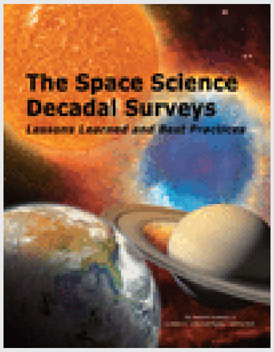

The Space Science Decadal Surveys: Lessons Learned and Best Practices

DETAILS

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Committee on Survey of Surveys: Lessons Learned from the Decadal Survey Process; Space Studies Board; Division on Engineering and Physical Sciences; The National Academies of Sciences, Engineering, and Medicine

The Space Science Decadal Surveys

Lessons Learned and Best Practices

Committee on Survey of Surveys: Lessons Learned from the Decadal Survey Process

Space Studies Board

Division on Engineering and Physical Sciences

The National Academies of
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COMMITTEE ON SURVEY OF SURVEYS: LESSONS LEARNED FROM THE DECADAL SURVEY PROCESS

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Preface

The National Research Council (NRC) has conducted 11 decadal surveys in the Earth and space sciences since 1964 and released the latest four surveys in the past 8 years. The concept for a "survey of the surveys" arose because each of the recent decadal studies met unforeseen challenges in its implementation, suggesting that a closer look at the decadal survey process is necessary so that this essential tool for strategic planning in the Earth and space sciences might be improved. As the first phase of this examination, the Space Studies Board hosted the November 12-13, 2012, workshop "Lessons Learned in Decadal Planning in Space Science." This event brought together a variety of major stakeholders in the space- and Earth-science communities who are impacted by and/or responsible for the formulation and implementation of the decadal surveys. A summary of the discussions during this workshop appear in the 2013 report *Lessons Learned in Decadal Planning in Space Science: Summary of a Workshop*.[1]

While many useful ideas, lessons learned, and suggestions for improving the decadal survey process surfaced during the November 2012 workshop, NRC workshop summaries contain no formal consensus conclusions or recommendations. In addition, summary reports do not contain any discussion or analysis beyond what was actually said by the workshop participants. These limitations prompted the Space Studies Board to propose a second phase to its examination of decadal survey process, leading to the drafting of this consensus report.

Phase two was initiated on February 6, 2014, when John M. Grunsfeld, Associate Administrator for the NASA Science Mission Directorate (SMD), requested that the Space Studies Board initiate a formal study of the decadal survey process (see Appendix C). Discussions between NASA and the NRC concerning the scope of the requested activity led to the adoption of the following statement of task:

> The NRC will convene an ad hoc committee to consider lessons learned from the most recent NRC decadal surveys in space science. Primary attention should be devoted to the most recent surveys—i.e., solar and space physics (2012), planetary science (2011), astronomy and astrophysics (2010), and Earth science and applications from space (2007)—but important lessons derived from earlier surveys may be noted. The study will also review and consider the first round of NRC mid-decade assessment reports in astronomy and astrophysics (2007), planetary science (2007), solar and space physics (2009), and Earth science and applications from space (2012). The issues identified during the NRC workshop Lessons Learned in Decadal Planning in Space Science held in November 2012 will be a major input to the committee's deliberations.

[1] National Research Council, *Lessons Learned in Decadal Planning in Space Science: Summary of a Workshop*, The National Academies Press, Washington, D.C., 2013.

The committee will formulate a set major lessons learned from the recent decadal survey planning process and present a set of options for possible evolutionary changes and improvements to this process, including the statement of task, advanced preparation, organization, and execution.

The proposed study aims to provide a foundation for strengthening future surveys by analyzing and integrating findings in the sources above to address, in particular, the following issues:

- The committee will identify best practices for a well-structured statement of task that will result in a report that reflects the consensus of the authoring community, meets short-term needs of the sponsoring agencies, and addresses the interests of other important constituencies, all while remaining relevant in the face of technology and science advancements, budget evolution, and international cooperation opportunities over the decade (and the following decade, for the largest projects). This analysis should recognize the primacy of science goals over implementing missions. The committee should consider, in particular, the pros and cons of a two-phase decadal survey process that results in a science prioritization report first and then, after a period of community interaction with NASA and mission formulation, a separate implementation prioritization report; and
- While not offering any recommendations to change them, the committee will examine the impacts of the procedures and policies of the NRC (regarding the confidentiality of committee deliberations) and of the Office of Management and Budget (OMB) (regarding the embargo of pre-release budget formulation) on the operation of decadal survey studies. The committee will consider how to mitigate the impact of these conditions (the so-called "blackout problem") and, in particular, the impacts of the fact that during critical phases of survey recommendations development, sponsors often cannot share budget (and budget-related planning) information due to the OMB's embargos on releasing information on the President's budget request, and the survey committee cannot share details of its ongoing deliberations with the sponsors.

An important consideration for the 2012 workshop and for the study described above is that both were initiated at the requested of, and solely funded by, NASA SMD. Moreover, SMD was the *only* common sponsor of the four decadal surveys that formed the centerpiece of the workshop's discussions and upon which the deliberations of this follow-on study would focus. Although representatives from all relevant agencies and organizations were invited to participate in the 2012 workshop, few were able to attend. As a result, the workshop's discussions focused primarily on issues relevant to and/or expressed by representatives from SMD. Thus, although this study considers all relevant agencies, the close alignment between the activities identified in the statement of task and issues discussed during the workshop resulted in a follow-on study focused more on NASA's use of the decadal process. Nevertheless, the committee considers the interests of other agencies in decadal surveys, particularly the strong participation of the National Science Foundation (NSF), in appropriate sections of the report.

The Committee on Survey of Surveys: Lessons Learned from the Decadal Survey Process was established in March 2014 and held its first meeting on June 23-24 at the National Academies' Keck Center in Washington, D.C. Additional presentations and discussions were heard during an August 14 teleconference, at an August 25-27 meeting in Washington, D.C., and during an October 16 teleconference. The committee's final meeting was held on December 8-10 at the Arnold and Mabel Beckman Center of the National Academies in Irvine, California. A complete draft of the committee's report was assembled in February 2015 and sent to external reviewers in early March. Twelve sets of reviewer comments were received in early April, and a revised draft of the report responsive to these comments was completed in late May.

The work of the committee was made easier thanks to the important help, advice, and comments provided by numerous individuals from a variety of public and private organizations. These include the following: Marc Allen (NASA/SMD), Steve Battel (Battel Engineering), Richard Behnke (NSF/Atmospheric and Geospace Sciences), Mike Freilich (NASA/SMD/Earth Sciences), James Green (NASA/SMD/Planetary Sciences), Tom Hammond (House Science, Space and Technology Committee), Paul Hertz (NASA/SMD/Astrophysics), Grace Hu (OMB), Jeffery Newmark (NASA/SMD/Heliophysics), Joel Parriott (American Astronomical Society), Ellen Stofan (NASA Headquarters), and James Ulvestad (NSF/Astronomical Sciences).

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

The committee wishes to thank the following individuals for their participation in the review of this report:

Joseph Alexander, Consultant, Oro Valley, Arizona,
Jeff M. Bingham, U.S. Senate (retired),
Antonio J. Busalacchi, Jr., University of Maryland,
Jill P. Dahlburg, Naval Research Laboratory,
Stephen A. Fuselier, Southwest Research Institute,
Neil Gehrels, NASA Goddard Space Flight Center,
Sarah Gibson, National Center for Atmospheric Research,
James F. Kasting, Pennsylvania State University,
Kristina B. Katsaros, University of Miami,
Jeremiah P. Ostriker, Princeton University (emeritus),
Louise M. Prockter, Johns Hopkins University, and
Graeme L. Stephens, California Institute of Technology.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by George Paulikas, Aerospace Corporation (retired), and Christopher McKee, University of California, Berkeley, who were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

APPENDIXES

Summary

Decadal surveys are a signature product of the National Academies of Sciences, Engineering, and Medicine.[1] Decadal surveys conducted by the Space Studies Board, singly or in collaboration with other boards of the Academies, provide community-consensus science priorities and recommendations for space and Earth science, principally to NASA and the National Science Foundation (NSF), but also to the Department of Energy (DOE), the National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey (USGS), the White House, and Congress. The Academies have established a reputation for decadal surveys as credible and unbiased science assessments and prioritization across the space sciences.

Decadal surveys are carried out with a cadence of approximately 10 years for each discipline. The four that are the focus of this report are Earth science and applications from space, astronomy and astrophysics, planetary science, and solar and space physics (also known as heliophysics). The Academies have conducted decadal surveys for more than 50 years, since astronomers first developed a strategic plan for ground-based astronomy in the 1964 report *Ground-Based Astronomy: A Ten-Year Program*.[2] The committees and panels that carry out the decadal surveys are drawn from the broad community associated with the discipline in review, and these volunteers comprise some of the nation's leading scientists and engineers.

The Academies' decadal surveys are notable in their ability to sample thoroughly the research interests, aspirations, and needs of a scientific community. Through a rigorous process lasting about 2 years, a primary *survey committee* and "thematic" *panels* of community members construct a prioritized program of science goals and objectives and define an executable strategy for achieving them. Decadal survey reports to agencies and other government entities play a critical role in defining the nation's agenda in that science area for the following 10 years, and often beyond.

Eleven decadal surveys have now been completed; the last four have been for Earth science and applications from space (Earth2007), astronomy and astrophysics (Astro2010), planetary science (Planetary2011), and solar and space physics (Helio2013).[3] The 2012 Academies' workshop "Lessons Learned in Decadal Planning in Space

[1] Activities of the National Research Council are now referred to as activities of the National Academies of Sciences, Engineering, and Medicine.

[2] National Academy of Sciences, *Ground-Based Astronomy: A Ten-Year Program*, National Academy of Sciences-National Research Council, Washington, D.C., 1964.

[3] The four decadal survey reports discussed are *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (2007), *New Worlds, New Horizons in Astronomy and Astrophysics* (2010), *Vision and Voyages for Planetary Science in the Decade 2013-2022* (2011), and *Solar and Space Physics: A Science for a Technological Society* (2013), all published by the National Academies Press, Washington, D.C.

Science," invited participants from recent surveys and "stakeholders," such as NASA and NSF division directors, congressional staffers, and representatives of the executive branch. Presentations and moderated panel discussions, with inputs from the gathered attendees, covered all aspects of these recent decadal surveys. The resulting report, *Lessons Learned in Decadal Planning in Space Science: Summary of a Workshop,*[4] captures the breadth and depth of this exceptional, challenging process.

The Committee on Survey of Surveys: Lessons Learned from the Decadal Survey Process (hereinafter "the committee") was appointed by the Academies with the task of distilling the content of the 2012 workshop, adding the input from presentations to the committee, and providing its own evaluations of the issues. The committee's goal has been twofold: (1) to provide a handbook to guide the organizers of future surveys, with a moderately detailed discussion of both "tried and true" and novel methods and (2) to identify *lessons learned* from prior surveys and *best practices* that have been gleaned from them. Along the way, the committee has identified valuable aspects of decadal surveys that could be taken further, as well as some challenges future surveys are likely to face in searching for the richest areas of scientific endeavor, seeking community consensus of where to go next, and planning how to get there. What decadal surveys are asked to do is no simple task.

The committee's conclusions are presented in the context of a successful round of recent decadal surveys that faced a few *challenges* but surprisingly few *issues*, considering the magnitude of the assignment. In particular, the task of defining the scientific frontier and deciding on a discipline's future direction is complex and difficult, but this has been done smoothly and reliably through the decadal survey process. The same is true for decadal surveys achieving community consensus on how to advance a field with a 10-year program. Indeed, the committee found no evidence of widespread dissatisfaction about the outcome of a decadal process of prioritizing science activities: no one at the 2012 workshop, or in any other communication to the committee, suggested the outcome was capricious or arbitrary, tied to the composition of the relevant survey committee, or not representative of a community consensus of its highest-priority science goals. On the contrary, the science communities, through individuals and associations, have given strong support in recommending each of the decadal survey reports to its stakeholders.

Likewise, support from the sponsoring agencies for decadal surveys has not wavered over their 50-year history. NASA and NSF officials, in particular, use words like "guidebook" and "blueprint" to describe the role that decadal survey recommendations play in the planning and execution of science programs of government agencies on behalf of the nation. Federal funding has long been an essential component of the entire U.S. science portfolio, but few fields have chosen a democratic process like the decadal survey for deciding how best to direct this resource. Decadal surveys have been praised as a "sword and shield"[5] as they work to advance the nation's science agenda—a sword for winning the approval of the most important programs, and a shield against cancellation when difficulties are encountered and against groups that lobby for certain programs that may not enjoy the consensus support of the community.

This report covers the entire decadal survey process in time order. Chapter 1 provides an overview of decadal surveys, outlines high-level implementation process, and discusses key issues associated with a decadal survey's statement of task. Chapter 2 reviews the decadal survey process in detail, including mission definition and formulation, prioritization, and the process of cost and technical evaluation (CATE). Chapter 3 covers the decadal survey report itself, including discussion of the importance of clarity of communication of recommendations, particularly with respect to "flagship," "strategic," or "high-profile" missions.[6] Chapter 4 focuses on "stewardship" of the decadal survey after the report is released, including discussion of the midterm assessment process and the vital roles played by international and interagency cooperation. Lessons learned and best practices are included as they arise throughout the report and are also collected in Appendix D. Appendix B provides additional material on the CATE process.

[4] National Research Council, *Lessons Learned in Decadal Planning in Space Science: Summary of a Workshop*, The National Academies Press, Washington, D.C., 2013.

[5] Attributed to Colleen Hartman at the 2012 Workshop; see National Research Council, *Lessons Learned in Decadal Planning in Space Science*, 2013, p. 39.

[6] The terms *flagship mission*, *strategic mission*, and *high-profile mission* are typically used interchangeably to mean large, expensive, technically ambitious, performance-driven activities that are initiated for strategic reasons because they are critical to the advancement of a specific discipline. The committee prefers to call such activities high-profile missions.

As the decadal process first developed for astronomy and astrophysics has been extended to planetary science, solar and space physics, and Earth science, different science themes and unique cultures have been expressed through variations in decadal structure and process, but overall the survey model has proven to be highly adaptable. There is no "one-size-fits-all" approach to a decadal survey: each discipline has heritage and science goals that cannot be directly mapped to any other group. However, there is also much in common—things that every decadal survey needs to do well. Each must draw extensive input from its community and adhere to a process that assures that all ideas are *heard*—the most important thing is that no good idea is simply *missed*. All surveys need to demonstrate that science is the prime motivator and develop a methodology of prioritization that identifies the most important science areas where substantial progress can be made, which also means demonstrating to skeptics and partisans that favored activities or highly lobbied missions do not drive the survey's recommendations.

Crucially, all surveys must put considerable effort into communicating their conclusions, goals, and recommendations to a wide audience of scientists, stakeholders, and the public. The decadal survey report must explain and justify the recommended program and provide clear direction, through priorities and "decision rules" that will help in the implementation of the survey, even as the budget, technology, and in some cases the science, change throughout the decade.

Finally, all survey programs require continued support and nurturing—stewardship, and even advocacy—after they are completed and released. The standing committees of the Space Studies Board play a key role in this stewardship. This committee thinks that this role could be strengthened by allowing the standing committees to continue their work while a decadal survey is in progress, provided they restrict their attention to the current program. In addition, while there are many groups that can speak to the progress in post-survey execution of a decadal program, one lesson learned is that the current advisory structure does not adequately provide for short-term tactical advice on strategic programs.

Although the decadal surveys' record concerning issues relating to international collaboration and cooperation is good, simple steps can be taken to improve communication before and during a decadal survey. With increasing dependence on international cooperation, activities before a survey begins that facilitate interactions with international groups can be used to better coordinate discussions of shared science goals that can—and should—be pursued through international collaboration.

Differences between the various disciplines are expressed in the organization of each survey. While there is much uniformity in decadal survey committees, the uniqueness of each discipline is reflected in the organization of thematic panels and study groups that are charged with *representing* the community's full science interests.

Differences among the disciplines are strongly expressed in the values that inform the survey's selection of the highest-priority science goals. For example, the discipline of astronomy and astrophysics has two distinct science "imperatives": "origins" science—how do galaxies, stars, and planets form (and lead to life)—and fundamental physics—the nature of black holes (space-time), cosmology (dark matter and dark energy), and the study of elusive gravity waves and neutrinos. Solar and space physics (also called heliophysics) similarly seeks to further understanding of the fundamental physics of the Sun and its variations in time, the acceleration of particles and the solar wind, Earth's geospace environment and its links to the Sun, and the Sun's connection to other bodies in the solar system and to the galaxy beyond. Heliophysics also explores astrophysical processes in the nearby cosmos as well as the impacts of space weather on human activities.

Planetary science has its strong link with the physics of complex matter—condensed matter, chemistry, geology, and biology. In the prioritization of planetary science goals, these disciplines underlie the "hottest topics": the search for water and life on Mars or within the icy moons of the outer solar system; the history of volcanism on Venus, the Moon, and on icy satellites; and the composition of comets, asteroids, and planetoids that hold clues to the solar system's formation.

Earth science and applications from space and, to a significant extent, heliophysics are focused on complex natural *processes*: both fields place a high priority on establishing decades of synoptic data. For Earth science, this entails, for example, measurements of land and sea temperatures and atmospheric composition and their collective effects—weather, climate, and climate change. Long-term heliophysics measurement of levels and characteristics of solar activity, cosmic rays, irradiance, and conditions in geospace can provide critical information about the causes and effects of the solar cycle, extreme events, and "space weather." These are matters of national interest and importance. For example, the degree to which weather satellites facilitate "routine" weather prediction is likely to dominate whether they bring fundamental knowledge to meteorology. In short, the variety of natural processes that drive each of these fields is enormous.

In addition, there are substantial differences in the targets of science programs and how science is done: from remote sensing of galaxies a billion light years away to observations of a planet orbiting a distant star; from visiting or roaming on solar system bodies to making continuous, precise, sensitive measurements of conditions on or near Earth over long temporal baselines. Working in the context of such variety of subject and methodology, the decadal process has proven highly adaptable and remained effective in its mission to prioritize science goals and make plans to accomplish them.

This report describes many other aspects of the decadal survey prioritization process, including balance in the science program and across the discipline; balance between the needs of current researchers and the development of the future workforce; and balance in mission scale—smaller, competed programs versus large, strategic missions. While engaging the public is important for all, Earth science and heliophysics have a special focus on societal benefit; outcomes here have unique, real consequences for life on Earth.

There seems little if any doubt that decadal surveys have succeeded in what they set out to achieve; yet, to paraphrase a philosopher, "no fruit of the human tree has ever lacked for improvement." In its examination of the process, the committee has identified challenges that have made the process of crafting a decadal survey more difficult and affected committees' ability to do the best possible job.

An important *lesson learned* has been that budget uncertainty complicates the development of an executable and affordable program. With only a few exceptions, decadal survey programs have been more ambitious than could be accomplished, or at least begun, within the decade ahead. Decadal surveys have been reluctant to adopt the "worst case scenario" budget for fear they will be given it, especially in times of tight budgets. On the other hand, "optimistic" or "aspirational" programs often turn out to be "overly optimistic" or even unreachable. In addition, some uncertainty results from the "blackout period" during which details of the federal budget are embargoed, something that suspends communication between the agencies and surveys on budget expectations. There is also a black-out period lasting several months when the main elements of a decadal survey's recommended program have been established but cannot be discussed with the agencies until the survey report's review by the Academies is complete and the report is made public.

Because budget uncertainties seem inevitable, a *best practice* might be to replace the extrapolations of a current or newly released budget with a baseline that reflects longer-term funding levels for NASA SMD and relevant partner agencies such as NSF and NOAA. Surveys could then build in budget scenarios that "trend-up" and "trend-down" over the decade, as alternatives to the nominal, "baseline" plan they have provided. Greater stability in agency budgets for science would be wonderful, but intentions of the executive branch and congressional priorities seem to guarantee fluctuations as large as 20 percent over a few-year timescale. It seems unwise to base a survey program on a budget run-out for a decade by primarily relying on what has happened only in recent years or on the latest projections of executive or congressional priorities.

Planning within tight budgets has led to increased specificity in the recommended programs of decadal surveys. Implementation plans, in particular, have included detailed descriptions of the facilities, missions, and observing system concepts that have been motivated by the desire to accomplish as much of the science program as possible. However, over-specified programs are a problem for program managers at the agencies for several reasons. One is that implementation of a particular mission architecture is often much more costly than the estimate derived from studying an immature concept (as was the case for the James Webb Space Telescope (JWST) and the Mars Science Laboratory (Curiosity rover). The full cost of ambitious, high-profile missions may not be knowable at the time the survey is conducted.

The *lesson learned* here is that decadal surveys, in pursuit of ever more accurate cost estimates, may dig too far into implementation details. Implementation descriptions for such missions in the survey report can be easily misconstrued as prescriptive advice. A *best practice* going forward is that missions described in the survey's recommendations might best be considered as "reference missions," except for the concepts that have been studied for many years—where committees explicitly state their intention to recommend a specific implementation approach. A reference mission is intended to serve as a proof of concept that there is a way to do the science within a certain cost bin, rather than as a detailed recommendation for implementation. After the survey process, the agencies will develop these ideas to take into account other programmatic goals, new technology, and a growing understanding of what it will take to do the mission or build the facility or observing system. The most important thing is for the decadal survey to state clearly the minimum set of requirements underlying a mission's recommendation and the rationale for its prioritization, including any necessary decision rules to be considered by implementers. After all, it is first and foremost the science that is being prioritized in a decadal survey, not any particular design for a mission or facility.

The committee was asked to consider another way of decreasing the attention given to implementation strategies: a two-phase approach in which decadal survey committees would be asked to prioritize science goals first—independently of the means to carry them out. However, participants at the 2012 workshop, other scientists the committee talked to, and the committee itself judged this is to be undesirable and, in fact, impossible. Fortunately, there is an example of the difficulty in prioritizing science goals first. The five science frontier panels (SFPs) of the Astro2010 produced a list of 20 science questions and six "discovery areas," all of equal priority; these high-priority questions were distilled from a much larger set of questions covering the field.[7] However, the survey committee did not ask the SFPs to go further, to prioritize the questions—nor did the SFPs want to. Consider this: Is answering "Do habitable worlds exist around other stars . . . ?" more important than knowing "How do black holes grow, and radiate . . . ?" Who can say? Anyone. Who can know? No one.

Nevertheless, these SFP questions were the *foundation* of Astro2010's recommended program. By stacking "what we want to do" against "what we can do," another essential dimension is added to judging science priority. Where can the most progress be made with available resources and existing or new technology? It is a matter of fact that, in all previous surveys, the science prioritization process has depended crucially on such mission and facility concepts—what they could do and what they would cost. This non-linear, almost organic, process has been at the very heart of every survey.

The committee was also asked to consider a related proposal: a two-phase decadal survey process where science is prioritized first, as in Astro2010, with a break to communicate the results to the community and the agencies to "tune" the formulation of missions, facilities, and observing systems to these science priorities. The committee is concerned that stretching the decadal process beyond 2 years would prove to be impractical and unaffordable. But, more to the point, the committee has concluded, from looking at the Astro2010 example, that a high-priority but unranked list of science goals would not facilitate the mission formulation process. In fact, participants in the 2012 workshop speaking on behalf of planetary science, Earth science, and heliophysics surveys insisted that their highly interactive (and successful) process of science and mission prioritization would be disabled by attempts to divorce the two. The committee concluded that decisions as to how a decadal survey will prioritize science and recommended programs are best left to the survey committee itself.

Despite, and also because of, these misgivings about the value of a stand-alone process for science prioritization, the committee endorses reviewing the "state of the science" before a new survey begins, as distinct from creating a new process to do "science prioritization." Fortunately, there are ongoing activities to facilitate that activity, including the midterm decadal review and the Space Studies Board with its discipline-specific standing committees. NASA advisory committees, including NASA's many assessment and analysis groups (like the Mars Exploration Program Analysis Group, the Cosmic Origins Program Anaysis Group, and the Geospace-Management Operations Working Group), NASA roadmap teams, and the Science Committee of the NASA Advisory Council, can all contribute to this task. White papers and society meetings can also be used to sample the thoughts of the broader community. A *best practice* to bring this all together would be to initiate processes to collect community input before a new survey begins. This process could include workshops, sessions at meetings of professional societies, white papers, and, perhaps, a process conducted under the aegis of the Academies under the direction of the Space Studies Board. The goal would be to assess how science has evolved from the last survey and call attention to emerging areas of promise. Community ideas for implementation of these science themes could lead to preparatory studies of missions and facilities. This kind of input could give the upcoming survey a running start

[7] National Research Council, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C., 2010.

in identifying their key science objectives. A similar activity, on a global scale, is to exploit international scientific meetings and conferences while encouraging communications between decadal surveys and analogous planning exercises abroad, to help lay the groundwork for future international missions.

The committee reviewed the CATE activity that was added to the decadal process in response to the 2008 NASA Authorization Act, which requires an independent cost estimate that can be compared to the budgets provided by mission advocates. The committee concluded that the CATE process has become a *best practice* of decadal surveys, adding credibility to their implementation plans. Furthermore, the CATE process will likely evolve to become more efficient and more easily adaptable to any particular decadal survey. The committee found little interest in returning to decadal surveys without CATE, but instead found widespread support of CATE and support for improving the CATE process.

This report focuses on whether the CATE process as it has been implemented is overly drawn out and expensive, and whether this puts a strain on its use if very many facilities and missions are under consideration. Worthwhile programs that might have been recommended could have been shut out by missions that—according to a "late CATE"—turn out to be unaffordable. A *best practice* for future CATEs could be to initially run a much larger number of candidate missions through a faster but coarser "cost-box" analysis, to provide a sense of scale for initial consideration. This extra step would reserve the full CATE process for missions that are likely to become part of the recommended program—that is, those that require more detailed estimates. This "two-step" approach would also help prevent CATE from pacing the survey process.

One rather obvious *lesson learned* is that a reliable CATE process is crucial for the largest, most ambitious missions—high-profile missions—where cost growth can threaten the health of a wide set of activities over a discipline, and beyond. A *best practice* for future surveys is to give greater attention and added care in assessing and recommending potentially "discipline-disrupting" programs. A thorough and rigorous CATE process can help, but too often the true cost of such a mission cannot be well established until the program is well under way. Surveys can provide clear decision rules and decision points that will effectively establish cost caps, with the intent of triggering reconsideration of the mission and the possibility, or necessity, of rescoping its science capability.

The committee concludes that the decadal survey process has been very successful. Indeed, decadal surveys set a standard of excellence that encourages the hope that similar processes could be applied more widely across the nation's science programs. While it has no major flaws, the survey process can, and should, improve and evolve. The remarkable record of decadal surveys makes the committee optimistic that useful changes can and will be made.

1

Decadal Surveys: Community Consensus in Science Priorities

INTRODUCTION

Decadal surveys are the most prominent and influential activity of the Space Studies Board (SSB) of the National Academies of Sciences, Engineering, and Medicine.[1] The Committee on Surveys of Surveys: Lessons Learned from the Decadal Survey Process was charged with studying the decadal survey process, emphasizing the four recent surveys in astronomy and astrophysics, solar and space physics (heliophysics), planetary science, and Earth science and applications from space (Box 1.1). NASA's Science Mission Directorate (SMD) was the common sponsor of all four of these surveys. The decadal surveys have been a model in the world of science for how community consensus can be achieved—on science goals and on a program of activities to achieve them—for four disciplines that have much in common, but also many differences in substance, style, and culture.

Major stakeholders in the space- and Earth-science communities impacted by and/or responsible for the formulation and implementation of the four most recent surveys participated in the November 2012 workshop "Lessons Learned in Decadal Planning in Space Science." The key issues discussed are summarized in Box 1.2, and additional details can be found in the 2013 report *Lessons Learned in Decadal Planning in Space Science: Summary of a Workshop*.[2]

This study was sponsored solely by NASA, and so the committee has focused on how NASA uses decadal surveys in support of its SMD science programs. However, other agencies are also involved in decadal surveys. Notably, the National Science Foundation (NSF) has a major involvement with astronomy and astrophysics decadal surveys because many ground-based facilities for astronomical research are funded by NSF. The ground-based telescopes and research programs of the solar and space physics program, to some degree included in the astronomy and astrophysics decadal surveys, are also part of the NSF portfolio. Although this report is primarily about the way NASA uses the decadal survey process, it covers many issues that are relevant to NSF and other agencies and discusses these issues as appropriate.

[1] Activities of the National Research Council are now referred to as activities of the National Academies of Sciences, Engineering, and Medicine.

[2] National Research Council, *Lessons Learned in Decadal Planning in Space Science: Summary of a Workshop*, The National Academies Press, Washington, D.C., 2013.

BOX 1.1
Four Recent Decadal Surveys

Astronomy and Astrophysics

Astronomy and astrophysics is concerned with the study of all extraterrestrial bodies and phenomena, including the universe as a whole (cosmology). Research in astronomy and astrophysics is supported by NASA Science Mission Directorate's (SMD's) Astrophysics Division, the National Science Foundation's (NSF's) Astronomical Science Division, the Smithsonian Institution, the divisions of other federal agencies such as the Department of Energy, and through a large contingent of private and university-funded research. The Astrophysics Division excludes studies of solar system bodies and the Sun, these being the responsibility of SMD's Planetary Science and Heliophysics divisions, respectively. The 2010 astronomy and astrophysics decadal survey, *New Worlds, New Horizons in Astronomy and Astrophysics*,[1] is referred to herein as Astro2010.

Solar and Space Physics (Heliophysics)

The discipline of heliophysics—also called solar and space physics, the terms being used interchangeably in this report—is the science of the Sun and its variability, Earth's upper atmosphere (magnetosphere, ionosphere, and thermosphere), the interactions of the solar wind with Earth and other planets, and the changing conditions in space (some of which is called space weather) out to the interstellar medium. Research in heliophysics is supported by SMD's Heliophysics Division, NSF's Division on Atmospheric and Geospace Sciences, the National Oceanic and Atmospheric Administration (NOAA), and a variety of other federal agencies. The 2013 solar and space physics decadal survey, *Solar and Space Physics: A Science for a Technological Society,*[2] is referred to herein as Helio2013.

Planetary Science

Planetary science, as its name implies, is concerned with remote sensing and in situ studies of the planetary bodies orbiting the Sun and supporting laboratory and theoretical studies. The discipline has a small but important overlap with heliophysics (in the general areas of planetary aeronomy and magnetospheres) and astronomy and astrophysics (in the theory and modelling of exoplanets). The principal support for planetary science comes from SMD's Planetary Science Division, but NSF provides vitally important ancillary support via access to, for example, its ground-based observing facilities. The 2011 planetary science decadal survey, *Vision and Voyages for Planetary Science in the Decade 2013-2022,*[3] is referred to herein as Planetary2011.

Earth Science and Applications from Space

In the context used in this report, Earth science is the study of Earth's atmosphere, lithosphere, hydrosphere, cryosphere, and biosphere as a single connected system. Improved understanding of the Earth system has important societal benefits in terms of improved forecasts of weather, climate, and natural hazards. Studies of Earth are supported by SMD's Earth Science Division and a host of other agencies, most notably, NOAA, NSF, and the U.S. Geological Survey. The 2007 Earth science and applications from space decadal survey, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*,[4] is referred herein as Earth2007.

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[1] National Research Council (NRC), *New Worlds, New Horizons in Astronomy and Astrophysics,* The National Academies Press, Washington, D.C., 2010.

[2] NRC, *Solar and Space Physics: A Science for a Technological Society,* The National Academies Press, Washington, D.C., 2013.

[3] NRC, *Vision and Voyages for Planetary Science in the Decade 2013-2022,* The National Academies Press, Washington, D.C., 2011.

[4] NRC, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007.

The committee was asked to do the following (see Preface):

- Consider the organization, process, prioritization, and programmatic aspects of these decadal surveys in terms of *lessons learned* and to "present a set of options—'*best practices*'—for possible evolutionary changes and improvements to this process, including the statement of task, advanced preparation, organization, and execution."
- "Identify best practices for the statement of task" that ensure a survey report is (1) broadly representative of its community in its principle responsibility of prioritizing science; (2) attentive to the needs of sponsoring agencies; and (3) mindful of technical advances, budget issues, and opportunities for international cooperation.
- "Recognize the primacy of science goals over implementation missions" and evaluate the "pros and cons" of performing a first-phase science-prioritization report and then a separate implementation prioritization report "after a period of community interactions with NASA."
- Review problems of recent surveys with respect to fiscal uncertainties and to specifically consider the effect of the "blackout-period" when NASA, NSF, and other federal agencies cannot share the details of the forthcoming federal budget and the Academies cannot share the progress on the decadal survey's recommendations.

The committee was also asked to compare and contrast the all-important science prioritization process used by recent decadal surveys and to review the workings of the independent cost and evaluation (CATE) process that has been essential in ensuring that a decadal survey's recommended program is executable. The implementation of a decadal survey program includes community participation in a crucial midterm review of the survey and in advice through SSB standing committees and advisory structures within the agencies. This report reviews and describes the important roles of international collaboration and interagency cooperation to the success of a decadal survey program and identifies *best practices* that can enhance both.

DECADAL SURVEYS—THE "SHORT COURSE"

What Is a Decadal Survey?

The decadal survey process, created by the National Academies of Sciences, Engineering, and Medicine, reviews a science discipline's progress in the previous decade and engages its community to prioritize science at the frontier. The goal is to reach consensus on a visionary 10-year program to advance the highest-priority science.

The report that emerges from the decadal process translates and transforms the scientific aspirations of the community into a program: new facilities, such as space missions; ground-based observatories; technology and infrastructure development; enhanced educational opportunities; and numerous enabling activities. Some of the federal agencies that fund decadal surveys are also those tasked with implementing the decadal program,[3] so in these cases, the recommended program is crafted with an awareness of their research and programmatic interests.

A successful survey program also serves societal goals, resonates with the interests and curiosity of the public, motivates Congress, aligns with the initiatives of the executive branch, and fits within the fiscal constraints of the federal budget. Decadal survey reports have been widely cited and praised, adopted as definitive roadmaps by some federal offices and agencies and Congress, and read as guidebooks by the universities and research centers whose science programs nourish and serve society.

What Disciplines Have Adopted the Decadal Process?

The first decadal survey was a modest undertaking: a single committee of distinguished astronomers focused on the need for more ground-based optical and radio telescopes.[4] With the lifting of astronomy into space, the scope

[3] The NSF does not construct, manage, or operate facilities, as NASA and some other federal agencies do. NSF solicits proposals for facilities and science programs and runs a competitive peer-review process, but it contracts to other organizations for their construction, management, and operation.

[4] National Academy of Sciences, *Ground-Based Astronomy: A Ten-Year Program*, National Academy of Sciences-National Research Council, Washington, D.C., 1964.

BOX 1.2
Lessons Learned in Decadal Planning in Space Science: A Workshop

On November 12-13, 2012, the Academies held a workshop in Irvine, California, to discuss the decadal survey process in general and, in particular, the challenges that arose during the implementation of the four most recent space science decadal surveys. A detailed account of the presentations and discussions can be found in *Lessons Learned in Decadal Planning in Space Science: Summary of a Workshop*.[1] The key issues identified by the workshop participants and documented in the summary provided the framework around which the current report was constructed. Key issues that surfaced during the workshop (and the respective chapters of this report where they are discussed) include the following:

- Organization of decadal surveys (Chapter 1).
- Importance of the statement of task (Chapter 1).
- Development of the statement of task (Chapter 1).
- Should decadal survey just focus on science goals and not their implementation (Chapter 2).
- Processes used by surveys to prioritize science goals (Chapter 2).
- How implementation initiatives are developed and evaluated (Chapter 2).
- Factors determining how surveys formulate their science and implementation priorities (Chapter 2).
- Budget guidance provided to surveys and its subsequent use (Chapter 3).
- Utility of panel reports as stand-alone volumes (Chapter 3).
- Cost, schedule, capabilities, and risk to mission success (Chapter 3).
- Risk management on large missions (Chapter 3).
- Integrating interagency and international cooperation into surveys (Chapter 4).
- Development of decision rules and their use in supporting decision making under changing circumstances (Chapter 4).
- The Space Studies Board standing committees and other groups as long-term stewards of the decadal surveys (Chapter 4).
- Mid-decadal reviews (Chapter 4).

[1] National Research Council, *Lessons Learned in Decadal Planning in Space Science: Summary of a Workshop*, The National Academies Press, Washington, D.C., 2013.

and complexity of the astronomy surveys grew. The Astro2010 survey was the most recent in a line of six surveys stretching back to the 1960s, commonly known by the names of the committee chairs—Whitford, Greenstein, Field, Bahcall, McKee and Taylor, and Blandford (Box 1.3). The astronomy series acquired such a stellar reputation that the planetary science community carried out its first survey in 2003 (Belton), with a second in 2011 (Squyres—Box 1.4). Earth science (Moore and Anthes—Box 1.5) completed its first survey in 2007, and solar and space physics in 2003 (Lanzerotti), with a second in 2013 (Baker—Box 1.6). These are the four divisions of SMD at NASA, a principal sponsor of the decadal surveys. NSF, with its substantial portfolio of astronomy programs and facilities in optical/infrared and radio astronomy, as well as solar observatories, has also been a major sponsor since the beginning. As scientific programs have expanded, more government agencies have participated in decadal surveys, including NOAA and U.S. Geological Survey (USGS) sponsorship of Earth2007 and the Department of Energy's (DOE's) growing involvement with astronomy and astrophysics.

The committee is aware of several attempts at decadal survey analogs that lie outside the realm of the classical, observational space sciences (e.g., in oceanography;[5] nuclear physics;[6] space biomedical and microgravity sciences;[7] solid-state physics;[8] plasma physics;[9] atomic, molecular, and optical science;[10] and aeronautics[11]).

[5] National Research Council (NRC), *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences*, The National Academies Press, Washington, D.C., 2015.

[6] NRC, *Nuclear Physics: Exploring the Heart of Matter*, The National Academies Press, Washington, D.C., 2012.

[7] NRC, *Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era*, The National Academies Press, Washington, D.C., 2011.

[8] NRC, *Condensed-Matter and Materials Physics: The Science of the World Around Us*, The National Academies Press, Washington, D.C., 2007.

[9] NRC, *Plasma Science: Advancing Knowledge in the National Interest*, The National Academies Press, Washington, D.C., 2007.

[10] NRC, *Controlling the Quantum World: The Science of Atoms, Molecules, and Photons*, The National Academy Press, Washington, D.C., 2007.

[11] NRC, *Decadal Survey of Civil Aeronautics: Foundation for the Future*, The National Academies Press, Washington, D.C., 2006.

BOX 1.3
Reflections on Astro2010

Roger D. Blandford, Chair, Committee for a Decadal Survey of Astronomy and Astrophysics

It is now nearly 5 years since we completed *New Worlds, New Horizons in Astronomy and Astrophysics*.[1] This allows time for reflection on the process and the outcome. My two strongest impressions at the time have stayed with me. The first is that the field has flourished and continues to thrive on all fronts in a manner that I never contemplated when I entered it. Enduring discoveries about exoplanets, the evolution of the universe, and black holes rest upon a secure foundation of interconnected understanding, and yet we are constantly being blind-sided by fresh discovery. The survey provided us all with a great opportunity to learn about and start to engage in new research. The second impression was how dedicated, objective, and open my colleagues were to new approaches—survey, panel, and study group members, the Academies' staff, other survey chairs, and agency folks; they all saw the value of the process and worked to execute it fairly and expeditiously. The blizzard of more than 500 white papers and proposals that demonstrated the engagement of the community was even more striking for the quality of its content. The missions adapted patiently and well to the cost and technical evaluation (CATE) process, which was being invented as it was being implemented. Of course, there were lessons learned, as discussed in this report, and the budget became very much bleaker for well-publicized reasons immediately after the survey was delivered. However, the agencies have been able to start more of what was recommended than at one time looked possible, and, if we take the long view, Astro2020, which is already being contemplated, will start from a very secure and exciting place. I am confident that the progress and prospects from Astro2020 will be every bit as exciting as those from Astro2010.

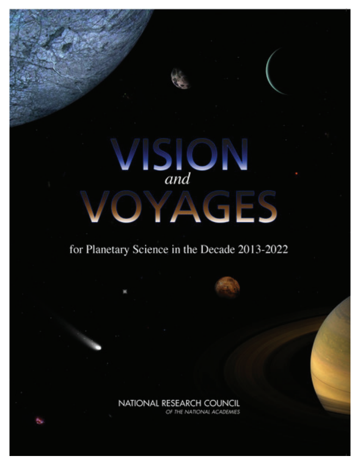
[1] National Research Council, *New Worlds, New Horizons in Astronomy and Astrophysics,* The National Academies Press, Washington, D.C., 2010.

BOX 1.4
Reflections on Planetary2011

Steven Squyres, Chair, Committee on Planetary Science Decadal Survey: 2013-2022

Following the lead of the astronomy and astrophysics community, the planetary science community produced its first decadal survey in 2003.[1] This report, led by Mike Belton, laid a solid foundation for a decade of planetary science. When the time came for the next planetary science decadal survey, we built on that foundation. While the previous decadal survey had led to the creation of NASA's powerful New Frontiers program of principal-investigator (PI)-led missions, some particularly important missions called for in that report, including missions to initiate sample return from Mars and in-depth exploration of Jupiter's moon Europa, still languished.

The second planetary decadal survey, *Vision and Voyages for Planetary Science in the Decade 2013-2022,*[2] drew upon widespread input from the science community, with 199 white papers submitted by more than 1,600 authors. (I was tempted to write one myself, just to bring the total to an even 200.) A couple of dozen missions were studied, and many of them were subjected to detailed cost and technical evaluations. In the end, the committee recommended a modest increase in funding for planetary research and analysis grants, a robust continuation of the Discovery program of small PI-led missions, and five candidate New Frontiers missions. Like the previous survey, the committee also endorsed Mars sample return and Europa missions, but in descoped forms that would be more affordable. And, importantly, a set of simple decision rules were provided that could be applied to adjust priorities if funding for planetary exploration fell below hoped-for projections.



Unfortunately, although not surprisingly, NASA's funding for planetary exploration was indeed threatened with deep cuts right around the time of the survey release. The community rose to this challenge and used the decadal survey as a rallying point to fight for restored funding. With strong support for the recommended program on Capitol Hill, some of the cut funding has indeed been restored.

Many of the planetary science community's decadal recommendations are being followed. As I write this, many of my colleagues are deeply engaged in writing proposals in response to the latest Discovery announcement of opportunity. A new Mars rover mission in 2020 will collect and cache a set of samples, beginning the long-hoped-for process of sample return. And a new mission called Europa Clipper is under serious consideration for a new start. The future is bright.

The message in all of this is that decadal surveys matter. They provide an opportunity for a broad community of scientists to speak with one clear and forceful voice. And the evidence says that decision makers in Washington are listening to that voice.

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[1] National Research Council (NRC), *New Frontiers in the Solar System: An Integrated Exploration Strategy,* The National Academies Press, Washington, D.C., 2003.

[2] NRC, *Vision and Voyages for Planetary Science in the Decade 2013-2022,* The National Academies Press, Washington, D.C., 2011.

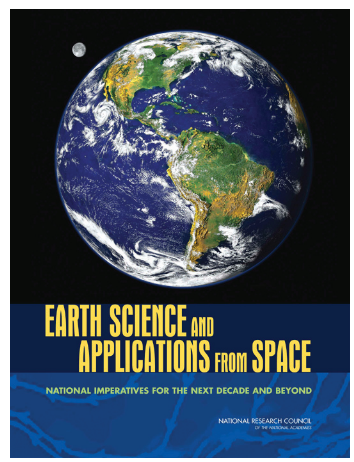
BOX 1.5
Reflections on Earth2007

Berrien Moore III, Co-Chair, Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future

In thinking back to the writing of the Earth science and applications from space decadal survey,[1] I am reminded of the opening of Charles Dickens's *A Tale of Two Cities*:

> It was the best of times, it was the worst of times,
> It was the age of wisdom, it was the age of foolishness . . .

In hindsight, the scales were certainly tilted toward the worst of times. Between fiscal year (FY) 2000 and FY 2007, the NASA Earth Science budget had fallen, in real terms, by more than 30 percent. It was against this backdrop that Richard Anthes, my co-chair, and I, ably assisted by a wide-ranging team reflecting the broad scope of the Earth sciences, met in August 2004 to begin work on the first Earth sciences decadal survey. Any expectation of leisurely academic pace quickly vanished: just as the newly formed survey committee began its work, it was asked by both the agency sponsors and Congress for "interim" report. In April 2005, the committee reported that the national system of environmental satellites was "at risk of collapse."[2] This unusually strong statement set the stage for a survey that was going to be "noticed" by the political process.



We did not know that things were only going to get worse. When the decadal report *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* appeared in 2007, it declared: "Since the publication of the interim report, budgetary constraints and programmatic difficulties at NASA and NOAA have greatly exacerbated this risk [of collapse]. . . . At a time of unprecedented need, the nation's Earth observation satellite programs, once the envy of the world, are in disarray."[3] The release of the decadal survey report was widely covered by the national press; it was even the subject of a lead editorial in the *Washington Post*.

In the end, this first Earth science decadal survey has had a significant impact. The NASA budget for Earth science began to improve almost immediately through congressional actions. Unfortunately, the economic recession reduced the scope of the increases, but the budget for Earth science has continued to improve. Finally, in January 2015 the Soil Moisture Active Passive mission, the first "decadal mission," was successfully launched.

While not the best of times, it is clearly no longer the worst of times.

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[1] National Research Council (NRC), *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007.

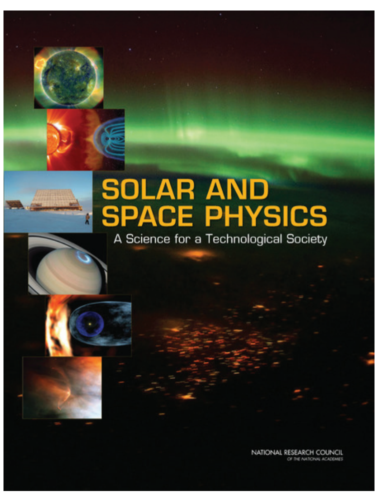
[2] NRC, *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation*, The National Academies Press, Washington, D.C., 2005, p. 2.

[3] NRC, *Earth Science and Applications from Space*, The National Academies Press, Washington, D.C., 2007, p. 19.

BOX 1.6
Reflections on Helio2013

Daniel N. Baker, Chair, Committee on a Decadal Strategy for Solar and Space Physics (Heliophysics)

The first major discovery of the Space Age was made by James A. Van Allen and coworkers in 1958. They found that Earth is enshrouded in toroids, or belts, of high-energy particles trapped in Earth's strong magnetic field. Since those early discoveries nearly six decades ago, we have made amazing further discoveries about our solar system and our space environment. We now understand vastly more about the atmosphere, the ionosphere, and the magnetosphere surrounding us. We have spectacular new views of the Sun, and we understand ever more deeply how the changing solar drivers affect in profound ways our home in space. Deep insight into the behavior of the Sun-Earth system has allowed us to extend our knowledge to remote planets and distant cosmic systems. The 2013-2022 decadal survey in solar and space physics[1] reminded me how far the discipline of "heliophysics" has progressed, but also how many challenging opportunities remain to be exploited. Solar and space physics has progressed to a point where it truly has two faces: There is the fascinating basic science that forms a core science related intimately to sister disciplines of Earth science, planetary exploration, and astrophysics. But space physics has also become a basic science with immense practical implications. Our technological society is vulnerable in countless ways to the effects of "space weather," and the 2013-2022 survey laid out a prudent and thoughtful plan to address these key societal issues. It made me immensely proud that the space physics community—through the efforts of hundreds of its members—presented in clear, concise terms what is possible over the next years in solar, interplanetary, and terrestrial exploration. Recognizing the budgetary realities, the community devised a consensus that offered exciting programs with affordable price tags with particular attention to low-cost enhancements in research and analysis and related programs—the "DRIVE" initiative—and the Explorer program. And in all of this, the community recognized its responsibilities to help protect and defend our technological society. I believe that the phenomenal missions now operating and the programs of observation, theory, and modeling presented in the 2013-2022 decadal survey will assure that the discipline of solar and space physics will continue its proud decades-long record of achievement, discovery, and service.



[1] National Research Council, *Solar and Space Physics: A Science for a Technological Society,* The National Academies Press, Washington, D.C., 2013.

Although these surveys are not explored here, it is the committee's hope that the lessons learned and best practices contained in this report will prove informative to any future such endeavors.

Who Are the Stakeholders?

The stakeholders of decadal surveys are, strictly speaking, the federal agencies, most prominently NASA and NSF, but also DOE, NOAA, and USGS. These agencies fund the Academies to carry out decadal surveys, committing to a strong linkage between the decadal survey programs and science activities at the agencies in the following years. Working with the Academies, agencies set the agenda by formulating a statement of task that defines the scope of work and boundary conditions. Specific questions and issues of particular importance to the agencies are often included.

There are many others who have an important stake in the outcome of decadal surveys, starting with the community that the survey represents. The prospects for future accomplishments in the discipline depend to a substantial extent on the soundness of the recommendations and their successful implementation.

In this broader sense, Congress, the Office of Management and Budget, the Office of Science and Technology Policy, and, potentially, other parts of the executive branch are "invested." They look to decadal surveys for a documented community consensus against which agency plans can be evaluated. Members of Congress and their staff often emphasize the value of decadal survey reports for promoting a consensus science policy as opposed to one driven by special interests.

More and more, the public has become a stakeholder of the decadal survey process because Earth science and heliophysics, two of the four divisions of NASA's space science program, are conducting research that is critical to the health and safety of all life on Earth. Society's dependence on vast systems of satellites that monitor and enable prediction of Earth's weather are not just essential information for commerce and for daily planning, they have now become key to protecting both technical infrastructure and human lives. Space weather reflects variable conditions on the Sun, throughout space, and in Earth's magnetic field and upper atmosphere. These physical processes can cause disruption of satellite operations, communications, navigation, and electric power-distribution grids, leading to a variety of socioeconomic losses and impacts on global security. Measurements over decades that record climate change and track the distribution of precious resources, especially water, are essential not only for human survival but for all living things. Indeed, there is little doubt as to who has the biggest "stake" in space science research.

Who Is the Audience?

There is a wide audience for a decadal survey report among those who make up the nation's scientific and technical enterprise. Scientific research centers pay close attention to the ranking and emphasis placed by decadal surveys on research themes, which influences their training of scientists and engineers, technology development, service to society, and community outreach. International science communities and their space agencies use decadal surveys as input to their own planning processes, to identify areas of mutual interest for new collaborations.

The audience for survey reports extends to many non-professionals as well—for example, the many astronomy clubs across the country. Surveys inspire students seeking careers in science, and the public engages in a decadal survey's science program by following discoveries from the newest space telescope, pictures of the martian surface or a giant explosion on the Sun, and from the service of societal needs—improved weather predictions, geomagnetic storm warnings, or climate modeling, for example.

Survey priorities are widely publicized by print and digital media, including non-technical articles by the popular press. A general-audience summary is published with each survey to reach both formal and informal educators in K-12 and higher education. Eventually, the decadal surveys themselves become the best historical records of the contribution of U.S. scientific communities to the quest to understand the natural world.

How Is a Survey Put Together?

The Space Studies Board, with input from its relevant standing committees, and other boards (e.g., the Board on Physics and Astronomy in the case of astronomy and astrophysics), as appropriate, work with the Academies' staff to initiate decadal surveys, beginning with the selection of a survey chair and the survey committee—about 20 accomplished scientists and engineers representing the full range of the discipline and a balance of demographic categories. Committee members are traditionally more experienced members of the community who are leaders in their field but are also active across the discipline. The survey committee produces the survey report that is responsive to the statement of task composed by the Academies and the agencies and representative of consensus vision of science goals and a program to accomplish them.

To ensure wide participation by the community, the Academies' staff and the survey committee populate panels organized by science themes (e.g., outer or inner planets, stellar or galaxy evolution, climate variability and change, solar wind-magnetosphere interactions), observational techniques (e.g., X-ray or radio observations), or facilities (ground-based versus space-based telescopes). The variety of these panels, which give a sense of what the field is all about, can be seen in the panel names in Box 1.7. Survey committees have also formed study groups (variously called "infrastructure study groups" or "national capability working groups") to explore other issues related to the health of the discipline, covering such subjects as infrastructure, research grants, workforce diversity, applications, and graduate education. The organization of a survey varies somewhat, reflecting the culture of the discipline and the preferences of the survey organizers.

How Are Surveys Conducted?

It takes about 2 years for the committee, panels, and study groups to do their work. Because of the large volume of information that is gathered, studied, and evaluated, the complexity of the process and the need for maintaining the high standards of studies conducted by the Academies, the workload is considerable.

A decadal survey receives broad community input through public meetings, "white papers," and direct presentations. Each thematic panel—sometimes in collaboration with the survey committee—alloys science and observational capabilities to construct a ranked program of missions and activities—for example, a mission to Mars, a ground-based radio telescope, a multi-satellite space observatory. Large space missions and ground-based facilities are subjected to independent cost and risk evaluation, as originally suggested in a 2007 Academies' workshop report[12] and subsequently mandated by Congress.[13] The survey's recommended program also identifies and prioritizes key activities—for example, technology development; programs for small-scale, competed science missions and facilities; and other projects.

After panels and study groups have finished their work, the survey committee studies the panels' suggested programs, ranks them *across* the discipline, and produces the definitive report that presents the survey's science goals and a recommended program to accomplish them. The survey report, like the reports of the supporting panels, undergoes independent review to validate that its conclusions are properly supported and well documented.

How Are Decadal Surveys Followed-Up?

The survey committee disbands after the publication of the survey report, formally ending the survey's work. The "stewardship" that is necessary to implement the decadal program cannot be as broadly representative of the community, but there are entry points for ongoing involvement. The Space Studies Board, through its standing committees, periodically reviews the progress of each survey's program, offering guidance to the agencies on decadal program implementation. Per congressional direction,[14] the Academies conduct a midterm review that focuses on agency progress and compares how well the activities that have been undertaken align with the science goals of the survey.

The subcommittees of the Science Committee of the NASA Advisory Council also follow progress on the NASA component of the survey. NSF gathers input only in the form of proposals to execute parts of the decadal

[12] NRC, *Decadal Science Strategy Surveys: Report of a Workshop*, The National Academies Press, Washington, D.C., 2007, pp. 21-30.

[13] Congress of the United States, National Aeronautics and Space Administration Authorization Act of 2008, Public Law 110-422, Section 1104b, October 14, 2008.

[14] National Aeronautics and Space Administration Authorization Act of 2005, Public Law 109-155, Section 301(a), December 30, 2005.

BOX 1.7
Thematic Panels of Four Recent Decadal Surveys

Earth Science and Applications from Space[1]

Earth Science Applications and Societal Benefits
Land-Use Change, Ecosystem Dynamics, and Biodiversity
Weather Science and Applications
Climate Variability and Change
Water Resources and the Global Hydrological Cycle
Human Health and Security
Solid-Earth Hazards, Natural Resources, and Dynamics

Astronomy and Astrophysics[2]

Cosmology and Fundamental Physics
The Galactic Neighborhood
Galaxies across Cosmic Time
Stars and Stellar Evolution
Planetary Systems and Star Formation
Electromagnetic Observations from Space
Optical and Infrared Astronomy from the Ground
Particle Physics and Gravitation
Radio, Millimeter, and Submillimeter Astronomy from the Ground

Planetary Science[3]

Inner Planets
Mars
Giant Planets
Satellites [of the Giant Planets]
Primitive Bodies

Solar and Space Physics (Heliophysics)[4]

Atmosphere-Ionosphere-Magnetosphere Interactions
Solar Wind-Magnetosphere Interactions
Solar and Heliospheric Physics

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[1] National Research Council (NRC), *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007.

[2] NRC, *New Worlds, New Horizons in Astronomy and Astrophysics,* The National Academies Press, Washington, D.C., 2010.

[3] NRC, *Vision and Voyages for Planetary Science in the Decade 2013-2022,* The National Academies Press, Washington, D.C., 2011.

[2] NRC, *Solar and Space Physics: A Science for a Technological Society,* The National Academies Press, Washington, D.C., 2013.

program. DOE has extensive internal mechanisms for evaluating progress on their component of the decadal programs (for example, the NSF's Large Synoptic Survey Telescope (LSST)—the top-priority ground-based facility in Astro2010). The Astronomy and Astrophysics Advisory Committee (AAAC), for example, advises NASA, NSF, and other agencies on multi-agency projects such as LSST. But other agencies have little or no formal advisory structure that can help assess and guide implementation of the decadal program.

What Are the Challenges for Future Surveys?

While no decadal survey has encountered a major problem that has significantly compromised its work, the experiences of the surveys conducted in the past decade suggest common challenges that might be considered in anticipation of future surveys. Some of these challenges are abstracted here, all of which are discussed in some detail in the report, in the form of questions that future surveys will need to answer.

The Biggest Missions and Facilities

The difficulty, complexity, and cost of "high-profile" ("flagship" or "strategic") missions and facilities have grown,[15] creating substantial challenges for decadal surveys. High-profile missions and facilities are discussed extensively in Chapter 3. Related questions include the following: How can a balance of large and small programs be achieved and maintained? How can robust evaluations of the costs of such missions be made, and cost growth be contained, to protect other missions and activities? Addressing such questions will be crucial to the deliberations of future surveys. Even after the survey is completed, high-profile missions and facilities present challenges as to how these multi-decade programs can be managed successfully. How might we protect important human resources, for example, the education and research support of the next generation of scientists, especially those with skills in technology development?

Better Understanding of Cost, Technical Difficulty, and Risk

The decadal surveys encompass programs with a broad range of scope and risk. Questions related to the inherent challenges include the following: How can surveys compare the costs, risks, and benefits of programs with such diversity? How can a survey's tendency to over-specify requirements of proposed missions and facilities—in part motivated by the need for better cost evaluations—be reconciled with the need for flexibility in an implementation strategy that has to also accommodate government, agency, and societal goals?

Better Definition of the Budget Available to a Decadal Survey

Each decadal survey needs a realistic budget envelope within which to "fit" a program of maximum science at minimum cost. In times of budget instability—common in recent years—can agencies project budgets that provide realistic bounds for survey planning? How can decadal programs be made more resilient to changes in budget profile? Can the effect of the "blackout period" for communicating with the agencies imposed by the federal budget process be minimized?

Interactions with, and between, Federal Agencies

When missions and facilities require the cooperation of different agencies of the federal government—each with its own culture and practices—what can be done to help accomplish decadal priorities?

[15] The terms *flagship mission*, *strategic mission*, and *high-profile mission* are typically used interchangeably to mean large, expensive, technically ambitious, performance-driven activities that are initiated for strategic reasons because they are critical to the advancement of a specific discipline. The committee prefers to call such activities high-profile missions.

International Cooperation

The most ambitious missions and facilities reach a scale that is beyond the capability of a single nation to accomplish: international collaboration continues to be essential. Can the decadal process help reconcile the very different planning processes of international communities and agencies? How can decadal surveys help international partners in the planning, execution, and operation of missions and facilities of mutual interest and benefit? How can international experience and expertise be exploited to benefit decadal surveys?

THE MOVING PARTS AND ORGANIZATIONAL STRUCTURE OF THE DECADAL SURVEY PROCESS

The Academies have conducted 11 decadal surveys—6 in astronomy and astrophysics, 2 each in planetary science and solar and space physics, and 1 in Earth science and applications from space—over the past 51 years (Table 1.1). All share the purpose of reaching community consensus and proposing a program of activities to advance the field in the decade ahead, and possibly beyond. Each decadal survey has employed a different organizational structure and study methodology. To varying degrees, these differences can be attributed to the differing scientific, programmatic, or budgetary circumstances under which they were performed, and to personal or community idiosyncrasies. Nevertheless, the most recent decadal surveys have broad similarities, as discussed here.

Initiating a Survey

A sponsoring agency or group of agencies may signal their interest in engaging the Academies' services to undertake a decadal survey in a number of ways. Once they do, a well-understood and rehearsed set of events is triggered. The first step is for the Academies' Space Studies Board (SSB) and other relevant boards (e.g., the Board on Physics and Astronomy in the case of astronomy and astrophysics) to charge their relevant disciplinary standing committee to begin laying the groundwork for the new decadal survey. The standing committee responds by hosting an organizational meeting where representatives of sponsoring agencies, members of the relevant scientific communities, and, when appropriate, participants in past surveys discuss the broad outlines of the task ahead. Agenda items for an organizational meeting typically include the following: the scientific and programmatic background against which the survey will be conducted; the timescale for the completion of the task; the scientific and programmatic scope—i.e., what is to be considered and what is to be assumed; an outline of how the committee undertaking the survey might be organized; and the expertise required to populate the committee. Ideally, the output of the organizing meeting will feed into the drafting of a statement of task by the sponsor(s) and its subsequent iteration with the Academies (see the "Statement of Task" section below for more details). Once all parties are satisfied with the statement of task, the Academies' staff can begin the task of formally requesting internal approval for initiating the survey and the drafting of a proposal to the sponsors for the requisite funding.

Organization

Survey Committee

Although they differ in detail, each survey has been organized around a leadership group—the survey committee (sometimes called the "steering committee" or "executive committee"). The survey committee typically has consisted of 15-20 senior members of the relevant discipline community whose collective expertise spans the entire range of scientific, programmatic, technical, and policy issues relevant to the survey's activities. The survey committee is responsible for the overall conduct of the decadal study, aggregating and adjudicating the recommendations of various thematic panels, and drafting a report of its top-level conclusions and recommendations.

TABLE 1.1 Fifty-One Years of Decadal Surveys

Publication Year	Title	Survey Committee Chair(s)	Committee Members	Panels	Working Groups	What Was Published
1964	Ground-based Astronomy a Ten-Year Program	A.E. Whitford	8	0	0	Survey report
1973	Astronomy and Astrophysics for the 1970s	Jesse L. Greenstein	23	9	3	Survey report Panel reports
1982	Astronomy and Astrophysics for the 1980s	George B. Field	21	6	7	Survey report Panel reports Working papers
1991	A Decade of Discovery in Astronomy and Astrophysics	John N. Bahcall	15	15	0	Survey report Executive summary Working papers
2001	Astronomy and Astrophysics for the New Millennium	Christopher F. McKee and Joseph H. Taylor, Jr.	15	9	4	Survey report Panel reports Popular version
2003	New Frontiers in the Solar System: An Integrated Exploration Strategy	Michael J.S. Belton	15	6	0	Survey report (including chapters by panels) Popular version
2003	The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics	Louis J. Lanzerotti	15	5	0	Survey report Panel reports Popular version
2007	Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond	Richard A. Anthes and Berrien Moore III	19	7	0	Interim report Survey report (including chapters by panels) Popular version
2010	New Worlds, New Horizons in Astronomy and Astrophysics	Roger D. Blandford	23	9	6	Survey report Panel reports Popular version
2011	Vision and Voyages for Planetary Science in the Decade 2013-2022	Steven W. Squyres	17	5	0	Survey report (including chapters by panels) Popular version
2013	Solar and Space Physics: A Science for Technological Society	Daniel N. Baker	19	3	5	Survey report (including chapters by panels) Popular version

Supporting Panels

Panels are organized by the Academies and the survey committee to cover the various thematic topics of the discipline. Panels typically have 10-15 members with specific expertise in some key subset of the decadal survey's range of responsibility. The decadal survey can involve a large cross section of community members through panels. To maintain lines of communication between the panels and the survey committee, panel chairs or vice chairs are either members of or advisors to the survey committee. Panels are the decadal survey's principal interface with the broad scientific and technical communities they represent, while the survey committee's principal interface is with its sponsoring agencies and organizations.

The number of panels and their thematic orientation has probably been the greatest variant among the four recent decadal surveys. The number of panels varied from three for Helio2013 to nine for Astro2010. The number of panels relates to the variety and complexity of the scientific and technical issues being addressed, the personal preferences of the survey's chair (or co-chairs), and the resources available to support the study.

Thematic Organization of Panels

The thematic organization of the panels (see Box 1.7) usually reflects the way each community conducts its scientific investigations. For example, because planetary science is intimately concerned with spacecraft observations on or near bodies in the solar system, the panels are essentially organized around these objects (e.g., inner planets or outer planets). For reasons of continuity, Planetary2011 explicitly chose, with one exception,[16] the same thematic organization used in the 2003 survey.

Solar and space physics concerns the physical processes occurring at the interfaces between various particle and/or electromagnetic field environments, so panels have been organized around these different domains. Helio2013 also featured semi-formal, cross-panel groups that addressed topics such as theory and modeling and instrument development.

Astro2010 adopted a complex substructure consisting of five science frontiers panels (SFPs) and four program prioritization panels (PPPs). The SFPs were charged with defining key science priorities in realms of the cosmos—extrasolar planets systems, stars, galaxies, and cosmology. Once their tasks were completed, the SFPs disbanded, and their priorities were passed on to the PPPs. These "formulation" panels were organized around different observing wavelengths, techniques, and regimes and were tasked with finding the best implementation strategies to achieve the science priorities outlined by the SFPs. The activities of these two sets of panels were supplemented by six informal (i.e., not appointed by the Academies) study groups, which addressed different aspects of the astronomical community.

The thematic orientation for Earth2007 differed significantly from the other three. Seven panels were organized around combinations of both scientific and societal benefit themes—for example, human health and security and solid Earth hazards, natural resources, and dynamics.

Quasi-Formal Supporting Groups

In addition to the Academies-appointed survey committees and their panels, many decadal surveys have drawn input from quasi-formal supporting groups. Such groups follow a spectrum of organizational structures. At one end of the spectrum, the Infrastructure Study Groups of Astro2010, which consisted of interested members of the community unaffiliated with the survey committee or its panels, provided input on topics not directly addressed by a specific panel and/or topics that "fell in the cracks" between two or more panels—issues like community demographics, public policy issues, and international and private partnerships. At the other end of the spectrum are cross-panel groups where members of two or more survey panels join to form short-lived, ad hoc groups that cover a topic not otherwise explicitly addressed by the survey (e.g., the group within Helio2013 that addressed NASA-posed questions not included in the statement of task concerning the scientific traceability of the goals of the Sun-grazing Solar Probe Plus mission[17]). Helio2013 also deployed "national capabilities working groups," a hybrid between the two panel types just described. These were populated by a mix of survey committee and panel members, supplemented by volunteer consultants, whose task it was to address issues in common with multiple panels or topics unrepresented in the panel structure.

[16] Unlike the 2003 planetary science survey, Planetary2011 did not include a panel on astrobiology.

[17] For details concerning the ad hoc Solar Probe Plus group see, for example, NRC, *Solar and Space Physics: A Science for a Technological Society*, The National Academies Press, Washington, D.C., 2013, p. xiii.

Irrespective of how such internal quasi-formal groups are organized, their output is typically not published. Rather, the material generated by such groups is shared with the survey committee and/or its panels to inform the Academies-reviewed decadal report documents.

Process

The decadal survey process takes place over approximately 18 to 24 months and includes information gathering, meetings, and teleconferences of the survey committee and its supporting panels; consultation with contractors; and report preparation, review, finalization, and dissemination. The major steps in a typical survey are shown schematically in Figure 1.1.

Committee and Panel Meetings

The decadal survey process typically begins with a meeting of the survey committee. Thereafter, meetings of the panels and survey committee alternate. Survey committees typically hold five or six full meetings plus numerous conference calls. Panels typically meet three times each (plus additional conference calls, as necessary) and complete their work prior to the third or fourth meeting of the survey committee.

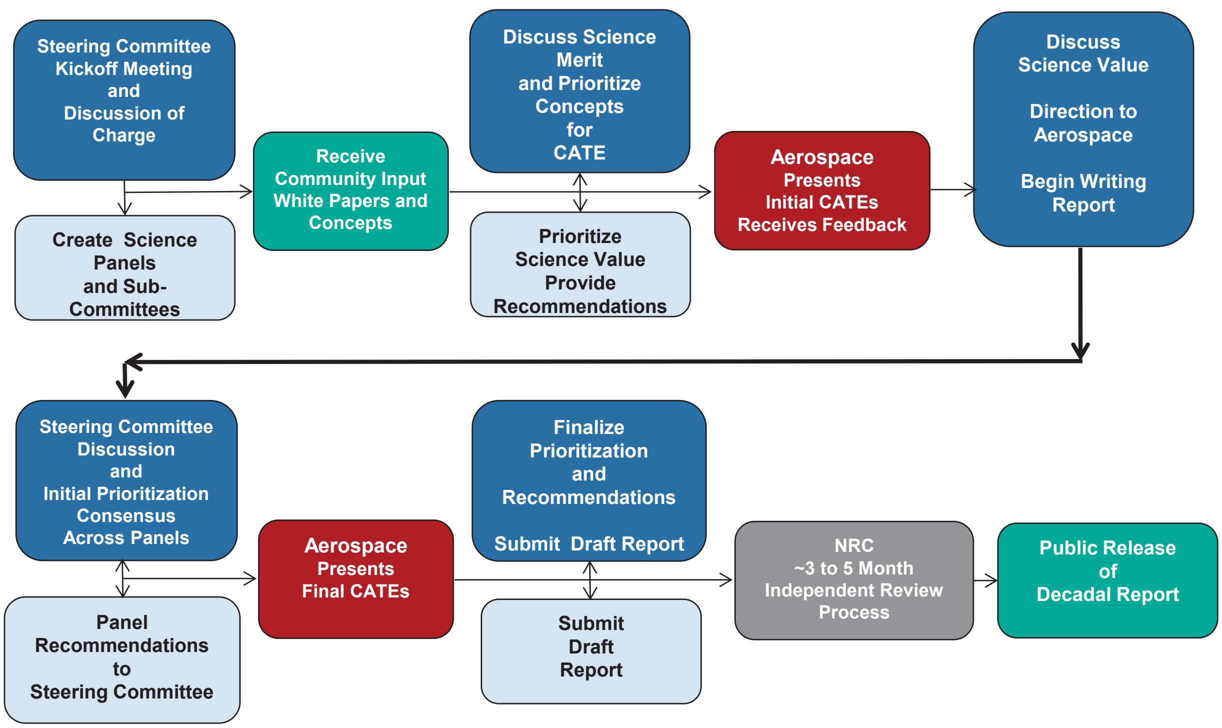

FIGURE 1.1 Decadal survey flow chart over approximately 18-to-24 months from committee charge to public release of the report. A detailed discussion of the CATE process can be found in Chapter 2 and Appendix B. This figure is repeated for convenience in the discussion of Chapter 2.

Community Input and Engagement

All four of the recent decadal surveys invited their communities to submit white papers on important scientific, technical, or programmatic issues. The solicitation typically occurs soon after the first meeting of the survey committee. Submission deadlines have been timed so that the white papers are available for consideration by the panels soon after their first meetings.

Engagement of a substantial fraction of a particular scientific community is a hallmark of a decadal survey. Webcasts have broadened the scope of community engagement beyond that traditionally achieved by town halls and other forums at major scientific conferences (e.g., American Astronomical Society, American Geophysical Union, and Lunar and Planetary Science Conference) and by holding survey committee and panel meetings at major research centers. For example, the Planetary2011 survey committee and its panels made a concerted effort to webcast and archive the open sessions of every meeting.[18] Community input and engagement are discussed further in Chapters 2 and 3 of this report.

Formulation of Science Priorities

Most if not all survey committees delegate the drafting of key science questions to their supporting panels, sometimes with the help of the survey committee. Astro2010 was the first survey to form a set of panels specifically (and only) for identifying an unranked list of science priorities in the form of science questions. However, most decadal surveys use one set of panels to do both the science prioritization and implementation strategies together, with varying participation and oversight of the survey committee. Planetary2011 had a head start in defining its science priorities, thanks to prior work undertaken by the various analysis or assessment groups (AGs) supported by NASA's Planetary Science Division (PSD). One of the roles of the semiformal, community-based AGs is to draft white papers and other documents describing their group's respective goals (see Chapter 4, "Short-Term Guidance").

Chapter 2 of this report contains a thorough discussion of the process used by decadal surveys for the prioritization of science and implementation strategies.

Mission Definition and Formulation

Mission (or program) definition and formulation is perhaps the most complex activity in a decadal survey, and also the most idiosyncratic. All four recent decadal surveys had a mission definition and formulation phase, but no two employed the same process. The differences were due mainly to (1) whether or not planning activities were available in the discipline at the time the survey began, (2) the resources available to support the survey, and (3) the survey's statement of task. For example, Astro2010 issued a request for information (RFI) to the scientific community for potential mission concepts. Many of the responses to this RFI were derived from concepts formulated in a pre-decadal round of community-based mission studies funded by NASA's Astrophysics Division.

Although NASA PSD sponsored several large mission studies (e.g., Europa Jupiter System Mission, the Titan Saturn System Mission, Enceladus flagship, Venus flagship) prior to (and independent of) its respective survey, there have been few such pre-decadal studies of mid-size (New Frontiers class) missions. However, Planetary2011 benefited greatly from the fact that PSD had sufficient resources to commission, at the request of the committee, more than 20 additional mission definition studies at leading design centers. The solar and space physics community had even fewer mission designs under study prior to Helio2013. However, a number of mission concepts had been proposed by the community and studied to various degrees during the drafting of NASA's triennial Heliophysics

[18] This experiment in community engagement can be judged a mixed success because of the challenges that remain in providing adequate audio coverage of the presenters and members of the audience—something that should improve as technology gets better.

roadmaps.[19] The design team at Aerospace Corporation had sufficient resources to study only preliminary implementations for a dozen heliophysics mission concepts.

The scope of mission formulation and design activities for Earth2007 was the least of the four surveys. Mission designers at several NASA centers assisted the survey committee in estimating the costs of key components of the mission concepts devised by the panels—for example, instruments, spacecraft buses, launch vehicles, and ground systems.

Chapter 2 of this report contains a more detailed description of the processes and strategies of mission definition and formulation used in the past four decadal surveys.

Cost and Technical Evaluation

A key facet of three of the four most recent decadal surveys has been the inclusion of an independent cost and technical evaluation (CATE) associated with mission concepts for high-priority science. Except for Earth2007, surveys selected the Aerospace Corporation to evaluate mission concepts using its proprietary CATE methodology. Results were reported to each survey committee immediately following the final set of panel meetings, enabling a rescoping of some mission concepts to conform to the desired science program. Revised mission concepts underwent another CATE "round" to validate that the revised concept achieved the intended cost and schedule. Figure 1.1 shows an example of how the CATE process fits into the decadal process. A more extensive discussion of the CATE process can be found in Chapter 2 and Appendix B of this report.

Report Drafting, Review, and Publication

The decadal survey report is the "document of record" of a survey and a plan for achieving the community's high-priority science goals. The Academies' report review procedures and subsequent copy editing of reports prior to publication have helped remove stylistic and other differences inherent in any committee-drafted document.

The panel reports of a decadal survey have an invaluable role in tracing how the decadal survey prioritized science and identified strategies to achieve science goals and objectives. However, panel reports have no official standing: the survey report authored by the committee is the only source of consensus recommendations—panel reports typically provide important context and history.

Up to this time, panel reports have been published either with or separate from the survey report. A more extensive discussion of panel reports can be found in Chapter 4.

Popular Version of the Survey Report

A decadal survey is primarily a visionary document. As such, its message needs to be readily understood by those responsible for authorizing, appropriating, and implementing its recommendations. However, the traditional executive summary and other background materials may be intimidating—too detailed, or simply too long—to engage non-technical readers, for example, congressional staffers, agency executives, or the public. As a result, all surveys completed since 2001 have drafted brief (less than about 30 pages) but richly illustrated summaries of the decadal report's science priorities and recommended program. These reports play an important role in communicating the "state of the science" and the "plan forward" to the general public.

[19] For the most recent roadmap, see 2009 Heliophysics Roadmap Team, *Heliophysics: The Solar and Space Physics of a New Era—Recommended Roadmap for Science and Technology 2009-2030,* NP-2009-08-76-MSFC 8-402847, NASA Marshall Space Flight Center, Huntsville, Ala., 2009.

THE ROLE OF THE STATEMENT OF TASK

All decadal surveys are defined through a statement of task. As noted in the 2012 workshop report,[20] the statement of task "like the decadal surveys themselves, speaks to multiple stakeholders who are involved in the negotiation of its content." The statement of task is negotiated by the Academies with the sponsoring agencies. Leading members of the scientific community[21] and members of SSB standing committees, as well as the Office of Management and Budget and the Office of Science and Technology Policy, have also been consulted in past cases. Statements of task have generally become much more detailed over the years as the methodology of executing surveys has become more sophisticated (see Box 1.8). The discussions to formulate them are correspondingly protracted, typically requiring as much as a year to finalize.

The statement of task is critically important because it sets the scope of the survey. It specifies which activities are in or out of scope for the prioritization exercise (e.g., which should be considered for inclusion in a recommended program and which are assumed to be already under way). The statement of task identifies any specific questions the sponsoring agencies want examined by the committee (e.g., applications priorities and interfaces between research and operations). It is also used to ensure appointment of a balanced committee. The statement of task also serves to manage expectations and helps those leading the survey to keep the discussions and the content of the report focused on facing hard choices that have to be made. A change in the statement of task after the survey has begun, which has occurred in some recent instances, can be quite disruptive and, ultimately, costly. For example, NASA changed the statement of task for Helio2013 in mid survey to specifically include, rather than exclude, a review of the responsiveness of Solar Probe Plus to the science goals of the Solar Probe mission discussed in Helio2003 and, in so doing, impacted the survey's budget and schedule.[22,23]

The Academies' reports are carefully reviewed, and the charge to reviewers is to ensure that the draft report corresponds well to the statement of task by addressing all the directives and not going beyond them. While it is not the job of the reviewers to question the judgment of the survey, they do ensure that it remains responsive to the statement of task. As aptly summarized by Charles Kennel and captured in the 2012 workshop report,[24] "In essence, everybody will get what they asked for, like it or not." It is vitally important to get the statement of task "right."

The content of the statement of task should be expected to vary from survey to survey to reflect the differing cultures of the four major space science disciplines, evolving science, and the changing priorities of the agencies. Further, space and Earth science are increasingly global endeavors, and the statement of task should reflect the reality of the discipline's international context. Indeed, reconciling the customs and expectations of the different agencies and other stakeholders is a major challenge, and this should be expected to take some time and care to finalize.

In general, it is important to find the right level of detail and specificity in the statement of task. The challenge is to craft it to stand the test of time and maintain relevancy throughout the entire decade.[25] An over-prescriptive set of questions and tasks makes the committee's difficult job much harder to accomplish. One example is how the Planetary2011 statement of task included language specifying that "flight and ground investigations to detect and characterize exoplanets are out of scope (these topics are being addressed in the astronomy and astrophysics decadal survey in concurrent development)."[26] This restriction did not, however, prevent the survey committee from drawing important scientific connections between disciplines by including text on the comparative planetology of solar system bodies and exoplanets.

Another example concerns decision rules; that is, explicit statements of how a survey committee advice will

[20] NRC, *Lessons Learned in Decadal Planning in Space Science*, 2013, p 78.

[21] A survey chair cannot be appointed until the survey is formally initiated by the Academies, thus he/she cannot be consulted about the statement of task, at least in its initial formulation.

[22] For the science goals of the Solar Probe mission discussed in Helio2003 see, National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., 2003, pp. 55-56; and NRC, *The Sun to the Earth—and Beyond: Panel Reports*, The National Academies Press, Washington, D.C., 2003, pp. 29-30.

[23] For Helio2013's discussion of Solar Probe Plus see, for example, NRC, *Solar and Space Physics*, 2013, pp. xiii and 132-133.

[24] NRC, *Lessons Learned in Decadal Planning in Space Science*, 2013, p. 78.

[25] Attributed to Steve Squyres at the 2012 workshop in NRC, *Lessons Learned in Decadal Planning in Space Science,* 2013, p. 15.

[26] NRC, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, The National Academies Press, Washington, D.C., 2011, p. 319.

BOX 1.8
Specificity of Statements of Task

In order to appreciate the increase in scope and specificity of the statements of task that launched the most recent decadal surveys, it is necessary to study and compare them. The following eight quotes give a flavor of what is now expected:

> Take into account the principal federal- and state-level users of these observations and identify opportunities and challenges to the exploitation of the data generated by Earth observations from space (Earth2007, p. 383).

> [T]he committee will consider what ground-based and in-situ capabilities are anticipated over the next 10-20 years and how future space-based observing systems might leverage these capabilities (Earth2007, p. 383).

> In contrast to previous surveys of the field, in view of the number of previously recommended but unrealized projects, the prioritization process will include those unrealized projects, and it will not be assumed that they will go forward (Astro2010, p. 266-267).

> [I]t will develop its own estimate of the costs of the activity with help from an independent contractor with expertise in this area. It will not uncritically accept estimates provided by activity proponents or the agencies (Astro2010, p. 267).

> The Committee shall review relevant programs of other nations and will comment on NSF opportunities for joint ventures and other forms of international cooperation (Planetary2011, p. 320).

> This summary should, to the extent possible, be accompanied by decision rules that could guide NASA in adjusting the queue in the event of major unanticipated technical, cost, or other programmatic changes (Planetary2011, p. 320).

> [T]he findings and recommendations in the present survey should be harmonized with those developed and reported by the ongoing astronomy and astrophysics decadal survey (Helio2013, p. 328).

> In proposing a decadal research strategy, the Committee will make recommendations within the boundaries of expected future budgets and address choices which may be faced, given a range of budget scenarios. To that end, it is anticipated that NASA and NSF will provide an up-to-date understanding of these limitations during the course of the survey (Helio2013, p. 328-329).

NOTE: The National Research Council decadal surveys Astro2010 (*New Worlds, New Horizons in Astronomy and Astrophysics*, 2010), Earth2007 (*Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007), Helio2013 (*Solar and Space Physics: A Science for a Technological Society*, 2013), and Planetary2011 (*Vision and Voyages for Planetary Science in the Decade* 2013-2022, 2011) were published by the National Academies Press, Washington, D.C.

change in the event of specific foreseen circumstances.[27] The statement of task can ask for guidance, through decision rules, in executing the program in the face of significance changes—for example, from the projected budget. However, it is not possible to foresee all the changes that will occur, so judicious flexibility in the statement of task is required to optimize the survey's recommendations at the time that they are delivered. The most important

[27] Decision rules are extensively discussed in Chapter 4.

function of a decadal survey is to prioritize the science and to do this from a broad and integrating perspective. A well-written statement of task is a key enabler for this task.

Suggestions for Future Statements of Task

The statement of task for this committee contained the following instruction:

> The committee will identify best practices for a well-structured statement of task that will result in a report that reflects the consensus of the community, meets short term needs of sponsoring agencies, and addresses the interests of other important constituencies, all while remaining relevant in the face of technology and science advancements, budget evolution, and international cooperation opportunities over the decade (and the following decade, for the largest projects).

The committee believes that, in fact, the items in its statement of task have become synonymous with what decadal surveys do and are. This means that the instructions given to surveys via their statements of task have consistently led to surveys that succeed in achieving these primary goals. As such, the committee believes that previous statements of task are a good starting point for the design of future surveys.

> ***Best Practice:*** Those drafting new statements of task do well to review the statements of task for the previous survey in the field as well as the most recent round from other disciplines for historical and comparative value.

This report examines all of these issues related to decadal survey planning and implementation and identifies a few places where the process might benefit from improvement simply by additions, clarifications, or emphasis in future statements of task. However, in most cases, how well a decadal survey accomplishes these well-recognized goals of the process comes down to improvements in the process. Comments at the 2012 workshop, and other input to this committee, make it clear that decadal survey committees have been well aware of and committed to doing the best they can in the matters identified in this committee's statement of task, and more. This report focuses on how the process can be adjusted, perhaps just tweaked, to do the job even better.

As identified throughout this report, there are a few places where further guidance on the statement of task would be helpful. Statements of task can, for example, be made more explicit with respect to consideration of multiple budgetary scenarios (Chapter 2) and the extent to which existing programs, projects, or prior surveys' recommendations are reviewed (Chapter 3). Agencies can also use the statement of task to identify any strong agency preferences with respect to how high-profile missions and interagency and/or international participation are considered in the survey (Chapter 3).

Finally, there is an issue where the committee thinks an addition to the statement of task would be very harmful to the decadal process. At the 2012 workshop, NASA division directors suggested that science prioritization independent of implementation strategies is something they believed would be very helpful in the decadal survey's recommended program. Indeed, this idea appears prominently in this committee's statement of task. The rest of the committee's statement of task reads as follows:

> The analysis should recognize the primacy of science goals over implementation strategies. The committee should consider, in particular, the pros and cons of a two-phase process that results in a science prioritization report first, and then, followed by a period of interaction with NASA and mission formulation prioritization process.

The committee has closely examined this idea. Carefully explained in this report (in particular, in Chapter 2, "A Two-Phase Decadal Survey Process") is the committee's conclusion that a separate prioritization of science divorced from implementation strategies would derail the decadal process in its pursuit of the consensus goals stated above. This committee finds this to be a good example of a modification to the statement of task that could be very harmful. In the spirit of "if it ain't broke, don't fix it," this report discusses adjustments in the decadal survey that could mitigate the problem that may have motivated this particular request.

ORGANIZATION OF THIS REPORT

The remainder of this report contains three chapters and five appendixes. Chapter 2 reviews the decadal survey process, including mission definition and formulation, prioritization, and the process of cost and technical evaluation, which has become a standard part of the decadal process. Further material on CATE can be found in Appendix B.

Chapter 3 covers the product of the decadal survey process—its program of science priorities and a strategy for implementation to achieve science goals and objectives. It also contains a thorough discussion of high-profile missions as well as sections on decadal program advice to the agencies and communication of the decadal program.

Chapter 4 focuses on the many stewardship issues, those activities after a decadal survey is completed that are key to a successful execution of the decadal program's science goals and objectives. The vital role of international collaboration is reviewed with an eye to strengthening and increasing it. Agency cooperation in accomplishing programs that involve more than one federal agency is another issue that deserves attention and is also covered in Chapter 4.

2

The Decadal Survey Process

The "moving parts" of a decadal survey are described in Chapter 1. This chapter describes how a typical decadal survey works and the variations that have developed as planetary science, Earth science and applications from space, and solar and space physics (heliophysics)—with their different scientific goals, methods, and cultures—have joined astronomy and astrophysics in developing their community's consensus on science goals and a program for achieving them. Different parts of the decadal process are discussed, including how a recommended program of activities is produced for the following 10 years.

COMMON FACTORS AND DIFFERENCES BETWEEN DISCIPLINES

Common Threads

Although decadal surveys have many discipline-specific science goals and objectives, there are also many similar factors that, during this committee's deliberations, were recognized as common themes that apply to all surveys.

First and foremost, each survey needs to engage its science community across a broad range of specific disciplines in order to identify the most important science questions and goals for the coming decade. Typically, concurrent with the beginning of the decadal process, the community is engaged to provide white papers on specific science goals and the tools—facilities, missions, capabilities, and associated activities—that should be pursued in the coming decade. The disciplinary or thematic panels of the decadal survey function as a conduit channeling ideas from the community at large to the decadal survey committee. The panels synthesize and prioritize community input in their panel reports. How the panels and committees interact and the fate of those panel reports varies between disciplines, as discussed below.

Another common theme is that all surveys have a much broader range of science and mission goals than can be implemented within resource constraints. The decadal survey committee assumes, or is given an outline of, the budget profile for the coming decade, but that budget may or may not fit the future fiscal reality. All surveys have faced the difficult task of distilling a wide range of potential possibilities down to a high-priority science program that fits within the projected budget profile, one that is balanced in terms of science areas, basic research versus societal needs, mission/facility scale, technology development versus infrastructure, and many more such choices. Each survey may consider alternative scenarios and develop decision rules to provide resilience to inevitable changes in expected funding.

As discussed in the "Mission Definition and Formulation" section below, a common difficulty encountered in surveys is that the short development timeframe limits the time available for detailed mission and facility concept studies. Similarly, all survey committees have considered the impact of cost overruns by large missions on overall program health and balance. Many must also consider the impacts of long-term operational costs for missions and facilities that live well beyond their original design lifetime. Finally, of concern to all disciplines is assuring the continuity of the research and analysis and technology development programs that foster community stability and the development of the next generation of scientists and engineers.[1]

Once the decadal survey is released, all disciplines face the need to engage their science communities to support the survey with a unified voice—however, there are sometimes vocal minorities that think their science has not received the priority it deserves. This is why it is critically important that decadal surveys widely sample their community's ideas and opinions at the beginning of the process (see Chapter 1, "Community Input and Engagement"). The community's perception of a "fair hearing for all comers" is essential: equality of opportunity must be assured where equality of outcome is not. The survey report and, in particular, the panel reports, record the paths taken through the process by the top science priorities and favored implementation strategies. By thoroughly laying out the rationale for these choices, their successes over other possibilities can be conveyed to the community at large. In order to be successful with program managers, politicians, the Office of Management and Budget (OMB), the Office of Science and Technology Policy (OSTP), and other stakeholders, the decadal survey report needs to be seen as a consensus document that is not circumvented by "special interests" pleading their priorities to their representatives in Congress and/or the administration.

Differences in Survey Structure

Prominent distinctions between decadal surveys can be attributed to differences in their disciplines, influencing the number of panels and the areas of focus, the interfaces between the committee and panels, the structure and roles of the committee versus the panels, how reports from the panels are provided to the survey committee for deliberation, and whether or not the panel reports are included in the final survey.[2]

In some communities, implementation is not separable from science goals, while in others the science goal takes precedence and might be implemented in a variety of ways. The former is exemplified by a facility that is capable of supporting multiple users addressing very different science goals—for example, the Hubble Space Telescope, where users with a huge range of different projects apply for observing time. In the latter case, with the focus on a science goal, multiple competitive proposals might be solicited for an identified science target (e.g., NASA's New Frontiers line of medium-class, principal-investigator (PI)-led, planetary science missions). In still other cases, measurements for multiple science goals may require multiple platforms or a system of measurements (e.g., up and down stream in the solar wind), suggesting a recommended *program* rather than series of isolated projects.

How each community defines its metrics for cutting-edge science also varies; for example, the survey may address fundamental questions with new technology or methods, focus on specific targets or measurement objectives (by wavelength or energy, location in space or in the solar system), or determine that the "answer" requires a long-term sustained observation of slowly changing processes (e.g., changes in the oceans and climate).

Some Discipline-Specific Differences

Earth Science and Applications from Space

As noted by its survey co-chair, Berrien Moore, the implementation of the first Earth science and applications from space decadal survey[3] (Earth2007) had many unique challenges, in particular how to create an integrated

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[1] A more complete discussion of the research and analysis and technology development programs can be found in Chapter 3.

[2] National Research Council (NRC), *Lessons Learned in the Decadal Planning in Space Science: Summary of a Workshop*, The National Academies Press, Washington, D.C., 2013, pp. 6-8, 17.

[3] National Research Council (NRC), *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007.

set of observations and missions for Earth system science and applications.[4] With an emphasis on Earth *system* science, panels were organized thematically rather than by discipline. The survey considered balancing societal needs and benefits with fundamental advances in scientific knowledge in a heavily politicized environment, at least with regard to climate change.[5] In addition, because this discipline engages many federal agencies beyond NASA—in particular the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Geological Survey, each of which has its own mission—data may be applicable across a broad range of agencies without clear lines of financial or operational responsibility. Earth2007 was the first in the most recent series of reports from each of the disciplines under consideration in this report. However, because it was completed prior to the enactment of the 2008 NASA Authorization Act, Earth2007 did not implement independent cost evaluations, as was required for all subsequent surveys.

Astronomy and Astrophysics

The 2010 astronomy and astrophysics decadal survey[6] (Astro2010) had the largest and arguably most complicated survey structure. Its survey committee included an executive committee and three subcommittees. Science and implementation strategies were separated into science frontiers panels (SFPs) and program prioritization panels (PPPs), and there were six infrastructure study groups (ISGs) that were populated by unpaid consultants rather than appointees of the Academies.[7] The priorities from the SFPs reports were first fed into the PPPs, whose reports, along with the SFPs reports, subsequently went to the survey committee for final integration in the survey report.[8] The working papers generated by the ISGs were shared with the PPPs and the survey committee but were not published. There is an especially strong synergy and codependence of orbiting and ground-based telescopes that require a degree of coordination between the National Science Foundation (NSF) and NASA. This discipline also addresses important questions in fundamental physics, leading in part to an important role for the Department of Energy (DOE) as a stakeholder. Interactions between federal investment, private philanthropy, and academic institutional assets are crucial in this discipline and often strongly affect survey discussions.

Planetary Science

Due to the nature of the science, Planetary2011 divided the planetary science discipline by solar system target or object class and by how specific targets (e.g., inner planets, small bodies, giant planets) contribute to human knowledge of current state and evolution of the solar system as a whole. Science and mission ideas that emerged during the survey were prioritized at the panel level and then integrated across the solar system by the survey committee. Most solar system targets have inflexible or limited launch windows that provide hard schedule constraints with associated budget implications, due to planetary and small body (e.g., comets, NEOs) orbits relative to Earth. The availability of launch windows was one deciding factor when considering whether Uranus or Neptune should have priority in the 2012-2023 decade.[9] The potential for long cruise phases for missions before initiation of data collection also means that missions may have significant financial impacts across multiple decades and can pose unique challenges with retaining scientific and engineering continuity from launch to arrival at the destination. This discipline has also provided explicit decision rules, but it is perhaps too early to assess their ultimate effectiveness.[10]

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[4] NRC, *Lessons Learned in the Decadal Planning in Space Science*, 2013, p. 14.
[5] NRC, *Lessons Learned in the Decadal Planning in Space Science*, 2013, pp. 18, 27-28.
[6] NRC, *New Worlds, New Horizons in Astronomy and Astrophysics,* The National Academies Press, Washington, D.C., 2010.
[7] Activities of the National Research Council are now referred to as activities of the National Academies of Sciences, Engineering, and Medicine.
[8] National Research Council (NRC), *Lessons Learned in the Decadal Planning in Space Science*, 2013, Figure 2.1 and p. 8.
[9] NRC, *Vision and Voyages for Planetary Science in the Decade 2012-2023*, The National Academies Press, Washington, D.C., 2011, pp. 7-35.
[10] National Research Council (NRC), *Lessons Learned in the Decadal Planning in Space Science*, 2013, p. 15.

Solar and Space Physics (Heliophysics)

The 2013 solar and space physics (heliophysics) decadal survey (Helio2013) explicitly did not "grandfather" prior mission recommendations from the previous decadal survey but later was asked by the NASA program manager to consider Solar Probe Plus with cost triggers and decision rules in the event of major programmatic changes. As Daniel Baker, chair for the latest decadal survey to occur in the round of four, noted, the Helio2013 committee benefitted from seeing the challenges to implementing the programs of the other surveys and chose to focus on achievable, smaller-scale activities.[11] The survey also utilized working groups that considered cross-cutting issues of relevance to all the panels. The statement of task for the survey, however, explicitly excluded the development of "specific mission or project design/implementation concepts,"[12] leading to difficulty in costing "science objectives" via the required cost and technical evaluation (CATE) process, leading to development of more notional mission concepts.[13]

Each community draws from the lessons learned and best practices of its earlier decadal surveys, and from the experiences of other disciplines that use the decadal survey process.

> ***Lesson Learned:*** There is no "one-size-fits-all" approach to a decadal survey. Each discipline has cultural heritage and scientific goals that cannot be directly mapped to any other group.

> ***Lesson Learned:*** The presently used process for conducting decadal surveys is able to accommodate these differences in the four disciplines and achieve the goal of community consensus on science goals and the activities that are required to achieve them.

> ***Best Practice:*** Because the disciplines are so different, clear articulation of their unique aspects is useful to readers of the survey reports who might expect "uniformity in approach" across the surveys.

MISSION DEFINITION AND FORMULATION

Where Do Missions Come From?

The primary role of a decadal survey is to a provide an overview and assessment of the current state of knowledge in a specific discipline, identify and prioritize the top-level science questions for the coming decade, and map these questions into a balanced implementation strategy that could be accomplished within projected budgets. Each decadal survey identifies a small set of overarching science questions or goals that drive the entire program; these often change little from decade to decade. Underlying each question or goal are a number of more detailed questions and objectives that can change significantly from decade to decade as new discoveries are made and prior objectives are achieved through missions or other activities. Science priorities can also change if technology developments are able to advance high-priority science that was previously beyond reach.

Because of the scientific breadth of each discipline, and the complexities and interrelationships of the science, it is not straightforward to move from the identification of high-priority science goals to an optimized program of missions, facilities, and associated activities that maximizes the science, maintains balance across the program, and fits within anticipated budgets. For the purposes of this discussion, the committee uses the term *mission* to apply to space missions, including multi-platform observing systems and ground-based facilities.

Mission concepts have been derived from a variety of sources, including the following:

- Concepts that had been studied during prior decadal survey(s) that had either not been selected or not survived Phase A study;

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[11] Ibid.
[12] NRC, *Solar and Space Physics: A Science for a Technological Society*, The National Academies Press, Washington, D.C., 2013, p. xii.
[13] NRC, *Lessons Learned in the Decadal Planning in Space Science*, p. 16.

- Concepts that had been studied by a community group or NASA center but have not been officially part of a previous decadal survey process;
- New concepts that were brought to the decadal survey either in white papers from across the community or from presentations by community groups (such as the analysis and assessment groups [AGs] within planetary science) or senior members of the community with a broad perspective on the field;[14] and
- Novel concepts that evolved from discussions during meetings of the decadal survey panels.

Before discussing more specific aspects of missions, it is useful to review their place in the decadal process. Regardless of their origin, all missions are discussed in detail by the panels before selections are made for further study, cost evaluation, and/or implementation recommendations. The panels then (typically) develop a notional program for that part of the discipline. These programs are passed to the survey committee, whose primary responsibility is to edit and blend this input into a coherent set of science goals, and the means to achieve them, across the discipline. In defining the strategy for the coming decade, each survey pays attention to a balance of activities, including missions, research and analysis, supporting facilities, technology development for the decade and beyond, and education and training. The implementation strategy for each decadal survey strives to be robust and achievable within appropriate timelines and budgets.

> ***Best Practice:*** A solicitation process to gather community input via white papers, together with invited presentations by community groups and field leaders, broadens survey participation and ensures there is opportunity to consider important activities for the coming decade. This approach recognizes emerging opportunities and innovative approaches to program implementation that may not be readily apparent to members of the survey committee and panels.

How Are Missions Formulated?

Within and between each of the four disciplinary areas in the NASA Science Mission Directorate (SMD), there are differences in mission classes, issues of cost-capped missions (see Box 2.1) versus performance-driven missions, science-focused versus time-series campaigns (notably in Earth science and space weather), significant differences in time from launch to science phase, and the availability of supporting resources and infrastructure. NSF faces analogous challenges for certain large-scale facilities. Not surprisingly, each decadal survey has followed a different approach in determining which concepts would go forward for study and in prioritizing the subsequent mission concepts, a complicated process that is described in detail in the following section.

Despite the differences in approach for the various decadal surveys, there are clear parallels in how mission concepts, large-scale facilities, and observing system infrastructure are defined, prioritized, and implemented between the disciplines. Priority science goals that are defined within each of the decadal surveys are used to develop and refine mission concepts, facilities, and infrastructure that optimize science return while minimizing mission cost and risk.

In general, concepts for lower-cost NASA missions in each of the disciplines (e.g., Discovery or Explorer-class missions) are not defined or studied in detail within the decadal survey process. Instead, surveys typically recommend that such missions address priority decadal survey science goals and objectives while leaving the implementation details to the agencies, proposers, and/or mission teams.

For higher-cost missions, both cost-capped (generally PI-led) missions and performance-driven missions (see the section "High-Profile NASA Missions"), more detailed studies are generally required to ensure a viable decadal science strategy based on a full understanding of the costs and risks associated with the recommended program. To support a realistic cost evaluation, a sufficient fidelity in mission definition is needed to identify sources of risk that could lead to cost growth, which could affect that committee's prioritization and recommendation. The extent

[14] For all decadal surveys, community input has been solicited on both science questions and implementation strategies for the coming decade. While community input can address the full spectrum of implementation activities, a significant percentage of community input is focused on particular space mission concepts.

BOX 2.1
Cost-Capped Missions in NASA's Science Mission Directorate

The *Heliophysics Division* supports the Heliophysics Explorer Program of competed principal-investigator (PI)-led small and medium Explorer-class missions ($50 million-$300 million), as well as directed missions in the Solar Terrestrial Probes Program (center-led but recommended for PI-led/cost-capped management; see Figure 2.1.1) and the Living with a Star Program, with a mix of medium ($300 million-$600 million) and large (>$600 million) missions.

The *Earth Sciences Division* supports competed Venture-class missions (space missions, hosted instruments, and suborbital campaigns with varying cost caps under $150 million that are managed by the Earth System Science Pathfinder Program) and directed systematic missions of various sizes (both cost-capped and performance-driven).

The *Planetary Science Division* supports the Discovery Program of smaller PI-led, competed missions (<$500 million); the New Frontiers Program of medium-sized PI-led competed missions ($500 million-$1 billion); and high-profile missions that are center-led, directed—i.e., non-competed—missions.

The *Astrophysics Division* supports the Astrophysics Explorer Program of small (<$120 million) and medium ($120 million-$180 million) missions, as well as the Physics of the Cosmos Program, the Cosmic Origins Program, and the Exoplanet Exploration Program, each with a mix of medium and large (>$1 billion) missions.

In addition, each of the divisions can support smaller Missions of Opportunity (MOOs), suborbital missions (balloons, sounding rockets, etc.) and cube satellites.

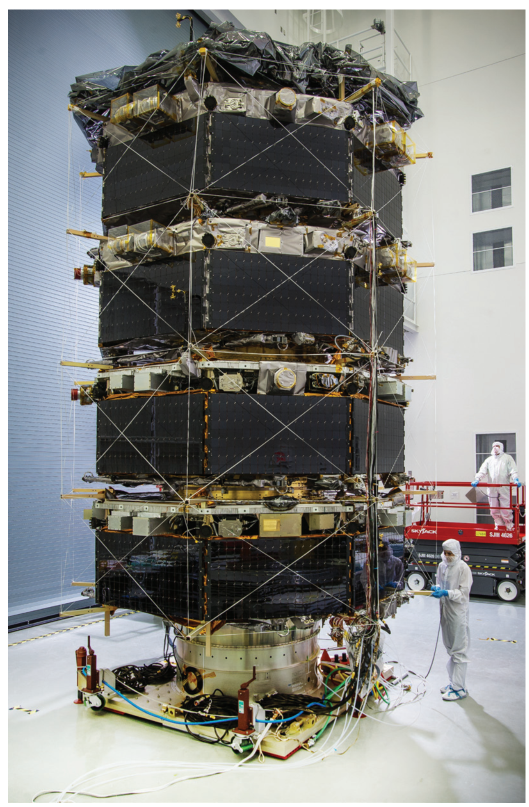

FIGURE 2.1.1 View of the fully stacked Magnetospheric Multiscale Mission (MMS) prior to its launch in March 2015. MMS is the fourth spacecraft in NASA's Solar-Terrestrial Probe program. SOURCE: Courtesy of NASA/Chris Gunn.

to which mission concepts are developed prior to versus during the decadal survey has varied between disciplines. For Astro2010, for example, the agencies sponsored detailed mission-concept studies that were fed directly into the decadal survey process for evaluation and prioritization. However, in Helio2013, mission concepts were developed within the decadal survey process based on proposed instrument concepts. Figures 2.2 and 2.3 from the "Cost and Technical Evaluation: The CATE Process" section (below) show the evolution of mission concepts were used in Astro2010 and Helio2013, respectively.

> ***Best Practice:*** The practice within decadal surveys of not defining specific NASA mission concepts for lower-cost and competed missions, yet recommending that such missions address priority decadal survey goals and objectives, allows flexibility to leverage innovative implementation approaches.

How Is Mission Affordability Assessed?

Assessing the *affordability* of recommended missions has been a challenge for decadal surveys. The cost-risk assessment process adopted by recent decadal surveys is described below (see the section "Cost and Technical Evaluation: The CATE Process"; the specific application of the CATE process for recent surveys is described in Appendix B). The intent of the process is to ensure that mission costs considered during the prioritization process are credible and associated risks are well understood.

The fidelity of cost evaluations depends strongly on the robustness of the mission design. Unfortunately, the decadal survey timescale and budget are limited, and mission studies can consume considerable portions of both. This restricts the total number of studies that can be performed prior to mission prioritization and drafting of the decadal survey. Given the time constraints involved, it is even possible that decisions have to be made on whether or not to study particular mission concepts prior to the identification of priority science questions and goals. Obviously, such occurrences must be avoided.

> ***Best Practice:*** A two-step CATE process that allows more concepts to remain in consideration in the early stages of the survey includes a faster, cruder "cost box" analysis for a longer list of candidate concepts. This would be followed by a detailed CATE for candidates for the final program that require more detailed assessment due to their cost, complexity, risk, or importance to the community.

Robust cost evaluation of mission concepts requires fairly detailed mission definition. The template process is to (1) start with the science goals, (2) trace them through science implementation—specific investigations and measurements, (3) identify or invent a candidate instrument or suite of instruments, and (4) develop a mission point design. Seeking a more accurate cost evaluation drives a tendency to over-specify instrument suites and missions. A negative consequence is that program directors and potential mission principal investigators can feel overly constrained in developing alternative mission concepts that might more efficiently address survey goals.

> ***Lesson Learned:*** The tendency to over-define mission concepts in pursuit of more accurate cost evaluation can stifle creative approaches to addressing survey goals.

> ***Best Practice:*** Decadal surveys can present their implementation strategies as *reference missions*—that is, a credible hardware configuration that can achieve the science goals and is sufficiently defined for robust cost evaluation—instead of blueprints for detailed implementation.

> ***Best Practice:*** It is desirable that the survey committee determine, as early in the process as possible, how robust a mission concept needs to be to provide sufficient cost certainty. An example is an ambitious mission where the survey committee needs to know—with reasonable confidence—that a mission team will be able to propose a credible design that meets science requirements and fits within the cost cap for the mission class.

Care is needed to prevent decadal survey discussions from interfering with ongoing competitions. For example, during Planetary2011, competition for the third mission in the New Frontiers program was under way. Ultimately, three mission concepts were selected by NASA for Phase A studies. The decadal survey's respective panels discussed all three, although cost assessments were not performed. In one case, a panel determined that a particular mission concept did not warrant consideration as a high-priority mission for the coming decade; this information was not shared with NASA so as not to interfere with an ongoing competition.

> ***Lesson Learned:*** Because each of the disciplines define and develop missions differently, there can be no uniform approach in dealing with mission concepts from prior decadal surveys, mission concepts that are under competition, or missions in Phase A study. Nonetheless, it is highly desirable for a survey committee to decide early on how to deal with such situations and to communicate this to the panels.

SCIENCE AND MISSION PRIORITIZATION

In the process of constructing a recommended program for a particular discipline, a decadal survey "must provide a compelling science narrative that communicates the importance and value of the science."[15]

Prioritization is an essential part of producing a strategic program that is feasible, executable, and sustainable over a decade-long horizon. The decadal survey prioritization process assimilates science goals, missions, facilities, observing systems, infrastructure, human capital, and public-benefit considerations into a programmatic vision that is coherent and integrated, with well-articulated goals and well-defined metrics.

It is in the prioritization process where "scientific aspirations—what we would like to do—come face-to-face with what we can do."[16] To accomplish this, decadal surveys must identify and weigh a number of goals, values, and challenges related to initiatives that could advance the highest-priority science programs. Some examples of these criteria are as follows:

- Is the proposed science transformational and/or fundamental, or is it incremental?
- Is the science primarily explorative, exploiting new technology or techniques to search for new kinds of celestial sources and/or phenomena that have been previously beyond reach?
- Is it practical, within state-of-the art technology, or does it require a substantial advancement from present capabilities?
- What is the breadth of the science to be achieved? Will its accomplishment have effects across the discipline, across multiple disciplines, across agencies, or around the world?
- What is the complexity of execution? Are multiple new technologies or system capabilities required? Are there substantial dependencies on infrastructure and/or workforce or a complex relationship among international partners?
- How will the execution of the program, including the scale of effort and potential risk, affect portfolio balance? Are substantial benefits to other science themes or disciplines likely?
- What is the return on investment? Is it simply science per dollar, or does it extend to national priorities or leadership?
- Are there other aspects of the activity that could affect its priority—for example, operational issues, links to human exploration, interagency and international cooperation, and the interests of other stakeholders?
- Would there be societal benefits or other impacts? Will the science notably serve the public interest, contribute to national imperatives, advance education or workforce development, or help build or retain areas of excellence?

It is clear from this incomplete list that prioritization is a very complicated process that involves the simultaneous assessment of very different qualities and characteristics, the ultimate "apples versus oranges versus plums versus grapes" comparison. The choice is multidimensional and unsymmetrical, with both correlation and anti-correlation

[15] National Research Council, *Lessons Learned in Decadal Planning in Space Science*, 2013, p. 3.
[16] NRC, *Lessons Learned in Decadal Planning in Space Science*, 2013, p. 33.

TABLE 2.1 Prioritization Criteria Used by Various Decadal Surveys

Survey	Broad Prioritization Criteria for Notional Mission Concepts, Measurement Systems, and Capabilities
Earth Sciences and Applications from Space (Earth2007)	• Scientific merit and societal benefit • The ability to address multiple science or applications goals • Technical readiness • Affordability
Astronomy and Astrophysics (Astro2010)	• Direct mapping of key science questions to correlated activities identified by program prioritization panels • The ability to address multiple questions in more than one subdiscipline • Extent to which activity contributes to the health of the community • Value to the nation • Technical readiness
Planetary Sciences (Planetary2011)	• Scientific merit • Science return versus investment for large and mid-size missions • Balance across solar system and mission sizes • Target trajectory opportunities • Technical readiness
Solar and Space Physics (Helio2013)	• Scientific merit • Relevance to societal issues • Technical readiness • Timing relative to the solar cycle or other missions • Support of system science • Programmatic balance

of pros and cons. This is why the process is so difficult and so powerful and why doing a good job is key to the success of a decadal survey.

What Do Decadal Surveys Prioritize?

A decadal survey committee's key role is in the prioritization of science goals and objectives. To accomplish these science goals, the decadal survey considers missions, facilities, observing systems, and associated activities that are judged to be necessary for making the key observations and measurements.

The term *missions and facilities* may capture the major elements of the decadal programs of the astronomy and astrophysics and planetary science, even though a single mission or facility may serve the needs of completely independent science programs. However, these words do not fully capture the richness of the observational tools needed for both Earth science and solar and space physics, where comprehensive understanding of diverse and coupled physical domains requires a coordinated observing network comprising distributed sensors, satellites, observatories and laboratories. Elements of a decadal program that contribute to an array that is capable of multiple types of measurements is referred to as an *observing system.* Especially in the committees' discussion of prioritization, this distinction is crucial.

For example, Earth2007 considered the possibility of placing a variety of instruments on single platforms in the same orbit, identifying multiple uses for similar or the same measurement, flying platforms/instruments in formation, and many other options. These coordinated elements provide a framework for the Earth information system to address "recognized national needs for Earth system science research and applications to benefit society."[17] Similarly, solar and space physics prioritization criteria (Table 2.1) include consideration of the relevance of measurement and data requirements to societal issues (space weather impacts and solar and terrestrial climate system measurements), timing relative to the solar cycle, exploitation of unique critical vantage points, and other missions delivering complementary data. Helio2013 explicitly discussed how "NASA's existing heliophysics flight missions

[17] NRC, *Earth Science and Applications from Space*, 2007, pp. 27-28.

and NSF's ground-based facilities form a network of observing platforms that operate simultaneously to investigate the solar system. This array can be thought of as a single observatory—the Heliophysics Systems Observatory."[18]

How Decadal Surveys Prioritize: The Roles of Committees and Panels

The prioritization process varies by discipline owing to different scientific methods and cultures. As discussed in Chapter 1, all decadal survey committees have used panels to organize and to winnow community inputs in order to guide the early steps of prioritization. As noted at the 2012 workshop, most survey committees delegate the *formulation* of key science priorities to supporting panels.[19] A variety of criteria and techniques have been used by the four SMD disciplines to prioritize science, observing systems, and supporting activities.

Earth Science and Applications from Space

The Earth2007 panels used guideline criteria to assess how the proposed concept contributed to the following:

- The most important scientific questions facing Earth sciences today (scientific merit, discovery, exploration),
- Applications and policy making (societal benefits), and
- The long-term observational record of Earth.

The Earth2007 panels also examined and assigned priority based on (1) complementarities with other observational systems, including planned national and international systems; (2) technical readiness and risk mitigation strategies; and (3) affordability with respect to the entire envisaged portfolio.[20]

The panels received more than 200 white papers outlining ideas or plans for missions. Individual panels discussed and winnowed community proposals and introduced ideas of their own to develop a program; the list of potential missions was much longer than could conceivably be implemented.

Individual Earth2007 panels had direct representation on the survey committee—panel chairs were also members of the survey committee. After the first round of panel prioritization, the survey committee met with the panels to look for synergies among the various individual proposals. Panels were able to consider various kinds of observing systems. This complex process enabled the survey committee to develop and optimize a suite of missions as components of an observing system, instead of having to simply choose among the priorities of individual panels.

A further objective of the Earth2007 prioritization process was to achieve a robust, integrated program—one that would not crumble if one or several of the prioritized missions were removed or delayed or if the mission list evolved to accommodate changing needs. The survey committee underscored the importance of maintaining a robust program over any particular mission on the list, stating, "It is the range of observations that must be protected rather than the individual missions themselves."[21] This strategy would also facilitate augmentation or enhancement of the program should additional resources become available beyond those planned for by the survey.

The Earth2007 report called for the U.S. government to renew its investment in Earth-observing systems, with specific recommendations concerning long-term observations and a listing of 17 recommended "new measurement" missions, organized into phases, for implementation by NASA and NOAA.[22]

Solar and Space Physics (Heliophysics)

Helio2013 developed a process for prioritizing science and observing systems that was driven by the overarching scientific goal of advancing understanding of the Sun and its interactions with Earth and the interstellar medium. A particular focus was placed on practical applications, such as the science needed to reliably forecast

[18] NRC, *Solar and Space Physics*, 2013, p. 4.
[19] NRC, *Lessons Learned in Decadal Planning in Space Science*, 2013, p. 8.
[20] NRC, *Earth Science and Applications from Space*, 2007, p. 7.
[21] NRC, *Earth Science and Applications from Space*, 2007, p. 7.
[22] NRC, *Earth Science and Applications from Space*, 2007, p. 8-9.

disruptive space-weather disturbances that threaten the economy and technology infrastructure. Three guiding principles for prioritization in the solar and space physics program were articulated: transformational science requires study of the Sun, Earth, and heliosphere as a coupled system; understanding the system requires measurable progress toward achieving major goals in each subdiscipline during the decade; and a successful program requires an effective mix of all program elements—theory, modeling, analysis, and technological innovation, as well as large, medium, and small missions and facilities. The survey committee, working in concert with panel chairs, developed four key science goals and a "discipline vision" that would help scientists to understand our home in the solar system, to predict the changing space environment and its societal impact, and to explore space to reveal universal physical processes.

Helio2013 solicited white papers on science topics and questions, but not for mission concepts. Nearly 300 white papers were received, and these—together with the relevant NASA roadmaps—were given to three panels organized by science theme (see Box 1.7). The panels developed detailed scientific "imperatives" that were then traced into concepts for reference missions. Eventually, the survey committee requested each of the three panels to identify its highest-ranked mission concepts for additional study by a design team.[23] Prioritization criteria included scientific merit, relevance to societal issues, technical readiness, and timing relative to the solar cycle or other missions.

The survey committee integrated scientific inputs, assessments, and priorities from the panels to provide an overall prioritization for new ground- and space-based initiatives. After completing the prolonged program that was already under way, the top recommendations called for modest investment in a number of innovative and effective scientific research activities called the "Diversify, Realize, Integrate, Venture, Educate" (DRIVE) initiative, followed by an increase in the cadence of competitively selected Explorer missions. Prioritization of new initiatives was heavily influenced by the Aerospace Corporation's CATE assessment (described below), because only a few viable choices were identified.

Planetary Science

Planetary2011 identified three priority themes for the coming decade that crosscut the planetary sciences:

- Building new worlds—understanding solar system beginnings;
- Planetary habitats—searching for the requirements of life; and
- Workings of solar systems—revealing planetary processes through time.

Planetary2011 used four criteria for selecting and prioritizing missions:

- Science return per dollar;
- Programmatic balance—striving to achieve an appropriate balance among mission targets across the solar system and an appropriate mix of small, medium, and large missions;
- Technological readiness; and
- Availability of trajectory opportunities within the 2013 to 2022 time period.

Although planetary science is "destination oriented," priorities for spacecraft missions to the Moon, Mars, and other solar system bodies were treated in a unified manner with no predetermined "set asides" for specific bodies,[24] a major departure from the 2003 planetary science decadal survey.[25]

As described at the 2012 workshop, Planetary2011 used a multistep process to develop priorities for both science goals and reference missions.[26] This involved continuous communication and feedback between the panels

[23] NRC, *Lessons Learned in Decadal Planning in Space Science*, 2013, p. 37.
[24] NRC, *Vision and Voyages*, 2011, pp. 9-10.
[25] NRC, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003.
[26] NRC, *Lessons Learned in Decadal Planning in Space Science*, 2013.

and the survey committee. The panels developed science questions based on input received from external sources (such as white papers generated by individuals and like-minded members of the relevant scientific communities), plus internal deliberations. The survey committee then integrated the science questions from across the panels. Next, the panels developed concepts for reference missions to address these science questions. Selected mission concepts were forwarded from the panels, via the survey committee, to leading mission design centers to assess their technical feasibility. Each center-based, mission-concept design team included at least one panel member who acted as the "science champion"—that is, the panel member charged to advocate on behalf of the mission's science goals. The individual panels used the results of the concept design studies to inform their ranking of the most promising mission concepts.[27]

Planetary2011 finalized a set of recommended missions intended to achieve the highest-priority science identified by the planetary science community and the panels within the projected budget resources.[28]

Astronomy and Astrophysics

Astro2010 used a model for prioritization that separated exploration of science goals from identification and ranking of concepts for missions, facilities, and associated activities. The survey committee's deliberations were informed by five SFPs and four PPPs. By running them sequentially, these two varieties of panels were run with minimal cross talk during their deliberations.[29] The decadal survey committee accepted community input using mechanisms similar to other disciplines, including the use of a series of requests for information (RFIs) addressed to the community. Once key scientific priorities where defined, the SFPs were disbanded, and their goals where passed on to the PPPs, which were charged with identifying and evaluating missions, facilities, and supporting activities, as described in the RFIs, that could make progress on the science priorities. This "science first" structure was intended to avoid "picking specific science goals because they were what a preselected mission was good at doing." [30]

An important aspect of Astro2010—highlighted at the 2012 workshop—was that the SFPs and PPPs were supplemented by six informal (i.e., not appointed by the Academies) infrastructure study groups addressing a broad range of topics, including education and public outreach, international and private partnerships, computation and data handling, and the demographics of the astronomical community.[31] This combination of formal panels and informal study groups worked well because it provided ample mechanisms for community input with low barriers for participation.

Astro2010 selected and ranked the highest-priority science objectives, as informed by the SFPs, and the concepts for mission and facilities to meet these objectives, from the PPPs. The survey committee's recommended program included not only missions and facilities but also programs at NSF (mid-scale innovations program) and NASA (Explorer Program augmentation) that are competitively selected. The prioritized science goals identified by Astro2010 have been used by proposers to validate the importance of their project, utilizing the independent science prioritization made by the survey.

The Astro2010 list of prioritized missions, facilities, programs, and supporting activities was intended to guide NASA, NSF, and Department of Energy in the implementation of the recommended program. The decadal survey report emphasized that optimizing the implementation of their decadal aspirations is the responsibility of agency managers.[32]

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[27] NRC, *Lessons Learned in Decadal Planning in Space Science*, 2013, p. 37.
[28] NRC, *Vision and Voyages*, 2011, pp. 26.
[29] NRC, *New Worlds, New Horizons*, 2010, p. xvii-xx.
[30] NRC, *Lessons Learned in Decadal Planning in Space Science*, 2013, p. 36.
[31] NRC, *Lessons Learned in Decadal Planning in Space Science*, 2013, pp. 7-8.
[32] NRC, *New Worlds, New Horizons*, 2010, p. 4.

Synergies Across Disciplines and the Changing Face of Research

Decadal survey committees have a responsibility to look broadly over the discipline priorities identified by supporting panels for synergies and connections. Astro2010 recognized that "the sociology of astronomy has also changed [resulting in a field today that] is more collaborative, more international, and more interdisciplinary."[33] For large ground-based facilities, the committee highlighted the synergy between the Large Synoptic Survey Telescope (LSST) and the Giant Segmented Mirror Telescope, noting that each "would be greatly enhanced by the existence of the other, and the omission of either would be a significant loss of scientific capability."[34] Astro2010 also stressed the need for both NSF's LSST and NASA's James Webb Space Telescope (JWST) to advance key, discipline-wide, science questions. As noted at the 2012 workshop, an "astronomy decadal survey that addressed only science questions and leading implementation issues for NASA would give short shrift to the interests of NSF," [35] and concomitantly to other agencies and stakeholders.

Similarly, NSF's Daniel K. Inouye Solar Telescope (DKIST, formerly the Advanced Technology Solar Telescope) is recognized as a key strategic element of the Heliophysics System Observatory that supports NASA's Heliophysics program and all of solar and space physics. Helio2013 repeatedly emphasized that the ground-based assets of NSF "provide essential global synoptic perspective and complement space-based measurements of the solar and space physics system" to enable frontier research.[36] The survey also recommended the new, cross-cutting DRIVE initiative as a focus for low-cost, high-impact ways to accomplish the science goals of the survey and integrate the recommendations across the agencies. The prioritizations of Helio2013 reflect the economic environment; they were made in the context of recommendations from other science areas and were intended to address operational needs as well. However, as noted at the 2012 workshop, decadal surveys should be mindful of "the principle agency and organizations that will receive the recommendations and define the scope of their responsibilities."[37]

Interactions between discipline panels may also help identify initial synergies and potential priorities for science and missions/facilities that are cross-cutting over the discipline. While it is exclusively the job of the survey committee to integrate panel priorities into a cohesive strategic plan, cooperation among panels may lead to more effective and/or affordable implementation of the program. A critique voiced at the workshop was that certain surveys adopted a posture that inhibited such conversations and led to narrow "stove-piping" of mission concepts,[38] a situation that might be avoided through advanced planning for inter-panel and panel-committee interaction.

A continual theme in the 2012 workshop discourse was that there were distinct differences in "how each decadal [survey] evaluated missions and science objectives for prioritization."[39] Agencies recognize that each decadal survey has adopted a discipline-specific strategy for developing a prioritized, executable science program. Questions of how to balance the prioritization of science and missions were discussed at length throughout the workshop.[40] With the exception of Astro2010, decadal surveys have used panels that prioritized science and missions together, and in Planetary2011, in particular, this process was augmented by contemporaneous involvement by the survey committee itself. Table 2.1 lists some of the criteria used by survey committees and panels, as articulated during 2012 workshop discussion.[41]

Different disciplines prioritize using different approaches and techniques. Common across disciplines is a tendency for survey committees to provide a broad set of prioritization criteria to guide the work of the panels, which individually have a sharper focus.

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[33] NRC, *New Worlds, New Horizons*, 2010, p. 80.
[34] NRC, *New Worlds, New Horizons*, 2010, p. 95.
[35] NRC, *Lessons Learned in Decadal Planning in Space Science*, 2013, p. 41.
[36] NRC, *Solar and Space Physics*, 2013, p. 5.
[37] NRC, *Lessons Learned in Decadal Planning in Space Science*, 2013, p. 25.
[38] NRC, *Lessons Learned in Decadal Planning in Space Science*, 2013, p. 20.
[39] NRC, *Lessons Learned in Decadal Planning in Space Science*, 2013, p. 16.
[40] NRC, *Lessons Learned in Decadal Planning in Space Science*, 2013, p. 16.
[41] NRC, *Lessons Learned in Decadal Planning in Space Science*, 2013, p. 37.

Lesson Learned: Although science goals may not be explicitly ranked, science priorities drive the rankings of missions, facilities, programs, and other activities.

Lesson Learned: Experience indicates that survey prioritization puts a high value on programmatic balance across missions and facilities and is also attentive to the need for long-term continuity in certain observational data.

Lesson Learned: Technical readiness and affordability can often influence science prioritization of missions and facilities. High-priority science may be deferred if needed technology is immature and there is a significant risk of cost growth that would affect both scope and schedule.

Survey prioritization implicitly recognizes the importance of strengthening the nation's workforce in space sciences and engineering. Workshop participants noted, "The space science community and NASA need to maintain core competencies within the workforce on how to carry out large-scale missions."[42] The science programs carried out by agencies crucially depend on the recently graduated scientists and engineers who will maintain and improve the mature technologies and pioneer new ones. A long hiatus in one part of a discipline can lead to decay in critical scientific and technological expertise. All disciplines need the opportunity to make progress during a decade in order to preserve their capability to create the next generation of instrumentation.

Workshop participants noted that for Earth2007 and Helio2013, the implementation of the decadal survey's recommended program relied on the cooperation of multiple agencies, and they expressed great concern that science priorities can be compromised if components are lost or data go uncollected.

In addition, tightly specified mission recommendations can be a problem for NASA in developing implementation plans. NASA has internal constraints (NASA centers, workforce issues, etc.) and is subject to congressional and executive branch decisions. Furthermore, new technologies and innovative approaches may produce a more effective mission, as can international and interagency cooperation. Therefore, a potential option for decadal surveys is to choose and describe reference missions (see the section "Suggested Changes in the Prioritization Process" below) that are judged capable of carrying out the science but to encourage agencies to follow, first-and-foremost, the *science objectives* of the prioritized missions.

Lesson Learned: The potential for international collaboration, interagency cooperation, and inclusion of the private sector impacts science and mission prioritization across all disciplines.

As noted at the 2012 workshop, comprehensive sampling of community opinions—using the best available practices for gathering and curating community input (e.g., solicitation of white papers, town hall meetings, committee and panel meetings at major research centers, and the use of broadly representative panels)—has been woven into the fabric of all decadal surveys.[43] Digesting and incorporating this input is an essential part in assessing community consensus and for initiating the survey's prioritization process.

Best Practice: Establishing a community-wide consensus is arguably the most important goal of a decadal survey, and community "buy-in" to the decadal survey's process is crucial. Community trust in the decadal survey process depends on a clear understanding of the prioritization methodology used by the survey committee and its supporting panels.

Challenges to Science and Mission Prioritization Processes

Clarity of task from sponsoring agencies and substantial involvement of the community are essential components in the process. The success of future decadal surveys lies in part with the following:

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[42] NRC, *Lessons Learned in Decadal Planning in Space Science*, 2013, p. 59.
[43] NRC, *Lessons Learned in Decadal Planning in Space Science*, 2013, pp. 5, 8, 17, 20, 26, 34, 36-37, 49, and 75.

- Clarifying that discussions and recommendations by the panels are an important element in "traceability" of survey process, but only the decadal survey committee's recommendations "count";
- Recognizing that "buy-in" to the decadal process by all participating agencies (and/or divisions within agencies, as appropriate) is essential, because carrying out national programs can require more than one agency;
- Minimizing the uncertainty in budgetary planning envelopes that decadal surveys use to construct a recommended program;
- Executing "CATE-like" assessment of affordability and technical difficulty; and
- Communicating effectively with the community

DECADAL SURVEY PRIORITIES AS INPUTS TO AGENCY GOALS AND OBJECTIVES

The science goals and objectives developed by each of the decadal surveys are an integral part of NASA's strategic planning process. Other agencies also use decadal surveys as part of their strategic planning process to varying degrees. While NASA must consider broader issues beyond the scope of the decadal surveys, such as facilitation of and synergy with the human space program, there exists a clear traceability between decadal recommendations and NASA strategic goals and objectives and the science goals of the SMD divisions, as delineated in Appendix B of NASA's 2014 Science Plan.[44] Clearly, decadal survey science goals support NASA's strategic goals to (1) expand the frontiers of knowledge, capability, and opportunity in space (Heliophysics, Planetary Science, Astrophysics, and Earth Science divisions) and (2) advance understanding of Earth and develop technologies to improve the quality of life on our home planet (Earth Science and Heliophysics divisions). Not surprisingly, a strong synergy remains between the science goals of each SMD division and the science goals of each decadal survey discipline.

SUGGESTED CHANGES IN THE PRIORITIZATION PROCESS

"Science Only" Decadal Surveys?

In a panel discussion at the 2012 workshop, NASA SMD division directors or their representatives suggested that decadal surveys focus on science prioritization, with less attention to missions, facilities, observing systems, and the means to accomplish them. Their concern was that surveys are becoming ever more prescriptive in their recommendations of specific architectures for missions, perhaps because surveys are trying too hard to optimize the recommended science program in the face of tighter budget constraints. Specific mission architectures can put NASA SMD in a "straightjacket" with respect to evolving capabilities and budgets, the division directors noted, and they may conflict with other programmatic, governmental, and societal priorities that the agency must accommodate while executing the decadal program.

Science priorities evolve slowly: decadal surveys—with their 10-year cadence—show a high level of correlation between the science priorities from one survey to the next. However, an implementation strategy may change over the decade due to new technical capabilities or instability in available budgets. There is some sense, then, to focusing decadal surveys on science, leaving implementation largely in the hands of the agencies.

However, the strong consensus of participants of the 2012 workshop was that prioritizing science alone—without including "missions" that juxtapose "what we want to do" with the critical "what we can do"—is not a good idea and probably not possible. The committee suggests that, in order to attend to the legitimate concerns of NASA SMD, future decadal surveys can choose to describe "reference missions" rather than explicitly recommend specific point designs for direct implementation. Reference missions are implementation architectures that are judged capable of addressing specific science goals. NASA would then have the flexibility it needs to optimize a reference mission and craft an implementation strategy that is more capable and/or more affordable and, thus, satisfy NASA's broader interests and constraints. Through the stewardship process following a survey, community scientists can work with NASA to rescope, adjust, or innovate to accomplish the survey's science objectives.

[44] NASA 2014 Science Plan, reprinted in Appendix A.

While this reference mission approach might be suitable for many recommended missions, certain *high-profile missions* (discussed in Chapter 3) can be mature concepts that have been refined and optimized over years of design studies and may indeed be intended as explicit recommendations for implementation. Decadal survey reports are well advised to explicitly note when they are discussing a reference mission and when they are not. In other words, survey reports need to signal when they are discussing a notional reference mission capable of achieving science goals X, Y, and Z and when they are discussing a specific implementation of a mission that achieves science goals X, Y, and Z. The New Frontiers mission candidates discussed in Planetary2011 are, for example, reference missions.[45] The Jupiter Europa Orbiter, discussed in the same document, is a specific implementation of a mission designed to conduct scientific observations of Europa from an orbital vantage point (Figure B.5).[46] Successful prioritization of science objectives in a decadal survey requires a clear understanding of the scope, scale, and feasibility of missions that could reach these objectives.

> ***Lesson Learned:*** It is important that decadal surveys explicitly note which proposed missions are *reference missions*—i.e., subject to further development—versus those intended as explicit implementation recommendations based on mature and well-refined concepts.

As noted above in the section "Mission Formulation and Development," decadal surveys can utilize reference missions in their science prioritization processes as "existence proofs"—i.e., demonstrations that spacecraft missions addressing specific science goals are feasible—that allow continued development of missions to best achieve a survey's science goals and serve the interests of all stakeholders.

A Two-Phase Decadal Survey Process?

The necessity of including mission concepts in the science prioritization process raises the question of whether the science prioritization might be undertaken to some degree before a survey begins. The committee was asked to consider this option for future surveys.

Planetary2011, Earth2007, and Helio2013 all chose a process that specifically prioritizes science and missions together. In contrast, the SFPs of Astro2010 identified high-priority science questions independently of missions, although they stopped short of actually ranking them within or across the subdisciplines. This process put a strain on the schedule for completing Astro2010 within the allotted 2-year period. Adding a "time out" to inform the community of the results of science prioritization, as has been suggested to help proposers of missions and facilities, is, in the committee's opinion, impractical in terms of schedule and budget. This motivates consideration of what the committee's statement of task calls a "two-phase approach"—prioritizing the science and then informing the community in a separate process that occurs before the survey begins.

It is clear that a pre-survey process cannot be on the scale of the decadal itself, so wide community involvement would be in the form of white papers and community meetings that might serve as input to the appropriate standing committee of the Academies, or a specially tasked committee run by the Academies by the Space Studies Board (SSB), in collaboration with other boards as appropriate. It would be challenging for such a review committee to represent the entire community and to prioritize across the discipline, something only achievable by a survey committee (with broad community representation and the help of panels). The best outcome would likely be a list of the 10 to 20 highest (but equally weighed by elements of the community) priorities for the different themes of the discipline.

This is, indeed, what resulted from a "science only—no missions considered" process in Astro2010. Five SFPs framed 4 questions each for their subdiscipline, adding 1 or 2 "discovery areas." The result was a list of 20 questions and 6 discovery areas: there was no attempt to prioritize across these—that job was left for the survey committee, with input from the panels. This crucial next step required consideration of the means to carry out the science—the missions and facilities. It is not obvious that the availability of such a long, unprioritized list would

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[45] NRC, *Vision and Voyages*, 2011, pp. 266-268, 243-246, 339, 344-347, and 352.
[46] NRC, *Vision and Voyages*, 2011, pp. 243-246 and 345.

have helped mission proposers to better "tune" to the community's science goals, whether it came in the middle of the survey or in an organized pre-survey process.

Given the richness of science in these NASA SMD disciplines and the demonstrated difficulty for a group of scientists to prioritize *within* their subdisciplines, the committee concludes that it is not possible—based on science alone—for any group to prioritize *across* their discipline. Are missions to Mars more important than visiting the icy moons of Jupiter? Is the discovery of Earth-like planets around nearby stars more interesting than a full understanding of how stars are born or when the first galaxies appeared? Is the heating of the Sun's corona a more urgent area of inquiry than the effect of the solar wind on Earth's atmosphere? Considering the capabilities of realistic candidate missions helps decadal survey committees choose which science programs should have the highest priority, based on where the greatest progress can be made. Otherwise, the decadal survey task would be difficult at best.

Updating Science Priorities Before a Survey Begins

An alternative approach would be to exploit the variety of existing advisory committees and regular community activities in the discipline under consideration. The community can be encouraged, and activities structured, to look at the evolution of science goals from the previous survey. The SSB standing committees and the midterm reviews of the decadal surveys could look for new science developments that indicate a shift of priorities in advance of the next survey. For example, evidence for an accelerating universe came to light in the middle of the Astro2000 process; the change in the science priorities of cosmology happened in between surveys.

Society meetings could include public forums to discuss the impact of important discoveries on the next survey. NASA could ask the "AGs" (e.g., the Mars Exploration Program Analysis Group) to contribute to the discussion.[47] The process of developing NASA roadmaps leads to development of new mission concepts to address new and topical science questions. To digest all of this, a modestly sized pre-survey science committee, perhaps run by the Academies on behalf of the relevant agencies, could prepare a report that synthesizes, from these activities and their own assessments, which areas of science might be promoted or added (or demoted or removed) from the discipline's long-term science goals. This report, although stopping short of prioritizing science, would help lay the foundation for the work of the next survey.

Moreover, the period between decadal surveys is an ideal time to work on mission concepts and to bring them up to a minimal standard of development. Similar thinking may apply to issues of international collaboration (see Chapter 4). International activities between surveys, including some sponsored by the agencies, could help prepare for collaborative missions proposed to decadal surveys or to, for example, the European Space Agency's (ESA's) process for selecting the medium- and large-class missions in its *Cosmic Vision* strategic plan.[48] Before a survey begins is, of course, also an opportunity for exploring new interagency collaborations. The Astrophysics Division of SMD recently proposed just such an activity to prepare for Astro2020. The opportunity of using the time between surveys to update the science and formulate possible missions is arguably the best way to achieve the goals of a two-phase process, without prolonging the decadal survey process.

> ***Lesson Learned:*** The community has many means, especially between decadal surveys, to address the evolution of science in the discipline. This forms the basis of a two-phase process without separating the decadal survey process itself in two.

> ***Best Practice:*** Agencies, committees of the Academies, community workshops and meetings, and white papers can contribute to pre-survey science priority identification as preparation for, and a valuable contribution to,

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[47] Additional information about MEPAG and the other analysis and assessment groups can be found at Lunar and Planetary Institute, "NASA Advisory, Analysis and Assessment Groups and Resources," last updated November 18, 2014, http://www.lpi.usra.edu/analysis/.

[48] European Space Agency, *Cosmic Vision: Space Science for Europe 2015-2025*, BR-247, ESA Publications Division, Noordwijk, The Netherlands, 2005, http://www.esa.int/esapub/br/br247/br247.pdf.

the next survey. These activities can also spur early development, evaluation, and maturation of concepts for new missions for potential priorities well in advance of the survey itself.

AGENCY FEEDBACK DURING THE DECADAL: THE "2-YEAR BLACKOUT PROBLEM"

Generally, the development of decadal survey recommendations is performed using a budget profile for the coming decade that is based on current and historical budget trends provided by NASA's SMD divisions and NSF's Astronomical Sciences Division (AST). Similar budgetary profiles are provided by other federal agencies to the survey committees. During the formulation of the decadal survey, changes from previous notional "out-year" budgets for NASA may occur in OMB's formulation of the president's budget request for the coming year and notional budgets for the following 4 years. Such changes may result in substantial variance from the assumed budget profile used in the development of decadal survey recommendations. Often, NASA, NSF, and other agencies cannot share budget (and budget-related planning) information due to OMB embargos. The net effect can be that a survey's recommendations may be inconsistent with the budget available when the decadal report becomes available. In addition, because the Academies cannot share the status of the survey's recommendations while committee deliberations are ongoing, the recommendations cannot be used to communicate science community planning to NASA or other agencies for use in formulating arguments to OMB for future funding.

There are several possible mitigation strategies to this issue, parts of which have already been tested in prior decadal surveys, including the following:

1. Utilize *decision rules* that can accommodate significant but reasonable deviations from the projected budget. Such decision rules should allow for both increases and decreases in the budget and provide guidance for maintenance of program balance (see Chapter 3). For example, when the budget of NASA's Planetary Science Division was cut from $1.5 billion to $1.2 billion just as Planetary2011 was released, its decision rules were sufficient to accommodate such cuts and maintain the overall viability of the decadal survey recommendations.
2. Ensure that the duration of the decadal survey process is kept as short as is reasonably possible to ensure that the recommended program aligns as closely as possible with the current fiscal environment. The 18 to 24 months required to complete the many activities of a survey committee, including input from the community, panel meetings, and survey deliberation, is unlikely to be significantly shortened. However, some pre-work with the scientific community and its representative groups prior to the official start of a survey could help ensure the survey completion in the minimum possible time. Such pre-work could reduce the pressure on a survey to define and refine concepts for study very early in its discussions. A recent policy announcement by the director of NASA's Astrophysics Division aims to do just this.[49]
3. Agencies can continue to engage the Academies' standing committees while the decadal survey is in process, even if at a reduced frequency. OMB will not release budget information to the Academies prior to official release of the president's budget, nor will the Academies share the deliberations while the survey is in progress; however, there are many other science-related issues that can and should be productively discussed during the approximately 2-year period of the decadal survey's preparation so that both the agencies and communities remain situationally aware. This also enables the agencies to request and receive advice in the interim, should it be needed to respond to emergent and/or time-sensitive opportunities. Continued engagement during the decadal survey preparation period ensures the advisory infrastructure remains in place to effectively steward the new decadal immediately upon its release.

Although the "2-year blackout problem" creates a degree of uncertainty for the implementation of the decadal surveys, the existing process is designed to accommodate modest levels of change to ensure that the decadal survey recommendations remain appropriate and valid for the decade in which they are to be implemented.

[49] For details see "Planning for the 2020 Decadal Survey: An Astrophysics Division White Paper," January 4, 2015, a NASA Astrophysics Division Strategic Planning Document available at http://science.nasa.gov/astrophysics/documents/.

Sidestepping the Budgetary Blackout Problem?

The committee thinks there is another approach that could minimize the effect of this blackout period. Decadal surveys are concerned with budgets over the next 10 years, so updates on the next one or two budgets are not central to the task. Rather, it is the projected out-year budgets that are important, and they are, by nature, even more uncertain. A different approach to setting anticipated funding levels, one separated from year-to-year expectations and fulfillment, would be to use the previous budgets of the particular NASA or NSF division, averaged over some number of years preceding the survey, as a "baseline" budget for the survey program. A flat budget, perhaps with a yearly adjustment for inflation, could be the starting point for planning a program, with a possible "up" and "down" adjustment assumed to provide a budget that would envelope future fluctuations in the division budgets.[50]

COST AND TECHNICAL EVALUATION: THE CATE PROCESS

In the 2008 NASA Authorization Act, Congress mandated a "lifecycle cost and technical readiness" review of proposed NASA projects.[51] Such reviews have become an important part of the decadal survey process. This section provides a detailed account of how this process has been used and how it has evolved as a critical tool in constructing an executable and affordable program for the highest-priority science.

NASA has a proud history of executing space missions in all four divisions of its Science Mission Directorate. Often, these missions are technically challenging and incorporate a high degree of innovation, and they have consistently delivered science discoveries, fresh understanding of phenomena, and durable measurements that go far beyond the original scope. There have been few instances of failures in launch, deployment, instrumentation, operation, or communication or underestimation of the scientific challenge.

Yet, space science is an intrinsically risky business, as well as an expensive business. In a few well-publicized cases, mission costs have risen by large factors, usually because of underestimating the technical challenge or true cost, and/or due to budget cuts that led to extended construction profiles that substantially increased costs and launch delays. Contingency for such occurrences has rarely been part of the planning, because of an insidious disincentive for those involved to include it in their proposal, especially for the most ambitious missions. A number of cost overruns, most notably those of JWST and the Mars Science Laboratory's Curiosity rover, begged the question, does the decadal process need a dimension of technical feasibility and cost evaluation? A 2006 report of the Academies drew the following conclusion:

> Major missions in space and Earth science are being executed at costs well in excess of the costs estimated at the time when the missions were recommended in the National Research Council's decadal surveys for their disciplines. Consequently, the orderly planning process that has served the space and Earth science communities well has been disrupted, and the balance among large, medium, and small missions has been difficult to maintain.[52]

In response to this concern, the report made the following recommendation:

> NASA should undertake independent, systematic, and comprehensive evaluations of the cost-to-complete of each of its space and Earth science missions that are under development, for the purpose of determining the adequacy of budget and schedule.[53]

An extended discussion of cost estimates and technology readiness of candidate missions took place during at the Academies' 2006 workshop "Decadal Science Strategy Surveys." Some workshop participants agreed that cost

[50] Colleen Hartman presented a version of this idea at the 2012 workshop. In discussing the difficulties of decadal program planning in the context of budget uncertainties, she imagined a "three worlds" approach, using the colorful terms "heavenly" or "evil" to describe the better and worse budgets that the survey might plan for, above and below the "nominal" expectations of a flat budget.

[51] Congress of the United States, National Aeronautics and Space Administration Authorization Act of 2008, Public Law 110-422, Section 1104b, October 15, 2008.

[52] NRC, *An Assessment of Balance in NASA's Science Programs*, The National Academies Press, Washington, D.C., 2006, p. 32.

[53] NRC, *An Assessment of Balance in NASA's Science Programs*, 2006, p. 33.

and technology readiness evaluations conducted independently of NASA estimates add value to decadal surveys. It was also suggested that uniform cost-estimating methods should be used within a given survey to facilitate cost comparisons among initiatives.[54]

With this guidance in hand, and prompted by congressional language inserted in the formulation of the fiscal year (FY) 2007 budget, NASA and DOE asked the Academies to prepare a report reviewing NASA's Beyond Einstein Program.[55] Specifically, the report was to assess the five Beyond Einstein missions and recommend a first mission for development and launch, utilizing a program funding "wedge" that would start in 2009. The report assessed five mission areas using criteria that addressed both potential scientific impact and technical readiness. The study committee considered the realism of preliminary technology and management plans as well as cost estimates. Criteria used by the committee included plans for the maturity of critical mission technology, technical performance margins, schedule margins, risk mitigation plans, and estimated costs versus independent probable cost estimates.

Coming out of the Beyond Einstein Program Advisory Committee and the reports and workshops noted above, it was consistently observed that previous decadal surveys significantly underappreciated mission costs and difficulty. This was noticed by Congress, and in 2008, the NASA Authorization Act, codifying the decadal surveys, mandated that the Academies "include independent estimates of the life cycle costs and technical readiness of missions assessed in the decadal survey wherever possible."[56] In response to this congressional mandate, the Academies chose an independent contractor, the Aerospace Corporation, to assist in this task. Earth2007 was already complete at that time, so starting with Astro 2010, a cost and technical evaluation (CATE) process was devised by the Academies in partnership with the Aerospace Corporation. The intention was to pay particular attention to assessing the risks associated with proposed missions. Experience gained in Astro 2010 was used to improve CATE in the subsequent planetary science and heliophysics surveys.[57]

Purpose of CATE

The CATE process is used by decadal surveys to provide an independent, standardized process to produce a *figure-of-merit* for technical and cost risk that aids in science prioritization. CATE as implemented by the Aerospace Corporation is based on historical and continuously updated and validated databases and methods. It is designed to evaluate diverse mission concepts of varying design maturity. It incorporates cost growth based on the historical record and design maturity. CATE assesses the technical risk and readiness. It then monetizes the technical risks into *design growth* and *schedule threats*. It is often more conservative than a typical independent cost estimate because of the addition of design evolution and growth due to unforeseen changes and challenges.

CATE is used to forecast the potential cost of the final program, which may undergo multiple iterations and may be very different than what was initially conceived. The objective of the CATE process, then, is to perform a cost and technical risk analysis for a set of concepts that may have a broad range of maturity and to assure that the analysis is consistent, fair, and informed by historical data.

Application of CATE

The CATE process has needed to fit within the existing decadal survey process, interface with various stakeholders, and deliver products to the survey committee in time to inform their deliberations. This schedule has driven the process of acquiring input documentation for the CATE process. As shown in Figure 2.1, the sequence of events typically calls for an initial CATE around the midpoint of the survey, leaving adequate time for feedback

[54] NRC, *Decadal Science Strategy Surveys: Report of a Workshop*, The National Academies Press, Washington, D.C., 2007, pp. 21-30.

[55] NRC, *NASA's Beyond Einstein Program: An Architecture for Implementation*, The National Academies Press, Washington, D.C., 2007, pp. 66-114.

[56] National Aeronautics and Space Administration Authorization Act of 2008, Public Law 110-422, Section 1104b, October 15, 2008.

[57] Planetary2011 did investigate the possibility of using one of several independent contractors to provide independent cost and technical assessments. After careful consideration of the relative merits of the services offered by different contractors, the leadership of the survey and the Academies selected the Aerospace Corporation, in part because of its experience working with Astro2010.

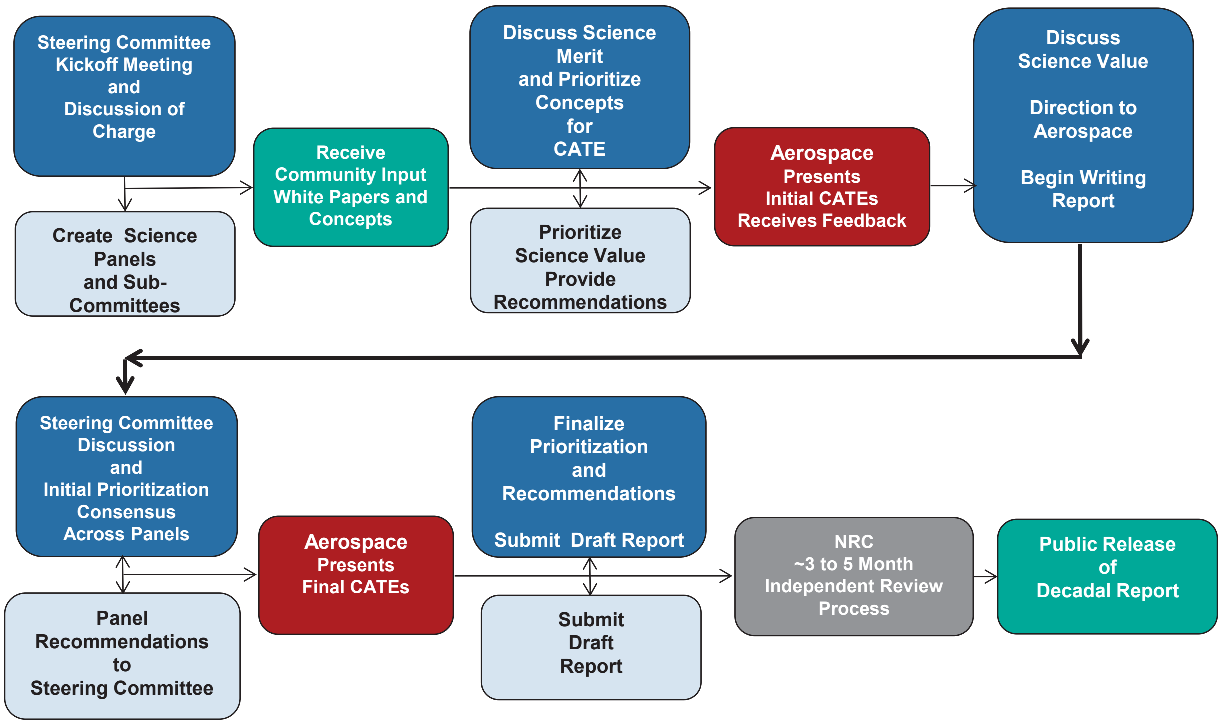

FIGURE 2.1 This flow chart (repeated from Chapter 1) shows how the cost and technical evaluation (CATE) phase of a decadal survey relates to the other activities conducted during the approximately 18-month period from the receipt of the committee's charge to the public release of the survey report.

and redirection, as needed. The 2012 workshop demonstrated that various stakeholders have (understandably) differing views on the CATE process, about its utility, and how they interacted with or were influenced by CATE.[58] These observations contributed to suggestions to modify or tailor the application of CATE in future decadal surveys, as discussed in this report.

Process

Appendix B includes specific examples of how the CATE methodology was applied during the past three decadal surveys. Although each of the three surveys evaluated mission concepts, the process was adapted for each survey to account for the different ways reference missions originated. Many of the mission concepts evaluated during Astro2010 and Planetary2011 had been studied in some depth by teams at NASA centers or at the Johns Hopkins University Applied Physics Laboratory prior to or during the course of the respective survey. Planetary2011 made effective use of science champions. Each mission concept was assigned to an appropriate member of the relevant decadal panel. These individuals advocated for science on the mission study teams at the various design centers. The science champions also tracked concepts as they matured throughout the CATE process, serving as liaisons between the study teams and the Aerospace Corporation, and keeping the relevant panels informed along the way.

However, Helio2013 did not rely on such preexisting concepts. This required an additional step to develop concepts that could then be evaluated. In some cases, when it was perceived that a mission concept might be unaf-

[58] NRC, *Lessons Learned in Decadal Planning in Space Science: Summary of a Workshop*, The National Academies Press, Washington, D.C., 2013, pp. 28-30.

fordable, a survey-team liaison participated in a "feedback loop" to consider descopes or variants of the initial concept. The flow and relative pros and cons of these various approaches are summarized in Figures 2.2 and 2.3.

CATE is performed on select missions above a certain cost/risk threshold. The threshold cost is a life-cycle cost, including mission development, build, launch, and operation. Although threshold levels differed among the decadal surveys, each had a threshold below which CATE analysis was not performed. In general, high-profile missions (agency and center-directed) were put through CATE because of their scale, complexity, and anticipated high cost. Competed missions managed by a principal investigator (PI), such as those in the Explorer or Discovery (but not New Frontiers) lines, were not. For Astro2010, eight space-based concepts (from $1 billion to $9 billion) and nine ground-based concepts were examined. For Planetary2011, 15 space-based concepts (from $1 billion to $7 billion) were assessed. In the course of Helio2013, 12 mission ideas, recommended by the panels, underwent a 5-week preliminary design study. Based on the study results, the panels, in consultation with the survey committee, selected six mission concepts for CATE analysis. Based on feedback during the CATE process, CATE results for three descoped mission variations were also provided.

Some commonalities and differences in the application of the CATE process across the decadal surveys are summarized in the Table 2.2.

CATE is also used to establish a program cost profile that is used to evaluate prioritized science with respect to future budget profiles (see Chapter 3). The premise is that without a technical and cost risk metric, relative science value between missions cannot be properly judged. For example, the expected science may be a good value at $500 million, but not at $1 billion. CATE was therefore designed to provide cost realism to the survey and community at large. Affordability analysis in some cases was used to identify a cost cap or as a constraint in composing a balanced program.

Related to affordability of extended programs of activities, the net impact for the future beyond the decade needs to be considered. In a number of cases, missions were so complex that they would not be realized within

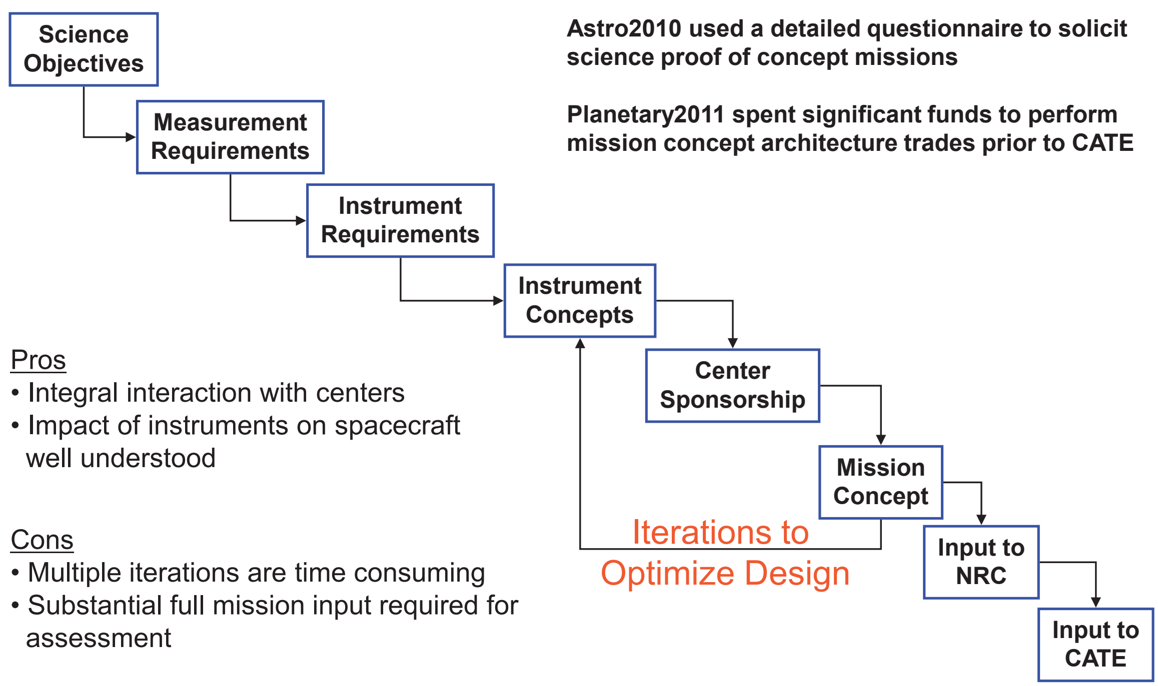

FIGURE 2.2 Mission formulation pathway used in the 2010 astronomy and astrophysics (Astro2010) and 2011 planetary science (Planetary2011) decadal surveys. The agencies sponsored study of specific mission implementation concepts, which fed into the cost and technical evaluation (CATE) process.

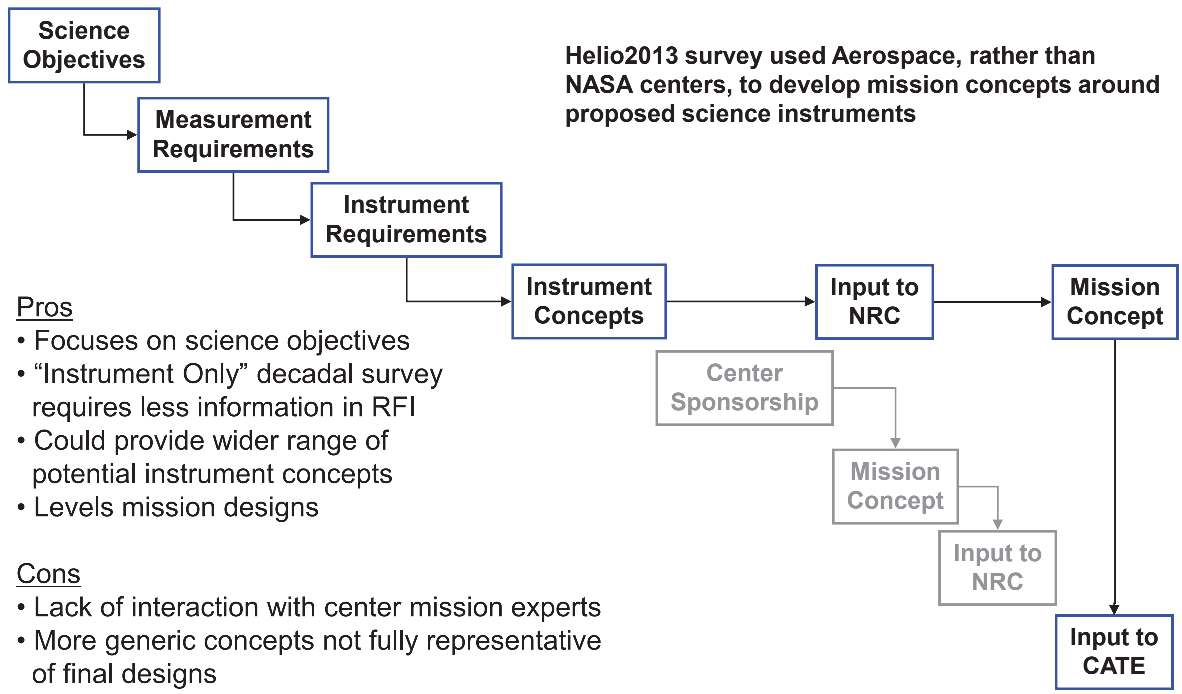

FIGURE 2.3 Mission formulation pathway used in the 2013 solar and space physics decadal survey (Helio2013), for which measurement requirements were understood but a representative mission concept did not yet exist.

a single decade. For example, in Planetary2011, the Mars Astrobiology Explorer-Cacher mission concept was evaluated on the promise of sample return and only successful as part of a campaign. The next two missions in the campaign would have to be flown in subsequent decades.

Lesson Learned: CATE involves assessment of a single point design to assess cost and technical risk. It is most useful as a reasonableness check on what is being recommended. Details used to support the CATE analysis are not necessarily indicative of how a mission will ultimately be implemented.

Best Practice: The survey committee can choose, and subsequently identify in its report, the role of the CATE in the survey. The CATE could provide, for example, a best-possible cost estimate for a point design or an independent, rough estimate for comparative purposes.

Best Practice: To prevent the CATE analysis from unnecessarily "driving" the decadal survey process, survey committees can consider implementation of a two-step CATE in which rough technical readiness and risk assessment feedback (accurate to a factor of two or three) would be provided for most, if not all, concepts early in the survey process. The more detailed and comprehensive CATE analysis (as used in recent surveys) would be reserved for those concepts that the committee identifies as worthy of further study.

The committee believes this practice will allow a fuller and fairer consideration of all proposed concepts and help rebalance resources, by providing timely and useful "cost-box" criteria for the initial rounds of prioritization and reserving resources for detailed studies of the concepts that have emerged from the first round.

International partnerships were handled in different ways by the CATE process across the surveys. Some survey committees struggled with how to handle lack of insight into the whole mission versus the U.S. contribution (e.g.,

TABLE 2.2 Similarities and Differences in Cost and Technical Evaluation (CATE) Application

	Earth Science and Applications from Space	Astronomy and Astrophysics	Planetary Science	Solar and Space (Heliophysics)
Process	Did not yet exist; however, a cost evaluation was performed.	Full CATE performed for space-based; qualitative assessment performed for ground-based.	Full CATE performed. Decision rules emerged during affordability assessment.	Full CATE performed; needed a precursor step to develop concepts.
Threshold		CATE not performed on projects expected to cost less than $350 million to $500 million. Announcement of Opportunity process to be used on MIDEX, Explorer, and SMEX missions.	CATE not performed on projects expected to cost less than $500 million or, more typically, $750 million. Science of New Frontiers concepts of ~$1 billion to $1.3 billion were prioritized (raised cap on New Frontiers because everything was coming in at $1 billion).	CATE not performed on projects expected to cost less than $400 million to $500 million.
Concepts		Ground-based systems used a modified process due to sparseness of empirical data. Issued second Request for Information for some concepts.	More effort spent upfront on concepts. Rapid mission architecture used to scope missions.	Concepts provided by scientists and the survey committee. The committee "owned" the concepts and, therefore, could descope and reassess technical feasibility and cost.
International		Large, international missions. Assumptions on portion funded by United States. Some missions (e.g., LISA), had dependency outcome of LISA Pathfinder.	Interwoven nature of Mars sample return mission—overall, deemed unaffordable. Missions of Opportunity include instruments on foreign platforms.	No international mission was considered for CATE. One option for a major (~$100 million) U.S. instrument contribution was not evaluated.

a single instrument). In cases where the U.S. portion did not reach a pre-established threshold, the concept may not have gone through CATE, even though the risk posture might have been high. Each survey committee has to decide whether and how to include international missions or mission components in the CATE.

Best Practice: Decadal survey committees are advised to determine a fair and consistent way to evaluate all international partnerships, which would be communicated to the panels early in the decadal process. The technical evaluation can be comprehensive and inclusive of the international portions and risks. However, assessment for affordability may need to be, in a pragmatic sense, for the U.S. portion only.

Lesson Learned: The combination of budgetary constraints (wedges) and large, complex mission concepts can lead to difficult choices, reinforcing the need for a thorough understanding of mission costs and risks as well as the establishment of clear decision rules.

Lesson Learned: The CATE process benefited from, and indeed depended on, survey committee and panel members serving as liaisons between Aerospace Corporation's CATE team and panels. Continuity of some individuals across multiple surveys also served a useful purpose as each survey had different experiences, and "lessons learned" were fed forward. Panels provided an important cross-check critique and key feedback to the CATE process.

Best Practice: When composing the survey committee, it is worth considering identification of one or more liaisons who will serve as go-betweens the panels, the committee, and the Aerospace Corporation's CATE team.

3

The Decadal Survey's Recommended Program

The mechanics of the decadal survey process for each of the disciplines, and the possibility of improvements to be implemented for future decadal surveys, were discussed in Chapter 2. This chapter addresses issues about how best to present the results of the decadal survey process to the stakeholder communities based on experience with past decadal surveys. Also discussed are the various ways a decadal survey takes the existing program into account, the content of the recommended decadal program, as well as the survey report itself.

THE EXISTING PROGRAM

Each decadal survey is conducted in the context of an existing program of missions (both space and suborbital), facilities, and observing systems, as well as agency programs that support research and analysis—including data archiving and analysis tools, technology innovation and development, education, laboratory measurements, public outreach, and workforce development. The extent to which the existing program is reviewed, including any unrealized recommendations from prior decadal surveys, has varied in prior decadal surveys.

The pre-survey program of large missions and facilities was taken as a starting assumption in the first five astronomy and astrophysics decadal surveys, but the 2010 astronomy and astrophysics decadal survey[1] (Astro2010) was directed by its statement of task to reconsider those programs of Astro2000[2] that *were not given a formal start by the sponsoring agency* (for NASA, this included, for example, ConX, TPF, SAFIR, and EXIST[3]) or *had not begun construction* (for the National Science Foundation [NSF], this included GSMT and LSST). The 2007 Earth science and applications from space decadal survey[4] (Earth2007) chose to assume completion of the existing program (including all projects in their implementation phase at the survey's start) as a baseline. Unfortunately, by the time the subsequent midterm assessment was completed in 2012,[5] that baseline had yet to be completed:

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[1] National Research Council (NRC), *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C. 2010.

[2] NRC, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001.

[3] Acronyms not defined in the text can be found in Appendix F.

[4] National Research Council (NRC), *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, The National Academies Press, Washington, D.C., 2007.

[5] NRC, *Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey*, The National Academies Press, Washington, D.C., 2012.

several components of the anticipated National Oceanic and Atmospheric Administration (NOAA) program had faltered, two missions were lost on launch, and recommended budgets did not materialize. As a result, the pace of implementation of Earth2007 was considerably slower than recommended. In its statement of task, the 2013 solar and space physics decadal survey[6] (Helio2013) was directed to start with a "clean slate," examining the existing and planned program and re-envisioning how a balanced program might be executed in the situation of a declining budget. At the time of the 2011 planetary science decadal survey[7] (Planetary2011), the recommended programs from Planetary2003[8] had only partially been realized, and NASA's Planetary Science Division was in the middle of a New Frontiers selection process. While the missions from the prior decadal survey that had not been started were included in panel discussions, they were not evaluated in the same way as new mission concepts, and not all were recommended as priority missions for the coming decade.

In summary, unimplemented priorities from prior decadal surveys have been variously assumed as part of the baseline, re-endorsed, reformulated, re-prioritized, and—recently—dropped. Astro2010, for example, is predicated on successful completion of the James Webb Space Telescope (JWST), which was recommended in Astro2000, but the several programs listed above were not carried over into the Astro2010 recommended program, including SIM for which a sizeable development investment had been made, even without a formal start.

For space missions, there is additional dimension when launch failures and on-orbit failures essentially "un-start" a mission that has begun. In such cases, the subsequent decadal survey has several options, including recommending re-launching duplicate hardware, incorporating some of the science goals of the failed mission into a new mission, or foregoing the objective altogether. Consultation with NASA, should this happen during the decadal survey process, is a necessary part of dealing with this unfortunate situation.

The criterion of started/not-started for facilities and missions seems sensible for future surveys in determining which missions are "on the table" for review. However, in this committee's discussions with NSF directors, the question was raised as to whether decadal surveys could also review existing facilities (such as ground-based telescopes) or space missions and make recommendations on their continued operation. Recommending the retirement of existing facilities or missions, especially those near the end of their term, could, of course, increase resources for the new survey's recommended program. However, this important responsibility has been held by the agencies themselves and implemented via NASA's senior review process and the NSF Division of Astronomical Science's (AST's) senior review and recent portfolio review.

A survey committee is constituted with an eye to broad across-the-discipline balance: it is unlikely to contain either the scientific or technical expertise to compare the merits of continuing or terminating a small group of extant missions or facilities. A group that is knowledgeable about the specific missions or facilities under consideration would serve better in that role. Thus, the committee concludes that the expertise required for evaluating the scientific productivity or cost-effectiveness of existing missions or facilities is more effectively held in, or solicited by, the agencies. However, it is not unusual for a decadal survey to comment on the issues relating to extended missions and facilities, especially in reference to their recommended program, in this way giving some indirect input into the agency processes of review.

Consideration of the status of previously recommended programs and the importance of existing missions and facilities is a key component in formulating and implementing the recommended program of the new decadal survey. However, the most relevant question for the new survey is the contribution of such capabilities that are desirable or even essential for accomplishing the new program. International collaboration may, of course, be another important factor for continued support. Existing missions and facilities, or those under construction, may have broad utility alongside the new science program, provide an integral part of the infrastructure that is part of a balanced program, and/or be an essential tool for achieving the goals of earlier surveys.

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[6] NRC, *Solar and Space Physics: A Science for a Technological Society*, The National Academies Press, Washington, D.C., 2013.
[7] NRC, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, The National Academies Press, Washington, D.C., 2011.
[8] NRC, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003.

Best Practice: Decadal surveys may review the recommended program from previous surveys and choose to endorse certain activities in their own recommendations. Such reviews are best if they focus on those missions and facilities that play a critical role in the proposed science of the survey report.

The freedom to review and endorse (or not) previously recommended program elements only applies to activities, such as missions, facilities, and observing systems, for which implementation has not yet begun. Decadal survey committees may choose to look at the cost-effective science return of existing missions and facilities and make evaluations based on their relevance and importance to the new proposed program, with the aim of increasing available resources for the next decade.

Best Practice: It is desirable that the statement of task explicitly address the extent to which existing programs or projects are to be reviewed and recommendations from prior decadal surveys are to be revisited.

THE DECADAL SURVEY'S RECOMMENDED PROGRAM

The decadal program typically includes recommendations regarding the continuation or change of existing program elements, as well as a new program of prioritized missions, facilities, observing systems, and/or activities to be started in the following 10 years. The program elements can include (1) space-based and suborbital missions and mission components (including instruments on international missions), (2) ground-based science facilities (including telescopes and large data centers), (3) research and analysis (R&A) activities, (4) technology development programs, and (5) supporting infrastructure and activities—including spacecraft communication systems, data management and archive facilities, and extraterrestrial sample curation, and/or analysis facilities, computation and/or simulation, and education and public outreach.

In this section, specific issues for the decadal survey committee to consider as it develops the content and scope of its recommended program are discussed.

The Primacy of Science

The principal and essential product of a decadal survey is the committee's consensus recommendation of science goals and objectives[9] for the coming decade. Achieving this requires a mapping of these goals into a decade-long program of missions and activities. As the basis for all other considerations, a clear presentation of the science goals and objectives forms the primary element of the decadal survey report from which all other elements must flow. The flow-down of mission science objectives into investigations allows clear traceability from science goals to mission definition and prioritization. Although the detailed structure of decadal survey reports may vary by discipline, each articulates a fundamental traceability of priority science goals and objectives for the next decade into an implementation strategy that involves the full spectrum of discipline activities.

Programmatic Advice

Programmatic Advice to NASA

Decadal survey reports provide advice to NASA on its programs and activities within the appropriate discipline for the coming decade. All such advice is rooted in the priority science goals and objectives that have been identified. The scope of the advice is delineated in the survey's statement of task, as described in Chapter 1. It generally covers all activities that are funded by the appropriate division and includes missions (both space and suborbital), R&A, technology development, ground-based observatories, ground-based support infrastructure and activities, and education, engagement, and workforce activities. The advice may also include recommendations about

[9] While discipline science *goals* tend to evolve relatively slowly compared to the decadal time frame, science *objectives* can evolve more rapidly as new discoveries are made, new technologies are developed and mature, and ongoing missions accomplish past objectives.

inter-disciplinary, inter-directorate (e.g., STMD or HEOMD), inter-agency (e.g., NSF, NOAA, the Department of Defense (DOE), the Department of the Interior-U.S. Geological Survey (USGS)), and/or international activities. Such advice and recommendations are clearly laid out in separate sections within the decadal survey report.

Programmatic Advice to NSF

The principal recommendations to NSF AST from the astronomy and astrophysics decadal surveys have been for facilities and infrastructure to accomplish those science objectives that require observations with ground-based facilities—for example, optical and radio telescopes and detection of cosmic rays and neutrinos coming from space. Unlike NASA or other agencies, NSF manages, but does not construct, the building of such facilities. Usually, decadal recommendations identify mature plans for large facilities that NSF can submit to NSF's Major Research Equipment and Facilities Construction (MREFC) program through competition and selection by the National Science Board. The VLA, VLBA, Gemini, ALMA, DKIST (formerly Advance Technology Solar Telescope), and most recently LSST, are all recommendations of astronomy and astrophysics decadal surveys that have been constructed through MREFC. A significant issue for NSF AST is that long-term operating funds for these major facilities must come out of the division budget line. Growth in operating costs has over-committed division resources; as a result, other decadal priorities have been put aside.

To address the concern that large facilities dominate the NSF portfolio, Astro2010 recommended the initiation of a mid-scale innovations program where smaller facilities and projects (such as mid-size facilities and major instrumentation for telescopes) could be chosen through peer-review competition. This program has been implemented, and first awards have been made, albeit at a significantly lower level of support than the decadal recommendation. Decadal recommendations often advise NSF on the funding levels of other R&A activities, the Astronomy and Astrophysics Research Grants Program, and Major Research Instrumentation (MRI) program.

Budget Profiles

The most challenging aspect of the decadal survey process is to assemble an optimal implementation strategy for the decadal science goals and objectives that accord with a reasonable estimate of the budget profile for the coming decade. This profile may be explicitly defined in the statement of task by the sponsoring agencies, which provide an initial budget for the appropriate NASA division (or for NSF AST) for the first year of the next decade with a rate of escalation for the following 10 years. The statement of task may also recommend several different models that might include more or less optimistic escalation rates (see Chapter 2, "Agency Feedback During the Decadal"). Within these budget profiles, the decadal survey fits the full spectrum of activities performed by the NASA Science Mission Directorate (SMD) division, or with NSF funding. Such an exercise is well illustrated using a budget profile, such as shown for planetary science in Figure 3.1 for the decade 2013-2022. The dark solid line shows the assumed budget wedge for planetary sciences that was used for the decadal survey process. The chart shows all programs for planetary sciences recommended by the decadal survey, including supporting R&A (SRA), Technology, Discovery, New Frontiers and high-profile missions. The chart does not explicitly show mission activities from the prior decade that extended beyond 2013.

Figure 3.1 also shows—very clearly—the challenge of including a high-profile mission, such as the proposed Jupiter Europa Orbiter mission (JEO), which can have a major impact on other elements of the decadal program. With its projected cost of $4.7 billion, it would have been impossible to fit JEO as designed into any acceptable suite of activities for the Planetary Science Division.

Budget profiles also illustrate another challenge associated with the decadal survey process. Although the survey is limited to recommendations for a specific decade, some activities that are planned to start within the decade may extend well into the next decade and may even have peak spending in that decade. As such, the true extent of the decadal survey program continues well beyond the planning period and may represent a significant lien on the next decadal survey process. In addition, budget profiles generally only include prime mission funding for any future missions and do not allow explicitly for extended mission phases, which are highly likely to be approved for productive space missions.

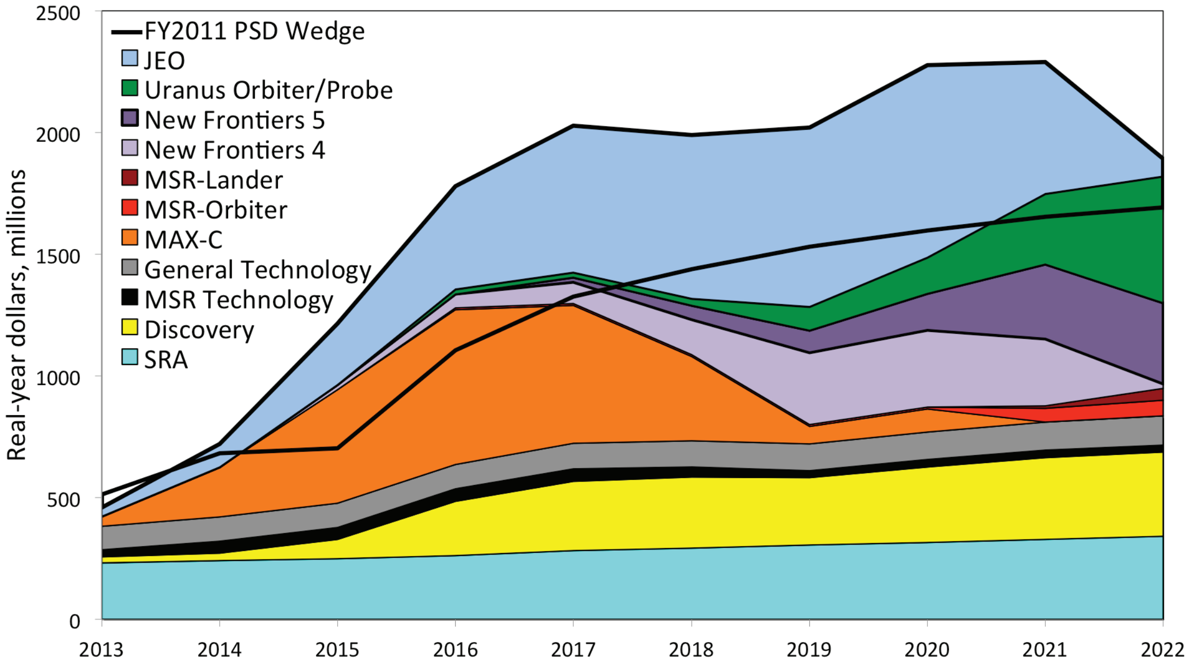

FIGURE 3.1 Notional funding profiles for the planetary science decadal survey with recommended programs, in real-year dollars, for fiscal years 2013-2022. The heavy black line shows the projected (at the time of the decadal survey) available funding for the NASA Planetary Science Division (PSD), accounting for all commitments at the time (including the Mars Trace Gas Orbiter). The available funding grows sharply in the first few years of the decade as some current programs come to an end. The cost assumed for the Jupiter Europa Orbiter (JEO) is $4.7 billion, illustrating clearly why a reduction in the scope and cost of this mission was necessary. NOTE: Acronyms are defined in Appendix F.

Lesson Learned: Although extended mission phases are not generally budgeted for future missions in the decadal survey process, they may present significant hidden costs that may influence decadal survey implementation cadence.

It is inevitable that some programs recommended for initiation in the coming decade will extend well into the future. Even when started in the decade addressed in the survey, construction and operation may continue well into the following decade. Similarly, large ground-based facilities and infrastructure may have run-outs well beyond a decade.

Best Practice: It is important for the decadal survey committee to estimate and clearly describe and illustrate in its report potential liens on the following decade from its recommended program.

Balance Within the Recommended Program

Decadal surveys also attempt to establish an optimal balance of programs and activities. First and foremost, a discipline strives to achieve balance among its different scientific areas so that even if one or more of the subdisciplines has gained priority through the survey process, the others are able to continue to do important science, maintain technical expertise, and, most importantly, attract good students. It is also desirable and necessary to have a component of exploratory science to complement the more common goal-oriented approaches that push particular parts of the discipline forward. Exploration comes about when new capabilities and sensitivities have been reached, and it is particularly effective in observatory-type activities where scientists are able to propose surveys and pointed observations beyond and apart from the scope of the original science objectives.

Balance must be considered between small, medium, and large missions; between competed and non-competed missions; between long time-continuity and science-focused missions (e.g., Earth sciences and heliophysics); between principal-investigator (PI)-led and (NASA) center-led missions; between missions and programs for research and those for technology, education, and workforce development; and between subdisciplines within each division (e.g., destination classes within the solar system for PSD). Lack of balance has negative consequences. For example, programs that strongly emphasize high-profile mission opportunities can make significant progress on one or two important topics but may lack the agility to respond to scientific developments, be unable to address questions that require diverse observations of complex systems, and lose scientific and technical expertise in disciplines that go too long without opportunities. Reducing support for theory, modeling, and data analysis may advance the start of the next project or continue existing programs, but will lead to inadequate exploitation of investments made in collecting observations and ultimately break the cycle that creates the scientific and technical innovations for the future. Given the importance of such balance to the health of the scientific community, it is important that the survey report describe how survey recommendations about balance were developed. Decision rules can be crafted to help ensure that balance is maintained in the program, as discussed in Chapter 4.

Best Practice: It is highly desirable that the decadal survey report includes clear discussions on how the decadal survey committee determined the optimal balance of programs and activities for the coming decade.

Interagency Issues

The primary role of the decadal surveys is to identify priority science goals and objectives and to provide an optimal implementation strategy that can be executed by one or more federal agencies. Most survey recommendations in planetary science and Earth science, and many in heliophysics and astronomy and astrophysics, are directed at the appropriate SMD division of NASA. Recommendations concerning ground-based observatories for astronomy and astrophysics and heliophysics are directed at NSF as part of the strategic planning process for these disciplines. In recent years, DOE has taken a greater interest in astrophysics research on the ground and in space, so it too is involved in the survey process. Similarly, an Earth sciences decadal survey is pertinent to and contains recommendations for NOAA and USGS. Cooperation among these agencies is obviously crucial to the success of a decadal program that requires the participation of multiple agencies. The important topic of interagency issues is revisited in Chapter 4.

Best Practice: It is incumbent on a decadal survey report to clearly delineate the respective roles of NASA, NSF, NOAA, USGS, and/or other federal agencies in implementing the science program when the capabilities and interests of multiple agencies are involved.

High-Profile NASA Missions

Within each division of NASA SMD, there are facilities and missions with the potential to have large-scale impacts on the program due to their strategic importance, scope, and/or size. These so-called high-profile missions[10] address critical science goals or questions for the decade. They are uniquely characterized by an implementation

[10] A variety of names have been used to refer to these missions. Perhaps the most common term used is *flagship;* however, the term *high-profile mission* has become synonymous with mission cost rather than strategic importance or impact to the program. Using NASA's Science Mission Directorate classification scheme, the missions under consideration here would be Category 1 (and occasionally Category 2) Strategic Missions per NASA Science Plan 2014, Appendix C, p. 115. High-profile missions, as the term is used here, refer to missions of significant importance to a program that are able to have substantial negative impact on program health if not implemented successfully or within fiscal constraints.

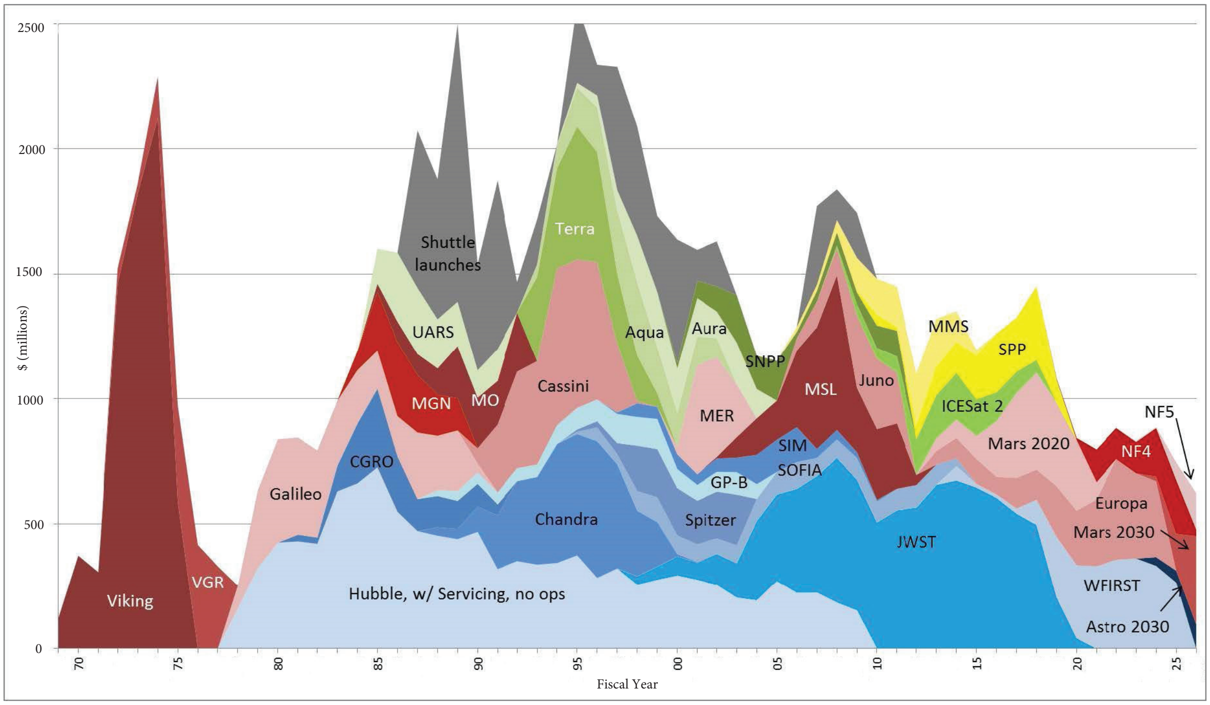

FIGURE 3.2 Annual expenditures in millions of dollars (normalized to fiscal year [FY] 2015) for the development and operation of high-profile science missions for all of the divisions within NASA's Science Missions Directorate from 1969 to 2026. Also shown are the estimated costs associated with science-focused space shuttle launches, such as Magellan, Galileo, Compton Gamma Ray Observatory (CGRO), Upper Atmosphere Research Satellite (UARS), Chandra X Ray Observatory, and Hubble Space Telescope and its five servicing missions. Decadal surveys pay attention to both the peak expenditures during development and the integrated cost (including operations) of recommended missions in order to ensure the maintenance of programmatic balance. The figures quoted for FY 2015 and beyond, and all missions after Solar Probe Plus, are notional. Following official NASA practice, the cost of each space shuttle launch was assumed to be $400 million and allocated over 3 fiscal years. NOTE: Acronyms are defined in Appendix F. SOURCE: NASA Science Mission Directorate.

strategy that is performance-driven rather than cost-constrained.[11] Although there are parallels to some large facilities in the NSF AST, this discussion focuses on NASA missions because the level of cost growth and its negative consequences has been a bigger problem for NASA.

High-profile missions tend to be associated with high life-cycle costs, as is illustrated in Figure 3.2 for NASA's large science missions dating back to 1969 and projected out to 2026. Because of their importance to the community's science ambitions, high-profile missions have the potential for a significant (negative) impact on performance across all activities within a division, and possibly across NASA SMD, for the coming decade if there is a mission failure or significant unanticipated cost growth. Because a substantial part of the science accomplished in a decade comes from smaller missions, it is important for surveys to strike a balance between larger, non-competed, high-profile missions and the competed line of smaller missions.[12] Yet, high-profile missions continue to be critical

[11] Performance-driven missions are driven by specific measurement or other requirements rather than cost constraints. This is contrasted with (typically) PI-led cost-capped missions where de-scopes are required if a performance requirement cannot be met within pre-established cost constraints.

[12] The 2007 Earth Science and Applications from Space survey committee recommended a "tilt away from facility-class implementations of large multi-instrumented platforms (such as EOS or NPOESS class) toward smaller missions to increase programmatic robustness" (NRC, *Earth Science and Applications from Space*, 2007, p. 76).

parts of the program because certain missions cannot simply be broken down in an efficient or effective manner into smaller components and still accomplish the science goal.

When a decadal survey committee considers recommending a high-profile mission for any agency, the associated risks need to be considered as well. In recommending a high-profile, performance-driven mission, it is highly desirable that the survey committee recognizes that costs can rise dramatically if requirements are not well understood and/or readily met with existing technology. Because NASA's high-profile missions often start with cost estimates of more than $1 billion, cost growth can pose a significant threat to programmatic balance, given individual division budgets of ≤$1.8 billion per year. It can be challenging, if not impossible, for a single NASA division to maintain a balanced portfolio of activities while supporting the development of a multibillion dollar mission in the face of significant cost growth. Thus, it is imperative that survey committees make clear which parts of a performance-driven mission are truly required, and where any compromises or de-scopes might be acceptable. Furthermore, these compromises must be sufficient to execute the high-profile mission within the discipline's own budget. Both can be accomplished through clearly stated decision rules that set forth the criteria by which the high-profile mission retains or loses its priority under various circumstances (e.g., Mission X is the highest priority as long as it provides Y performance at a cost of less than Z; if Mission A performs at less than the predefined level, then Mission B becomes a higher priority).

When the projected costs of a mission grow large enough to threaten the balance of activities within its division, there can be consequences for the other NASA SMD divisions and possibly other NASA directorates. Because of its cost, JWST is the "poster child" of such high-profile missions, having already demonstrated this potential (see Box 3.1).

> ***Lesson Learned:*** High-profile missions are special cases within each of the disciplinary areas, presenting great opportunities for major advances in understanding, but also carrying significant risk for maintaining a balanced portfolio of activities—should unanticipated cost growth occur.

Causes of Cost Growth in High-Profile Missions

Because cost growth in high-profile missions can have major impacts on other programs within a NASA SMD division or NSF AST, it is important to identify possible sources of cost growth early in mission/facility definition and development and to have a clear strategy for dealing with them should they occur. Cost growth can result from "science creep," where science requirements for a mission or facility evolve and grow during development, and when unanticipated expenses result from technical and engineering requirements. Performance-driven missions are particularly susceptible to science creep (see Box 3.2)—members of the science team and external science community see opportunities to leverage a mission to address broader science goals, usually without fully appreciating the implications for cost or programmatic balance.[13] This can be insidious; although the "creep" of requirements and its associated cost growth appear incremental, the effect is often cumulative, resulting in substantial cost growth over the long implementation timescale of a high-profile mission.

While it may be difficult to adequately account for future cost growth due to unanticipated engineering or technical challenges, early identification of potential issues and assignment of appropriate cost reserves can limit the impact on total cost. For this reason, although mission creep is essentially a program management issue, a decadal survey needs to think hard and—to the extent possible—anticipate the potential for cost growth of a high-profile mission. Later, as implementation begins, effective use of reviews at key development milestones, tied to clear decadal survey decision rules for continuation of a program or enactment of de-scope options, can provide some degree of protection from damaging cost growth (see Box 3.3).

This issue is not exclusive to NASA. For example, NSF's participation in the Atacama Large Millimeter/submillimeter Array (ALMA), an international endeavor, was a high priority for Astro2000. This facility is the

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[13] As highlighted in the Earth science midterm assessment, mission implementation teams tended to have a narrower focus on discipline priorities, in contrast to the decadal survey committee's broader emphasis on Earth system science, leading to mission creep and cost growth (NRC, *Earth Science and Applications from Space*, 2012).

BOX 3.1
James Webb Space Telescope

The recent, most serious case of a high-profile mission that exceeded its division resources is the James Webb Space Telescope (JWST). Early estimates of technical difficulty were substantially understated, and the project was critically underfunded throughout its development phase to 2011. This resulted in significant increases in cost and major launch delays, which led to further cost escalation.[1] Ultimately JWST was determined to be an agency-wide priority mission, and the funding was moved out of the Astrophysics Division into its own funding line within the Science Mission Directorate.

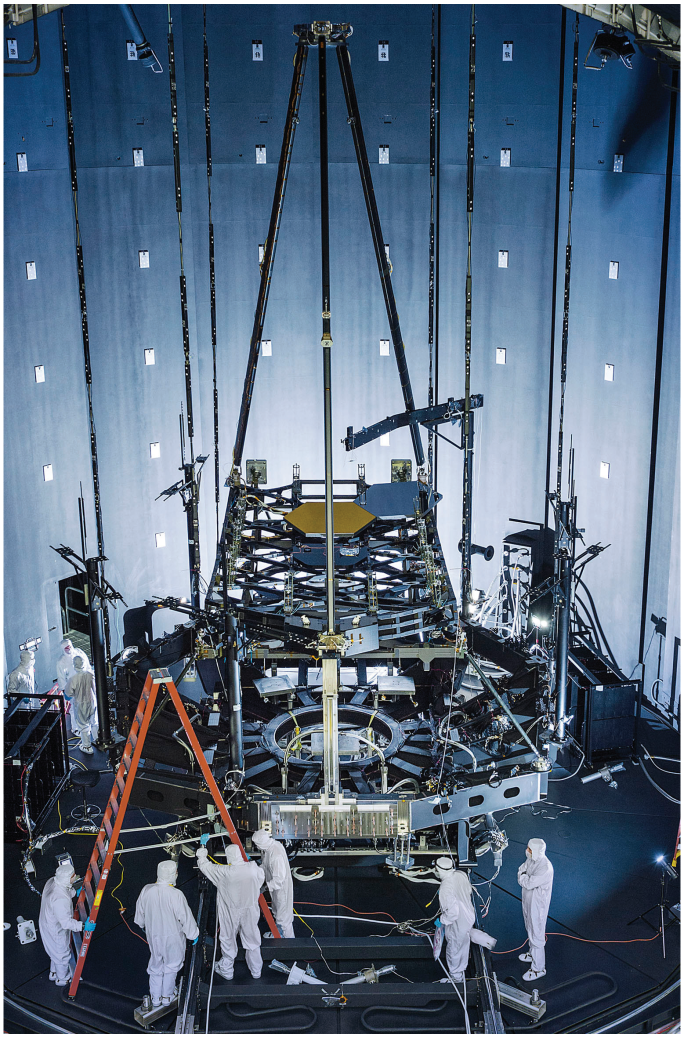

FIGURE 3.1.1 Major structural components of the James Webb Space Telescope being prepared for a cryogenic test. SOURCE: Courtesy of NASA/Chris Gunn.

[1]See JWST Independent Comprehensive Review Panel, *Final Report*, October 29, 2010, http://www.nasa.gov/pdf/499224main_JWST-ICRP_Report-FINAL.pdf.

BOX 3.2
Requirements Creep

Mission creep can occur in missions of any size. The 2007 Earth science and applications from space decadal survey warned that "NASA and the scientific community must avoid 'requirements creep' and the consequent damaging cost growth." [1] Yet, as noted in that survey's midterm assessment, "absent a countervailing mechanism, there is a natural tendency for individual missions to become more responsive to single communities or disciplines rather than to the overall Earth system science community. For example, changes to the survey-recommended ICESat-2 mission were, in part, the result of pressures from a disciplinary community whose desires for a more advanced and capable mission than envisioned by the survey were not restrained by consideration of the budgetary impact on development of future missions serving different communities."[2] Changes in mission science emphasis led to technology development challenges, significant mission cost growth, and launch delay.[3]

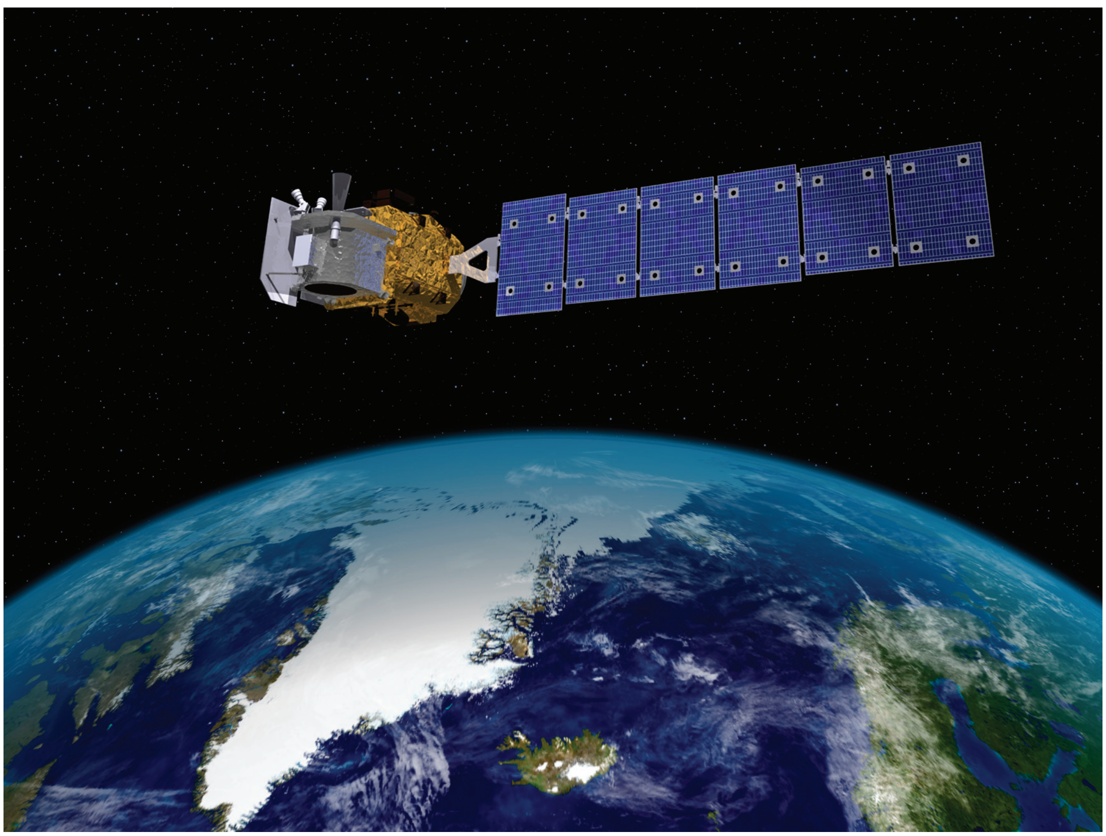

FIGURE 3.2.1 The Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) is the second generation of the laser altimeter ICESat mission and is scheduled for launch in July 2016. SOURCE: Courtesy of Orbital ATK.

[1] National Research Council (NRC), *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, The National Academies Press, Washington, D.C., 2007, p. 43.

[2] NRC, *Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey*, The National Academies Press, Washington, D.C., 2012, p. 29.

[3] See Dan Leone, "NASA's IceSat-2 Busts Budget, Report Headed to Congress," *Space News*, December 3, 2013, http://spacenews.com/38475nasas-icesat-2-busts-budget-report-headed-to-congress/.

BOX 3.3
Decision Rules

Five large high-profile missions were identified and prioritized by 2011 planetary science decadal survey.[1] The highest ranked of these missions were a Mars rover with sample-caching capability—as the first step toward Mars sample return—and a Europa orbiter mission (Jupiter-Europa Orbiter). The decision rules developed by the survey committee required both missions to trim their budgets significantly to retain their priority ranking. The decision rules further required that high-profile missions be de-scoped or delayed rather than negatively impact the other aspects of the planetary science portfolio. Following these rules—despite much lower-than-anticipated funding levels for the Planetary Science Division, the Mars community was able to develop a credible Mars 2020 mission that addressed most of the key goals of the decadal survey, while minimizing impact on the rest of the program. A re-scoped Europa mission was granted a new start in the administration's budget request for fiscal year 2016.

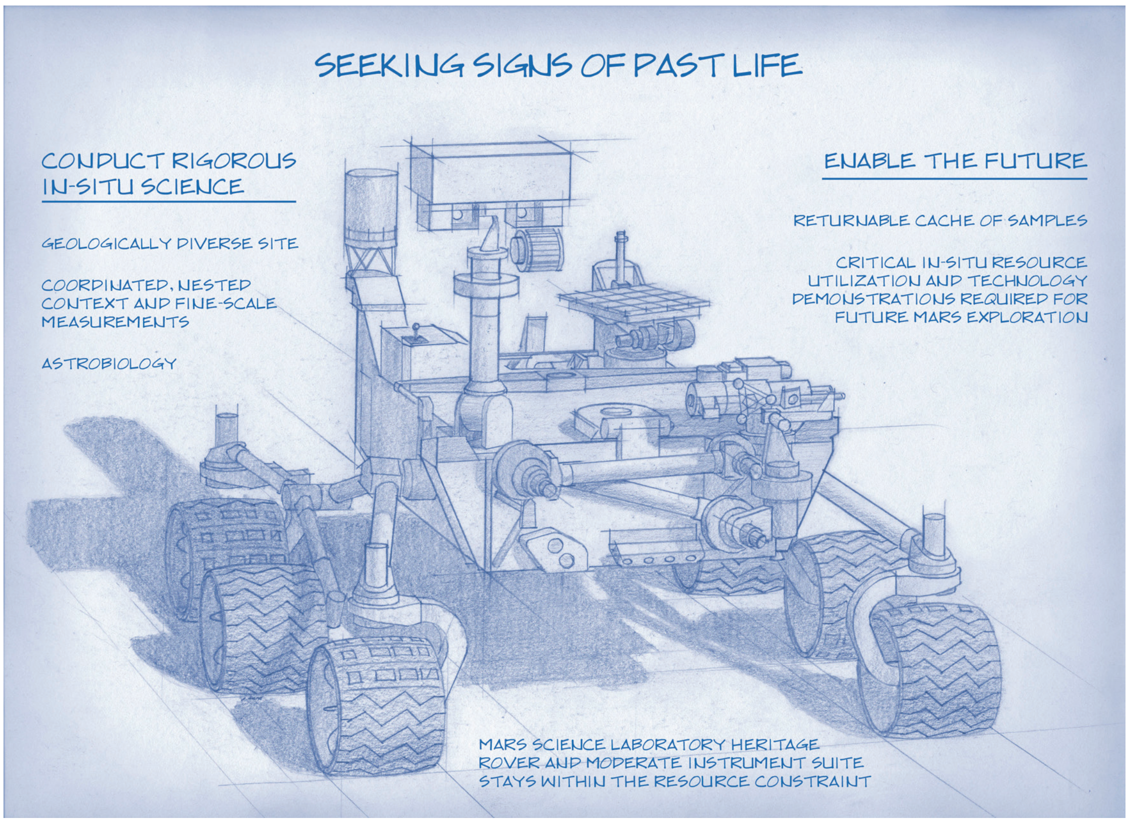

FIGURE 3.3.1 An artist's sketch of the Mars 2020 rover, NASA's implementation of the 2011 planetary science decadal survey's sample-caching rover. SOURCE: Courtesy of NASA/JPL-Caltech.

[1] National Research Council, *Vision and Voyages for Planetary Science in the Decade 2013-2022,* The National Academies Press, Washington, D.C., 2011.

premier facility of submillimeter radio astronomy in the world. However, cost growth in ALMA construction and operations has been substantial, resulting in an erosion in NSF's support for ground-based optical telescopes, particularly those "open-access" facilities run by the National Optical Astronomy Observatories, and also for the program of research grants run by NSF AST.

In summary, high-profile missions remain a vital part of most decadal programs, but their execution within a containable budget remains a challenge, one that decadal surveys must address throughtfully and thoroughly. Smaller-scale competed missions, such as the Explorer and Discovery programs, are also key to accomplishing a decadal survey's science goals and objectives, so it is imperative that survey committees consider both the benefits and risks of recommending high-profile missions in their deliberative process. High-profile missions should be reserved for the highest-priority science goals, those that cannot be accomplished in any other way. When a high-profile mission is recommended, it should be accompanied by clearly stated expectations regarding its implementation, denoting which aspects of the mission are essential to retaining the mission's consensus priority and which can be further considered during design development to enable cost control.

Lesson Learned: Mission creep within high-profile missions and large facilities and a general unwillingness to de-scope or cancel large missions or facilities during development can result in large, negative impacts on other programs at the division and directorate level.

Best Practice: When recommending high-profile missions, survey committees are advised to explicitly state which aspects of the project are essential to retaining the mission's consensus priority and which can be further considered during design development to enable cost control.

Best Practice: Clear decision rules for high-profile missions and large facilities that include both de-scope and cancellation options can provide some level of protection against unconstrained cost growth and possible collateral damage to other programs.

Consequences of the Long Timescales of High-Profile Missions

High-profile space missions are often multi-decadal in nature. The concepts for such missions often mature over many years before funding decisions are made and implementation can begin. During this early conceptual stage, significant evolution can occur in its science goals and objectives and its instrument and mission capabilities. While this evolution almost always results in cost escalation, it can also result in a mission or observing system that is significantly different from that originally conceived in a decadal survey. As an example, the high-profile Mars Science Laboratory mission (Curiosity) within NASA PSD evolved significantly in both architecture and cost from the original concept (as delineated in the 2003 planetary science decadal survey[14]) before the mission was launched in 2011. Despite such evolution, there is a tendency to keep the original mission as the highest priority for the program due to the large amount of resources already committed.

Best Practice: While high-profile missions are likely to retain their high ranking from one decadal survey to the next, evolution in mission concepts and changing science priorities may occur over time. As such, it is desirable that the survey committee and panels carefully evaluate all candidate mission concepts on their merits, rather than be unduly influenced by advocacy and inertia.

Once a NASA high-profile mission is launched, the mission lifetime often greatly exceeds the prime mission timescale, resulting in one or many proposals for extended mission phases that are evaluated in a congressionally mandated senior review process. Given the high development cost of these missions, there is a sensible desire to exploit them fully by gleaning as much science as possible from the mission before termination. While it is certainly true that science return on an extended mission is less costly than developing a new mission, the cost

[14] NRC, *New Frontiers in the Solar System,* 2003.

of maintaining existing capability can preclude the initiation of new missions that could make quantum advances in the field. While the senior reviews that evaluate extended mission proposals are more an issue of stewardship, the surveys can and should inform the senior review process by clearly articulating science and mission goals and relative priorities. As described above (see the section "The Existing Program"), a survey committee may choose to endorse existing activities that play an important role in addressing the survey's science goals.

International and Interagency Collaboration on High-Profile Missions

High-profile NASA missions often fall in the upper range of cost envelopes that are possible within a division budget without adversely affecting the balance of programs within the division. NSF has faced similar challenges. Consequently, it is highly desirable to offset some costs through participation of other domestic agencies, foreign space agencies, or foreign governmental science agencies. While such participation is dealt with elsewhere in this report (see the Chapter 4 sections "Interagency Issues" and "International Activities") and treated in detail in a 2011 National Research Council report,[15] high-profile missions with international or interagency components are a special case.

Participation of organizations outside NASA can result in a far more capable mission than would be possible with division funding alone (see Box 3.4). The Cassini-Huygens mission to Saturn, a joint mission between NASA and the European Space Agency (ESA), is an excellent example. In particular, the Huygens probe developed by ESA provided significant complementary science capability in understanding the unique environment on Titan. Space programs like HST, Spitzer, Hayabusa, Planck, Herschel, SOHO and LISA; airborne platforms such as SOFIA; and ground-based NSF programs such as the Gemini Observatories and ALMA are other excellent examples of the benefits of international collaboration.

Despite the clear advantages of such collaborative missions, the challenges to successful implementation can be large, with differing planning cycles, funding systems, and priorities.[16,17,18] Such issues present major challenges for decadal surveys, particularly for high-profile missions, where joint participation is often required to meet decadal budget requirements. As such, sponsoring agencies may wish to provide specific instructions to survey committees on how they deal with such missions.

> ***Best Practice:*** Strong preferences by the agencies on how to deal with high-profile missions and interagency and/or international participation in missions and facilities need to be spelled out in the statement of task.

Supporting Research Infrastructure and Activities

Decadal surveys provide NASA and, where appropriate, NSF and other federal agencies, with recommendations on the highest-priority science for the coming decade. To accomplish these science objectives, the survey recommends a suite of missions that could be flown and facilities that might be developed in the coming decade, as well as the infrastructure and activities needed to support the science for that field, prepare technologies and workforce for future missions, and educate and engage the public in space sciences (see Box 3.5). These recommendations reflect the need to maintain a level of scientific research and analysis that maximizes the return on past and current missions and prepares the way for futures ones. They also identify where funding is needed to maintain technology development and facilities that are essential for future missions.

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[15] NRC, *Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions*, The National Academies Press, Washington, D.C., 2011.

[16] For a detailed discussion of this topic see, NRC, *Assessment of Impediments*, 2011.

[17] See, also, NRC, *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement Capabilities Lost in Program Restructuring,* The National Academies Press, Washington, D.C., 2008.

[18] For specific examples relating to the NASA/NOAA/DoD NPOESS program see, for example, NRC, *Earth Science and Applications from Space*, 2012.

BOX 3.4
Collaborative Missions

Joint international missions are common in all the NASA Science Mission Directorate (SMD) disciplines. In heliophysics, Solar Heliospheric Observatory (SOHO, 1995 launch) and Cluster (relaunched in 2000 after a 1996 launch failure) are two shining examples with extensive European Space Agency (ESA) partnership. Yohkoh (1991 launch, a.k.a. Solar-A) and Hinode (2006, a.k.a. Solar-B) are examples NASA-Japan Aerospace Exploration Agency (JAXA) partnership on smaller-scale missions. International cooperation between NASA and ESA has been critical to the success of large Earth science system missions Aqua, Aura, and Terra (the Earth Observing System (EOS) platforms, a collaboration between NASA, ESA, Canada, Japan, and Brazil) and smaller-scale missions such as Global Precipitation Measurement (GPM, a collaboration between NASA and JAXA). NASA-ESA collaborations on astrophysics missions include the Hubble Space Telescope, Spitzer Space Telescope, Chandra X-ray Observatory, Herschel, Planck, and the James Webb Space Telescope (JWST, also with Canadian Space Agency [CSA]). NASA has collaborated on numerous satellites built by JAXA missions, most recently Astro-H (JAXA) and Astro-E2 (Susaku).

FIGURE 3.4.1 An artist's conception of the core observatory spacecraft of the Global Precipitation Measurement mission, a joint activity with NASA and the Japan Aerospace Exploration Agency. SOURCE: Courtesy of NASA.

BOX 3.5
Supporting Research Infrastructure and Activities

Supporting research infrastructure and activities include the following:

- Research and analysis (including theory and modeling),
- Technology development,
- Rockets and launch infrastructure,
- Deep Space Network and Near-Earth Network,
- Shared facilities (ground networks, telescopes, calibration/validation facilities or assets),
- Laboratory-based experimentation and sample curation,
- Data management and archiving facilities, such as the Planetary Data System,
- Education and engagement/public outreach, and
- Workforce development activities.

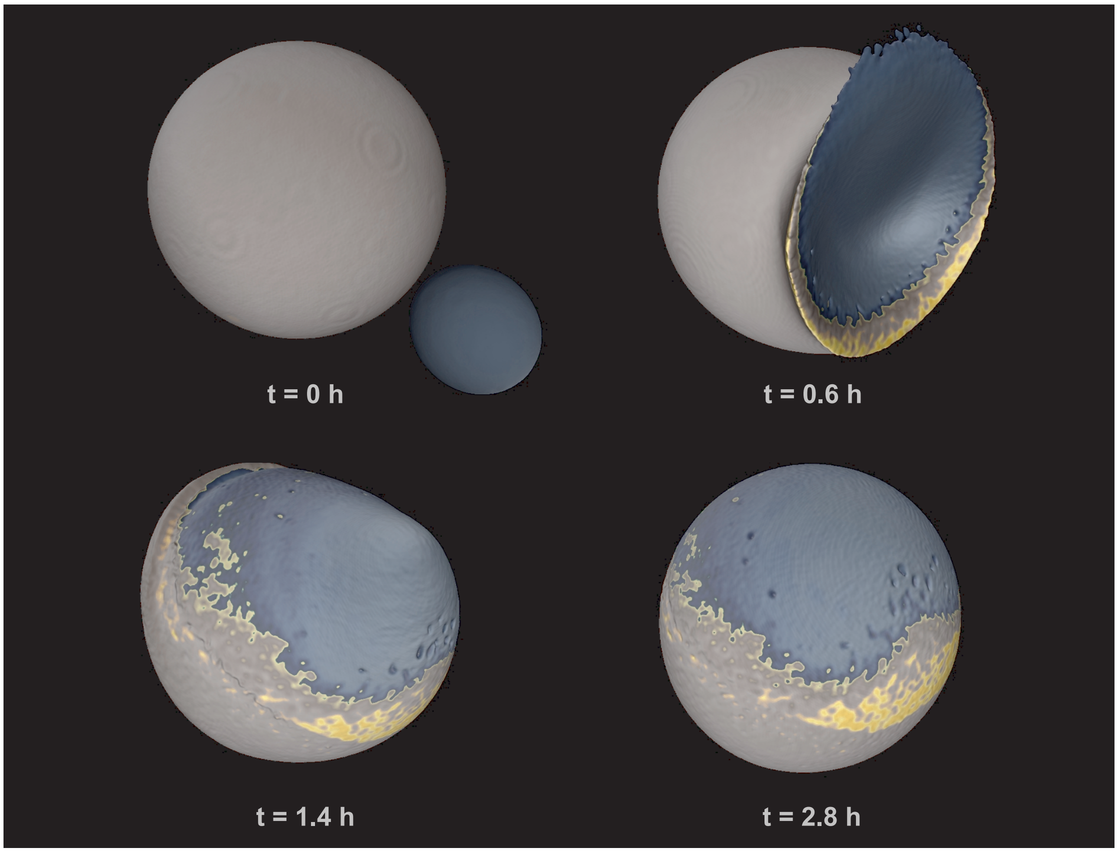

FIGURE 3.5.1 Theory and modeling are an important component of the scientific enterprise. Illustrated here are four time steps from a complex, three-dimensional computer simulation of an impact between the Moon and a hypothetical satellite, roughly 4-billion-years ago. SOURCE: Courtesy of Erik Asphaug (Arizona State University) and Martin Jutzi (University of Bern).

Best Practice: In developing the recommended decadal program, survey committees and panels are advised to include explicit consideration of various forms of programmatic balance. This might include, for example, the balance across the subdisciplines, between mission and non-mission activities, between novel and continued observations, across mission and facility cost, and between program elements (e.g., R&A, technology, infrastructure, missions) and activities (e.g., education, engagement, and workforce development).

Research and Analysis

R&A activities are the principal means by which the scientific community addresses the science goals of current decadal surveys and lays the scientific and technical foundations for future surveys. They cover a wide range of activities. For NASA, they are mostly associated with analysis and application of space science data. For NSF, R&A is funded through its divisions to support data analysis in a variety of ground-based facilities, such as radio and optical telescopes. Theoretical and laboratory research is also supported in the portfolio of both agencies.

Data analysis supported by NASA's R&A programs may come from space missions, suborbital missions, NASA-supported ground-based observatories, or laboratory experiments and/or analysis. R&A at NASA is traditionally funded through subdisciplinary grant programs within each SMD division, as delineated in the annual solicitations for research opportunities in space and Earth-sciences (ROSES).[19] Grants funded through ROSES, and through the grants programs of NSF and other agencies, are a critical component in realizing decadal science goals and objectives, providing essential support the broader scientific community needs to use the wealth of information collected through science activities at the agencies. Full exploitation of hard-won data and measurements requires adequate funding for analysis by individuals and teams of scientists. Decadal surveys typically acknowledge the importance of R&A activities and may also provide recommendations on associated programs to ensure appropriate funding balance is achieved or maintained between collecting data and the analysis and application of that data.

Technology Development

The scope and scale of technology development can vary between highly specific or broadly supported and, thus, involve considerations beyond a particular subdiscipline or even discipline. In the context of a decadal survey, it is expected that individual subdiscipline panels will recommend both short-term needs for technology development as well as more forward-looking, long-lead development priorities.[20] The decadal survey committee prioritizes these and incorporates them into its recommendations for across-the-discipline technology development for the decade. The full program of activities for each discipline for the coming decade is laid out in the decadal survey report, including recommendations on a balance of missions, research, technology, and supporting infrastructure and activities that are needed to sustain the program and engage stakeholders and the public.

Best Practice: It is desirable that discussion of technology development in the decadal report be included in both the survey recommendations section and in the panel reports, so that technology requirements for the coming decade (and beyond) can be adequately captured, while identifying subdiscipline-specific requirements.

Rockets and Launch Infrastructure

Launch costs continue to be a significant and uncertain cost driver for NASA SMD missions. In noting the influence of escalating launch costs on the scope of missions that can be performed within a specific cost category, decadal surveys are able to review the current status of launch vehicle options and provide recommendations as

[19] For more information about ROSES see, for example, NSPIRES, NASA Research Announcement "Research Opportunities in Space and Earth Sciences (ROSES)–2015," Solicitation NNH15ZDA001N, released February 13, 2015, http://nspires.nasaprs.com/external/solicitations/summary.do?method=init&solId={9F1341A9-6D0F-F075-C993-276263B186ED}&path=future.

[20] Examples of long-lead-time technology development include nuclear powered energy generation for probes to the outer solar system (planetary), large mirrors and energy-resolving detectors (astrophysics), active cooling for operation on the surface of Venus (planetary—inner solar system), and active cooling for cryogenic sample containment (planetary—primitive bodies).

to whether or not launch expenses should be included in proposals for cost-capped missions and what additional options may be available (such as dual manifesting or hosted payloads on commercial launches).[21] In addition, where radioisotope power or heating systems are included in a spacecraft, decadal surveys are able to make recommendations about how the costs associated with compliance with the National Environmental Policy Act may be apportioned by NASA.

Support Infrastructure

NASA ground-based support infrastructure and activities include those involved with spacecraft communication and data downlink, data management and archiving, sample receiving and curation, cross-cutting program support (e.g., planetary protection considerations), as well as analysis of extraterrestrial samples. Such infrastructure and facilities need to be discussed in the decadal surveys and their importance noted, in as much as they are needed in support of the implementation of the decadal survey science goals. Without such support from the decadal surveys, needed upgrades and improvements may fall victim to declining budgets and a tendency to support mission activities over necessary supporting infrastructure and activities for the coming decade and beyond. NSF also provides key programs in technology development, such as detectors, and the building and maintenance of advanced scientific instrumentation for ground-based telescopes and other facilities.

Education, Engagement, and Workforce Development

The decadal surveys also have a role in ensuring that the science associated with implementation of decadal survey goals is translated into the broader community, including into the educational environment. A full discussion of this topic and its ramifications is beyond the scope of the current report.[22] Nevertheless, the committee is compelled to note that NASA and NSF are uniquely placed to engage people of all ages in science and encourage young people into careers in science, technology, engineering, and mathematics, which are critical to the future health and vitality of this nation.

There are no more important resources than human capital. Capturing the minds of young people—potential scientists and engineers, making sure educational opportunities are widely available to them, and having them spend their careers in pursuit of the science goals of the survey, is the ultimate goal. Through the excitement of the recommended science program, and success in communicating it to the public, decadal surveys open doors to the future.

COMMUNICATION OF THE RECOMMENDED PROGRAM

Most of the time and energy of the survey committee and panels is spent developing priority science goals and objectives and then tracing these into a recommended program of activities. Once defined, it is imperative that appropriate attention be paid to communicating the program through the decadal survey report. Most stakeholders will be unaware of what went into shaping the decisions that were made—and not made—and so it is incumbent upon the survey committee to communicate sufficient context and depth that its recommendations can be correctly understood.

The Decadal Survey Report

The decadal survey report is the principal medium in the communication of decadal survey findings and recommendations. The printed report can be a single volume (e.g., Planetary2011, Earth2007, and Helio2013) or two volumes (Astro2010). There may also be web-based supporting documentation, including community white

[21] See, for example, NRC, *Vision and Voyages*, 2011, pp. 266 and 276-278.

[22] For a more complete discussion of issues associated with the communication of space science goals and achievements with the public and the educational community respectively, see NRC, *Sharing the Adventure with the Public: The Value and Excitement of "Grand Questions" of Space Science and Exploration—Summary of a Workshop*, The National Academies Press, Washington, D.C., 2011; and *Sharing the Adventure with the Student: Exploring the Intersections of NASA Space Science and Education—A Workshop Summary*, The National Academies Press, Washington, D.C., 2015.

papers. The survey committee, with supporting chapters or volumes representing the work of the panels, prepares the main component of the report. Additional communication after the termination of the decadal survey process occurs through presentations by members of the survey committee to the sponsoring agencies, the Office of Science and Technology Policy, the Office of Management and Budget, congressional offices and committees, and other appropriate federal agencies. In addition, congressional hearings and town halls at scientific conferences and society meetings are used to disseminate decadal survey recommendations and clarifications to the broader scientific community and interested public. Popularized descriptions of the decadal survey report are important vehicles for conveying the highlights of the survey to the general public.

> ***Lesson Learned:*** While the survey report is the primary result of the decadal process, engagement of stakeholders and the broader community in the survey recommendations is also critical to the success of decadal surveys. Communication by the decadal survey committee leadership and members with science community groups and at science and society meetings promotes broad community buy-in.

> ***Best Practice:*** Community acceptance and buy-in on decadal survey recommendations requires careful documentation and communication by the survey committee of their decision-making process for developing science goals and objectives and tracing these into a recommended program of activities for the decade.

> ***Best Practice:*** When drafting the decadal survey report, it is best that authoring committees remain mindful of the wide audience for the report, including the international discipline community, federal agencies, Congress, the federal executive branch, and the public, to ensure clear and effective communication of the community's consensus science priorities as expressed in the decadal survey report. Professional societies, such as the American Astronomical Society and the American Geophysical Union, can be very effective in disseminating the survey program to a wide audience.

Clarity of Intent

Based on lessons learned from recent decadal surveys, the following areas merit particular attention during report preparation: cost appraisal, strength of priorities, implementation detail, scope of review, and use of lists.

Cost Appraisal

Although much attention has already been paid to assessing the fidelity of cost appraisal (see Chapter 2 and Appendix B on the CATE process), effectively communicating how cost estimates will be used is equally important. As discussed in the Earth science midterm assessment,[23] the committee's intention to use provided costs as a sense of relative scale was unclear to the Earth Science Division director at SMD; as a result, cost estimates were simply discarded as overly optimistic, rather than used to push back against significant early cost growth, as the committee intended.

> ***Best Practice:*** When drafting a decadal survey, it is important to clarify the intended use of the cost appraisal for each mission or facility. Is it for a configuration that is intended to serve as (1) a "proof of a concept" that merely establishes the scale of the project; (2) a cost estimated for a mature, well-studied concept; (3) a cost cap; or (4) something else entirely.

Strength of Priorities

It is desirable that decadal survey committees consider how best to capture the degree to which the community's priorities remain constant for an array of foreseeable eventualities. If the top-priority mission overruns significantly,

[23] NRC, *Earth Science and Applications from Space*, 2012.

does it remain the top priority, or is there a limit beyond which consensus fails due to competing priorities and/or a need to maintain a balanced program? A survey committee can provide guidance in such circumstances via decision rules (see Box 3.3). A more complete discussion of decision rules can be found in Chapter 4.

Best Practice: To the extent possible, it is desirable that survey committees craft text that describes the priority activities—*why* they are the priorities and under what circumstances those priorities might change. So-called "decision rules" that are clearly identified in the survey report can help with this process. Collections of all decision rules in a single section, with traceability back to the body of the report, will facilitate clear communication of the decadal survey's intent.

Implementation Detail

In drafting the survey report, it is best if the committee describes the extent to which implementation details are provided. Is the recommend mission a *reference mission* subject to further post-survey development, or is the recommendation for a specific implementation architecture, likely one that has a history in the discipline? For example, planetary science decadal surveys often recommend a specific mission architecture that represents years of careful consideration by the community. In contrast, in Earth science, where access to space is comparatively routine, there are likely to be several acceptable implementation options.

Best Practice: It is important for the survey report to clarify the extent to which implementation details are prescriptive or notional, in order to ensure that agencies understand the committee's intent when developing implementations strategies.

Scope of Review

What is not said can have as much impact as what is said. Failing to mention specific program elements or current projects can easily be taken as a sign of low priority. Similarly, claims can be made that a particular program was not appropriately considered (even if it was considered and not prioritized) if the program is not explicitly mentioned. Erring on the side of over-communicating can be helpful, particularly to make clear cases where a program was indeed considered but a consensus was reached that it should *not* be prioritized, as was the case with Space Interferometry Mission in Astro2010.

Best Practice: In some cases, it is desirable for the survey committees to document not only the missions and facilities that are part of the recommended program, but also those that were considered but not prioritized, as well as the rationale behind decisions.

Usage of Lists

Lists and tables can be very helpful in itemizing priorities in a clear and concise way. Those in the community who treat them as the only recommendations, however, may use them out of context. Earth2007, for example, made numerous recommendations; however, most consider the list of missions for making new measurements as the primary recommendation from this survey. In fact, a closer read makes clear that the overarching recommendation is for a balanced program emphasizing *Earth system science*. The table of missions represents explicit priorities for only one part of the program (new measurements) and is listed in phased mission groups rather than priority order—however, since the survey report's release, the term "tier" has been repeatedly used by non-committee stakeholders to imply a relative priority. Similarly, in Helio2013, an integrated Heliophysics Systems Observatory was a key recommendation aimed at providing balance opportunities.

Lesson Learned: A single, unified list is expected by many stakeholders—and when one is not provided, the closest thing to it will be used—more often, misused. It is very important that the survey report carefully describes the recommended program in its entirety, with proper emphasis on lists of prioritized missions and facilities.

Panel Reports: Publish or Perish?

The panel reports of a decadal survey are key elements because they provide traceability of the survey's recommended program back to the community. In each panel, science priorities and technological capabilities are weighed and joined to produce an optimal science strategy for that part of the discipline. Therefore, panel reports provide the most complete description and rationalization for the missions and facilities recommended to and by the survey committee. However, the survey committee must choose among many worthy programs and activities that have been prioritized by the subdiscipline panels and prioritize across the discipline. It is unavoidable that the committee's description—in the survey report—of the disposition, emphasis, and specifics of each prioritized activity will differ from what has been written in the panel reports.

The survey committee's decadal report is the "document of record" but, not infrequently, panel reports have been quoted for their more detailed or somewhat different descriptions or evaluations of elements of the program, including those that have been incorporated into the survey program, but also those that have not. Consumers of the report, for example, the agencies or Congress, have been petitioned by stakeholders using selected material from panel reports which have, essentially, no standing when differing or elaborating beyond the survey committee's recommendations. This can, and sometimes does, lead to confusion, if not deliberate misdirection.

Lesson Learned: Individual chapters representing the work of the panels provide important information and the back-story to the final recommendations of the decadal survey in terms of both science priorities and implementation strategies. As panels represent subdisciplines within the decadal survey; all of their priorities do not necessarily align with the survey committee, but are used as critical input into the discussions of the survey committee.

Best Practice: Development by each panel of prioritized science goals and implementation strategies ensures that its community's science priorities are fully understood and considered for incorporation into the recommended program for the coming decade.

Best Practice: A clear articulation of the roles played by the survey committee and panels in absorbing, analyzing, and prioritizing the community's science goals, within and across the discipline, is essential for securing community support for the finished survey—a crucial element of a decadal survey's credibility to stakeholders.

Lesson Learned: As the best and most detailed record of community input, a decadal survey's panel reports are a fundamental part of the survey's work product. It is essential that they be made public along with the committee report. Publishing the survey committee report and the panel reports together, as has often been done, has the important advantage of providing traceability within one document of the decadal survey process of science and program prioritization.

Because only the committee report expresses the consensus recommendations of the survey, it is important that "*For Reference Only*" or similar warnings appear in the margin of each page of the panel reports. Also, by presenting the panel "program" as a set of priorities rather than "recommendations," panels can avoid confusion and ambiguity relative to the decadal survey's recommended program.

Best Practice: To make clear the utility of panel reports and to reduce ambiguity as to their use, decadal committees can choose to publish the panel reports in the same volume as the survey report, adding clear labeling that the panel reports are for reference only.

4

Implementing the Decadal Survey

In this chapter, the committee explores the parts of the decadal process and activities following the survey that contribute to a successful implementation of the survey program. This includes elements of the program that support agencies and other government entities in the implementation of specific recommendations, as well as advice on what to do—in the opinion of the survey committee—in the case of changes in the assumptions that underlay the survey. Advisory structures have evolved at the National Academies of Sciences, Engineering, and Medicine[1] and at the agencies that can provide tactical advice in executing the missions and furthering the activities of the recommend program, including an agency-sponsored, Academies-led midterm review to evaluate progress on the survey's strategic goals. Opportunities for international and interagency collaboration are increasingly important for accomplishing the goals of decadal surveys, yet fostering and improving these collaborations remains a challenge.

DECISION RULES

The prioritized science goals of decadal surveys are developed with implicit and explicit assumptions about opportunity, cost, funding, schedule, and risk. A resilient strategic implementation plan accommodates some level of deviation from the anticipated circumstances. However, as time passes and conditions in the scientific, technical, political, and social environment change, executing the original plan may become difficult, impractical, or even counterproductive. While the specific challenges to be encountered may be unpredictable, considering alternatives to deal with likely perturbations can be useful. Recent decadal survey committees have been tasked with developing decision rules to help the agencies deal effectively with evolving reality.

Decision rules serve several purposes. First, simply by considering alternative scenarios, the survey committee can clarify its process for setting priorities. The prioritization process (described in Chapter 2) invariably involves trades among capability, cost, schedule, scope, project size, scientific balance, and risk. For example, considering the sensitivity of a priority program to cost helps both the writers and the recipients of the survey report to understand how and why choices have been made. When tactical decisions or implementation adjustments must be made, understanding the rationale is useful for agencies, policy makers, and future science advocates.

[1] Activities of the National Research Council are now referred to as activities of the National Academies of Sciences, Engineering, and Medicine.

Second, reality rarely matches expectations. When external priorities shift, swings in the national economic situation take place, scientific or technical advances occur, or management ground rules change, a plan developed with quite reasonable initial assumptions can become suboptimal, if not obsolete. To the extent that decision rules anticipate such changes, they can help preserve the relevance of the strategic goals, even if the original implementation can no longer be realized.

Decision rules also provide agencies and policy makers with flexibility and insight. Flexibility is important because tactical adjustments will be much more effective and more readily accepted by all parties when they are consistent with the community's considered judgment as expressed in the decadal survey. Insight is valuable because, if expectations cannot be met or are exceeded, all of the stakeholders will better understand what will be substituted, sacrificed, or added.

Decision rules can be as simple as contingency planning, addressing, for example, what to do when an international partner makes a particular selection. Decision rules may also define alternative strategies in case a better or worse budget scenario comes to pass. In other situations, decision rules can provide on-ramps and off-ramps for priorities that depend on anticipated scientific discoveries or technical advances.

Decision rules are less helpful when attempting to proscribe responses to unlikely or unforeseen circumstances when tactical responses are more appropriate. Responding to disasters, such as mission failure, is best handled by the relevant agencies themselves, in consultation with the scientific advisory system. Similarly, decisions on narrower issues, including evaluation of specific design details or trade studies, can best be addressed in other ways.

Examples of Decision Rules

A formal request for decision rules in the decadal survey statement of task is a relatively recent addition that began with the 2010 astronomy and astrophysics decadal survey (Astro2010) and continued with the 2011 planetary science decadal survey (Planetary2011) and the 2013 solar and space physics decadal survey (Helio2013); the 2007 Earth science and applications from space decadal survey (Earth2007) also provided some decision rules. In each discipline, the decision rules have been different because of programmatic experience, technical feasibility, specific requests, community requirements, and discipline-specific culture.

Earth Science and Applications from Space

Earth2007 was not required to provide formal decision rules, but the survey report did provide a list of programmatic decision strategies and rules for three areas: leveraging international efforts, managing technology risk, and responding to budget pressures and shortfalls.[2] The survey recognized that implementation of the Earth science program should be adjusted depending on the development of international programs, advances enabled by technology development programs, cost growth in prioritized missions, and changes to the Earth science budget. The list primarily contained strategic advice—for example, implementing a system-wide independent review process to inform decisions and accepting increased mission risk rather than descoping missions. However, two elements served as more explicit decision rules:

- Delay downstream missions in the event of small (~10 percent) cost growth in mission development. Protect the overarching observational program by canceling missions that substantially overrun.
- If necessary, eliminate specific missions related to a theme rather than whole themes.

Astronomy and Astrophysics

Astro2010 was the first survey officially tasked to consider decision rules. The survey committee's approach was to develop an ordered, prioritized list of projects in each size category for the field as a whole, and to con-

[2] National Research Council (NRC), *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, The National Academies Press, Washington, D.C., 2007, p. 75.

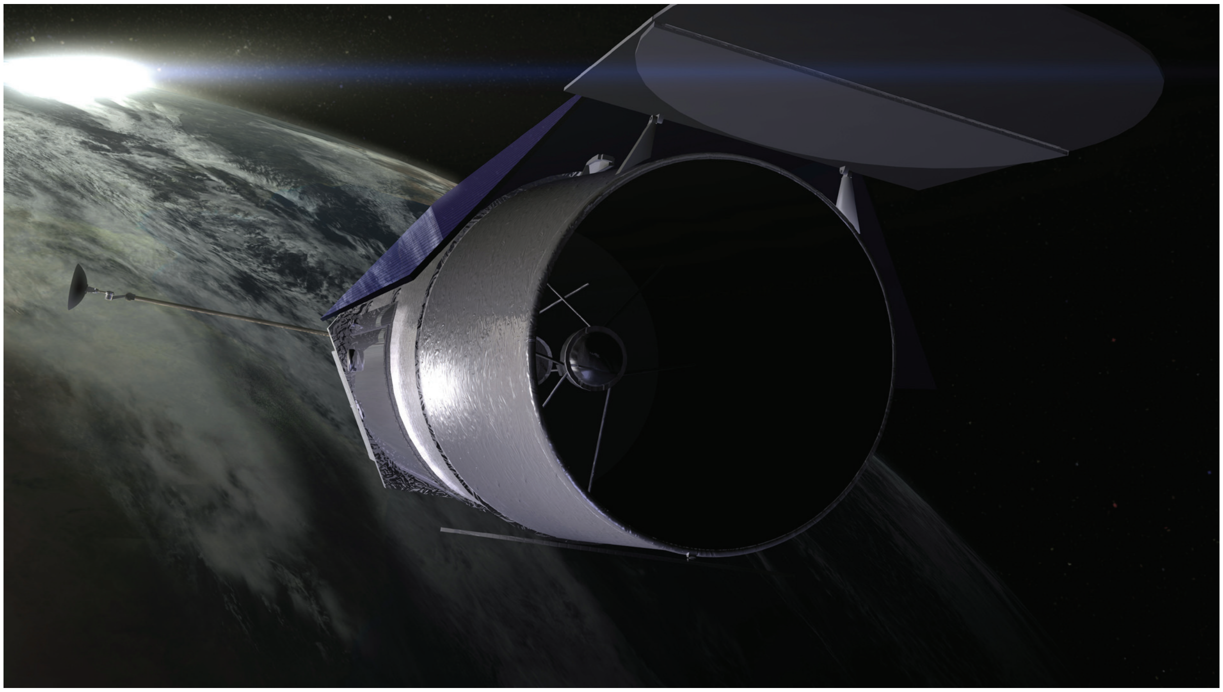

FIGURE 4.1. An artist's concept of NASA's proposed Wide-Field Infrared Survey Telescope. SOURCE: Courtesy of NASA Goddard Space Flight Center/CI Lab.

struct a baseline program that would fit the expected budget scenario provided by each agency. Decision rules, not necessarily identified as such in the report, were generally embedded in the discussion of recommended program elements. "Decision points" were identified for some major missions where future information about technology, cost, or programmatics might influence the ordering of projects. The committee in some cases went on to identify an alternative approach for achieving the science goals of the survey should less than the anticipated funding be provided. For NASA, the response to inadequate funding had often been to simply delay projects with postponed start dates, and in some cases to withdraw from a future international mission. A specific cadence was recommended for smaller competed lines, but the possibility of slowing the cadence in response to budget shortfalls was not explicitly indicated in the recommendation. The approach was similar for the National Science Foundation (NSF) and the Department of Energy (DOE). The decision rules of Astro2010 were developed as the impact of the great recession on federal spending was rapidly developing and before the true cost of the James Webb Space Telescope (JWST) was revealed. In each case, the available resources were significantly lower than anticipated, and to date, only the highest-priority activities and programs have been started. Examples of embedded decision rules and decision points include the following:[3]

- *Programmatic*. The recommendation for the top-priority large space project included a statement that mounting a joint mission with the European Space Agency (ESA) "could be a positive development if it leads to timely execution of a program that fully supports all of the key science goals of WFIRST (Figure 4.1) and leads to savings overall" (pp. 207-208). The eventual outcome was only a moderate U.S. contribution to Euclid—a full collaboration would have been delayed by lack of available funding, mainly due to JWST cost growth.

[3] NRC, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C., 2010.

- *Scientific.* The recommendation for the second-priority medium-sized space mission depended on "the combined space and ground-based program [being] successful in making a positive detection of B-modes from the epoch of inflation" (p. 217). Telescopes that are being designed and built have the capacity to make this discovery if the signal is as large as some theoretical expectations, so it is possible that this decision rule will soon come into effect.
- *Cost and technical.* The fourth-priority large space mission, International X-ray Observatory (IXO), support required achieving sufficient technical progress to begin a mirror technology downselect. Moreover, IXO was to be descoped if the cost exceeded $2 billion. "Prior to a start, NASA . . . should ensure that IXO's principal risks are retired . . . with sufficient maturation to demonstrate the performance, mass, and cost" (p. 215). In practice, this rule was moot on account of the JWST overrun and the evolution of the European X-ray program.

Planetary Science

The Planetary2011 survey committee benefited from the experience of Astro2010 and had better, but still overly optimistic, expectations about future budgets. The basic approach of Planetary2011 was to specify strict cost caps for the major recommended missions in order to maintain scientific balance. The committee went on to define compliant missions with less capability than initially proposed by the community. Specific mission decision rules depending on future selections in competed programs were also included. In the end, the survey recommend two flight programs for the decade: a somewhat optimistic scenario and a cost-constrained program matched to the budget guidance provided by NASA. By the time the report was published, even the cost-constrained budget proved to be too optimistic. The guidance provided to NASA for this scenario stated as follows:

> It is also possible that the budget picture could be less favorable than the committee has assumed. If cuts to the program are necessary, the first approach should be to descope or delay flagship missions. Changes to the New Frontiers or Discovery programs should be considered only if adjustments to flagship missions cannot solve the problem. And high priority should be placed on preserving funding for research and analysis programs and for technology development.[4]

Solar and Space Physics (Heliophysics)

By the time of Helio2013, the full impact of the economic slow-down on the federal budget had been realized. While straining to include hints of optimism, Helio2013 adopted a conservative outlook and emphasized completing the existing program. The survey report[5] recommended a pay-as-you-go approach that focused first on (1) modest changes to the science research program, (2) augmentation of the cadence of small, competed Heliophysics Explorer missions, and (3) initiation of larger directed missions in the Solar Terrestrial Probe (STP) and Living With a Star (LWS) programs. The survey also responded to specific requests for decision rules from NASA's Heliophysics Division to address programmatic balance if the Solar Probe Plus mission grew significantly early in the decade. By this stage, an explicit list of decision rules addressed toward future cuts appeared in the summary:

> *Decision Rule 1.* Missions in the STP and LWS lines should be reduced in scope or delayed to accomplish higher priorities. Chapter 6 gives explicit triggers for review of Solar Probe Plus.
>
> *Decision Rule 2.* If further reductions are needed, the recommended increase in the cadence of Explorer missions should be scaled back, with the current cadence maintained as the minimum.
>
> *Decision Rule 3.* If still further reductions are needed, the DRIVE [Diversify, Realize, Integrate, Venture, Educate initiative] augmentation profile should be delayed, with the current level of support for elements in the NASA research line maintained as the minimum.[6]

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[4] NRC, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, The National Academies Press, Washington, D.C., 2011, p. 7.
[5] NRC, *Solar and Space Physics: A Science for a Technological Society*, The National Academies Press, Washington, D.C., 2013.
[6] NRC, *Solar and Space Physics*, 2013, p. 11.

Helio2013 also indicated priorities for augmentations, but as of fiscal year (FY) 2015, Decision Rule 3 is operative.

Decision rules have become a more prominent feature of recent surveys because the recommended programs could not be executed with the available resources without significant deviations in scope and schedule; therefore, additional guidance was required. Decadal surveys are by nature ambitious statements of scientific goals: a better understanding of the relative importance of the goals is provided through explicit decision rules. Scientific disciplines differ—some must choose between destinations, while others rely on instruments serving large numbers of users; some require continuity or comprehensive coverage, while others attempt to address operational needs or focus on specific events or vantage points. The scientific cultures differ and so do the kinds of decision rules each discipline adopts. Each of the last four surveys also emphasized the importance of balance, both among competing scientific topics and among the various programmatic means used to achieve scientific goals. Balance is difficult to define, let alone maintain, when timing changes and when large and small programs must compete for constrained resources, but each of the disciplines has shown a strong commitment to the effort.

> ***Lesson Learned:*** Decision rules provide deeper insight into the survey's scientific priorities and reflect the wisdom and consensus of the scientific community.

Decision rules are written based on current understanding of future conditions and plausible alternatives. Not all eventualities can be anticipated, whether political, economic, technical, or scientific. Thus, care must be taken with decision rules as with all other survey recommendations, particularly as time passes. Midterm survey reviews provide an appropriate opportunity for reconsidering decision rules.

Decision rules have proven useful to NASA and other agencies, as well as to advisory committees and other stakeholders. Decision rules are particularly relevant to decisions about the scope and timing of new missions and large facilities and programs.

Although only "downside" rules have been implemented so far, having rules for positive developments, such as budget increases, is also important.

> ***Best Practice:*** Decision rules ordinarily are best when strategic in nature rather than tactical. The objective is to provide insight into how science priorities evolve or change under specific circumstances without overconstraining implementation. Long-term advice that advances the scientific goals of the community is useful, whereas short-term rules quickly become obsolete or are better determined by administrators, policy makers, and community members familiar with the immediate situation.

> ***Best Practice:*** The best decision rules are clear, unambiguous, and easy to implement without being overly prescriptive. Decision rules are best designed to support the achievement of survey priorities, without overly specifying the means by which they are achieved. Clear if-then rules are more useful, whereas decision rules that require interpretation may often be less helpful. For example, references to general concepts (like balance) are difficult to understand, implement, and evaluate without specific definition and guidance.

> ***Best Practice:*** Decision rules need to be clearly identified and labeled as such in the survey report. In order to facilitate clear communication, all of the decision rules from the entire survey should be collected in one section, with each being traceable back to the body of the report.

> ***Best Practice:*** Decision rules can be evaluated as part of the midterm assessment process. This may include reviewing existing decision rules, assessing their status, and considering whether any specific decision rule requires reevaluation due to emerging circumstances.

Whether or not decision rules are utilized depends on events that occur well after the survey is completed, but decision rules are a legacy from the decadal survey that will help in understanding and implementing the decadal survey's science program.

STEWARDSHIP

Role of SSB Standing Committees

Strategic versus Tactical Advice

There are currently two distinct entities that advise NASA Science Mission Directorate (SMD) and its four divisions: the Space Studies Board (SSB) of the Academies' and the NASA Advisory Council (NAC). Strategic advice pertaining to the forward vision for NASA programs and activities and evaluation of program performance against long-term planning metrics is generally provided through activities organized under the auspices of the SSB and its discipline-specific standing committees.[7] The NAC and its committees and subcommittees generally provide tactical advice that addresses ongoing activities where scientific input is needed to ensure effective and efficient performance for an active program or mission.

Strategic Advice from the Academies' Space Studies Board

Long-term strategic advice for NASA SMD comes from the scientific community through its representatives on the SSB's ad hoc committees and the convening power and expertise of the SSB's standing committees. In particular, the ad hoc committees requested by NASA and other appropriate federal agencies to produce the decadal surveys address the science of each of the four SMD divisions. Decadal survey committees and their subdiscipline panels solicit broad input from scientific and stakeholder communities, scientific society groups, and the analysis/assessment groups that provide input into the NAC. The decadal survey committees, like other ad hoc committees of the SSB, produce documents with findings and recommendations based on the consensus of the committee members in response to an approved statement of task. These findings and recommendations are provided as advice to NASA and other sponsoring agencies. Often they are regarded as only part of the input into the decision-making process. Nonetheless, both Congress and the administration take these reports seriously, and, indeed, NASA's authorizing legislation calls on NASA to "take into account the current decadal surveys from the National Academies' Space Studies Board when submitting the President's budget request to the Congress" (P.L. 111-267).

Standing Up the Standing Committees

It has been traditional for the SSB standing committees of a particular discipline to "stand down" during the 2 years or more that its new decadal survey is in progress. This began early in the history of decadal surveys and is thought to have resulted from a concern that federal agencies might receive contradictory input from a discipline's decadal survey and its SSB standing committee's activities. It also reduces the workload for the community and the cost to the agencies. The actual benefits of this practice are uncertain, but the disadvantage is clear: a hiatus of 2 years or more during which NASA and other agencies are unable to engage with a standing committee on implementation of the *previous* decadal survey and any other time-sensitive issues that may arise.

The inability of the Academies to routinely organize activities to provide timely advice because the relevant standing committee has stood down is a serious problem. The events in the months following the release the Astro2010 report, *New Worlds, New Horizons in Astronomy and Astrophysics,*[8] provide a telling example. The survey report was released in August 2010, but, for a variety of reasons, the relevant standing committee—the Committee on Astronomy and Astrophysics (CAA)—was not reestablished until February 2012. So, for a period of 18 months, there was no appropriately constituted interface between the Academies and the agencies implementing Astro2010's recommendations. However, within weeks of the release of the Astro2010 survey report, the Office of Science and Technology Policy (OSTP) requested input from the Academies concerning several astrophysical

[7] In addition to the Space Studies Board, the Academies' Board on Physics and Astronomy collaborates with the SSB on studies and activities related to astronomy and astrophysics, and several boards of the Academies' Division of Earth and Life Sciences collaborate with the SSB on studies and activities related to Earth science and applications from space.

[8] NRC, *New Worlds, New Horizons*, 2010.

issues, including synergies and complementarities between the science goals of NASA's Wide-Field Infrared Space Telescope (WFIRST) and ESA's Euclid dark-energy mission.[9] Similarly, a year later, NASA asked the Academies' to review its proposed plans for participation in Euclid.[10] The absence of CAA's expertise, convening power, and ability to organize activities significantly complicated the Academies' response to these two requests. Both tasks were ultimately handled expeditiously, due, in large part, to a fortuitous combination of circumstances. However, a price was paid in terms of continuity of assistance that CAA and its associated advisory activities could have provided.

Lesson Learned: As long as the standing committee restricts its work to the current program, there is no meaningful conflict that would preclude continuation of the SSB standing committees during the execution of a decadal survey.

Best Practice: SSB standing committees can continue their work throughout the period when a new decadal survey is in progress in order to provide an uninterrupted channel of communication between these committees and NASA and other agencies, with respect to strategic issues *that concern the current program.*

NASA Advisory Structure

The NAC, a committee reporting to the NASA Administrator and chartered under the Federal Advisory Committee Act (FACA), provides rapid *tactical advice* to NASA SMD and its divisions and performs annual evaluation of performance of individual programs and projects—including space science missions. Reporting to the NAC are committees representing the various NASA directorates. In the case of SMD, the appropriate advisory group is the NAC Science Committee.

While the activities of the NAC Science Committee follow FACA guidelines, it is not officially a FACA committee and cannot provide official advice to NASA in the form of findings or recommendations, except through the NAC. Thus, the Science Committee does not officially advise the associate administrator (AA) for SMD except by providing input to the NAC that is then passed either through the NASA Administrator and back down to the AA or, more recently, directly to the AA with the NAC's concurrence. Unofficially, the AA or deputy AA may participate in the Science Committee meetings, allowing unofficial communication of the committee's sentiment at the directorate level. Similarly, the subcommittees of the NAC Science Committee that represent the four SMD disciplines cannot provide official advice to the appropriate division directors, except through the Science Committee and the NAC and through their oversight of the triennial division roadmaps. As the sole representative of the Science Committee and its subcommittees, the chair of the Science Committee is the singular voice charged with transmitting all science input (with all the nuances involved) to the NAC. Because the various committees and subcommittees of the NAC meet only every few months, official tactical advice at the divisional level is rarely rapid, and discipline-level issues do not often qualify as sufficiently important to justify attention from the NAC during its meetings. This situation is additionally compounded by the more frequent use of virtual meetings, which are generally less effective as a forum of discussion leading to the development of consensus advice across subdisciplines.

Short-Term Guidance

Neither the SSB and its standing committees nor the NAC Science Committee and its subcommittees are truly empowered to provide timely advice or input to NASA associate administrator for SMD or the subordinate division directors when short-term tactical advice on strategic programs is needed. While NASA can request advice from the community through the SSB in the form of a report from an ad hoc committee on an issue of

[9] For details see NRC, *Report of the Panel on Implementing Recommendations from the New Worlds, New Horizons Decadal Survey*, The National Academies Press, Washington, D.C., 2012.

[10] For details see, NRC, *Assessment of a Plan for U.S. Participation in Euclid*, The National Academies Press, Washington, D.C., 2012.

importance, such activities can take significant time to perform. The NAC's Science Committee, because it lacks a FACA charter, is also ill-equipped to provide formal advice. NASA-supported community groups, such as the discipline-specific assessment or analysis groups within the Planetary Science Division (see below), may be more facile, yet these are not FACA groups, so their input must be fed through the NAC structure to conform to legal requirements. Congress may also solicit input on decadal survey science issues from members of the SSB or its standing committees in the form of participation in hearings. However, there are few ways for any community group to be a proactive guardian or steward of a decadal survey should Congress, the administration, or the agency elect to deviate significantly from a decadal survey's recommended program.

In addition to the NAC and its associated committees, NASA maintains a number of assessment and analysis groups that function as a link between the science community and the discipline scientists at NASA Headquarters. While these groups do not recommend or advise, they do comment on strategic planning and science priorities and provide input on the health of their subdiscipline in the context of NASA missions. For example, COPAG (Cosmic Origins Program Assessment Group) has been focusing on full utilization of the general-purpose observatory JWST, the first-priority space mission for the 2001 astronomy and astrophysics decadal survey,[11] and on the planning for WFIRST, Astro2010's first priority.

Similarly, the planetary assessment and analysis groups represent many of the field's subdisciplines—MEPAG (Mars Exploration), OPAG (Outer Planets), SBAG (small solar system bodies), VEXAG (Venus Exploration), LEAG (Lunar Exploration), and CAPTEM (sample analysis).[12] Their activities concern longer-term strategic planning—mission scenarios and science goals and priorities that evolve in response to new missions and observations. At one time, the chair or a representative of each of these groups served on the NAC Planetary Science Subcommittee, which provided "findings" to the NAC Science Committee on issues that were more tactical in nature. This practice of cross-membership has been discontinued.

NASA's Heliophysics Division has MOWGs (management operations working groups), informal groups that help the discipline scientists maintain close relationships with the solar and space physics community. Among other things, the MOWGs provide perspectives on strategic planning, methodologies, mission concepts, and initiatives. There are three MOWGs—the SH-MOWG, the G-MOWG, and the LWS-MOWG (solar-heliosphere, geospace, and Living With a Star, respectively). Like the assessment and analysis groups, MOWGs do not provide formal advice but do pass findings on to the Heliophysics Subcommittee of the NAC Science Committee.

> ***Lesson Learned:*** The current advisory structure does not provide an effective mechanism for short-term tactical guidance from the scientific community (i.e., tactical guidance for accomplishing strategic visions).

While SSB's standing committees have a clear connection to the appropriate NAC science subcommittees, enabling cross-communication, such connections with the advisory structures of the other federal agencies involved in space science activities are often less well established. As such, effective stewardship of decadal survey recommendations in these agencies may be less effective than with NASA.

When an agency has a need for the Academies' advice, the appropriate standing committee would work with it to draft a statement of task. Subsequently, the Academies would appoint an ad hoc committee consisting of appropriate members of the standing committee, augmented by other experts as needed depending on the nature of the specific request.

> ***Best Practice:*** NASA division directors and program officers for other interested agencies (e.g., NSF, the National Oceanic and Atmospheric Administration [NOAA], the U.S. Geological Survey [USGS]) can work with the SSB's standing committees to commission letter reports, meetings of experts, or workshops when specific advice is needed on a more rapid turnaround basis.

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[11] NRC, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001.

[12] Additional information about these and other assessment and analysis groups can be found at Lunar and Planetary Institute, "NASA Advisory, Analysis and Assessment Groups and Resources," last updated November 18, 2014, http://www.lpi.usra.edu/analysis/.

Tactical Advice from the AAAC

The Astronomy and Astrophysics Advisory Committee (AAAC) is a FACA-chartered committee resulting from one of the primary recommendations of the 2001 report *U.S. Astronomy and Astrophysics: Managing an Integrated Program*.[13] The relevance of the AAAC to stewardship of decadal surveys lies in two components of the AAAC charter: (1) to assess, and make recommendations regarding coordination of astronomy and astrophysics programs of NSF, NASA, and DOE and (2) to assess, and make recommendations regarding the status of activities of NSF, NASA, and DOE as they relate to recommendations contained in the decadal survey reports. The AAAC findings and recommendations are communicated in letter reports directly to the NASA Administrator, the NSF Director, the Secretary of Energy, and the chairs of various congressional committee and members on Capitol Hill.

While the AAAC has a role as shepherd over the decadal survey results, it is charged with providing tactical advice on project and program development, particularly for those that involve more than one agency.[14] Since Astro2010, AAAC deliberations have including issues surrounding development of JWST, international cooperation in mission development (Euclid/WFIRST), heliophysics (the Daniel K. Inouye Solar Telescope—NASA mission synergies), and plutonium-238 production restart for deep space missions, as well as technology development, workforce issues, and midterm survey review. The AAAC has repeatedly emphasized the need for portfolio balance among small and medium grants, projects and facilities, and programs across different disciplines—reiterating common decadal survey themes.

Dialogue between the AAAC, the standing committees of the SSB, and other stakeholders is important for effective stewardship of the survey. Unanimity of voice when in agreement, and clarity on differences when in disagreement, is important to provide agencies, Congress, the executive branch, and the scientific community with continuity as implementation of the decadal survey progresses. In addition, the AAAC can provide a vehicle for more prompt responses to tactical challenges faced by the disciplines and agencies in advancing priorities in astronomy and astrophysics.

> ***Lesson Learned:*** The AAAC can play an important and unique role in stewardship of a decadal survey through its focus on interagency cooperation.

Midterm Reviews

The 2005 NASA Authorization Act (P.L. 109-155) requires that "the performance of each division in the Science directorate of NASA shall be reviewed and assessed by the National Academy of Sciences at 5-year intervals." Thus, approximately 5 years into a decadal survey's implementation period, a study is requested by NASA and an ad hoc committee is appointed by the Academies to prepare and release a midterm assessment. The midterm assessment details the progress made on decadal survey priorities to date and provides a chance for the scientific community to formally recommend any course corrections needed in response to programmatic or budgetary changes since the release of the decadal survey. Science priorities are typically not revisited at the time of a midterm assessment. However, changes in program implementation to better align with decadal survey recommendations may be recommended.

The structure and content of midterm assessment reports has varied among the disciplines, as driven by their statements of task (see Box 4.1), but most include a survey of recent scientific progress as well as an assessment of the implementation of decadal survey recommendations.

Midterm assessment committees need to consider how best to convey a summary of the program's progress while remaining mindful of the wide range of audiences and uses for the report. The most recent planetary science[15] and

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[13] NRC, *U.S. Astronomy and Astrophysics: Managing an Integrated Program*, National Academy Press, Washington, D.C., 2001.

[14] Astronomy and Astrophysics Advisory Committee, *Report of the Astronomy and Astrophysics Advisory Committee*, letter report, March 15, 2011, p. 7, http://www.nsf.gov/mps/ast/aaac/reports/annual/aaac_2011_report.pdf.

[15] National Research Council (NRC), *Grading NASA's Solar System Exploration Program: A Midterm Review*, The National Academies Press, Washington, D.C., 2008.

BOX 4.1
Midterm Reviews

Midterm assessments (or mid-decadal reviews) are mandated by Congress to occur at 5-year intervals as specified by the 2005 NASA Authorization Act (P.L. 109-155). To date, four midterm assessments have been completed.[1]

The statements of task for each of these midterm assessments share several common features. Each was charged to

- Assess how well NASA's current program addresses the "strategies, goals, and priorities" outlined in the decadal survey and other National Research Council reports;
- Assess "Progress toward realizing these strategies, goals, and priorities";
- Identify any actions that could be taken to maximize the science return/optimize the scientific value "in the context of current and forecasted resources"; and
- Provide guidance about implementing the recommended mission portfolio in preparation for the next decadal survey—but "not revisit or alter the scientific priorities of mission recommendations."

The next astronomy and astrophysics midterm is currently under way. Its statement of task includes two additional items that expand its scope compared to the previous round. In particular, the 2015 midterm is charged to

- Describe the most significant scientific discoveries, technical advances, and relevant programmatic changes in astronomy and astrophysics over the years since the publication of the decadal survey; and
- Review the strategic advice provided for the agencies' programs by federal advisory committees.

[1] See the National Research Council reports *Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey* (2012); *A Performance Assessment of NASA's Heliophysics Program* (2009); *Grading NASA's Solar System Exploration Program: A Midterm Review* (2007), *A Performance Assessment of NASA's Astrophysics Program* (2007), all published by the National Academies Press, Washington, D.C.

solar and space physics (heliophysics)[16] midterm assessments used a grading system to convey relative progress on specific recommendations. Grading systems have the advantage of being relatively straightforward to implement and readily provide a logical structure for the report. However, grades also can be easily misused. For example, is a low grade cause to increase investment in an area, or a reason to cut its funding? Including explanatory text that specifies the desired response is helpful. However, it does not ensure the grades or scores will not be used out of context. The astronomy and astrophysics[17] and Earth science and applications from space[18] midterm assessment committees chose not to use a grade/scoring system and instead provided specific summary findings to indicate the status of each program element (see Table 4.1).

> ***Lesson Learned:*** Providing scores or grades in a midterm assessment report can result in unintended consequences when used by a wide audience. When grades are used, it is best if narrative text clearly indicates the desired response to a good or bad grade.

[16] NRC, *A Performance Assessment of NASA's Heliophysics Program*, The National Academies Press, Washington, D.C., 2009.
[17] NRC, *A Performance Assessment of NASA's Astrophysics Program*, The National Academies Press, Washington, D.C., 2007.
[18] NRC, *Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey*, The National Academies Press, Washington, D.C., 2012.

TABLE 4.1 Gross Characteristics of the Four Midterm Decadal Reviews Completed So Far

	Earth Science and Applications from Space	Solar and Space Physics (Heliophysics)	Planetary Science	Astronomy and Astrophysics
Scientific progress since last decadal	Yes	Yes	Yes	Yes
Program/project implementation status	Yes	Yes	Yes	Yes
Technology development status	Yes	Yes	Yes	No
Description of challenges to implementation	Yes	Yes	Yes	Yes
Budget history	Yes	Yes	No	Yes
Used grades/scores	No	Yes	Yes	No

In the course of its work, a midterm assessment committee is typically briefed by the agencies involved and other important stakeholders (e.g., congressional representatives, OSTP, the Office of Management and Budget [OMB]). This provides insight into how the program of record was developed. The midterm assessment report provides an important opportunity to share this contextual information with the broader community. The first Earth science midterm assessment,[19] for example, took the approach of dissecting what happened since Earth2007 to try to elevate the community discussion beyond anecdotal concerns and to explicitly discuss the many reasons that implementation was not proceeding as envisioned. The report detailed how Earth2007 priorities were convolved with the administration's priorities to develop a so-called "climate-centric architecture," which was then considered the operating plan for SMD's Earth Science Division.[20]

The Earth science midterm report[21] went on to detail how the funding for that plan was subsequently reduced, resulting in slower than expected progress on decadal survey priorities. The report called out missions by name, explained what happened and why, and discussed what worked well and what did not. Key figures from Earth2007 (e.g., budget profiles, missions in operation) were updated to provide the community with a sense of how resources had (or had not) changed since the survey's release. The midterm assessment thus serves an important role in making the broader community aware of the implementation plan and how it evolved from the decadal survey's priorities.

Best Practice: Midterm assessment reports are most useful when they engage and inform the broad community by providing a progress report on implementing the decadal program, together with sufficient context to understand the rationale behind the program's current implementation strategy.

While midterm assessments cannot solicit community input in the same way as the decadal survey process, the assessment committee members are selected to represent the breadth of the disciplinary community. Additionally, they provide expertise across science, missions, technology, and supporting infrastructure, allowing a complete assessment of the division's performance over the approximately half-decade since the decadal survey. Corrective actions for underperforming areas and evolving scientific foci are identified in the report. In this way, midterm assessments are both a review of past performance and a document to guide activities in the following half-decade. In that sense, they act as the first step in the process for the next decadal survey and can be used to guide the community in the development of new concepts for activities in the following decade. Such concepts can then be developed and matured over the subsequent 5 years as input into the next decadal process, with consequent improvement in efficiencies.

[19] NRC, *Earth Science and Applications from Space*, 2012.

[20] NASA, *Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space*, June 2010, http://science.nasa.gov/media/medialibrary/2010/07/01/Climate_Architecture_Final.pdf.

[21] NRC, *Earth Science and Applications from Space*, 2012.

Lesson Learned: Midterm assessments offer an opportunity to initiate the process of concept development for the next decadal survey. While primarily serving to provide a report on progress to date, the assessments can also act as forward-looking documents in the preparation for future decadal planning.

INTERNATIONAL ACTIVITIES

There is strong consensus about the importance of international cooperation in space missions as having both potential and often very concrete benefits to the participants. However, effectively engaging international participants at both individual and institutional levels in decadal surveys remains challenging. The global economic situation today begs for avoiding duplication of efforts and, instead, combining means and human resources for large and medium-sized science projects. There are many examples where collaboration has been critical to mission success. In planetary science, for example, the Cassini-Huygens mission developed as a very successful collaboration among ESA, NASA, and the Agenzia Spaziale Italiana. Other examples include the following: TOPEX/POSEIDON, ASTER, and a succession of ocean color measurements in Earth science; SOHO, Cluster, Hinode, and Yohkoh in heliophysics; and HST, Hayabusa, Planck, Herschel, and SOFIA in astrophysics. Ground-based programs, such as ALMA, also demonstrate how fruitful international collaboration can be.

At the 2012 workshop's session on "Incorporating International Perspectives into Future Decadal Planning," NASA's Dennis McSweeney stated, "International cooperation is a founding principle of NASA."[22] He went on to list the five guidelines established in the 1950s, among them, (1) NASA looks for specific programs, rather than general science, upon which to build collaborations; (2) joint projects must be of mutual scientific interest; and (3) each partner accepts financial responsibility for its contribution. Today, NASA SMD, alone, maintains more than 4,000 cooperative agreements with 100 nations, with some 50 active international collaborations.

The benefits of international collaborations, McSweeny said, come from many directions. Coordination of individual missions and/or mission architectures (e.g., orbital crossing times); coordination of different observations (e.g., ocean color); and provision of instruments (e.g., ASTER), spacecraft, or launch capabilities are all familiar examples. All scientific communities, especially heliophysics and Earth science, have embraced a large range of international collaborations. NASA is already sophisticated and motivated in its approach to collaborations that increase the science return.[23] Specifically, international collaborations have the potential to bring on board assets such as:

- Optimizing the mission definition,
- Enabling missions that could not be afforded by individual agencies,
- Enhancing mission capabilities,
- Accelerating mission implementation,
- Reducing mission cost in some tangible way to one or more partners, and
- Strengthening the national commitment to the mission.

The challenge for the decadal survey process is to determine how opportunities for international partnerships can be appropriately introduced, discussed, and prioritized. Coordinating groups exist in some areas—for example, the World Meteorological Organization, the Committee on Earth Observing Satellites, and the Committee on Space Research (COSPAR).

Interagency/Inter-Governmental Relationships

Although international cooperation is a founding principle of NASA, there is a difference between NASA's relationships with individual national space agencies and multinational organizations, such as ESA. For example,

[22] NRC, *Lessons Learned in the Decadal Planning in Space Science: Summary of a Workshop*, The National Academies Press, Washington, D.C., 2013, p. 62.

[23] NRC, *Lessons Learned in the Decadal Planning in Space Science*, 2013, pp. 62-63.

NASA's Earth Science Division has a history of strong collaborations with individual national space agencies, but less so with ESA. Other scientific disciplines within NASA have different approaches, but overall the agency seeks scientific/mission cooperation quite broadly.

In addition, decadal surveys will have to recognize the increasing diversity of the world's space community. Many national space agencies have achieved significant successes in space activities (e.g., those of China, India, Brazil, and Russia) beyond those routinely involved in collaborations with the United States (e.g., those of Japan, Canada, and Europe). However, while the number of nations with considerable capability in space missions continues to grow, there has been little progress in developing ways to coordinate international planning, align goals of different players, and assure complementary programs—at least instead of competitive ones. There are many essential benefits to collaborating internationally; however, there are also some very real barriers. Impediments to international collaboration include, but are not limited to, the following:

- Mission selection processes that may be asynchronous and have substantial differences.
- Difficulty in securing commitment to a joint project—Who will commit first to a program that one nation cannot accomplish on its own?
- Technologies are often proprietary and not easily shared (e.g., issues associated with the International Trafficking in Arms Regulations); citing D. Southwood, ESA's former director of science and robotic exploration, "European scientists are very reluctant to become involved in hardware exchange because of the economic and political sensitivities of Earth remote-sensing technologies."
- Differences in data policy.
- Community building and mission-concept development processes that may vary greatly over the world's space agencies.
- Varying planning processes.
- Different relationships between agencies and their governments, in particular in terms of commitments to funding or the cancellation of existing commitments.
- Concerns about security and sharing of resources—for instance, the security requirements for launching missions using nuclear power sources from Europe on a European launcher, and vice-versa (now that Europe is developing its own radioisotope power systems based on americium-243).
- Organizational communication and managerial issues.
- International politics.
- Cost evaluation of foreign contribution.
- Impediments to U.S. participation in foreign meetings, given current federal restrictions on travel and conference attendance.

A specific example in the field of heliophysics illustrates the difficulty and complexity of putting together an international mission in connection with a decadal survey. The Japan Aerospace Exploration Agency (JAXA) was in the process of selecting their next solar mission during the early and middle phase of the solar and space physics (heliophysics) decadal survey. JAXA ultimately selected a high-resolution telescope to observe small-scale features on the Sun. The Solar-C mission crucially required a \$100 million to \$200 million contribution for a U.S. instrument, but at that point the decadal survey committee was unwilling to commit. Science considerations aside, this was partly because of uncertainty with the cost and technical evaluation (CATE) process for a relatively small U.S. contribution to an international mission, partly because of the timing relative to the establishment of priorities by the panels, and partly because of funding constraints early in the decade. The decadal survey ultimately endorsed the mission as a possible competitor in the Explorer/Mission of Opportunity program. Because the U.S. contribution was an essential component of their next major mission, the uncertainty engendered by the survey's endorsement of a competition was not well received by JAXA. Solar-C is currently waiting for a new start.

Informed estimates of cost (i.e., the CATE process) need not be a "show-stopper" for international collaborations. However, attempting to get reliable estimates of mission costs when there is significant international sharing of costs raises a number of complications. If, for example, a major instrument is flown on a foreign spacecraft, the cost may be low enough that it does not meet the threshold for independent costing by the decadal survey.

Even with all good intentions, of course, an international collaboration may still fail. Sometimes foreign partners have to withdraw from partnerships. Examples abound: the United Kingdom pulled out of the Solar Dynamics Observatory mission during development and withdrew from the operation of the twin Gemini 8-meter ground-based telescopes after many years of involvement. Similarly, the United States has dropped out of important established collaborations for space missions in the recent past, even when the deal was to its advantage, as was the case in the proposed ExoMars 2016 and 2018 and the Europa Jupiter System Mission collaborations with ESA.

Best Practice: By identifying the essential features and potential challenges of international collaborative missions and projects early on, decadal surveys can recommend processes and procedures for avoiding breakdowns, thus limiting the impact in science and cost on both sides.

Channels of Communication and Coordination

The extent of international participation in a fundamentally U.S.-driven prioritization process will need to be considered as each new decadal survey enters the planning phase. There is no true analog to the Academies' decadal surveys in other countries. Nevertheless, roadmaps and other scheduling information can be shared via bilateral discussions, forums, and meetings, or by including international members in the survey committees. Pre-decadal survey discussion of science priorities with international partners, and full understanding of the plans of other international agencies, is needed. The intent is to achieve a better alignment and implementation of space programs. Mutual representation on panels and survey committees serve the important purpose of information exchange, but they are not the source of collaborations—these more commonly develop from the bottom up between science teams (e.g., the International X-ray Observatory). International "forums" have also been suggested as a way to communicate the aspirations and plans of different space agencies.[24] COSPAR or the International Space Science Institute can potentially play that role.[25,26] In Earth science, the Committee on Earth Observing Systems (CEOS) already plays such a role.[27] Representation of individuals from other countries on decadal survey committees and panels can be augmented by invited presentations from other space agencies, so as to gain a more institutional perspective on future plans and programs. The intent is to achieve a better alignment and implementation of space programs. Furthermore, after a decadal survey is complete, communication with potential partners can be encouraged, both to seek collaborations and to clarify the decadal survey program.

Best Practice: Decadal studies can use a combination of existing scientific conferences, meetings, and symposia, as well as more targeted dialogues between survey committees and their closest analogs in the scientific advisory apparatus of other countries, to ensure that lines of communication are open.

[24] At the 2012 workshop, J.-P. Swings (former chair of the European Science Foundation's European Space Science Committee [ESSC]) proposed a global forum for established spacefaring nations and newcomers alike. The forum would generate a sense of global community; it could be organized jointly by the SSB and ESSC, for example.

[25] COSPAR, the Committee on Space Research of the International Council for Science, for example, recently developed an international, interdisciplinary roadmap to advance the understanding of space weather. For details, see C.J. Schrijver, K. Kauristie, A.D. Clezio, M. Denardini, S.E. Gibson, A. Glover, et al., Understanding space weather to shield society: A global road map for 2015-2025 commissioned by COSPAR and ILWS, *Advances in Space Research* 55:2745-2807, 2015. Prior to this, COSPAR completed a roadmap for space astrophysics; see P. Ubertini, N. Gehrels, I. Corbett, P. de Bernardis, M. Machado, M. Griffin, et al., Future of space astronomy: A global road map for the next decades, *Advances in Space Research* 50:1-55, 2012. More details about COSPAR, its roadmaps, and other activities can be found at the COSPAR website at https://cosparhq.cnes.fr/ (accessed June 22, 2015).

[26] The International Space Science Institute (ISSI), headquartered in Bern, Switzerland, seeks to integrate the results of space missions, ground-based observations, and laboratory experiments and add value to those results through multidisciplinary research by teams of international researchers, workshops, working groups, forums, or individual visiting scientists. For more details, see the ISSI website at http://www.issibern.ch/index.html and ISSI-Beijing at http://www.issibj.ac.cn/ (both accessed June 23, 2015).

[27] CEOS was established in 1984 under the aegis of the G7 Economic Summit of Industrial Nations Working Group on Growth, Technology, and Employment and serves as the primary forum for the international coordination of space-based Earth observations. More details can be found at http://ceos.org (accessed June 23, 2015).

Best Practice: Individual, non-U.S. scientists can be invited to participate in a decadal survey. Participants need to be selected for their scientific backgrounds and expertise, not as institutional representatives, and be cognizant of a broad range of international activities. International representatives that are experienced and senior enough can provide information that will open avenues for collaboration and strengthen channels of communication back to their home space agencies and national space societies and organizations.

Best Practice: Decadal reports can include specific descriptions of the types of international collaboration that the decadal survey committee finds desirable (e.g., cost-sharing, development of instrumentation, coordination of individual missions, or mission architecture).

Best Practice: Decadal reports can explicitly identify any significant programmatic uncertainties and/or craft decision rules that might be required when considering international collaborations. This may be particularly important when international collaborations are a significant component of the survey's recommended program—in terms of budget or scientific strategy.

INTERAGENCY ISSUES

In its 2011 report about interagency cooperation, the Academies made the strong recommendation that any given space program of the U.S. government be carried out—if at all possible—by a single responsible agency.[28] However, it was recognized that, in some instances, a particular agency might not have the mix of experience and technical capability to carry out the requisite programmatic functions to assure space mission success. In these cases, interagency cooperation would be deemed essential. Examples included certain kinds of instrument designs unique to DOE laboratories for NASA Astrophysics missions and NSF-funded facilities (e.g., the Dark Energy Camera for the 4-meter Blanco Telescope at Cerro Tololo Inter-American Observatory and the giant focal plane detector for LSST). Another example is the extensive use of NASA's capabilities in support of the National Oceanic and Atmospheric Administration's (NOAA) weather mission.

The committee recognizes that, in some instances, programs and community objectives in the Earth and space sciences must be carried out in an interagency or multi-agency fashion. Although a primary focus of decadal surveys, from the congressional perspective, is to provide guidance for NASA's research-mission priorities, the implication from a national policy perspective is that decadal surveys will include in their recommended programs crucial science activities that involve DOE, NOAA, NSF, USGS, the Department of Defense, and other federal agencies, as appropriate for each of the space science disciplines.

Yet, it has been clear that not all agencies consider themselves to be involved in or subject to the Academies' decadal process. That is to say, some agencies have considered the surveys to be aimed primarily at NASA's flight program, much like the congressional perspective. As such, some agencies have not been inclined to support the planning or funding of the decadal process, nor have they embraced the recommendations made to them as part of the decadal survey plan.

Decadal surveys are exercises in which the relevant scientific communities develop a consensus about what the United States should accomplish over the next 10 years. This is advice given on behalf of the *entire* community, not just a portion (i.e., the NASA-supported portion) of the discipline. This advice cannot be truly effective if agencies—whose participation is essential for implementation—are not consulted, do not participate, and do not feel the need to respond to a survey's recommendations. The integrity of the decadal survey process and its utility as a community and national exercise is undermined when agencies that should be involved choose not to be.

Decadal surveys are national in scope and extent. Each is intended to provide the best advice possible from, to, and for an entire scientific discipline. An agency's involvement in a given disciplinary area implies a strong connection between that agency and its decadal survey process. To fully realize the nation's investment, any agen-

[28] NRC, *Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions*, The National Academies Press, Washington, D.C., 2011.

cies that have commerce with a scientific discipline need to include in their own planning the science goals of the discipline's decadal survey.

Best Practice: Achieving the science goals of a decadal survey and successfully implementing survey recommendations requires that the science program be acknowledged as an interagency, multi-agency activity, one that typically extends beyond the purview of a NASA SMD division.

Best Practice: Participation by all relevant agencies is optimized when decadal reports include specific descriptions of the types of interagency collaboration that the decadal survey committee finds desirable.

Appendixes

A

NASA Strategic Goals and Objectives

Table A.1 lists NASA's Science Mission Directorate (SMD)-generated science goals and correlates them with the agency's overall goals and science strategic objectives, the decadal survey priorities, and the SMD missions (adapted from Appendix B of NASA's 2014 Science Mission Directorate Science Plan.[1]

[1] NASA, *2014 Science Plan*, 2014, http://science.nasa.gov/media/medialibrary/2014/05/02/2014_Science_Plan-0501_tagged.pdf.

TABLE A.1 Decadal Survey Priorities for NASA Science Mission Directorate (SMD) Science Goals and Missions

NASA Strategic Objective	SMD Division Science Goals	**Decadal Survey Priority** (Associated SMD Division Science Goals in parentheses)	**SMD Missions** (Associated Decadal Survey Priorities in parentheses)
NASA Strategic Goal: Expand the frontiers of knowledge, capability, and opportunity in space.			
HELIOPHYSICS Understand the Sun and its interactions with Earth and the solar system, including space weather.	1. Explore the physical processes in the space environment from the Sun to the Earth and throughout the solar system. 2. Advance our understanding of the connections that link the Sun, the Earth, planetary space environments, and the outer reaches of our solar system. 3. Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth.	a. Determine the origins of the Sun's activity and predict the variations of the space environment. (1, 3) b. Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs. (2, 3) c. Determine the interaction of the Sun with the solar system and the interstellar medium. (1, 2) d. Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe. (1, 2)	ACE (a, c, d) AIM (b) ARTEMIS (d) CINDI (b) Cluster-ESA (d) Geotail-JAXA GOLD (b) Hinode (Solar B)-JAXA (a, d) IBEX (a, c) ICON (b) IRIS (a, d) MMS (b, d) RHESSI (a, d) SDO (a, d) SOC-ESA (a, c, d) SOHO-ESA (a, c, d) Solar Probe Plus (a, c, d) STEREO (a, c, d) THEMIS (d) TIMED (b) TWINS (b) Van Allen Probes (d) Voyager (a, c, d) Wind (a, c, d)
PLANETARY SCIENCE Ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere.	1. Explore and observe the objects in the solar system to understand how they formed and evolve. 2. Advance the understanding of how the chemical and physical processes in our solar system operate, interact and evolve. 3. Explore and find locations where life could have existed or could exist today. 4. Improve our understanding of the origin and evolution of life on Earth to guide our search for life elsewhere. 5. Identify and characterize objects in the solar system that pose threats to Earth, or offer resources for human exploration.	a. Building New Worlds—advance the understanding of solar system beginnings (1, 2) b. Planetary Habitats—search for the requirements for life (3, 4) c. Workings of Solar Systems—reveal planetary processes through time (1, 2, 5)	BepiColumbo (a, c) Cassini (a, b, c) Curiosity (a, b, c) Dawn (a, c) ExoMars 2016 (c) ExoMars 2018 (a, b, c) Hayabusa 2 (a, c) JUICE (a, b, c) Juno (a, c) LADEE (a, c) LRO (a, c) Mars Express (c) Mars Rover 2020 (a, b, c) MAVEN (c) MESSENGER (a, c) MRO (a, b, c) New Horizons (a, c) Odyssey (a, b, c) Opportunity (a, b, c) OSIRIS-REx (a, c) Rosetta (a, c) Venus Climate Orbiter (a, b, c) Venus Express (a, b, c)

continued

TABLE A.1 Continued

NASA Strategic Objective	SMD Division Science Goals	**Decadal Survey Priority** (Associated SMD Division Science Goals in parentheses)	**SMD Missions** (Associated Decadal Survey Priorities in parentheses)
ASTROPHYSICS Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars.	1. Probe the origin and destiny of our universe, including the nature of black holes, dark energy, dark matter and gravity. 2. Explore the origin and evolution of the galaxies, stars and planets that make up our universe. 3. Discover and study planets around other stars, and explore whether they could harbor life.	a. Search for the first stars, galaxies, and black holes (1, 2) b. Seek nearby habitable planets (3) c. Advance understanding of the fundamental physics of the universe (1, 2)	ASTRO-H-JAXA (c) Chandra (a, c) Euclid-ESA (b, c) Fermi (a, c) Hubble (a, b, c) JWST (a, b, c) Kepler (b) LISA Pathfinder-ESA (c) NICER (c) NuSTAR (a, c) SOFIA^ (a, b) Spitzer (a, b) Suzaku-JAXA (c) Swift (a, c) TESS (b) XMM-Newton-ESA (a, c)
NASA Strategic Goal: Advance understanding of Earth and develop technologies to improve the quality of life on our home planet			
EARTH SCIENCE Advance knowledge of Earth as a system to meet the challenges of environmental change, and to improve life on our planet.	1. Advance the understanding of changes in the Earth's radiation balance, air quality, and the ozone layer that result from changes in atmospheric composition. 2. Improve the capability to predict weather and extreme weather events. 3. Detect and predict changes in Earth's ecological and chemical cycles, including land cover, biodiversity, and the global carbon cycle. 4. Enable better assessment and management of water quality and quantity to accurately predict how the global water cycle evolves in response to climate change. 5. Improve the ability to predict climate changes by better understanding the roles and interactions of the ocean, atmosphere, land, and ice in the climate system. 6. Characterize the dynamics of Earth's surface and interior, improving the capability to assess and respond to natural hazards and extreme events. 7. Further the use of Earth system science research to inform decisions and provide benefits to society.	a. Understand the complex, changing planet on which we live, how it supports life, and how human activities affect its ability to do so in the future. (3, 5, 6, 7) b. Revitalize the nation's research satellite system, providing near-term measurements to advance science, underpin policy, and expand applications and societal benefits* (5) c. Advance climate research, multiply applications using the full set of available (NASA and non-NASA) satellite measurements for direct societal benefit, and develop/mature technologies required for the next generations of Earth observing missions* (1, 2, 4) *NASA's 2010 climate-centric architecture plan	AirMOSS (c) Aqua (a, c) Aquarius (a, c) ATTREX (a) Aura (a, c) CALIPSO (a, c) CARVE (a) CloudSat (a, c) CYGNSS (b) DISCOVER-AQ (b) EO-1 (b) GPM (a, c) GRACE (a, c) GRACE FO (a, c) HS-3 (a) ICESat-2 (a, b, c) IIP (c) Landsat-8 (a, b, c) OCO-2 (a, c) Operation IceBridge (a, c) OSTM/Jason 2 (a, c) QuikSCAT (a, c) SAGE III (a, b, c) SMAP (a, b, c) SORCE (a, c) Suomi NPP (b) SWOT (a, c) TEMPO (a, b) Terra (a, c) TRMM (a, c)

^ The fiscal year 2015 budget greatly reduces funding for SOFIA.

B

Implementing the CATE Process

IMPLEMENTING THE CATE PROCESS

In the 2008 NASA Authorization Act, Congress mandated a "lifecycle cost and technical readiness" review of proposed NASA projects. Such reviews have become an important part of the decadal survey process. The cost and technical evaluation (CATE) process described in this appendix has been developed for the decadal surveys in order to provide an independent, standardized process to produce a *figure-of-merit* for technical and cost risk that aids in science prioritization. CATE, as implemented by the Aerospace Corporation in partnership with the decadal survey committee of the National Academies of Sciences, Engineering, and Medicine, is based on historical and continuously updated and validated databases and methods. It is designed to evaluate diverse mission concepts of varying design maturity.

The CATE methodology incorporates cost growth based on the historical record and the state of the design or development. CATE assesses the technical risk and readiness. It then monetizes the technical risks into potential *design growth* and associated *cost and schedule threats*. The objective of the CATE process is to perform a cost and technical risk analysis for a set of concepts that may have a broad range of maturity, and to assure that the analysis is consistent, fair, and informed by historical data.

Nature of System Development

The CATE is intended to forecast the potential cost of the final system as built, one that has typically undergone multiple iterations and that is often very different from the one initially conceived. A CATE estimate is therefore often more conservative than a conventional independent cost estimate because it accounts for design evolution and changes due to typical and unforeseen changes and challenges.

Missions evolve in cost and complexity, as notionally illustrated in Figure B.1. Experience shows that in most cases the cost of a space mission is not well understood until it has completed its preliminary design review (PDR). Even then, unexpected mass, cost, and schedule growth ordinarily occurs during the later phases of design and development. Historically, such changes have resulted in cost growth. For example, 20 space missions from 2008 to 2010 showed 37 percent and 41 percent mass and power growth, respectively, from Phase B to launch. The

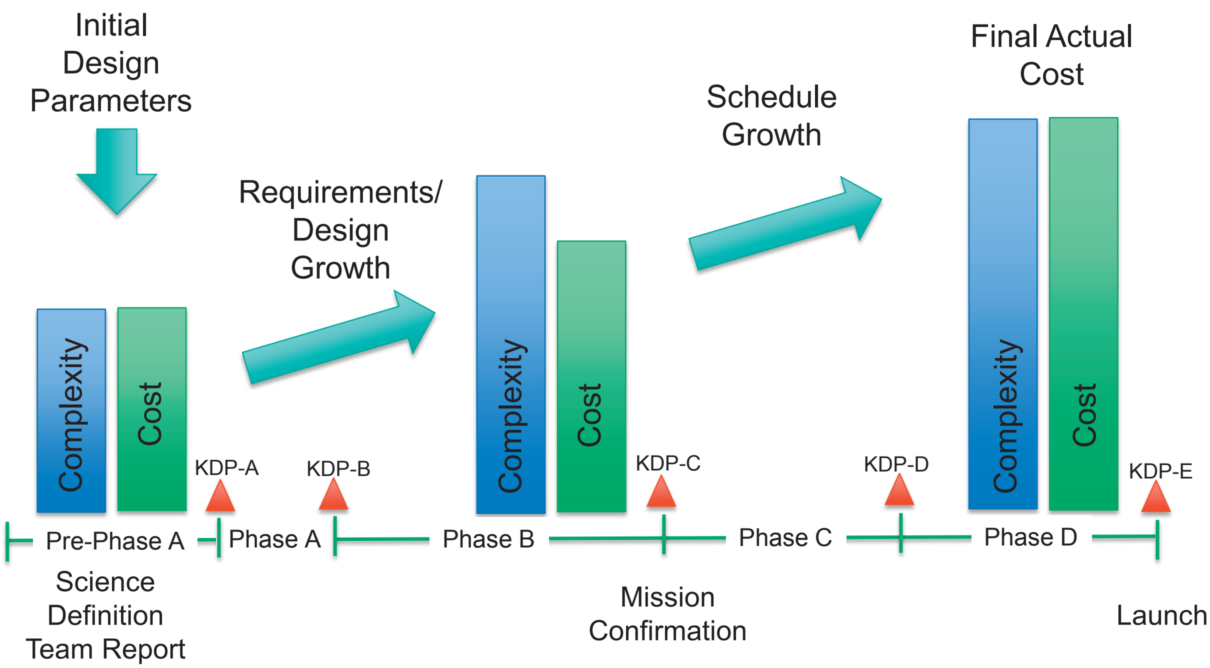


FIGURE B.1 Cost and complexity evolution during the life cycle of a project.

associated cost and schedule growth was 56 percent and 38 percent respectively.[1] Historical data like these were used to develop the CATE heuristics used to predict potential design evolution and, ultimately, potential cost growth.

Typically, concepts evaluated via the CATE process are early in their life cycle, and therefore liable to undergo significant design changes. The CATE process attempts to capture this potential growth by defining figures of merit based on cost and complexity. Fair evaluation requires that the relative maturity of concepts be taken into account. Some pre-Phase A concepts are more mature than others because greater resources have been devoted to their formulation. The CATE allows comparison of one concept of low maturity relative to another that has undergone several iterations and review. Also, recognizing that the organization that proposed or studied the mission may not be the one that ultimately implements it, the CATE process makes no assumptions about the eventual choice of an organization to implement the mission.

Application of CATE within the Decadal Survey Process

The CATE process operates within the committee and panel structure of a decadal survey. The 2011 planetary science decadal survey[2] (Planetary2011) provides a good case study. Before concepts were submitted to CATE, significant trades were considered. The initial steps were led by a representative from the survey's appropriate science panel, who considered the science value or science returned for an initial cost estimate provided by the advocates. A key aspect of the CATE process is that multiple interactions took place between the survey committee and the CATE contractor. In some cases, the Aerospace Corporation was directed to consider alternative solutions identified by the committee that might lower cost and risk, while maintaining science return.

[1] C.W. Freaner, R.E. Bitten, and D.L. Emmons, "Inherent Optimism in Early Conceptual Designs and Its Effect on Cost and Schedule Growth: An Update," 2010 NASA Program Management Challenge, February 2010.

[2] NRC, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, The National Academies Press, Washington, D.C., 2011.

The major elements of the standard CATE process and interactions with the CATE contractor and survey committee are shown in Figure B.2. The survey committee receives concepts through a variety of mechanisms, including requests for information (RFIs), as discussed in Chapter 2. The survey committee then provides a subset of those concepts to the CATE team for evaluation. The evaluation includes a technical assessment of risk, notional or estimated cost, and schedule for the mission. The CATE team performs its assessment of the concepts in parallel. In some cases, multiple iterations are required based on review and feedback from the panels and/or survey committee.

Each concept is examined in terms of heritage—for example, whether something similar has recently been developed or fielded—as much as possible making use of analogies with already-built systems with demonstrated costs and understood performance. Likewise, schedule evaluation makes use of analogies to determine expected development time. Historical data from previous analogous NASA missions, properly adjusted, are used in the CATE schedule analysis to gauge the realism of the proposed durations of the development phases. The time to critical mission reviews (e.g., preliminary design review and critical design review) and the time required for integration and testing are evaluated for each mission concept based on comparison with appropriate historical experience. In this way, CATE provides an independent estimate of cost and schedule of new concepts anchored by data from previously built hardware.

The CATE Process

A CATE consists of both a *technical evaluation* and a *cost evaluation*. The evaluation of technical risk and maturity, summarized in Figure B.3, focuses on the identification of the most important technical risks to achieving

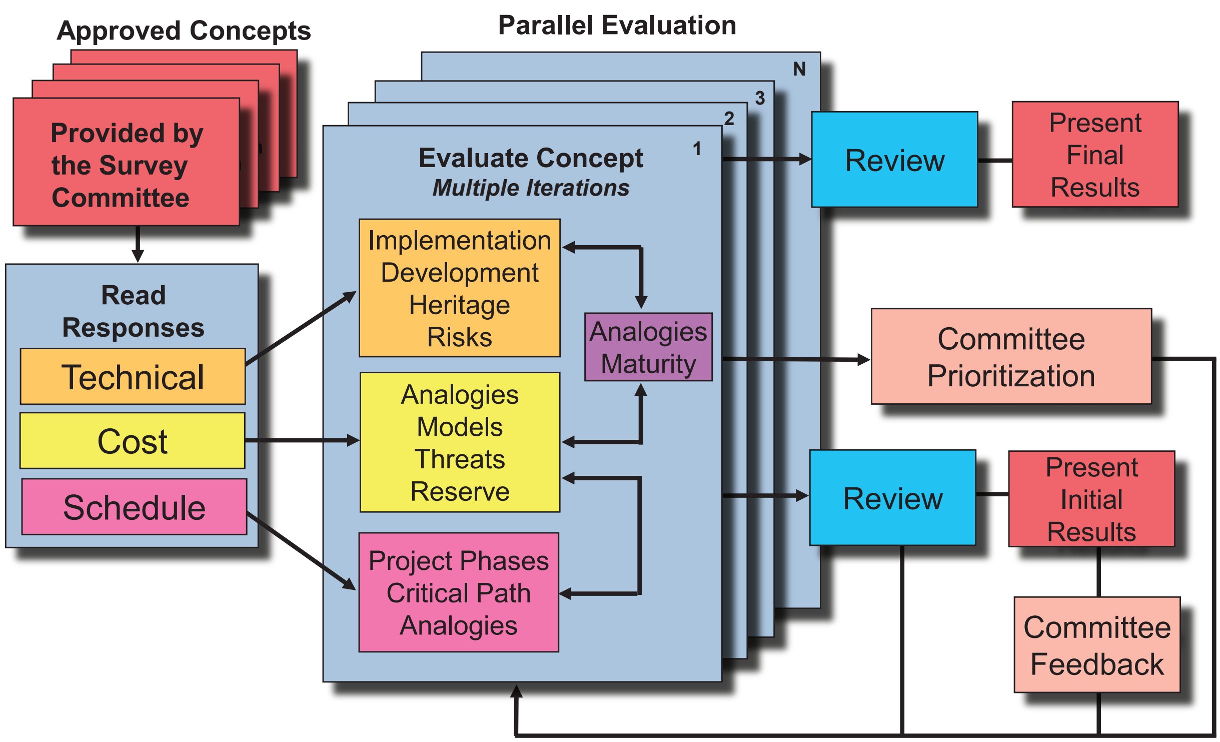


FIGURE B.2 Decadal cost and technical evaluation (CATE) process showing key elements and interactions with the Academies and the survey committee.

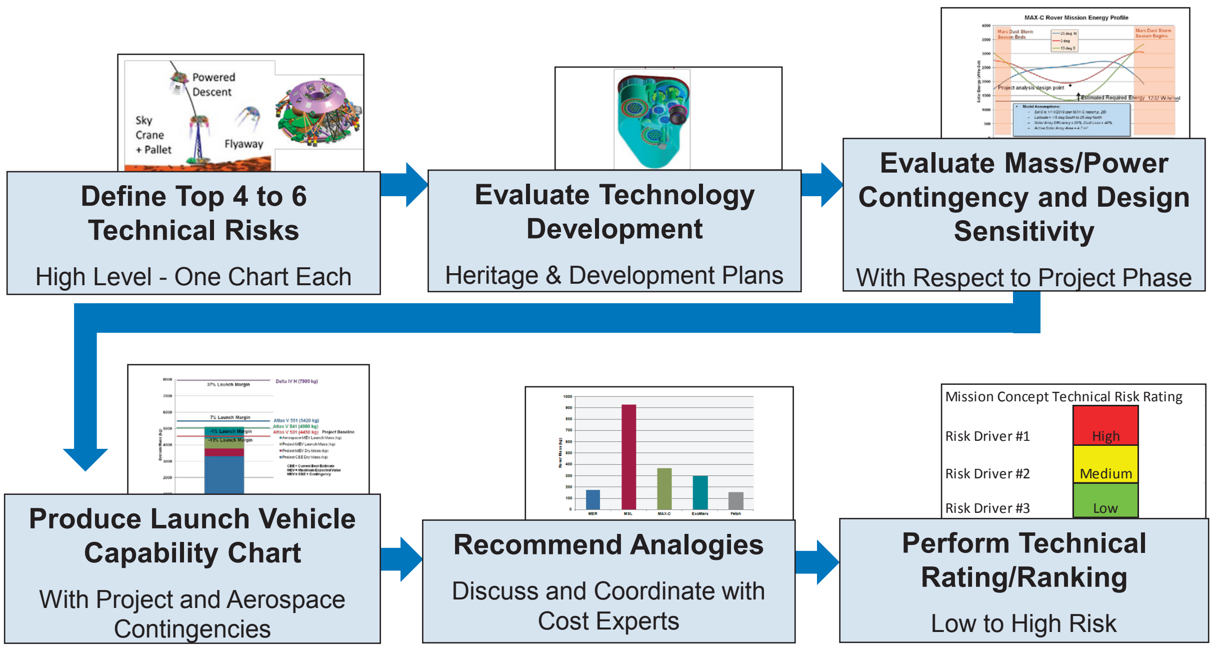


FIGURE B.3 The technical evaluation of the cost and technical evaluation (CATE) methodology includes a technology readiness evaluation and a peer-review of technical risks and rankings.

the required mission performance and stated science objectives. For the 2013 solar and space physics (heliophysics) decadal survey[3] (Helio2013) and Planetary2011, the technical evaluation consisted of two parts: (1) the proposed concept compared with previously developed systems for which the performance is known and (2) launch-vehicle "mass-to-orbit" capability—if the spacecraft weighs too much, it could exceed the launch-vehicle capability and require either a reduction in mass and/or a more capable, more costly launch vehicle.

Deviations from the current state of the art, as well as system complexity, operational complexity, and integration concerns associated with the use of "heritage components," are all identified. Technical maturity and the need for mission-specific technology development are evaluated by the CATE technical team to assess readiness levels of key technologies and hardware. During the assessment, the technical team interacts with the cost and schedule teams so that technical risks can be translated into schedule and cost risk. The key output is a technical risk rating: low, medium, or high.

The cost evaluation illustrated in Figure B.4 uses analogies and models to estimate cost for major elements, estimate reserves based on historical growth, and estimate design and schedule growth. The CATE employs multiple methods and databases representing past space systems such as proprietary models (e.g., Aerospace Small Satellite Cost Model) and space-industry standards (e.g., the NASA/Air Force Cost Model [NAFCOM]). The use of multiple methods such as analogies and standard cost models ensures that no one model or database biases the estimate. The use of system-level estimates and arriving at total estimated costs by statistically summing the costs of all individual work breakdown structure (WBS) elements ensures that elements are not omitted and that the system-level complexity is properly represented in the cost estimate. Tools such as the Complexity Based Risk Assessment (CoBRA) are used to cross-check cost and schedule estimates for internal consistency.

In an integrated fashion, the CATE process seeks to quantify the total "threats" to costs from schedule growth,

[3] NRC, *Solar and Space Physics: A Science for a Technological Society,* The National Academies Press, Washington, D.C., 2013.

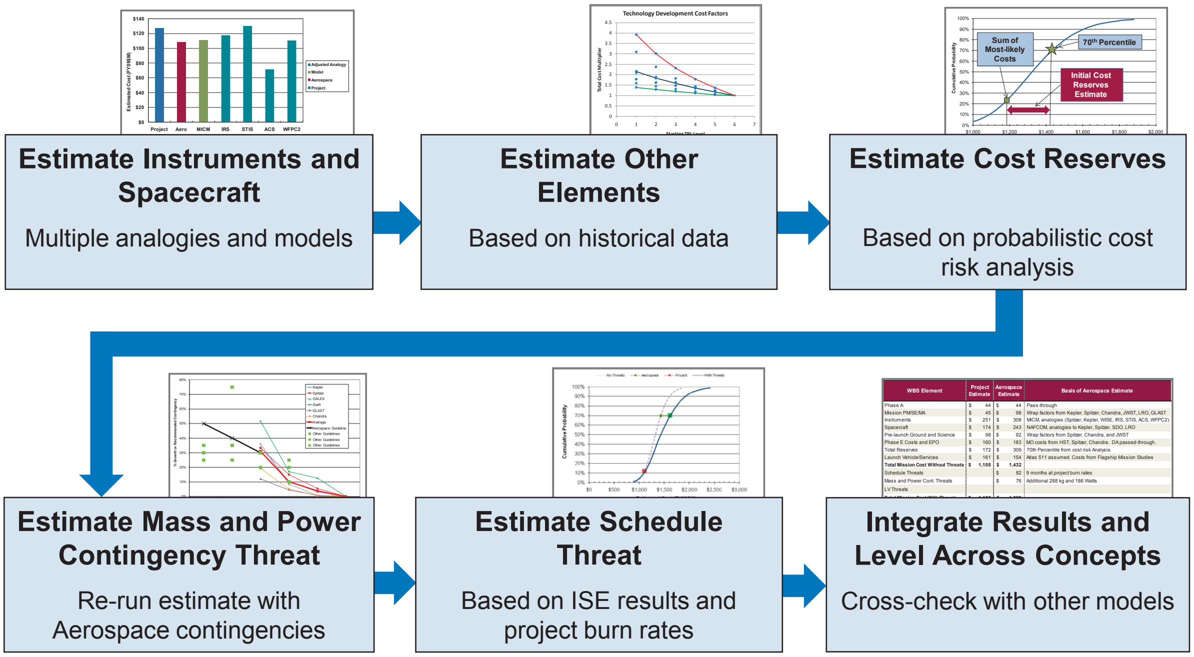


FIGURE B.4 The cost and technical evaluation (CATE) cost-estimating approach is a comprehensive, probabilistic assessment of potential mission cost and cost risk.

the costs of maturing technology, and from mass growth that would result in the need for a larger, more costly launch vehicle. The output is a probabilistic view of potential cost that envelopes the potential evolution of the system over time.

CATE Output

For all concepts, the CATE process estimates the cost increases associated with increased contingency mass and power, increased schedule, increased required launch vehicle capability, and other cost threats, depending on the concept maturity and specific risk assessment of a particular concept.

Traditional S-curves of cost probability versus cost are provided for each concept, with the project's internal and/or external estimate compared to the CATE estimate at the 70th percentile (as set by the survey committee). To aid in the assessment of concept risk, independent schedule estimates are incorporated as part of the CATE cost estimate. This is especially useful for assessment of risk with respect to proposed mission development and execution timelines.

An example of CATE summary output is shown in Figure B.5 for the Jupiter Europa Orbiter (JEO) mission concept from Planetary2011.[4] While the science was compelling and prioritized very highly, this particular mission concept was deemed unaffordable.

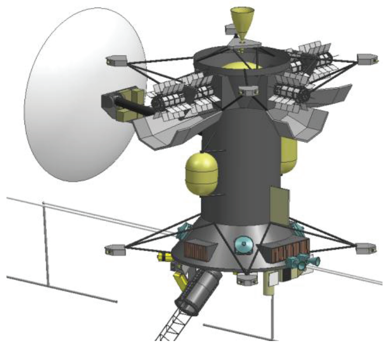
Summary

After its use in three decadal surveys, CATE has become a recognized and appreciated element of the survey process. CATE is useful for prioritizing elements of the program because it provides a standardized set of credible,

[4] NRC, *Vision and Voyages*, 2011.

Jupiter Europa Orbiter

Flagship-Class Europa Orbiter



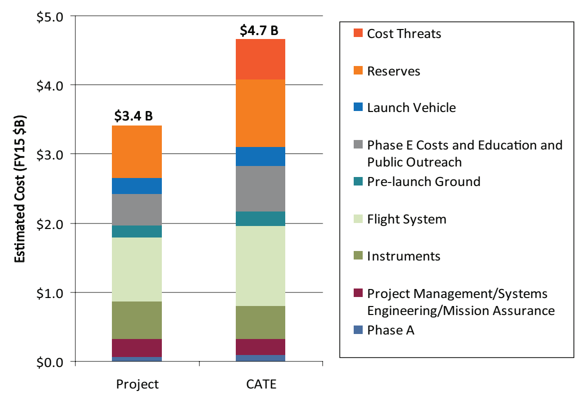
Key Challenges

- **Radiation**
  - *Systems engineering for electronics vault repartitioning*
  - *"Fail operational" fault management to handle environment*
- **Mass**
  - *Uncertainty in instrument and shielding mass*
  - *Low launch margin for this development phase*
  - *Overall sensitivity of system mass to changes*
- **Power**
  - *System impacts of changing number and design of radioisotope power system units*
  - *Availability of plutonium-238*
- **Instruments**
  - *Uncertainties in design of model payload*

Science Objectives

- **Explore Europa to investigate its habitability**
- **Key science issues addressed:**
  - *Characterizing the extent of the europan ocean and its relation to the deeper interior*
  - *Characterizing the ice shell and any subsurface water, including the nature of the surface-ice-ocean exchange*
  - *Determining global surface compositions and chemistry, especially related to habitability*
  - *Understanding the formation of surface geology, including sites of recent or current activity, and characterizing sites for future in situ exploration*
  - *Understanding Europa in the context of the Jupiter system*

Key Cost Element Comparison



Key Parameters

- **Model Payload**
  - *Ocean: Laser Altimeter, Radio Science*
  - *Ice: Ice Penetrating Radar*
  - *Chemistry: Vis-IR Imaging Spectrometer, Ultraviolet Spectrometer, and Ion and Neutral Mass Spectrometer*
  - *Geology: Thermal Instrument, Narrow Angle Imager, Wide and Medium Angle Imager*
  - *Particles and Fields: Magnetometer, Particle and Plasma Instrument*
- **Five Multi-Mission Radioisotope Thermoelectric Generators**
- **Launch Mass: 4,745 kg**
- **Launch Date: 2020 (on Atlas V 551)**
- **Orbit: 100-200 km Europa Orbit + Jovian Tour**

Cost Risk Analysis S Curve

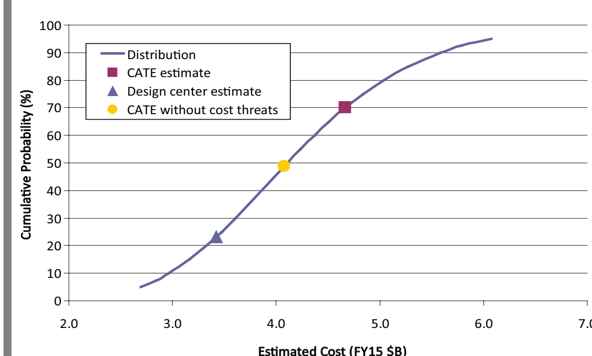


FIGURE B.5 Example of cost and technical evaluation (CATE) output including mission summary, key characteristics, risk assessment and cost-risk distribution. This information was used by panels and committee to assist in the prioritization process. SOURCE: National Research Council, *Vision and Voyages for Planetary Science in the Decade 2014-2022*, The National Academies Press, Washington, D.C., 2011.

objective, and independent information about cost, as well as technical and cost risk, for mission concepts. As discussed in Chapter 2, the interface with the CATE process has been customized for each survey. Although the discussion in this report has concerned the utility of CATE for evaluating space-mission concepts, attempts have been made to apply the CATE process ground-based systems and instruments as well, a likely issue for future surveys.[5]

A key value of CATE for the prioritization process is in understanding the "cost box" a particular concept fits within. The CATE information helps to start the discussion of what can be accomplished relative to a particular science question for a particular cost—even if the eventual implementation strategy turns out to be very different from what is assessed. The CATE process needs to be periodically reassessed and updated to ensure it remains both independent and true to its original goals.

[5] Notably, the 2010 astronomy and astrophysics decadal survey (Astro2010) performed a CATE analysis on the Large Synoptic Survey Telescope and the two "Giant Segmented Mirror Telescope" concepts, the Thirty Meter Telescope (TMT) and the Giant Magellan Telescope (GMT). Despite the Aerospace Corporation's lack of experience with these types of facilities, their analyses have been born out, including predicting the approximate amount of cost growth for both TMT and GMT.

C

Letter Requesting This Study

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

FEB 6 2014

Reply to Attn of: Science Mission Directorate

Dr. Charles Kennel
Chair, Space Studies Board
National Research Council
500 5th Street, NW
Washington, DC 20001

Dear Dr. Kennel:

The National Research Council's (NRC) decadal surveys in each of NASA's major science themes form the basis of long ranging planning in the Agency's research and flight mission programs. The delivery of the Heliophysics survey in 2012 marked the completion of the current round of updates. To take advantage of the experience obtained during the development of these complex and comprehensive outreach activities and the collateral analysis of options and opportunities, the NRC held a comprehensive workshop in November 2012 to hear from many of the participants in these processes. With the information collected at that workshop and the resulting workshop report, this is a good time to integrate and enunciate key findings from the experience and the workshop forum.

Developed during our discussions over the intervening months since the workshop, the enclosure provides a Statement of Task for a Space Studies Board follow-on study to consolidate the lessons-learned and record them in a format that will facilitate their use in the upcoming new round of surveys. Although the core funding for the Board includes resources for meetings of the Board, it is anticipated that supplemental funding will be needed to organize an ad hoc panel for this study, support the participation of invited task group members, and assemble the report.

A separate Annex, not part of the formal Statement of Task, is also provided for use in orienting the study panel and raising important issues relevant to the thrust of the proposed study. This Annex can be reflected in the work plan of the committee in the NRC's proposal to NASA for this activity.

We request that the NRC submit a plan for execution of a study responsive to the goals and schedule of the enclosed Statement of Task. Once agreement with the NRC on the scope and cost for the proposed study has been achieved, the NASA Contracting Officer will issue a task order for implementation. Dr. Marc Allen will be the SMD technical point of contact for this effort and may be reached at (202) 358-0733 or marc.allen@nasa.gov.

Sincerely,

Dr. John M. Grunsfeld
Associate Administrator
for Science Mission Directorate

Enclosure

cc: Science Mission Directorate/Ms. Dolores Holland
- Dr. Marc S. Allen

STATEMENT OF TASK

Survey of Surveys: Lessons Learned from the Decadal Survey Process

Background

Among the Space Studies Board's (SSB) projects and activities, its decadal surveys are the most prominent and influential. Since the first decadal survey was undertaken in the early 1960s the space science community, working under the leadership of the NRC, has drafted decadal surveys in astronomy and astrophysics (six times), planetary science (twice), solar and space physics (twice) and Earth science and applications from space (once).

Each survey represents a best estimate of the most important science and mission priorities for the coming decade based upon an assessment of the status of a specific scientific discipline at a particular moment in time. Moreover, the recommendations of each survey are implemented in widely differing fiscal and policy environments. Implementation has been challenged by a combination of fiscal, technical, programmatic, and policy factors, suggesting that the approach to future decadal surveys needs to be examined and possibly modified or improved. The decadal surveys initiated after 2007 incorporated new features and applied new procedures to address some of the issues responsible for the problems identified in the NRC's 2007 report *Decadal Science Strategy Surveys: Report of a Workshop*.

On November 12-13, 2012, the Space Studies Board hosted *Lessons Learned in Decadal Planning in Space Science: A Workshop* at the Beckman Center of the National Academies. The event brought together a variety of major stakeholders in the space community, both inside and outside of NASA, who are impacted by and/or are responsible for the formulation and implementation of the decadal surveys. While many ideas were surfaced at the workshop, no formal consensus conclusions can be reported from NRC workshop proceedings. Refining the participants' suggestions for new or revised approaches to decadal planning from the workshop and reporting the results of this deeper analysis are the principal goals for the present proposed study.

Statement of Task

The NRC will convene an ad hoc committee to consider lessons learned from the most recent NRC decadal surveys in space science. Primary attention should be devoted to the most recent surveys--i.e., heliophysics (2012), planetary science (2011), astronomy and astrophysics (2010), and Earth science and applications from space (2007)--but important lessons derived from earlier surveys may also be considered. The study will also review and consider the first round of NRC middecade assessment reports in astronomy and astrophysics (2007), planetary science (2007), solar and space physics (2009), and Earth science and applications from space (2012). The issues identified during the NRC's November 2012 lessons-learned workshop (as cited in the Annex to the Statement of Task), will be a major input to the committee's deliberations.

The committee will formulate a set of major lessons-learned from the recent decadal survey planning process and present a set of options for possible evolutionary changes and improvements to this process, including the statement of task, advance preparation, organization, and execution. The committee will not make specific recommendations.

The proposed study aims to provide a foundation for strengthening future surveys by analyzing and integrating findings in the sources above to address the following issues.

- The committee will identify best practices for a well-structured statement of task that will result in a report that reflects the consensus of the authoring community, meets short-term needs of the sponsoring agencies, and addresses the interests of other important constituencies, all while remaining relevant in the face of technology and science advancements, budget evolution, an international cooperation opportunities over the decade (and the following decade, for the largest projects). This analysis should recognize the primacy of science goals over implementing missions. The committee should consider, in particular, the pros and cons of a two-phase decadal survey process that results in a science prioritization report first and then, after a period of community interaction with NASA and mission formulation, a separate implementation prioritization report; and
- While respecting the procedures and policies of the NRC and of the Office of Management and Budget's (OMB) formulation of the President's budget request, the committee will also consider how to mitigate the impact of the so-called "two-year blackout problem." During the critical phases of survey recommendations development, NASA often cannot share budget (and closely budget-related planning) information due to OMB embargos and the NRC cannot share the status of ongoing deliberations on final recommendations.

Period of Performance

March 1, 2014 to August 31, 2015

Deliverables

Prepublication release of results	May 15, 2015
Final report and end of task	August 31, 2015

Survey of Surveys Task

Annex to the Statement of Task

- How did past surveys prioritize science goals, what lessons can be drawn from the various science prioritization processes and criteria they employed, and what are the best practices that can ensure that the science-first underpinning of the decadal surveys process is sound and clearly communicated to all the stakeholder constituencies?
- What factors led each of the most recent decadal surveys to take different approaches to the formulation of their respective science and mission priorities? For example:
  - What would be the pros and cons of, as suggested at the workshop, a two-phase decadal survey process that produces a science prioritization report first and then, after a period of community reflection and mission formulation, a separate implementation prioritization report?
  - How, by whom, and when should reference missions concepts, a key component of the decadal prioritization process, be formulated?
  - What are the options for establishing community-based candidate mission formulation and definition?
- How should mission concepts be prepared for the CATE analysis?[1] How should the purpose, goals, and implementation of the CATE process be clarified to help outside stakeholders understand better how the CATE process is implemented and used in future decadals?
- How can budget guidance provided to future decadal survey committees be improved and how should the survey committees and panels use this information in formulating their priorities so that their recommended programs will fit within fiscal constraints?
- How can U.S. interagency collaboration and international cooperation be efficiently integrated into the decadal process to deliver the best science? What are the possible mechanisms to improve alignment among the goals, motivations, and strategic planning activities of potential U.S. and non-U.S. partner agencies and organizations?
- To what extent can decadal survey committees use decision rules to support decision-making under changing circumstances during the decade, and what are the best ways to develop and articulate such rules? Are there promising alternatives to decision rules for promoting survey adaptability in the face of changing circumstances?
- What are the roles and responsibilities of: SSB standing committees; informal, community-based, analysis groups; and formal advisory committees in the planning and the long-term stewardship of the decadal surveys?

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[1] The Cost and Technical Evaluation, or "CATE" process is an analytical process devised by the NRC and the Aerospace Corporation to evaluate cost, schedule, and technical risk associated with the mission concepts considered for prioritization.

- What are the pros and cons of producing a stand-alone survey subpanel reports volume published alongside the survey committee's report versus an integrated committee/panel survey report in a single document?

D

Lessons Learned and Best Practices for Decadal Surveys

This appendix contains all the lessons learned and best practices that were identified in Chapters 1 to 4 of this report. They are provided by section in the preceding report, with the lessons learned listed first followed by best practices. Lessons learned have been identified during the current study as those activities or approaches by past decadal surveys that provide important insight into how to approach and perform the decadal-survey process. Best practices are activities from past surveys and concepts identified during this study that could be utilized during future decadal surveys to facilitate the survey and maximize their ultimate utility to the agencies and to the scientific community.

DECADAL SURVEYS: COMMUNITY CONSENSUS IN SCIENCE PRIORITIES

Statement of Task

Best Practice

- Those drafting new statements of task do well to review the statements of task for the previous survey in the field as well as the most recent round from other disciplines for historical and comparative value.

THE DECADAL SURVEY PROCESS

Common Factors and Differences Between Disciplines

Lessons Learned

- There is no "one-size-fits-all" approach to a decadal survey. Each discipline has cultural heritage and scientific goals that cannot be directly mapped to any other group.
- The presently used process for conducting decadal surveys is able to accommodate these differences in the four disciplines and achieve the goal of community consensus on science goals and the activities that are required to achieve them.

Best Practices

- Because the disciplines are so different, clear articulation of their unique aspects is useful to readers of the survey reports who might expect "uniformity" in approach across the surveys.

Mission Definition and Formulation

Lessons Learned

- The tendency to over-define mission concepts in pursuit of more accurate cost evaluation can stifle creative approaches to addressing survey goals.
- Because each of the disciplines define and develop missions differently, there can be no uniform approach in dealing with mission concepts from prior decadal surveys, mission concepts that are under competition, or missions in Phase A study. Nonetheless, it is highly desirable for a survey committee to decide early on how to deal with such situations and to communicate this to the panels.

Best Practices

- A solicitation process to gather community input via white papers together with invited presentations by community groups and field leaders broadens survey participation and ensures there is opportunity to consider important activities for the coming decade. This approach recognizes emerging opportunities and innovative approaches to program implementation that may not be readily apparent to the members of the survey committee and panels.
- The practice within decadal surveys of not defining specific NASA mission concepts for lower cost and competed missions, yet recommending that such missions address priority decadal survey goals and objectives, allows flexibility to leverage innovative implementation approaches.
- A two-step CATE process that allows more concepts to remain in consideration in the early stages of the survey includes a faster, cruder "cost box" analysis for a longer list of candidate concepts. This would be followed by a detailed CATE for candidates for the final program that require more detailed assessment due to their cost, complexity, risk, or importance to the community.
- Decadal surveys can present their implementation strategies as *reference missions*—that is, a credible hardware configuration that can achieve the science goals and is sufficiently defined for robust cost evaluation—instead of blueprints for detailed implementation.
- It is desirable that the survey committee determine, as early in the process as possible, how robust a mission concept needs to be to provide sufficient cost certainty. An example is an ambitious mission where the survey committee needs to know—with reasonable confidence—that a mission team will be able to propose a credible design that meets science requirements and fits within the cost cap for the mission class.

Science and Mission Prioritization

Lessons Learned

- Although science goals may not be explicitly ranked, science priorities drive the rankings of missions, facilities, programs, and other activities.
- Experience indicates that survey prioritization puts a high value on programmatic balance across missions and facilities, and is also attentive to the need for long-term continuity in certain observational data.
- Technical readiness and affordability can often influence science prioritization of missions and facilities. High-priority science may be deferred if needed technology is immature and there is a significant risk of cost growth that would affect both scope and schedule.
- The potential for international collaboration, interagency cooperation, and inclusion of the private sector impacts science and mission prioritization across all disciplines.

Best Practices

- Therefore, the best practice for decadal surveys is to choose and describe reference missions (see below, "Suggested Changes in the Prioritization Process") that are judged capable of carrying out the science, but to encourage agencies to follow, first-and-foremost, the *science objectives* of the prioritized missions.
- Establishing a community-wide consensus is arguably the most important goal of a decadal survey, and community "buy-in" to the decadal survey's process is crucial. Community trust in the decadal survey process depends on a clear understanding of the prioritization methodology used by the survey committee and its supporting panels.

Suggested Changes in the Prioritization Process

Lessons Learned

- It is important that decadal surveys explicitly note which proposed missions are *reference missions*—i.e., subject to further development—versus those intended as explicit implementation recommendations based on mature and well-refined concepts.
- The community has many means, especially between decadal surveys, to address the evolution of science in the discipline. This forms the basis of a two-phase process without separating the decadal survey process itself in two.

Best Practice

- Agencies, committees of the Academies, community workshops and meetings, and white papers can contribute to pre-survey science priority identification as preparation for, and a valuable contribution to, the next survey. These activities can also spur early development, evaluation, and maturation of concepts for new missions for potential priorities well in advance of the survey itself.

Cost and Technical Evaluation: The CATE Process

Lessons Learned

- CATE involves assessment of a single point design to assess cost and technical risk. It is most useful as a reasonableness check on what is being recommended. Details used to support the CATE analysis are not necessarily indicative of how a mission will ultimately be implemented.
- The combination of budgetary constraints (wedges) and large, complex mission concepts can lead to difficult choices, reinforcing the need for a thorough understanding of mission costs and risks as well as the establishment of clear decision rules.
- The CATE process benefited from and indeed depended on, survey committee and panel members serving as liaisons between Aerospace Corporation's CATE team and panels. Continuity of some individuals across multiple surveys also served a useful purpose as each survey had different experiences, and "lessons learned" were fed forward. Panels provided an important cross-check critique and key feedback to the CATE process.

Best Practices

- The survey committee can choose, and subsequently identify in its report, the role of CATE in their survey. The CATE could provide, for example, a best-possible cost estimate for a point design or an independent, rough estimate for comparative purposes.
- To prevent the CATE analysis from unnecessarily "driving" the decadal survey process, survey committees can consider implementation of a two-step CATE in which rough technical readiness and risk assessment feedback (accurate to a factor of two or three) would be provided for most, if not all, concepts early in the survey process. The more detailed and comprehensive CATE analysis (as used in recent surveys) would be reserved for those concepts that the committee identifies as worthy of further study.
- Decadal survey committees are advised to determine a fair and consistent way to evaluate all international partnerships, which would be communicated to the panels early in the decadal process. The technical evaluation can be comprehensive and inclusive of the international portions and risks. However, assessment for affordability may need to be, in a pragmatic sense, for the U.S. portion only.
- When composing the survey committee, it is worth considering identification of one or more liaisons who will serve as go-betweens the panels, the committee, and the Aerospace Corporation's CATE team.

THE DECADAL SURVEY'S RECOMMENDED PROGRAM

The Existing Program

Best Practices

- Decadal surveys may review the recommended program from previous surveys and choose to endorse certain activities in their own recommendations. Such reviews are best if they focus on those missions and facilities that play a critical role in the proposed science of the survey report.
- It is desirable that the statement of task explicitly address the extent to which existing programs or projects are to be reviewed and recommendations from prior decadal surveys are to be revisited.

The Decadal Survey's Recommended Program

Lessons Learned

- Although extended mission phases are not generally budgeted for future missions in the decadal survey process, they may present significant hidden costs that may influence decadal survey implementation cadence.
- High-profile missions are special cases within each of the disciplinary areas, presenting great opportunities for major advances in understanding, but also carrying significant risk for maintaining a balanced portfolio of activities—should unanticipated cost growth occur.
- Mission creep within high-profile missions and large facilities and a general unwillingness to de-scope or cancel large missions or facilities during development can result in large, negative impacts on other programs at the division and directorate level.

Best Practices

- It is important for the decadal survey to estimate and clearly describe and illustrate in their report potential liens on the following decade from their recommended program.
- It is highly desirable that the decadal survey report includes clear discussions on how the decadal survey committee determined the optimal balance of programs and activities for the coming decade.
- It is incumbent on a decadal survey report to clearly delineate the respective roles of NASA, NSF, NOAA, USGS, and/or other federal agencies in implementing the science program when the capabilities and interests of multiple agencies are involved.
- When recommending high-profile missions, survey committees are advised to explicitly state which aspects of the mission are essential to retaining the mission's consensus priority and which can be further considered during design development to enable cost control.
- Clear decision rules for high-profile missions and large facilities that include both de-scope and cancellation options can provide some level of protection against unconstrained cost growth and possible collateral damage to other programs.
- While high-profile missions are likely to retain their high ranking from one decadal survey to the next, evolution in mission concepts and changing science priorities may occur over time. As such, it is desirable that the survey committee and panels carefully evaluate all candidate mission concepts on their merits, rather than be unduly influenced by advocacy and inertia.
- Strong preferences by the agencies on how to deal with high-profile missions and interagency and/or international participation in missions and facilities need to be spelled out in the statement of task.
- In developing the recommended decadal program, survey committees and panels are advised to include explicit consideration of various forms of programmatic balance. This might include, for example, the balance across the subdisciplines, between mission and non-mission activities, between novel and continued observations, across mission and facility cost, and between program elements (e.g., R&A, technology, infrastructure, missions) and activities (e.g., education, engagement, and workforce development).

- It is desirable that discussion of technology development in the decadal report be included in both the survey recommendations section and in the panel reports, so that technology requirements for the coming decade (and beyond) can be adequately captured, while identifying subdiscipline-specific requirements.

Communication of the Recommended Program

Lessons Learned

- While the survey report is the primary result of the decadal process, engagement of stakeholders and the broader community in the survey recommendations is also critical to the success of decadal surveys. Communication by the decadal survey committee leadership and members with science community groups and at science and society meetings promotes broad community buy-in.
- A single, unified list is expected by many stakeholders—and when one is not provided, the closest thing to it will be used—more often, misused. It is very important that the survey report carefully describes the recommended program in its entirety, with proper emphasis on lists of prioritized missions and facilities.
- Individual chapters representing the work of the panels provide important information and the backstory to the final recommendations of the decadal survey in terms of both science priorities and implementation strategies. As panels represent subdisciplines within the decadal survey, all their priorities do not necessarily align with the survey committee, but are used as critical input into the discussions of the survey committee.
- As the best and most detailed record of community input, a decadal survey's panel reports are a fundamental part of the survey's work product. It is essential that they be made public along with the committee report. Publishing the survey committee report and the panel reports together, as has often been done, has the important advantage of providing traceability within one document of the decadal survey process of science and program prioritization.

Best Practices

- Community acceptance and buy-in on decadal survey recommendations requires careful documentation and communication by the survey committee of their decision-making process for developing science goals and objectives and tracing these into a recommended program of activities for the decade.
- When drafting the decadal survey report, it is best that authoring committees remain mindful of the wide audience for the report, including the international discipline community, federal agencies, Congress, the federal executive branch, and the public, to ensure clear and effective communication of the community's consensus science priorities as expressed in the decadal survey report. Professional societies, such as the American Astronomical Society and the American Geophysical Union, can be very effective in disseminating the survey program to a wide audience.
- When drafting a decadal survey it is important to clarify the intended use of the cost appraisal for each mission or facility: Is it for a configuration that is intended to serve as (1) a "proof of a concept" that merely establishes the scale of the project; (2) a cost estimated for a mature, well studied concept; (3) as a cost cap; or (4) something else entirely.
- To the extent possible, it is desirable that survey committees craft text that describes the priority activities—*why* they are the priorities and under what circumstances those priorities might change. So-called "decision rules" that are clearly identified in the survey report can help with this process. Collections of all decision rules in a single section, with traceability back to the body of the report, will facilitate clear communication of the decadal survey's intent.
- It is important for survey report to clarify the extent to which implementation details are prescriptive or notional, in order to ensure that agencies understand the committee's intent when developing their implementations strategies.

- In some cases, it is desirable for survey committees to document not only the missions and facilities that are part of the recommended program, but also those that were considered but not prioritized, as well as the rationale behind decisions.
- Development by each panel of prioritized science goals and implementation strategies ensures that its community's science priorities are fully understood and considered for incorporation into the recommended program for the coming decade.
- A clear articulation of the roles played by the survey committee and panels in absorbing, analyzing, and prioritizing the community's science goals, within and across the discipline is essential for securing community support for the finished survey—a crucial element of a decadal survey's credibility to stakeholders.
- To make clear the utility of panel reports and to reduce ambiguity as to their use, decadal committees can choose to publish the panel reports in the same volume as the survey report, adding clear labeling that the panel reports are for reference only.

IMPLEMENTING THE DECADAL SURVEY

Decision Rules

Lesson Learned

- Decision rules provide deeper insight into the survey scientific priorities and reflect the wisdom and consensus of the scientific community.

Best Practices

- Decision rules ordinarily are best when strategic in nature rather than tactical. The objective is to provide insight into how science priorities evolve or change under specific circumstances without over-constraining implementation. Long-term advice that advances the scientific goals of the community is useful, whereas short-term rules quickly become obsolete or are better determined by administrators, policy makers, and community members familiar with the immediate situation.
- The best decision rules are clear, unambiguous, and easy to implement without being overly prescriptive. Decision rules are best designed to support the achievement of survey priorities, without overly specifying the means by which they are achieved. Clear if-then rules are more useful, whereas decision rules that require interpretation may often be less helpful. For example, references to general concepts (like balance) are difficult to understand, implement, and evaluate without specific definition and guidance.

- Decision rules need to be clearly identified and labeled as such in the survey report. In order to facilitate clear communication, all of the decision rules from the entire survey should be collected in one section, with each being traceable back to the body of the report.
- Decision rules can be evaluated as part of the mid-term assessment process. This may include reviewing existing decision rules, assessing their status, and considering whether any specific decision rule requires reevaluation due to emerging circumstances.

Stewardship

Lessons Learned

- As long as the standing committee restricts its work to the current program, there is no meaningful conflict that would preclude continuation of the SSB standing committees during the execution of a decadal survey.
- The current advisory structure does not provide an effective mechanism for provision of short-term tactical guidance from the scientific community (i.e., tactical guidance for accomplishing strategic visions).
- The AAAC can play an important and unique role in stewardship of a decadal survey through its focus on interagency cooperation.
- Providing scores or grades in a midterm assessment report can result in unintended consequences when used by a wide audience. When grades are used, it is best if narrative text clearly indicates the desired response to a good or bad grade.
- Midterm assessments offer an opportunity to initiate the process of concept development for the next decadal survey. While primarily serving to provide a report on progress to date, the assessments can also act as forward-looking documents in the preparation for future decadal planning.

Best Practices

- SSB standing committees can continue their work throughout the period when a new decadal survey is in progress in order to provide an uninterrupted channel of communication between these committees and NASA and other agencies, with respect to strategic issues *that concern the current program*.
- NASA division directors and program officers for other interested agencies (e.g., NSF, the National Oceanic and Atmospheric Administration, the U.S. Geological Survey) can work with the SSB's standing committees to commission letter reports, meetings of experts, or workshops when specific advice is needed on a more rapid turnaround basis.
- Midterm assessment reports are most useful when they engage and inform the broad community by providing a progress report on implementing the decadal program, together with sufficient context to understand the rationale behind the program's current implementation strategy.

International Activities

Best Practices

- By identifying the essential features and potential challenges international collaborative missions and projects early on, decadal surveys can recommend processes and procedures for avoiding breakdowns, thus limiting the impact in science and cost on both sides.
- Decadal studies can use a combination of existing scientific conferences, meetings, and symposia, as well as more targeted dialogues between survey committees and their closest analogs in the scientific advisory apparatus of other countries, to ensure that lines of communication are open.
- Individual, non-U.S. scientists can be invited to participate in a decadal survey. Participants need to be selected for their scientific backgrounds and expertise, and not as institutional representatives, and be cognizant of a broad range of international activities. International representatives that are experienced and senior enough can provide information that will open avenues for collaboration and strengthen channels of communication back to their home space agencies and national space societies and organizations.
- Decadal reports can include specific descriptions of the types of international collaboration that the decadal survey committee finds desirable (e.g., cost-sharing, development of instrumentation, coordination of individual missions, or mission architecture).
- Decadal reports can explicitly identify any significant programmatic uncertainties and/or craft decision rules that might be required when considering international collaborations. This may be particularly important when international collaborations are a significant component of the survey's recommended program—in terms of budget or scientific strategy.

Interagency Issues

Best Practices

- Achieving the science goals of a decadal survey and successfully implementing survey recommendations requires that the science program be acknowledged as an interagency, multi-agency activity, one that typically extends beyond the purview of a NASA SMD division.
- Participation by all relevant agencies is optimized when decadal reports include specific descriptions of the types of interagency collaboration that the decadal survey committee finds desirable.

E

Committee and Staff Biographies

COMMITTEE

ALAN DRESSLER, *Chair*, is an observational astronomer at the Observatories of the Carnegie Institution. His principal areas of research cover the formation and evolution of galaxies and the study of star populations of distant galaxies. Dr. Dressler has made significant contributions in the understanding of galaxy formation and evolution, including effects of the environment on galaxy morphology. He was a leader in the identification of the “great attractor,” which causes a large distortion of the Hubble expansion. From 1993-1995, he chaired the Associated Universities for Research in Astronomy committee “HST & Beyond: Exploration and the Search for Origins” that presented NASA with “A Vision for Ultraviolet-Optical-Infrared Space Astronomy,” which now forms a substantial component of the NASA program in astrophysics. Dr. Dressler received his Ph.D. in astronomy from the University of California. He is a member of the National Academy of Sciences and has previously served on a number of committees of the National Academies of Sciences, Engineering, and Medicine, including the Planning Committee on Lessons Learned in Decadal Planning in Space: A Workshop (co-chair), the 2010 astronomy and astrophysics decadal survey (Astro2010) Panel on Electromagnetic Observations from Space (chair), the Committee on the Assessment of a Plan for U.S. Participation in Euclid, the Panel on Implementing Recommendations from New Worlds, New Horizons Decadal Survey, and as a member of the Space Studies Board.

DANIEL N. BAKER is director of the Laboratory for Atmospheric and Space Physics at the University of Colorado, Boulder (CU-Boulder). He is distinguished professor of planetary and space physics and is the Moog-Broad Reach Endowed Chair of Space Sciences. Dr. Baker holds appointments as professor of astrophysical and planetary sciences and as a professor of physics at CU-Bolder. His primary research interest is the study of plasma physical and energetic particle phenomena in planetary magnetospheres and in the Earth’s vicinity. Dr. Baker conducts research in space instrument design, space physics data analysis, and magnetospheric modeling. He currently is an investigator on several NASA space missions, including the MESSENGER mission to Mercury, the Magnetospheric MultiScale mission, and the Radiation Belt Storm Probes mission. Dr. Baker is a fellow of the American Geophysical Union (AGU), the International Academy of Astronautics, the American Institute of Aeronautics and Astronautics (AIAA), and the American Association for the Advancement of Science (AAAS). Among his awards are University of Colorado’s Robert L. Stearns Award for outstanding research, service, and teaching (2007) and the AIAA James A. Van Allen Space Environments Award for excellence and leadership in space research (2010). He was selected as the Vikram A. Sarabhai Professor of the Indian Physical Research Laboratory (2015) and also has received the Shen Kuo Medal of the International Association of Geomagnetism and Aeronomy (2015). Dr. Baker served as president of the Space Physics and Aeronomy section of the AGU (2002-2004), and he presently serves on advisory panels of the U.S. Air Force and the National Science Foundation (NSF). He earned his Ph.D. in physics from the University of Iowa. Dr. Baker is a national associate of the National Research Council and a member of the National Academy of Engineering. His most recent service for the Academies includes the Committee on the Review of the National Science Foundation's Division on Atmospheric and Geospace Sciences Draft Science Goals and Objectives, the Committee on the Effects of Solar Variability on Earth's Climate: A Workshop, the Committee on a Decadal Strategy for Solar and Space Physics (chair), the Committee on the Assessment of Impediments to Interagency Cooperation on Space and Earth Science Missions (co-chair), and the Space Studies Board.

DAVID A. BEARDEN is general manager of the Civil and Commercial Programs Division within Civil and Commercial Operations at Aerospace Corporation and is responsible for management technical leadership of the company's support to NASA Headquarters and centers. He leads a multidisciplinary team of scientists and engineers that develops and sustains technical consulting business from civil agencies, commercial companies, and international space clients. Through training courses and daily involvement in the delivery of technical expertise to customers, Dr. Bearden has gained considerable expertise concerning the issues, risks, and potential solutions in many cutting-edge technical fields, including technology insertion analysis balancing benefit, cost and risk, as well as telecommunication and remote sensing. He is a nationally recognized cost analysis expert, and has more than 20 years of technical and management experience in the acquisition and development of advanced technology space systems. Since joining Aerospace in 1991, Dr. Bearden led the Hubble Space Telescope Servicing Analysis of Alternatives, which earned him the 2006 Aerospace Corporation's President's Award. In the summer of 2009, he led the Aerospace team that served as the technical arm of the Augustine Committee. Dr. Bearden has led various mission studies, including the Lunar Robotic Exploration Architecture and Mars Sample Return studies. He has served on a number of standing review boards and Academies panels, including the Beyond Einstein Program Assessment Committee . Most recently, he served as a member of the SMAP, Aquarius, OCO-3, Heavy Ion Sensor, and ICON Standing review boards. In 2013, Dr. Bearden was among the recipients of a NASA Group Achievement Award for Technical Support to Aquarius/SAC-D Standing Review Board. He has authored chapters in *Space Mission Analysis and Design* and *Reducing the Cost of Space Systems*. He was the recipient of the Aviation Week & Space Technology Annual Aerospace Laurels in 2000 for conducting the first quantitative assessment of NASA's faster-better-cheaper initiative in space exploration. Dr. Bearden was awarded a Ph.D. in aerospace engineering from the University of Southern California. He also earned an M.S. in aerospace engineering from the University of Southern California and a B.S. in mechanical engineering and computer science from the University of Utah, Salt Lake City. His previous service for the Academies includes the Committee on the Assessment of Impediments to Interagency Cooperation on Space and Earth Science Missions and the Beyond Einstein Program Assessment Committee.

ROGER D. BLANDFORD is the Luke Blossom Professor in the School of Humanities and Sciences and a professor of physics at Stanford University and at SLAC National Accelerator Laboratory. He is also on the faculty at the Kavli Institute for Astrophysics and Cosmology (KIPAC) at Stanford University. Dr. Blandford is a distinguished theorist with broad expertise in high-energy and plasma astrophysics, active galactic nuclei, x-ray astronomy, and black holes. His research interests include cosmology, black hole astrophysics, gravitational lensing, galaxies, cosmic rays, neutron stars, and white dwarfs. Most recently, Dr. Blandford was the chair of Astro2010. Prior to this he was chair of the NSF Division of Astronomical Sciences Senior Review, which recommended significant changes in some NSF programs. He is a member of the National Academy of Sciences, the American Astronomical Society (AAS), a fellow of the Royal Society, a fellow of the Royal Astronomical Society, and a fellow of the American Academy of Arts and Sciences. Dr. Blandford is a recipient of the AAS Helen B. Warner Prize, the AAS Dannie Heineman Prize, the Royal Astronomical Society Eddington Medal, and the Humboldt Research Award. From 2003 to 2013, he was the Pehong and Adele Chen Director of KIPAC. He received his Ph.D. in 1974 from Magdalene College, Cambridge, U.K., in astrophysics. Dr. Blandford's most recent service for the Academies includes the Committee on the Science of Team Science (current member), the Committee on an Assessment of the Astrophysics Focused Telescope Assets (AFTA) Mission Concepts, and the 2010 Committee on the Decadal Survey on Astronomy and Astrophysics (chair).

STACEY W. BOLAND is a senior systems engineer at Jet Propulsion Laboratory and is the project systems engineer for ISS-RapidScat. Previously she served as the observatory system engineer for the Orbiting Carbon Observatory-2 Earth System Science Pathfinder mission. She is also a cross-disciplinary generalist specializing in Earth mission concept development and systems engineering and mission architecture development for advanced (future) Earth observing mission concepts. Dr. Boland received her B.S. in physics from the University of Texas, Dallas, and her M.S. and Ph.D. degrees in mechanical engineering from California Institute of Technology. She was awarded NASA's Exceptional Achievement Medal in 2009. Her participation in activities of the Academies includes current membership on the Committee on Earth Science and Applications from Space and prior membership on the Planning Committee on Lessons Learned in Decadal Planning in Space: A Workshop, the Committee on the Assessment of NASA's Earth Science Program, and the Committee on the Assessment of Impediments to Interagency Cooperation on Space and Earth Science Missions.

WENDY M. CALVIN is a professor at the Department of Geological Sciences of the University of Nevada, Reno. Her research focuses on understanding the nature and association of water, volatile ices, and minerals in order to better understand physical and chemical processes occurring in a variety of planetary and space environments. Her studies include meteorites, asteroids, icy satellites, Mars, and Earth. Dr. Calvin helped discover oxygen in the surface of Jupiter's moon Ganymede and ammonia ices on Pluto's satellite Charon, and she has an active research program to understand the polar regions of Mars. She was a participating scientist with the Mars Exploration Rovers, and she was co-investigator on the MARCI camera for the Mars Reconnaissance Orbiter. Dr. Calvin received her Ph.D. in geophysics from the CU-Boulder. Her previous service for the Academies includes the Committee on the Planetary Science Decadal Survey: 2013-2022, the Planetary Science Decadal Survey: Mars Panel (vice chair), and the Review of the NASA Strategic Roadmaps: Science Panel.

ATHENA COUSTENIS is a director of research with the National Centre for Scientific Research of France and is currently based at Paris Observatory in Meudon. Dr. Coustenis works in the field of planetology. Her research focuses on the use of ground- and space-based observatories to study solar system bodies. Dr. Coustenis' current interests include planetary atmospheres and surfaces, with particular emphasis on the satellites of the giant planets. She is also interested in the characterization of the atmospheres of extrasolar planets. In recent years, she has been leading efforts to define and select future space missions to be undertaken by the European Space Agency (ESA) and its international partners. She is the chair of the European Science Foundation's European Space Science Committee—the nearest equivalent to the SSB in Europe. She earned her Ph.D. in astrophysics and space techniques from the University of Paris. She has also chaired and served on numerous ESA and NASA advisory groups.

J. TODD HOEKSEMA is a senior research scientist in the W.W. Hansen Experimental Physics Laboratory at Stanford University. His professional experience includes research administration, system and scientific programming, and the design, construction, and operation of instruments to measure solar magnetic and velocity fields from both the ground and space. He is co-investigator and magnetic team lead for the Helioseismic and Magnetic Imager on NASA's Solar Dynamics Observatory and was instrument scientist for the Michelson Doppler Imager instrument on the Solar and Heliospheric Observatory that was launched by NASA and ESA. He has been associated with the Wilcox Solar Observatory at Stanford for three sunspot cycles and now serves as director. His primary scientific interests include the physics of the Sun and the interplanetary medium, solar-terrestrial relations, the large-scale solar and coronal magnetic fields, solar velocity fields and rotation, helioseismology, and education and public outreach. Dr. Hoeksema currently serves as secretary of the Solar and Heliospheric Physics subsection of Space Physics and Aeronomy in the AGU. He chaired the Solar Physics Division of the AAS and has served on the heliophysics subcommittee of the NASA Advisory Council Science Committee. Dr. Hoeksema led NASA's Heliophysics Roadmap team in 2005. He has been awarded the NASA Distinguished Public Service Medal and is a member of the AAS, the AGU, the International Astronomical Union, the American Scientific Affiliation, and the AAAS. For several years, Dr. Hoeksema was vice chair of Commission E.2 of the Committee on Space Research, and from 2000 to 2004, he served as discipline scientist in heliophysics at NASA Headquarters. He earned his B.A. from Calvin College and a Ph.D. in applied physics from Stanford University. Dr. Hoeksema is the current co-chair of the Committee on Solar and Space Physics, and previously served on the Committee on the Assessment of the NASA Science Mission Directorate 2014 Science Plan, the Planning Committee on Lessons Learned in Decadal Planning in Space: A Workshop, the Committee on a Decadal Strategy for Solar and Space Physics, and the Astro2010 Panel on Optical and Infrared Astronomy from the Ground.

ANTHONY C. JANETOS joined Boston University in May 2013 as director of the Frederick S. Pardee Center for the Study of the Longer Range Future and the Frederick S. Pardee Professor of Earth and Environment. Previously, he served as director of the Joint Global Change Research Institute at the University of Maryland, where for 6 years he oversaw an interdisciplinary team of natural scientists, engineers, and social scientists committed to understanding the problems of global climate change and their potential solutions. Earlier, he was a senior research fellow and vice president at the H. John Heinz III Center for Science, Economics, and the Environment. In 1999, he joined the World Resources Institute as senior vice president and chief of program. Previously, he served as senior scientist for the Land Cover and Land Use Change Program in NASA's Office of Earth Science and was program scientist for the Landsat 7 mission. He has many years of experience in managing scientific research programs on a variety of ecological and environmental topics, including air pollution effects on forests, climate change impacts, land-use change, ecosystem modeling, and the global carbon cycle. Dr. Janetos received his B.A. in biology from Harvard University and his M.A. and Ph.D. degrees in biology from Princeton University. He was a co-chair of the U.S. National Assessment of the Potential Consequences of climate Variability and Change and an author of *Land-Use, Land-Use Change, and Forestry* (an IPCC special report) and the *Global Biodiversity Assessment*. His most recent Academies experience includes service on the Planning Committee on Lessons Learned in Decadal Planning in Space: A Workshop, the Committee on the Assessment of NASA's Earth Science Program, and the Committee to Advise the U.S. Global Change Research Program. Dr. Janetos is currently a member of the Board on Atmospheric Sciences and Climate and the Space Studies Board.

STEPHEN MACKWELL is the director of the Lunar and Planetary Institute in Houston, Texas, and is an adjunct professor of Earth science at Rice University. Prior to his current appointment, Dr. Mackwell served as the director of the Bayerisches Geoinstitut at the University of Bayreuth, Germany. He has served as program director for geophysics for NSF's Division of Earth Sciences (1993-1994); as member, group chief, and panel chair of the review panel for NASA's Planetary Geology and Geophysics Program; as expert reviewer for the Department of Energy's Geosciences Research Program (1993); and as expert consultant for NSF's Division of Earth Sciences (1995). Dr. Mackwell conducts laboratory-based research into the physical, chemical, and mechanical properties of geological materials under conditions relevant to the mantle and crust of Earth and other terrestrial planets. He has served on numerous committees of the Academies, including the Committee on New Opportunities in Solar System Exploration, the Committee to Review Near-Earth-Object Surveys and Hazard Mitigation Strategies, the Committee on the Planetary Science Decadal Survey, the Planning Committee on Lessons Learned in Decadal Planning in Space: A Workshop, the Committee on Review of the Draft 2014 Science Mission Directorate Science Plan, and the Committee on Astrobiology and Planetary Science.

NORMAN H. SLEEP is a professor of geophysics at Stanford University. Dr. Sleep's research interests include studying convection at the base of the lithosphere and the interaction of the lithosphere with mantle plume material. He is also currently investigating the microphysics of friction and applying the results to nonlinear attenuation and ground damage by strong seismic waves. Dr. Sleep is currently applying this work to interaction of tides with ice tectonics on the Saturn moon Enceladus. He is a fellow of the AAAS, the Geological Society of America, and the AGU. He has received a number of awards for his work, including the James B. Macelwane award, the George P. Woollard Award from the Geological Society of America, and the 2008 Wollaston Medal from the Geological Society of London. Dr. Sleep earned a B.S. in mathematics from Michigan State University and his M.S. and Ph.D.

degrees in geophysics from the Massachusetts Institute of Technology (MIT). He is a member of the National Academy of Sciences, and his current service for the Academies includes the Committee on Astrobiology and Planetary Science and the Panel on Earth and Atmospheric Sciences, and he is the current section liaison for the NAS Section 15.

CHARLES E. WOODWARD is a professor of astronomy at the University of Minnesota. He is an observational astronomer who conducts studies on astronomical dust particles produced in the atmosphere of evolved stars and cometary dust in the solar system. He is vice chair of the Large Binocular Telescope Corporation, an elected vice president of the AAS, former board chair of the International Gemini Observatories, and served on the Astronomy and Astrophysics Committee. Dr. Woodward served as a presidential faculty fellow at the University of Wyoming where he was a professor and an NSF presidential fellow. His published research has covered X-ray/optical/infrared spectroscopy, star formation, evolved stellar populations, novae, comets, asteroids, and exoplanets. He co-authored a 1997 article on the baffling dark matter halo in Galaxy NGC5907 for *Nature*, as well as a 2015 article describing spatially resolved imagining of lo's Loki Patera volcanoes using infrared Fizeau interferometry for *The Astrophysical Journal*. Dr. Woodward earned an A.B. in physics from Dartmouth College and M.A. and Ph.D. degrees in physics and astronomy from the University of Rochester. His most recent participation in activities of the Academies includes the Space Studies Board and the Astro2010 Panel on Optical and Infrared Astronomy from the Ground.

A. THOMAS YOUNG is executive vice president, retired, at Lockheed Martin Corporation. He is past chair of the board of SAIC. Mr. Young was previously the president and chief operating officer of Martin Marietta Corporation. Prior to joining industry, Mr. Young worked for 21 years at NASA where he directed the Goddard Space Flight Center, was deputy director of the Ames Research Center, and directed the Planetary Program in the Office of Space Science at NASA Headquarters. Mr. Young received high acclaim for his technical leadership in organizing and directing national space and defense programs, especially the Viking program. He is currently a fellow of the AIAA and the AAS. He earned his engineering degree from the University of Virginia and a M.S. in management from MIT. Mr. Young is a member of the National Academy of Engineering, and his participation in activities of the Academies includes membership on the Committee on Astronomy and Astrophysics and prior membership on the Committee on the Assessment of the Astrophysics Focused Telescope Assets Mission Concepts, the Planning Committee on Lessons Learned in Decadal Planning in Space: A Workshop, the Committee on the Planetary Science Decadal Survey: 2013-2022, the Panel on Implementing Recommendations from New Worlds, New Horizons Decadal Survey, the Committee on the Decadal Survey on Astronomy and Astrophysics 2010, and the Space Studies Board (vice chair).

STAFF

DAVID H. SMITH, *Study Director*, joined the Space Studies Board (SSB) of the Academies in 1991. He is the senior staff officer and study director for a variety of activities at the Academies in planetary science, astrobiology, and astrophysics. He also organizes SSB's Lloyd V. Berkner Summer Policy Internship program and supervises most, if not all, of the interns. He received a B.Sc. in mathematical physics from the University of Liverpool in 1976, completed Part III of the Mathematics Tripos at Cambridge University in 1977, and earned a D.Phil. in theoretical astrophysics from Sussex University in 1981. Following a postdoctoral fellowship at Queen Mary College, University of London (1980-1982), he held the position of associate editor and, later, technical editor of *Sky and Telescope*. Immediately prior to joining the staff of the SSB, Dr. Smith was a Knight Science Journalism Fellow at MIT.

MICHAEL MOLONEY is the director for Space and Aeronautics at the Space Studies Board and the Aeronautics and Space Engineering Board of the Academies. Since joining the ASEB/SSB, Dr. Moloney has overseen the production of more than 40 reports, including four decadal surveys—in astronomy and astrophysics, planetary science, life and microgravity science, and solar and space physics—a review of the goals and direction of the U.S.

human exploration program, a prioritization of NASA space technology roadmaps, as well as reports on issues such as NASA's Strategic Direction, orbital debris, the future of NASA's astronaut corps, and NASA's flight research program. Before joining the SSB and ASEB in 2010, Dr. Moloney was associate director of the BPA and study director for the decadal survey for astronomy and astrophysics (Astro2010). Since joining the Academies in 2001, Dr. Moloney has served as a study director at the National Materials Advisory Board, the Board on Physics and Astronomy, the Board on Manufacturing and Engineering Design, and the Center for Economic, Governance, and International Studies. Dr. Moloney has served as study director or senior staff for a series of reports on subject matters as varied as quantum physics, nanotechnology, cosmology, the operation of the nation's helium reserve, new anti-counterfeiting technologies for currency, corrosion science, and nuclear fusion. In addition to his professional experience at the Academies, Dr. Moloney has more than 7 years' experience as a foreign-service officer for the Irish government—including serving at the Irish Embassy in Washington and the Irish Mission to the United Nations in New York. A physicist, Dr. Moloney did his Ph.D. work at Trinity College Dublin in Ireland. He received his undergraduate degree in experimental physics at University College Dublin, where he was awarded the Nevin Medal for Physics.

KATIE DAUD is a research associate for the SSB and the ASEB. Previously, she worked at the Smithsonian National Air and Space Museum's Center for Earth and Planetary Studies as a planetary scientist. Ms. Daud was a triple major at Bloomsburg University, receiving a B.S. in planetary science and Earth science and a B.A. in political science.

DIONNA J. WILLIAMS is a program coordinator with the SSB, having previously worked for the Academies' Division of Behavioral and Social Sciences and Education for 5 years. Ms. Williams has a long career in office administration, having worked as a supervisor in a number of capacities and fields. Ms. Williams attended the University of Colorado, Colorado Springs, and majored in psychology.

ANGELA DAPREMONT, recently graduated from the College of Charleston with a B.S. in geology and a minor in French and francophone studies. Ms. Dapremont developed an interest in the merging of science and policy as a result of participating in meetings with congressional aides about science education and funding during her final year of undergraduate study. She has conducted research in the field of planetary geology at NASA Johnson Space Center and NASA Goddard Space Flight Center. As an SSB intern, she has had the opportunity to utilize her research skills and has accomplished her goal of gaining insight into the formulation and implementation of space policy. She hopes to continue working in science policy and use her experiences as a guide for the next steps in her research career.

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Acronyms and Abbreviations

AA	Associate Administrator
AAAC	Astronomy and Astrophysics Advisory Committee
ACE	Advanced Composition Explorer
AGs	assessment groups
AIM	Aeronomy of Ice in the Mesosphere
AirMOSS	Airborne Microwave Observatory of Subcanopy and Subsurface
ALMA	Atacama Large Millimeter Array
ARTEMIS	Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun
AST	NSF Astronomical Sciences Division
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
Astro2000	2000 astronomy decadal survey: *Astronomy and Astrophysics in the New Millennium*
Astro2010	2010 astronomy and astrophysics decadal survey: *New Worlds, New Horizons in Astronomy and Astrophysics*
ATTREX	Airborne Tropical Tropopause Experiment
CAA	Committee on Astronomy and Astrophysics
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAPTEM	Curation and Analysis Planning Team for Extraterrestrial Materials
CARVE	Carbon in Arctic Reservoirs Vulnerability Experiment
CATE	cost and technical evaluation
CEOS	Committee on Earth Observing Systems
CGRO	Compton Gamma Ray Observatory
CINDI	Coupled Ion-Neutral Dynamics Investigation
CoBRA	Complexity Based Risk Assessment
ConX	Constellation-X Observatory
COPAG	Cosmic Origins Program Analysis Group
COSPAR	Committee on Space Research
CSA	Canadian Space Agency
CYGNSS	Cyclone Global Navigation Satellite System

DISCOVER-AQ	Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality
DKIST	Daniel K. Inouye Solar Telescope
DOE	Department of Energy
DOI	Department of the Interior
DRIVE	Diversify, Realize, Integrate, Venture, Educate
DSN	Deep Space Network
Earth2007	2007 Earth science and applications from space decadal survey: *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*
EO-1	Earth Observing-1
EOS	Earth Observing System
ESA	European Space Agency
EXIST	Energetic X-ray Survey Telescope
FACA	Federal Advisory Committee Act
FY	fiscal year
G-MOWG	Geospace Management Operations Working Group
GMT	Giant Magellan Telescope
GOLD	Global-Scale Observations of the Limb and Disk
GP-B	Gravity Probe-B
GPM	Global Precipitation Measurement
GRACE	Gravity Recovery and Climate Experiment
GRACE FO	Gravity Recovery and Climate Experiment Follow On
GSMT	Giant Segmented Mirror Telescope
Helio2013	2013 solar and space physics decadal survey: *Solar and Space Physics: A Science for a Technological Society*
HEOMD	NASA Human Exploration and Operations Mission Directorate
HS-3	Hurricane and Severe Storm Sentinel
HST	Hubble Space Telescope
IBEX	Interstellar Boundary Explorer
ICESat-2	Ice, Cloud, and Land Elevation Satellite-2
ICON	Ionospheric Connection Explorer
IIP	Instrument Incubator Program
IRIS	Interface Region Imaging Spectrograph
ISG	infrastructure study group
ISSI	International Space Station Institute
IXO	International X-ray Observatory
JAXA	Japan Aerospace Exploration Agency
JEO	Jupiter Europa Orbiter
JUICE	Jupiter Icy Moon Explorer
JWST	James Webb Space Telescope
LADEE	Lunar Atmosphere and Dust Environment Explorer
LEAG	Lunar Exploration Analysis Group
LISA	Laser Interferometer Space Antenna

LRO	Lunar Reconnaissance Orbiter
LSST	Large Synoptic Survey Telescope
LWS	Living With a Star
LWS-MOWG	Living With a Star Management Operations Working Group
MAVEN	Mars Atmosphere and Volatile EvolutioN Mission
MAX-C	Mars Astrobiology Explorer-Cacher
MEPAG	Mars Exploration Program Analysis Group
MER	Mars Exploration Rover (Spirit and Opportunity)
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MGN	Magellan (Venus Radar Mapper)
MMS	Magnetospheric Multiscale Mission
MO	Mars Observer
MOO	Mission of Opportunity
MOWG	management operations working group
MREFC	NSF Major Research Equipment and Facilities Construction
MRI	Major Research Instrumentation
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
MSR	Mars Sample Return
NAC	NASA Advisory Council
NAFCOM	NASA/Air Force Cost Model
NASA	National Aeronautics and Space Administration
NEO	Near-Earth Object
NF4	New Frontiers 4
NF5	New Frontiers 5
NICER	Neutron Star Interior Composition Explorer
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NRC	National Research Council
NSF	National Science Foundation
NuSTAR	Nuclear Spectroscopic Telescope Array
OCO-2	Orbiting Carbon Observatory-2
OMB	Office of Management and Budget
OPAG	Outer Planets Analysis Group
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer
OSTM	Ocean Surface Topography Mission
OSTP	Office of Science and Technology Policy
PDR	preliminary design review
PDS	Planetary Data System
PI	principal investigator
Planetary2011	2011 planetary science decadal survey: *Vision and Voyages for Planetary Science in the Decade 2013-2022*
PPP	program prioritization panel
PSD	NASA Planetary Science Division
QuikSCAT	Quick Scatterometer

R&A	research and analysis activities
RFI	request for information
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
ROSES	research opportunities in space and Earth sciences
SAFIR	Single Aperture Far-InfraRed observatory
SAGE III	Stratospheric Aerosol and Gas Experiment
SBAG	Small Bodies Analysis Group
SDO	Solar Dynamics Observatory
SFP	science frontier panel
SH-MOWG	Solar-Heliosphere Management Operations Working Group
SIM	Space Interferometry Mission; originally proposed in the 1990 astronomy decadal survey as AIM: Astronomical Interferometry Mission
SMAP	Soil Moisture Active-Passive
SMD	NASA Science Mission Directorate
SOC	Spacecraft Operations Centre
SOFIA	Stratospheric Observatory for Infrared Astronomy
SOHO	Solar and Heliospheric Observatory
SORCE	Solar Radiation and Climate Experiment
SPP	Solar Probe Plus
SRA	supporting research and analysis
SSB	Space Studies Board
STEREO	Solar Terrestrial Relations Observatory
STMD	NASA Space Technology Mission Directorate
STP	Solar Terrestrial Probe
Suomi NPP	Suomi National Polar-orbiting Partnership
SWOT	Surface Water Ocean Topography Mission
TEMPO	Tropospheric Emissions: Monitoring of Pollution
TESS	Transiting Exoplanet Survey Satellite
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TIMED	Thermosphere Ionosphere Mesosphere Energetics and Dynamics
TMT	Thirty Meter Telescope
TOPEX/POSEIDON	Topography Experiment/Poseidon
TPF	Terrestrial Planet Finder
TRMM	Tropical Rainfall Measuring Mission
TWINS	Two Wide-Angle Imaging Neutral-Atom Spectrometers
UARS	Upper Atmosphere Research Satellite
USGS	U.S. Geological Survey
VEXAG	Venus Exploration Analysis Group
VGR	Voyager
VLA	Very Large Array
VLBA	Very Long Baseline Array
WBS	work breakdown structure
WFIRST	Wide-Field Infrared Survey Telescope
XMM-Newton	X-ray Multi-Mirror Mission Newton