings within the second quarter of 2019. The technical point of contact for this effort will be Dr. Louis Barbier and can be reached at louis.m.barbier@nasa.gov or 202-358-1421.

Sincerely

James L. Green
NASA Chief Scientist

B

Studies of the Accuracy of the Near Earth Asteroid Thermal Model

A disadvantage of the Near Earth Asteroid Thermal Model (NEATM) is the assumption of zero thermal emission on the night side of the asteroid. Without knowledge of the spin vector and thermal inertia, it is not possible to estimate the amount of thermal energy emitted on the night side. At low solar phase angles, the telescope receives thermal radiation predominantly from the day side, so the neglect of emission from the night side is significant only for very large values of thermal inertia (Figure B.1). At large phase angles, however, thermal emission enters the telescope from the night side too, leading to overestimation of sizes by the NEATM; in this case, the Fast Rotating Model (FRM) is the model of preference if thermal inertia is likely to be large.

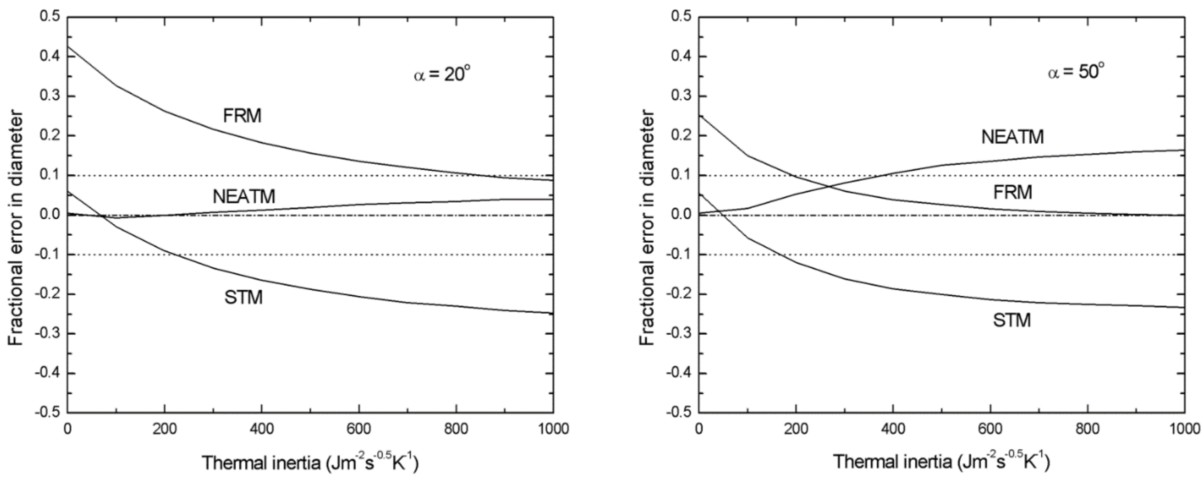

FIGURE B.1 Plots of the relative performances of the Standard Thermal Model (STM), the Near Earth Asteroid Thermal Model (NEATM), and Fast Rotating Model (FTM) against thermal inertia for solar phase angles of α = 20 degrees and α = 50 degrees. Test data were generated using a smooth spherical model incorporating the effects of thermal inertia. In the STM, the beaming parameter, η, was set to unity. The model asteroid had a rotation period of 6 hours and the subsolar and sub-Earth latitudes were zero; other parameters were chosen to be typical of near Earth objects. The sense of the phase angle is such that the cooler, morning side of the asteroid was viewed. For the circumstances of this test, the results indicate that NEATM outperforms the other models, except when the thermal inertia and solar phase angles are large. SOURCE: A.W. Harris, 2006, "The Surface Properties of Small Asteroids from Thermal-Infrared Observations," p. 449-463 in *Proceedings IAU Symposium 229, Asteroids, Comets, and Meteors* (D. Lazzaro, S. Ferraz-Mello, and J.A. Fernández, eds.), Cambridge: Cambridge University Press.

Mommert et al. (2018) investigated the performances of the NEATM and the FRM in a study of one million synthetic, thermophysically generated NEOs with physical properties, spin vectors, and observational circumstances randomly selected from within realistic bounds.[1] They concluded that the NEATM provides statistically more robust diameter estimates for solar phase angles less than ~65 degrees. The Mommert et al. (2018) results are consistent with the results shown in Figure B.1, given that the performance advantage of the FRM over the NEATM at high solar phase angles is reduced for realistic nonzero subsolar latitudes (note that the results in Figure B.1 are for subsolar latitude equal to 0 degrees, which favors the FRM). Mommert et al. also provided statistical functions to correct NEATM- and FRM-derived diameters and albedos for the dependence on solar phase angle.

Harris et al. (2011) investigated the accuracy of the NEATM when used in the fixed-η mode and found that, in the case of Spitzer observations of NEOs in the 3.6 μm and 4.5 μm bands, root-mean-square errors are ±20 percent in diameter and ±50 percent in albedo (note that the 3.6 μm band is normally contaminated with reflected solar radiation; see Figure 5.3).[2]

Using the single thermal-emission dominated band of the Warm Spitzer mission, Trilling et al. (2016)[3] acknowledge the large uncertainty in the η parameter in their thermal modeling and derive diameter and albedo uncertainties by applying the full distribution of previously measured η values. This approach leads to estimated typical diameter uncertainties of 40 percent and albedo uncertainties of 70 percent. These numbers highlight the benefit of acquiring thermal-infrared observations at least two different wavelengths.

Ryan and Woodward (2010) compared the performances of the NEATM and the Standard Thermal Model (STM) on thermal-infrared fluxes of 1,517 main-belt asteroids taken from the IRAS and MSX catalogues, finding that the STM underestimates asteroid diameters by ~10 percent and the NEATM underestimates diameters by ~4 percent when compared to radar- and occultation-derived diameters. They concluded that the NEATM approach produces more robust estimates of albedos and diameters.[4]

Hanus et al. (2018)[5] compared the diameters of main-belt asteroids derived from thermophysical modeling of Wide-Field Infrared Survey Explorer (WISE) thermal-infrared data with those published by NEOWISE based on the NEATM, concluding that on average their results are consistent with the radiometric sizes and 10 percent uncertainties reported by Mainzer et al. (2016).[6] (See Figure B.2.) Similar results are reported by Wright et al. (2018) in a comparison of WISE data from the fully cryogenic mission phase with occultation diameters.[7]

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[1] M. Mommert, R. Jedicke, and D.E. Trilling, 2018, An investigation of the ranges of validity of asteroid thermal models for near-Earth asteroid observations, *Astronomical Journal* 155:74.

[2] A.W. Harris, M. Mommert, J.L. Hora, M. Mueller, D.E. Trilling, B. Bhattacharya, W.F. Bottke, et al., 2011, ExploreNEOs II: The accuracy of the Warm *Spitzer* Near-Earth Object Survey, *Astronomical Journal* 141:75.

[3] D.E. Trilling, M. Mommert, J. Hora, S. Chesley, J. Emery, G. Fazio, A. Harris, M. Mueller, and H. Smith, 2016, Neosurvey I: Initial results from the Warm *Spitzer* Exploration Science Survey of Near-Earth Object Properties, *Astronomical Journal* 152(6):172.

[4] E.L. Ryan and C.E. Woodward, 2010, Rectified asteroid albedos and diameters from *IRAS* and *MSX* photometry catalogs, *Astronomical Journal* 140:933.

[5] J. Hanus, M. Delbo, J. Durech, and V. Ali-Lagos, 2018, Thermophysical modeling of main-belt asteroids from WISE thermal data, *Icarus* 309:297-337.

[6] A.K. Mainzer, J.M. Bauer, R.M. Cutri, T. Grav, E.A. Kramer, J.R. Masiero, C.R. Nugent, S.M. Sonnett, R.A. Stevenson, and E.L. Wright, 2016, NEOWISE diameters and albedos V1.0, *NASA Planetary Data System* 247.

[7] E. Wright, A. Mainzer, J. Masiero, T. Grav, and J. Bauer, 2018, Response to "An empirical examination of WISE/NEOWISE asteroid analysis and results," arXiv:1811.01454v1.

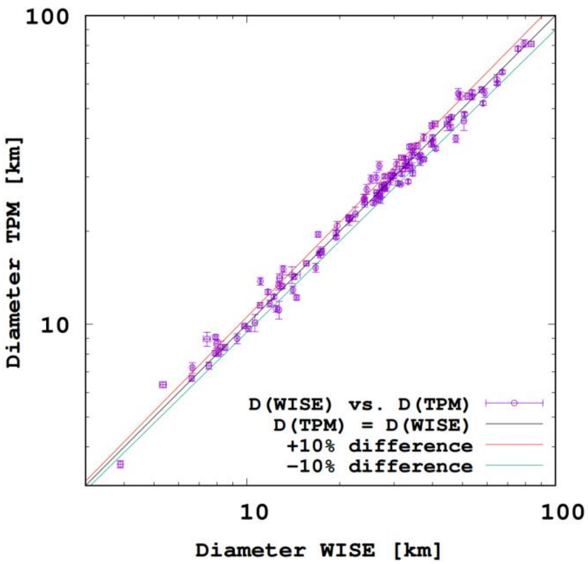

FIGURE B.2 Comparison between thermophysically modeled sizes and those derived using the Near Earth Asteroid Thermal Model (NEATM) from Mainzer et al. (2016). Both methods use the same thermal-infrared data sets. NOTE: TPM, thermophysical modeling; WISE, Wide-Field Infrared Survey Explorer. SOURCE: Hanus et al. (2018).

C

Advantages and Disadvantages of Ground- and Space-Based Options for Infrared and Visible Observations of Near Earth Objects

System	Advantages	Disadvantages
Visible/Radar Systems—Ground- and Space-Based		
Ground-Based Survey (e.g., PanSTARRS, CSS, LSST)	• Very good accuracy of orbit • Obtains H (required for albedo, once size is determined) and some data on rotation and space; can give likely albedo range, based on determination of taxonomic type and ranges of associated albedos • Relatively low cost going forward (LSST already under construction)	• Uncertainty in assessing size ~100% • Will take decades to even approach 90% completeness—cannot meet the George E. Brown, Jr. Near-Earth Object Survey Act limit
Ground-Based Visible Characterization Using Photometry and Spectroscopy	• Visible characterization using photometry and spectroscopy gives us rotation rate, constrains shape and provides taxonomy, mineralogy and surface composition	• ?
Ground-Based Radar Characterization (e.g., Goldstone, Arecibo)	• Can measure accuracy of size of known objects if they pass sufficiently close to Earth • Can dramatically increase the accuracy of orbit after discovery by other sources • Best attainable size from remote observations, albedo (via size and H), rotation, shape • Arecibo, Goldstone already exist; maintenance costs are known. Each also has non-NEO users	• Radar field of view impractical for searches; effective only for characterizing known objects

System	Advantages	Disadvantages
Space-Based Survey (e.g., 0.5, 1.0, 1.5 m space-based platforms)	• Very good accuracy of orbit • Good characterization if multi-filter or spectrometer in which case can infer albedo; measure light curves via imaging, providing rotation and ultimately shape	• Same uncertainty of accuracy of size as ground-based • Many tens of years; to make significant contribution would need to observe near the Sun, tradeoff between aperture size, cost, and contribution beyond LSST • Options to reduce cost below Discovery missions, but will take longer to achieve completion
Space-Based Visible Survey (SmallSat platform)	• Lower cost than other options —approximately $40 million per satellite	• Insufficient sensitivity for assessing accuracy of size to reach George E. Brown, Jr. Near-Earth Object Survey Act criterion • Software for detection of orbit does not exist but under development
Infrared Systems—Ground and Space Based		
Air-Based Characterization—Aircraft Mid-Infrared (5-35 μm) (e.g., SOFIA)	• No advantages with respect to accuracy of size, orbit or characterization	• Small field of view, low sensitivity due to Earth's atmosphere make searches impractical
Ground-Based Characterization—Mid-Infrared (e.g., Keck, LBT, Gemini)	• Can measure albedo given H; Size via mid-infrared	• Small field of view, low sensitivity due to Earth's atmosphere make searches impractical • Can measure rotation rate, etc., but no benefit over visible wavelength measurements
Survey—Infrared (50 cm at L1)	• Very good accuracy of size • Feasible to characterize albedo (via size and H) • Able to complete survey roughly 10 years after launch of telescope	• Potentially expensive at $550 million plus launch

D

Committee and Staff Biographical Information

H. JAY MELOSH, *Chair*, is a Distinguished Professor of Earth and Atmospheric Sciences, Physics, and Aerospace Engineering at Purdue University. Dr. Melosh's previous positions include professor of planetary sciences at the Lunar and Planetary Laboratory, University of Arizona; associate professor of planetary science at the California Institute of Technology; and associate professor of geophysics at the State University of New York. Dr. Melosh has made many important contributions to Earth and planetary sciences, including definitive studies of the collisional origin of the Moon and the process of impact cratering. His other major contributions include acoustic fluidization, dynamic topography, and planetary tectonics. He is active in astrobiological studies relating chiefly to microorganism exchange between the terrestrial planets. Dr. Melosh is a member of the National Academy of Sciences. He received his A.B. in physics from Princeton University and his Ph.D. in physics and geology from the California Institute of Technology. Dr. Melosh has previously served on committees of the National Academies of Sciences, Engineering, and Medicine, including the Committee on NASA Technology Roadmaps, the Committee to Review Near-Earth Object Surveys and Hazard Mitigation Strategies, and the Committee on Planetary and Lunar Exploration.

ALAN HARRIS is a senior scientist, retired, at the German Aerospace Center (DLR) Institute of Planetary Research in Berlin, and holds an honorary chair at Queen's University Belfast, UK. Dr. Harris leads research projects in solar system science, including observations and modeling of the physical properties of asteroids, and has pioneered radiometric data analysis techniques applicable to the study of small asteroids. Derivatives of his Near Earth Asteroid Thermal Model (NEATM) have been incorporated into data processing pipelines used by NASA's NEOWISE project, and by researchers using NASA's WISE and Spitzer space telescopes, as well as other facilities. Dr. Harris has served as chair of the European Space Agency (ESA) Near-Earth Object Mission Advisory Panel and as a member of ESA's Solar System Exploration Working Group. He was the coordinator of the European Commission-funded NEOShield project and currently advises the German delegation to the UN-mandated International Asteroid Warning Network and Space Mission Planning Advisory Group. Dr. Harris received his Ph.D. and B.S. in physics from the University of Leeds, UK.

BHAVYA LAL is a research staff member at the IDA Science and Technology Policy Institute (STPI). Dr. Lal's research and analysis focuses on space technology and policy and is frequently incorporated in national policy documents. Recent and ongoing projects include supporting the Office of Science and Technology Policy and other federal agencies in developing a national space technology strategy, improving detection of near Earth objects (NEOs), evaluating a civilian space situational awareness capability, documenting global trends in space, and examining recent commercial activities in space, including their legal ramifications related to the Outer Space Treaty. Before joining STPI, Dr. Lal was president of C-STPS, LLC, a science and technology policy research and consulting firm in Waltham, Massachusetts. Prior to that, she was a researcher and the director of the Center for Science and

Technology Policy Studies at Abt Associates, Inc., in Cambridge, Massachusetts. Dr. Lal holds a B.S. and M.S. in nuclear engineering from the Massachusetts Institute of Technology (MIT), an M.S. from MIT's Technology and Policy Program, and a Ph.D. in public policy and public administration from George Washington University. She has served on the National Academies Committee on Space Radiation Effects Testing Infrastructure for the U.S. Space Program, the Committee on Achieving Science Goals with CubeSats, and the Committee on Space-Based Additive Manufacturing of Space Hardware.

LUCY MCFADDEN is a physical scientist, emerita, at NASA Goddard Space Flight Center, where her research focused on the study of small bodies in the solar system, primarily asteroids and comets. Dr. McFadden was a science team member of the Near-Earth Asteroid Rendezvous mission and co-investigator of the Deep Impact, EPOXI, and Dawn missions. Dr. McFadden was an editor of *The Encyclopedia of the Solar System*, first and second editions. She received her B.A. from Hampshire College, M.S. from MIT, and Ph.D. from the University of Hawaii. She is a fellow of the American Association for the Advancement of Science and has previously served on the National Academies Committee on Planetary and Lunar Exploration and the Committee on Data Management and Computation.

MICHAEL MOMMERT is an assistant astronomer at Lowell Observatory. Dr. Mommert specializes in the physical characterization of asteroids and comets, mainly using thermal-infrared observations. He is the data analysis lead of a number of Spitzer Space Telescope observing programs characterizing the physical properties (diameters and albedos) of NEOs. Dr. Mommert also has an interest in the investigation of objects in the asteroid-comet continuum, data mining from archival data, the application of data science methods to scientific problems, and the development of open-source scientific software. He received his Ph.D. in geosciences from the Free University in Berlin and his M.Sc. in physics from the University of Heidelberg.

GEORGE RIEKE is a Regents Professor of Astronomy and Planetary Sciences at the Steward Observatory at the University of Arizona. Dr. Rieke has worked extensively in the development of innovative infrared detectors and instrumentation, and their astronomical applications, including the first infrared-optimized telescope. He was the principal investigator for the multiband imaging photometer, which provided imaging data at far-infrared wavelengths for NASA's Spitzer Space Telescope, and is the lead scientist on the mid-infrared instrument for NASA's James Webb Space Telescope. Dr. Rieke earned his B.A. in physics from Oberlin College and his M.S. and Ph.D. in physics from Harvard University. He has previously served on the National Academies Astro2010 Panel on Electromagnetic Observations from Space.

ANDREW RIVKIN is a planetary astronomer at Johns Hopkins University's Applied Physics Laboratory. Dr. Rivkin's research involves taking and analyzing infrared spectra of asteroids. He has researched asteroids for over 20 years, with 26 first-author peer-reviewed papers on asteroids and small bodies and as a co-author on an additional 55 peer-reviewed papers as of mid-2018. Many of these focused on NEOs specifically. In addition to these papers, Dr. Rivkin has led chapters in both the *Asteroids III* and *Asteroids IV* books, has led and contributed to chapters in other books, and has written a textbook on small bodies. He has led the update to the *Small Bodies Assessment Group Science Goals Document*. With a research focus of asteroids, including NEOs, Dr. Rivkin has been involved in many planetary defense studies over the years. He was a participant in the 2006 NASA Near-Earth Object Detection and Threat Mitigation Workshop in Vail and contributed to the final report, and he participated in several of the American Institute of Aeronautics and Astronautics (AIAA) Planetary Defense Conferences since then. Dr. Rivkin is the investigation co-lead for the Double Asteroid Redirection Test (DART), now in Phase C. He earned his Ph.D. in planetary science from the University of Arizona.

DANIEL J. SCHEERES is the A. Richard Seebass Endowed Chair and professor at the University of Colorado, Boulder, in the Smead Department of Aerospace Engineering Sciences. Dr. Scheeres has studied the dynamics of the asteroid environment from a scientific, engineering, and navigation perspective since 1992 and has been involved with NASA's NEAR mission to asteroid Eros and the Japanese Hayabusa missions to asteroids Itokawa and Ryugu. He is currently a co-investigator on NASA's OSIRIS-REx mission to asteroid Bennu and leads the Radio Science team of that mission. Dr. Scheeres has published a Springer-Praxis book on orbital mechanics about small bodies titled *Orbital Motion in Strongly Perturbed Environments: Applications to Asteroid, Comet and Planetary Satellite Orbiters*. Asteroid 8887 is named "Scheeres" in recognition of his contributions to the scientific understanding of the dynamical environment about asteroids. Dr. Scheeres is a fellow of both the AIAA and the American Astronautical Society. He has been awarded the Dirk Brouwer Award from the American Astronautical Society. Dr. Scheeres earned his Ph.D. for aerospace engineering from the University of Michigan. He has served on the National Academies Committee on Assessment of the U.S. Air Force's Astrodynamic Standards and the NEO Mitigation Panel.

EDWARD TEDESCO is a senior scientist at the Planetary Science Institute. Dr. Tedesco has been making and interpreting physical observations of asteroids since 1975. He was among the first to note that the size-frequency distributions for some asteroid families differed from that for nonfamily asteroids (Tedesco, 1979) and that asteroid rotation rates are not inversely proportional to size, and to recognize the detailed compositional structure of the main asteroid belt. Dr. Tedesco played a key role in establishing the second-generation asteroid taxonomy, in the data reduction and publication of the IRAS Minor Planet Survey, and he was the first to model the efficiency of discovering NEOs using a space-based infrared sensor. Dr. Tedesco has made astrometric, light curve, multicolor photometry, phase curve, polarimetric, and radiometric observations using 0.4- to 8-meter ground-based telescopes and the IUE, IRAS, MSX, ISO, and Spitzer spacecraft (and was to have done the same on the WIRE mission). He was principal investigator on a project providing support for U.S. members of the Canadian NEOSSat mission. Dr. Tedesco received a B.S. in physics from St. John's University, an M.S. in physics from Fordham University, an M.S. in astronomy from New Mexico State University, and a Ph.D. in astronomy from New Mexico State University.

STAFF

DWAYNE A. DAY, *Study Director,* a senior program officer for the ASEB, has a Ph.D. in political science from the George Washington University. Dr. Day joined the National Academies as a program officer for SSB. He served as an investigator for the Columbia Accident Investigation Board in 2003, was on the staff of the Congressional Budget Office, and worked for the Space Policy Institute at the George Washington University. He has also performed consulting for the Science and Technology Policy Institute of the Institute for Defense Analyses and for the U.S. Air Force. He is the author of *Lightning Rod: A History of the Air Force Chief Scientist* and editor of several books, including a history of the CORONA reconnaissance satellite program. He has held Guggenheim and Verville fellowships at the National Air and Space Museum and was an associate editor of the German spaceflight magazine *Raumfahrt Concrete*, in addition to writing for such publications as *Novosti Kosmonavtiki* (Russia), *Spaceflight*, *Space Chronicle* (United Kingdom), and the *Washington Post*. He has served as study director for over a dozen National Academies' reports, including *3-D Printing in Space* (2013), *NASA's Strategic Direction and the Need for a National Consensus* (2012), *Vision and Voyages for Planetary Science in the Decade 2013-2022* (2011), *Preparing for the High Frontier—The Role and Training of NASA Astronauts in the Post-Space Shuttle Era* (2011), *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies* (2010), *Grading NASA's Solar System Exploration Program: A Midterm Review* (2008), and *Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity* (2008).

SARAH C. BROTHERS

E

Acronyms

ATLAS	Asteroid Terrestrial-Impact Last Alert System
AU	astronomical unit
CSS	Catalina Sky Survey
DART	Double Asteroid Redirect Test
DoD	Department of Defense
EAC	Earth approaching comet
ESA	European Space Agency
FRM	Fast Rotating Model
GSFC	Goddard Space Flight Center
IR	infrared
IRAS	Infrared Astronomical Satellite
IRSA	Infrared Science Archive
ISO	Infrared Space Observatory
JFC	Jupiter-family comet
JPL	Jet Propulsion Laboratory
K-T	Cretaceous-Tertiary
LINEAR	Lincoln Near-Earth Asteroid Research
LONEOS	Lowell Observatory Near-Earth Object Search
LPC	long-period comet
LSST	Large Synoptic Survey Telescope
MIT	Massachusetts Institute of Technology
MPC	Minor Planet Center
NASA	National Aeronautics and Space Administration
NEA	near Earth asteroid
NEAT	Near-Earth Asteroid Tracking
NEATM	Near Earth Asteroid Thermal Model
NEO	near Earth object

NEOCam	Near-Earth Object Camera
NEOO	Near Earth Objects Observation
NEOWISE	Near Earth Object Wide-Field Infrared Survey Explorer
NRC	National Research Council
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System
PDCO	Planetary Defense Coordination Office
PDS	Planetary Data System
ROSES	Research Opportunities in Earth and Space Sciences
SDT	Science Definition Team
SmallSat	small satellite
SST	Space Surveillance Telescope
STM	Standard Thermal Model
STPI	Science and Technology Policy Institute
TRL	technology readiness level
WISE	Wide-Field Infrared Survey Explorer