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An Enabling Foundation for NASA's Earth and Space Science Missions

Committee on the Role and Scope of Mission-Enabling Activities
in NASA's Space and Earth Science Missions
Space Studies Board
Division on Engineering and Physical Sciences
NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

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This study is based on work supported by Contract NNH06CE15B between the National Academy of Sciences and the National Aeronautics and Space Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the agency that provided support for the project.

International Standard Book Number-13: 978-0-309-XXXXX-X
International Standard Book Number-10: 0-309-XXXXX-X

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Printed in the United States of America

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Preface

NASA's space and Earth science program can be viewed as being composed of two principal components: (1) spaceflight projects, including the design, development, launch, and operations of Earth-orbiting and deep-space missions, and (2) mission-enabling activities. Most of the budget of NASA's Science Mission Directorate (SMD) is applied to spaceflight missions, but NASA identifies nearly one quarter of the SMD budget as "mission enabling." The principal mission-enabling activities, which traditionally encompass much of NASA's research and analysis (R&A) programs, include support for basic research, theory, modeling, and data analysis; suborbital payloads and flights and complementary ground-based programs; advanced technology development; and advanced mission and instrumentation concept studies.

While the R&A program is essential to the development and support of NASA's diverse set of space and Earth science missions, defining and articulating an appropriate scale for mission-enabling activities have posed a challenge throughout NASA's history. Practically all relevant external advisory reports have emphasized the importance of mission-enabling activities and have urged NASA to support a balanced program of flight missions and supporting research, data analysis, and technology development.

In the fiscal year (FY) 2008 omnibus appropriations bill for NASA and other agencies and departments (HR 2764, enacted December 27, 2007), Congress directed NASA "to enter into an agreement with the National Research Council [NRC] for an assessment of NASA's research and analysis activities." In subsequent discussions with NRC representatives, congressional staff members indicated that members of Congress were especially interested in advice about how to assess whether levels of support for mission-enabling activities were too high, about right, or too low.

In response to that direction, the NRC established the Committee on the Role and Scope of Mission-Enabling Activities in NASA's Space and Earth Science Missions (member biographies are provided in Appendix E) and charged it to identify the appropriate roles for mission-enabling activities and metrics for assessing their effectiveness. The committee also was asked to evaluate how, from a strategic perspective, decisions should be made about balance between mission-related and mission-enabling elements of the overall program as well as balance between various elements within the mission-enabling component. (The full statement of task is provided in Appendix A.)

The committee was not tasked by the NRC to provide a specific assessment regarding the appropriateness of the current budget allocation between the mission-enabling and spaceflight components of SMD (or among the various elements within the mission-enabling component), nor would it have been possible to do so without having more detailed insight into how mission-enabling activities are distributed and budgeted. Accordingly, consistent with the statement of task, the committee's efforts included identifying the fundamental roles of mission-enabling activities in the context of the total SMD mission, defining principles and metrics for a robust and relevant portfolio of mission-enabling programs to fulfill these fundamental roles, and maximizing the effectiveness of mission-enabling programs through identification of best practices in the strategic management of complex R&D portfolios. Collectively, these efforts will, the committee hopes, help SMD to make a good program even better.

The committee met on January 21-23, March 11-13, and May 20-22, 2009, to gather information and to develop its response to the study charge. (See Appendix B for a list of presentations to the committee.) During the study, the committee received extensive briefings and much useful, relevant information from Max Bernstein, Richard Fisher, Michael Freilich, Paul Hertz, Jack Kaye, Mary Mellott, Michael Meyer, Jon Morse, Michael New, Andrew Roberts, Wilton Sanders, and Edward Weiler (all from NASA headquarters); Yvonne Pendleton (NASA Ames Research Center); and Chris Martin (Caltech). This committee also extends its appreciation to Space Studies Board space policy interns Jordan Block, Abby Fraeman, and Angie Wolfgang for their assistance in gathering material for the committee's use in this report.

This report provides the committee's conclusions and recommendations. Chapter 1 presents the committee's definition of mission-enabling activities and discusses their roles in the broader context of the responsibilities of SMD. Chapter 2 summarizes the committee's assessment of concerns and issues that deserve NASA's attention, and Chapter 3 discusses the committee's recommendations for a set of principles and metrics for managing an effective mission-enabling program portfolio. Chapter 4 presents the committee's views on best practices for actively and strategically managing mission-enabling activities and on three specific mission-enabling activities—innovative research, interdisciplinary research, and technical workforce development. Chapter 5 presents a consolidated summary of the committee's principal findings and recommendations.

Acknowledgment of Reviewers

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 National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Daniel N. Baker, University of Colorado,
Michael J. Drake, University of Arizona,
Inez Y. Fung, University of California, Berkeley,
John P. Huchra. Harvard-Smithsonian Center for Astrophysics,
Molly K. Macauley, Resources for the Future,
Alfred U. MacRae, MacRae Technologies,
W. Allen Marr, Jr., Geocomp Corporation, and
Franklin D. Martin, Martin Consulting.

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 Christopher McKee, University of California at Berkeley. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Summary

NASA's space and Earth science missions have achieved an extraordinary record of accomplishments during the 50-year history of the space age. Spacecraft have provided in-depth, global observations of Earth's land surface, biosphere, cryosphere, oceans, and atmosphere; unraveled many mysteries about the behavior of Sun and its influence on Earth and other solar system bodies; explored planets, comets, and asteroids and approached the region where the solar system interacts with the local interstellar medium; and carried astronomical observatories above Earth's atmosphere to permit studies of the cosmos across the full electromagnetic spectrum. Much of the success of these spaceflight missions has been due to an underlying foundation of mission-enabling research and technology. These activities have framed the scientific questions on which plans for the flight missions have been based; developed advanced technologies that have made new, complex missions feasible; provided supporting terrestrial facilities and observations necessary to complement and interpret spaceflight data; and synthesized and translated the data from spaceflight missions into new scientific understanding.

In 2007 Congress called for the National Research Council (NRC) to examine issues regarding balance between mission-enabling activities and spaceflight missions, and this report presents the conclusions of the NRC Committee on the Role and Scope of Mission-Enabling Activities in NASA's Space and Earth Science Missions, which was organized to undertake that task. The committee defined mission-enabling activities to be the ensemble of non-spaceflight-mission-specific programs that create the scientific and technological expertise and associated infrastructure necessary to define, execute, and benefit from the spaceflight missions. (See Box S.1.) In some cases these activities can lead directly to significant scientific accomplishments that advance the strategic goals of NASA without being linked to a spaceflight mission. All of these activities are managed by four science divisions—astrophysics, heliophysics, planetary science, and Earth science—within the NASA headquarters Science Mission Directorate (SMD). The same SMD divisions also manage the spaceflight missions for the corresponding scientific discipline areas.

Chapter 1 of this report discusses each of the purposes of mission-enabling activities, relates them to specific elements of SMD's programs, and provides examples of how mission-enabling activities have contributed to NASA space and Earth science programs. These activities play essential roles in maximizing the scientific return on investment in space and Earth science spaceflight missions and in providing a foundation for an effective and robust program for the future, and they also constitute an integral part of the nation's overall R&D effort. Therefore, the committee's first major finding and recommendation are as follows:

Finding 1. The mission-enabling activities in SMD—including support for scientific research and research infrastructure, advanced technology development, and scientific and technical workforce development—are fundamentally important to NASA and to the nation.

BOX S.1 Defining Mission-enabling Activities

NASA's space and Earth science program comprises two principal components:

1. Spaceflight projects, including the design, development, launch, and operations of Earth-orbiting and deep-space missions, and
2. Activities that are not dedicated to a single specific spaceflight mission but that provide a broad enabling foundation for NASA's scientific spaceflight projects. The committee refers to this latter component as mission-enabling activities.

The principal purposes of mission-enabling activities are to provide

- A knowledge base that allows NASA and the scientific community to explore new frontiers in research and to identify, define, and design cost-effective space and Earth science missions required to address the strategic goals of the agency;
- A wide range of technologies that enable NASA and the scientific community to equip and conduct spaceflight missions to pursue the agency's scientific goals; and
- A robust, experienced technical workforce to plan, develop, conduct, and utilize the scientific missions.

NASA's principal programs to accomplish these purposes are as follows:

- Research projects (especially via the research and analysis grants programs) and special research facilities (including suborbital flight payloads and operations, ground-based telescopes and dedicated laboratories, and high-end computer systems and data archives);
- Development of advanced sensors, research instruments, and spaceflight mission system technologies;
- General data analysis (including archival data studies and synthesis of new and/or long-term data sets from multiple spaceflight missions); and
- Earth science applications (including research to apply NASA Earth science results to fields such as agriculture, ecology, and public health and safety).

Recommendation 1. NASA should ensure that SMD mission-enabling activities are linked to the strategic goals of the agency and of SMD and that they are structured so as to

- **Encompass the range and scope of activities needed to support those strategic goals,**
- **Provide the broad knowledge-base that is the context necessary to interpreting data from spaceflight missions and defining new spaceflight missions,**
- **Maximize the scientific return from all spaceflight missions,**
- **Supply a continuous flow of new technical capabilities and scientific understanding from mission-enabling activities into new spaceflight missions, and**
- **Enable the healthy scientific and technical workforce needed to conduct NASA's space and Earth science program.**

OPPORTUNITIES FOR IMPROVEMENT

During its review of SMD's mission-enabling activities the committee identified aspects of current approaches to managing science division research and technology portfolios where proven practices did not appear to be widely or adequately applied and where there appear to be opportunities for improvement so that mission-enabling activities can most effectively fulfill their roles (See Chapter 2.). An effectively structured program would have the following attributes:

1. Mission-enabling activities, and the criteria for establishing their priorities and resource allocations, that are clearly traceable to division mission statements and strategic goals.
2. Portfolio allocations based on systematic criteria and metrics of program effectiveness.
3. Continual interaction with and assessment by the science community via a well-structured advisory apparatus.
4. Transparent budget structure in which all mission-enabling activities are aggregated into visible budget lines so as to facilitate more effective portfolio management decisions and communication about the value and impacts of mission-enabling programs.
5. Explicit statement of the role of mission-enabling activities in sustaining a capable technical workforce in the overall program strategy.
6. Adequate staff to devote an appropriate amount of time to the responsibilities of properly managing mission-enabling activities.

PRINCIPLES AND METRICS FOR EFFECTIVE MISSION-ENABLING PORTFOLIOS

The committee was charged to make recommendations regarding portfolio allocation criteria and metrics of program effectiveness. In addressing this task, the central roles of mission-enabling activities enumerated in Recommendation 1 provide the basis for guiding principles to be considered in planning, conducting, and evaluating the program. Workable metrics also need to be framed and applied from the perspective of the following implementation principles:

1. Investment needs will be different across SMD divisions. Each SMD science division has distinct strategic goals, different kinds of spaceflight missions, and different dependencies on supporting research and data analysis.
2. Division-level mission statements should clearly articulate the division's strategic priorities and should provide a rational framework for assessing how the division's portfolio ensures support for the full range of activities.
3. Balance between mission-enabling and spaceflight mission portfolios is never rigid. The principle of balance does not mean using a fixed ratio across all programs; it does not mean that all components of an overall program should receive equal funding, and it need not be constant over time.
4. Programmatic relationships of mission-enabling activities to spaceflight programs should be clearly communicated so that mission-enabling portfolios can be effectively prioritized and managed.
5. Balance within portfolios requires active management. Determining whether investments are appropriately balanced within schedule and budget constraints to achieve the intended near, mid, and far-term goals and objectives requires continuing assessment.
6. Budget transparency enhances active management by facilitating analysis, advocacy, and stability.

Performance metrics are essential tools for making effective portfolio management decisions. Establishing metrics for each component of mission-enabling activities also helps inform the administration, Congress, and the science community of the purpose of the component and the extent to which it is being successful. Such transparency, when properly established, provides justification for the essential roles of mission-enabling activities in the success of SMD, while also allowing the broad national science community to engage with NASA in providing the most effective mission-enabling program. The committee presents the following template for what should be provided by a metric for each of an SMD division's mission-enabling activities:

1. A simple statement of what the component of the mission-enabling activity is intended to accomplish and how it supports the strategic or tactical plans of the division.
2. A statement as to how the component is to accomplish its task.
3. An evaluation of the success of the activity relative to the stated mission, unexpected benefits, and lessons learned.
4. A justification for the resource allocation that is being applied to the component vis-à-vis other mission-enabling activities within the division.

This report discusses examples of how this template could be applied to the different, individual kinds of mission-enabling activity.

MAXIMIZING PROGRAM EFFECTIVENESS VIA STRATEGIC MANAGEMENT

The committee identified several elements of an effective portfolio management approach that NASA officials should consider as they address concerns identified in the committee's assessment of the mission-enabling programs. The committee's second and third finding and recommendation address these items.

Finding 2. Adoption of an active portfolio management approach is the key to providing an effective program of mission-enabling activities that will satisfy the intent of this committee's first finding and recommendation.

Recommendation 2. NASA's Science Mission Directorate should develop and implement an approach to actively managing its portfolio of mission-enabling activities.

Active portfolio management should include the following elements:

- **Clearly defined science division mission-enabling mission statements, objectives, strategies, and priorities that can be traced back to the overall strategic goals of NASA, SMD, and the division.**
- **Flexibility to accommodate differences in the scientific missions and programmatic options that are most appropriate to the different science discipline divisions.**
- **Clearly articulated relationships between mission-enabling activities and the ensemble of ongoing and future spaceflight missions that they support.**
- **Clear metrics that permit program managers to relate mission-enabling activities to strategic goals, evaluate the effectiveness of mission-enabling activities, and make informed decisions about priorities, programmatic needs, and portfolio balance.**
- **Provisions for integrating support for innovative high-risk/high-payoff research and technology, interdisciplinary research, and scientific and technical workforce development into mission-enabling program strategies.**
- **Active involvement of the scientific community via an open and robust advisory committee process.**
- **Transparent budgets that permit program managers to effectively manage mission-enabling activity portfolios and permit other decision makers and the research community to understand the content of mission-enabling activity programs.**

Finding 3. The NASA SMD headquarters scientific and technical staff is not adequately sized to manage mission-enabling activities effectively.

Recommendation 3. NASA should increase the number of scientifically and technically capable program officers so that they can devote an appropriate level of attention to the tasks of actively managing the portfolio of research and technology development that enables a world-class space and Earth science program.

In making this recommendation the committee is convinced that having mission-enabling program managers divide their time between mission-enabling activities and duties related to spaceflight programs is desirable and that management of mission-enabling activities is properly a NASA headquarters, not a NASA field center, function.

1

Overview of the Science Mission Directorate's Mission-enabling Activities

NASA's Science Mission Directorate (SMD) sponsors, develops, and conducts research in and from space in the disciplines of Earth science and applications, heliophysics (i.e., solar and space physics), scientific exploration of the planets and other solar system bodies, and astronomy and astrophysics. NASA's strategic plan[1] provides the following set of strategic objectives for SMD:

- Study Earth from space to advance scientific understanding and meet societal needs.
- Understand the Sun and its effects on Earth and the solar system.
- Advance scientific knowledge of the origin and history of the solar system, the potential for life elsewhere, and the hazards and resources present as humans explore space.
- Discover the origin, structure, evolution, and destiny of the universe, and search for Earth-like planets.

SMD advances these goals by developing and operating spaceflight missions conducted primarily from spacecraft operated in Earth orbit; in interplanetary space; and in orbit around, or on the surfaces of, other solar system bodies. These spacecraft missions are managed within SMD by four science divisions—one for each of the four science discipline areas noted above.

Important complementary activities carried out in addition either are mission-enabling or directly address SMD strategic goals in other ways. As emphasized in the NASA Science Plan: "Long-term outcomes are science based, not mission based; thus suborbital and research and analysis (R&A) programs are part of the discussion—it is not simply a matter of weighing a mission in one area against a mission in another."[2]

MISSION-ENABLING ACTIVITIES—DEFINITION

The Committee on the Role and Scope of Mission-Enabling Activities in NASA's Space and Earth Science Missions defined mission-enabling activities as including the following:

- Research projects (especially via the research and analysis grants programs) and special research facilities (including suborbital flight payloads and operations, ground-based telescopes and dedicated laboratories, and high-end computer systems and data archives);
- Development of advanced sensors, research instruments, and spaceflight mission system technologies;
- General data analysis (including archival data studies and synthesis of new and/or long-term data sets from multiple spaceflight missions); and

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[1] NASA, 2006 NASA Strategic Plan, NP-2006-02-423-HQ, Washington, D.C., 2006.
[2] NASA, Summary of the Science Plan For NASA's Science Mission Directorate 2007-2016, NP-2007-03-462-HQ, Washington, D.C., 2007, p. 13.

- Earth science applications (including research to apply NASA Earth science results to fields such as agriculture, ecology, and public health and safety).

The committee characterizes mission-enabling activities as the ensemble of non-spaceflight-mission-specific programs that create the scientific and technological expertise and associated infrastructure necessary to define, execute, and benefit from the spaceflight missions. In some cases these activities can lead directly to significant scientific accomplishments that advance the strategic goals of NASA without being linked to a spaceflight mission. This infrastructure includes

- A knowledge base that allows NASA and the scientific community to explore new frontiers in research and to identify, define, and design cost-effective space and Earth science missions required to address the strategic goals of the agency;
- A wide range of technologies that enable NASA and the scientific community to equip and conduct spaceflight missions to pursue the agency's scientific goals; and
- A robust, experienced technical workforce to plan, develop, conduct, and utilize the scientific missions.

Other essential elements of SMD's space and Earth science programs that do not fall within the committee's definition of "mission-enabling"—and that the committee has not included in its examination of mission-enabling activities—are as follows:

- Spaceflight mission science team activities,
- Post-launch spaceflight mission operations and data analysis (both during the prime mission phase and during extended mission operations),
- Mission-specific technology development,
- Guest-observer programs and participating scientist programs for spaceflight missions (but depends on discipline-unique approaches),
- Education and public outreach, and
- Space and ground communications systems (e.g., Deep Space Network and the Tracking and Data Relay Satellite System, both of which are currently budgeted and managed outside SMD in the Space Operations Mission Directorate).

Nearly one quarter (~$1 billion) of the total SMD budget of $4.5 billion is identified by NASA as mission enabling, as shown in Figure 1.1.[3]

In briefing the committee, NASA SMD officials explained that the present balance between spaceflight-mission and mission-enabling activities is largely a product of the SMD program's evolution over its 50-year history rather than of a more systematic planning and implementation process. Although having data to trace historical trends in the relative allocations of funding for spaceflight missions and mission-enabling activities would have benefitted the committee's deliberations, such data were not available.

Top-level goals and scientific priorities for all four SMD science divisions are traceable to NRC decadal surveys, which identify the highest-priority scientific directions for a field and present ranked priorities for facilities and missions to pursue the science over the span of a decade. Thus the decadal surveys serve to provide some long-term stability to each division's scientific goals.

[3] Slightly more than half of the $4.5 billion total SMD budget is applied to missions in phases A (preliminary analysis) through D (fabrication and launch) and mission operations. The remaining quarter of the SMD budget is allocated to support for specific flight mission science teams and to program-wide communications, data archives, and computing infrastructure.

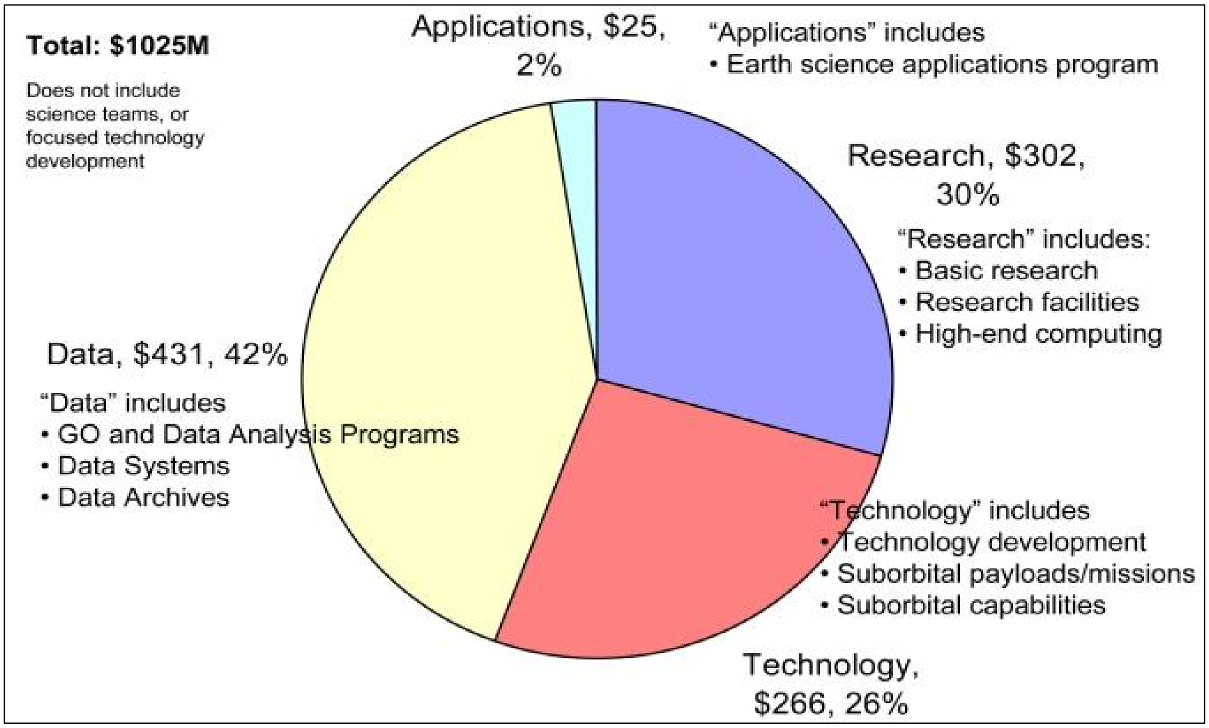

FIGURE 1.1 The approximate distribution of all mission-enabling activities for fiscal year 2008. Funding levels are given in millions. SOURCE: NASA Science Mission Directorate briefing to the committee on January 22, 2009.

Research and technology development projects supported by mission-enabling programs are almost always managed and conducted by principal investigators or principal-investigator-led teams. NASA officials reported to the committee that, based on a sampling of fiscal year (FY) 2007 projects, approximately 60 percent of the total mission-enabling funding goes to universities with 33 percent going to NASA centers, and the remainder going to other non-NASA institutions.

Management of SMD research activities is currently driven by several annual administrative cycles. They include the annual budget cycle, during which portfolios are reviewed and overall budget allocations are made; annual proposal solicitations, during which budgets for new awards are set; and proposal selection and award decision-making, which is based on scientific merit and programmatic needs. SMD officials indicated that when a need is identified to expand research efforts in a given area it is easier for them to create new programs and redistribute resources among portfolios than to expand portfolios already covering that area.

The committee found that there are important differences between the research management practices and level of mission-enabling research funding of the four different SMD science divisions. Those differences include whether the divisions invite open-ended or targeted research topics for proposals, how data analysis activities are treated within and outside flight mission budgets, management of data archives and suborbital programs, roles of interdisciplinary and large-scale modeling efforts, and the roles of other funding agencies. Table 1.1 provides a summary of the relative sizes of the four divisions' programs.

SMD maintains an Internet site, Service and Advice for Research and Analysis,[4] that provides a relatively comprehensive listing of mission-enabling research proposal opportunities and deadlines, proposal submission and award statistics, names of NASA points of contact, and other program information.

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[4] See http://nasascience.nasa.gov/researchers/sara/.

TABLE 1.1 Comparative Statistical Data for SMD Science Division Mission-enabling Programs

	Astrophysics	Heliophysics	Planetary Science	Earth Science	SMD Total
Total budget ($M, FY 2009)[a]	1,206	592	1,326	1,380	4,503
Total mission-enabling budget ($M, FY 2009)[b]	127	77	312	556	1,072
Mission-enabling budget as a percentage of total budget	10	13	24	40	24
Proposals received (for 2008)	824	407	1,115	1,338	4,039[c]
Overall acceptance rate (%, 2008)	36	29	28	31	31
Number of NESSF graduate student awards (2008)	8	4	17	51	79
Number of program officers	11	9	23	31	78

NOTE: Data on proposal volume, acceptance rate, graduate fellowships, and SMD staff are from NASA's Service and Advice for Research and Analysis Web site. NESSF is the NASA Earth and Space Science Fellowships program.

[a] Totals do not include the one-time 2009 American Recovery and Reinvestment Act supplement of $75 million for astrophysics and $325 million for Earth science.

[b] Total does not include the one-time 2009 American Recovery and Reinvestment Act supplement of $74 million for Earth science research and technology.

[c] SMD total includes 355 proposals for cross-directorate programs.

PURPOSES SERVED BY MISSION-ENABLING ACTIVITIES

Research and development (R&D) is important to the future of the nation. The NRC report *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*[5] emphasized the importance of research and technological innovation and recommended strengthening science and engineering research "to maintain the flow of new ideas that fuel the economy, provide security, and enhance the quality of life." In a speech before the National Academy of Sciences on April 27, 2009, President Barack Obama reaffirmed the importance that his Administration places on investments in R&D, and he committed to fund the nation's total R&D effort at 3 percent of the gross domestic product, which in effect would double the national R&D effort.

The mission-enabling programs within NASA in general and SMD in particular are an essential, although often overlooked, component of the nation's R&D endeavors. They serve all of the purposes expected of an investment in R&D: the development of innovative technologies; the creation of new knowledge through basic research in a broad range of disciplines; and technical workforce development. They enable a specific set of program objectives, in this case the mission of SMD, and they help sustain the fundamental underpinning of the technological capabilities on which U.S. economic and national security depend.[6]

Box 1.1 illustrates the interplay of many of these mission-enabling activities as researchers sought to understand the heating of the sun's outer atmosphere to million-degree temperatures.

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[5] National Academy of Sciences-National Academy of Engineering-National Research Council, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, The National Academies Press, Washington, D.C., 2005.

[6] Technological, economic, and societal benefits of NASA programs in the broader national context are discussed in the recent NRC report *America's Future in Space: Aligning the Civil Space Program with National Needs*, The National Academies Press, Washington, D.C., 2009.

Over the course of its history SMD has demonstrated many mission-enabling successes across all four of its mission disciplines, and it has clearly established the importance of the mission-enabling portion of the program to SMD's overall success. Communicating these successes in the broader community is very important to NASA's future success, especially in an environment of restricted or diminishing fiscal resources. The paragraphs below describe and illustrate the three key areas of intellectual, technical, and human-capital mission-enabling elements in more detail. The committee's intent is to present a few examples in each area rather than to provide a comprehensive list.

Knowledge Base to Enable Spaceflight Missions

Science mission spacecraft developed by SMD represent a significant investment of national resources. As such the science mission teams require the best possible knowledge of mission objectives and their science context if spaceflight missions are to be developed in a cost-effective manner that maximizes the return on investment. As missions become more complex, the knowledge base necessary to support the strategic goals of SMD is constantly growing across all science disciplines and consists of activities that span all modes of basic and applied research. These modes include theoretical investigations and modeling; acquisition and analysis of supporting data from ground-based facilities, laboratories, aircraft, balloons, and sounding rockets; analysis of mission data (separate from the mission-funded analysis); establishment and/or maintenance of computational, curatorial, and other ground-based facilities; and establishment and maintenance of data archive facilities.

Theoretical Investigations and Modeling

Modeling, usually by numerical simulations, and theoretical research are required to turn measurements and observations into physical understanding. The predictions from modeling and theory also serve as motivation for future missions. For example, Earth system models, constrained by observations, are used to predict changes in the Earth's environment and design requirements of future sensors by means of Observation System Simulation Experiments. In planetary science, modeling of the dynamical evolution of the early solar system has offered explanations for the Late Heavy Bombardment of the Moon and the capture of the Jovian Trojan population of asteroids, and models of the accretion of the terrestrial planets strongly suggest that material from the outer asteroid belt is the source of the Earth's ocean water. These models give focus to the analysis of terrestrial, meteorite and returned lunar samples, and the interpretation of crater populations on planetary surfaces. In astrophysics, modeling of nucleosynthesis in supernovae has led to understanding of the abundances of elements in the solar system and in the interstellar medium. Modeling of hydromagnetic shocks around supernova explosions has lead to an understanding of the acceleration of cosmic rays. (For a further example, see Box 1.2.)

BOX 1.1 Case Study: Mission-enabling Activities Advance Study of the Solar Corona

Research on why the solar corona is millions of degrees hotter than the sun's surface offers a case study of the essential importance that mission-enabling activities play for space science. The story begins with NASA-funded theoretical research in the 1980s. Eugene Parker noted that convective motions at the solar surface displace the footpoints of coronal magnetic field lines in random directions. This causes the field lines to become wrapped and braided in complicated ways, perhaps resembling a bowl of tangled spaghetti. He further surmised that magnetic energy should be explosively released at the interfaces between the misaligned field lines, and, after estimating the size of each event, he coined the term "nanoflare."

The idea was very appealing. However, observations at the time were not sufficient to provide a rigorous test, and so NASA funded new instrument development. Normal-incidence, multi-layer optics were developed to replace grazing-incidence telescopes, and the technology has now revolutionized our understanding of coronal structure and dynamics and is now standard on currently operating and upcoming solar missions.

Laboratory work is another mission-enabling activity has contributed to our understanding of coronal heating, including nanoflares. Spectroscopic observations cannot be interpreted quantitatively without the relevant atomic rate coefficients, and there is a long history of measuring (and calculating) these coefficients under NASA support.

Finally, ever improving space and ground-based observations have motivated a new round of theoretical investigations to understand the details of how magnetic field footpoint motions in the photosphere lead to magnetic reconnection and nanoflares in the corona. Meanwhile, numerical simulations are showing that the spatial and temporal dependence of the energy release can have a fundamental influence on the resulting loop dynamics and structure, and help explain certain mysteries in the space mission observations.

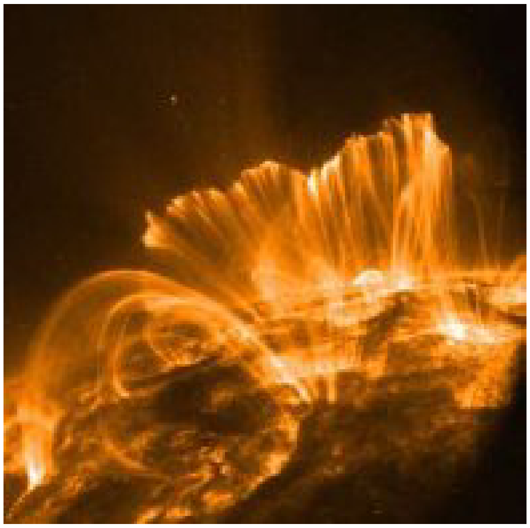


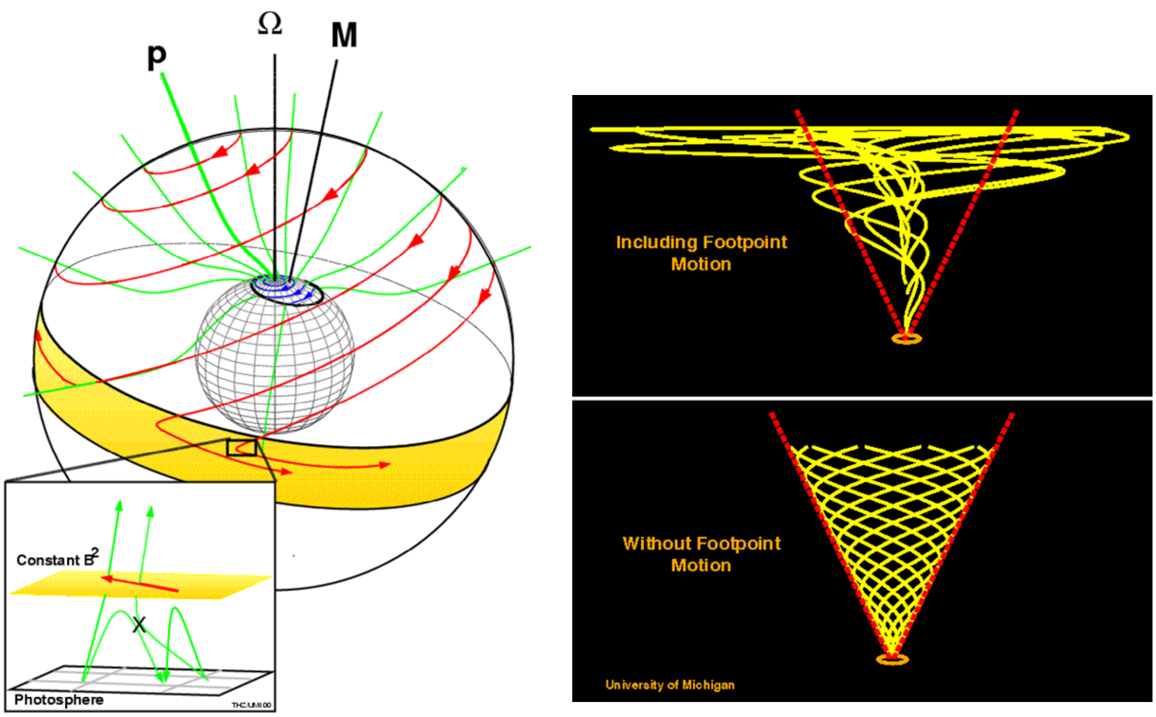
FIGURE 1.1.1 This X-ray image shows loops of magnetic fields extending high above the solar limb into the corona and indicates that energy deposition occurs on very small scales and in a complex pattern. The spectacular images from the Transition Region and Coronal Explorer mission were made possible by the optics developed from earlier rocket experiments funded through the NASA suborbital program SOURCE: Courtesy of NASA Transition Region and Coronal Explorer (TRACE) team.

BOX 1.2 Theory Links Old Measurements to New Missions

One of the most interesting discoveries of the Ulysses heliophysics mission was that low-energy charged particles, known to be accelerated in the solar wind at low heliographic latitudes, are seen at the highest heliographic latitudes. The magnetic field in the heliosphere was thought to lie, on average, along cones of constant latitude, and particles, particularly low-energy ones, follow the magnetic field. It was therefore a puzzle as to how the particles seen at high latitudes were able to propagate there, from their acceleration site.

When a new and interesting discovery such as this is made, theorists, supported through the mission-enabling program, attempt to explain it. Thus, a model was developed that challenged the concept that the heliospheric magnetic field lies on cones of constant latitudes, and rather suggested that global motions of the heliospheric field near the Sun would introduce pathways in latitude for the accelerated particles in the heliosphere, accounting for their observations at high latitudes.

The revised theory for the heliospheric magnetic field has many implications for better understanding our star, the Sun. When the global motions of the heliospheric field at the Sun were considered in more detail, researchers realized that the motions offer an explanation for such diverse observations as the origin of the solar wind, the differences in the composition between fast and slow solar wind, and even the reversal in the magnetic field of the Sun during the solar cycle. The original Ulysses observation stimulated many new theories, which in turn stimulated the need for new observations, which will be carried out on upcoming missions such as Solar Dynamics Observatory or the planned Solar Orbiter mission.



The component of the Sun's magnetic field that forms the heliospheric magnetic field (green lines) moves through the outer corona as shown by the red arrows. SOURCE: After L.A. Fisk, Motion of the foot points of heliospheric magnetic field lines at the Sun: Implications for recurrent energetic particle events at high heliographic latitudes, *Journal of Geophysical Research* 101:15547-15553, 1996. Copyright 1996 American Geophysical Union.

BOX 1.3 Suborbital Measurements Enhance Atmospheric Science and Astrophysics

NASA's atmospheric chemistry program used balloon-borne instruments to provide the initial observations of key stratospheric species necessary to understand the processes, both human and natural, that impact the abundance of stratospheric ozone. Balloon-borne observations in the 1970s showed the destruction of Chlorofluorocarbons (CFCs) and production of chlorine monoxide (ClO). Measurements made on the ER-2 aircraft during the Antarctic Airborne Ozone Expedition in 1987 first showed a negative correlation between ClO and ozone. These measurements were cited in Congressional hearings as the "smoking gun" linking CFC-derived chlorine to the ozone hole.

Within a few months of the February 24, 1987 optical discovery of a supernova explosion (SN1987a) in the nearby Large Magellanic Cloud galaxy, a balloon-borne instrument detected gamma rays from the ejecta of a supernova for the first time. Over the next 2 years, a series of payloads flown from Australia measured gamma-ray lines from freshly produced radioactive nuclei and confirmed the basic theory of supernovae. According to this theory, after a massive star has spent its nuclear fuel the core collapses in a massive explosion causing a burst of radiation that creates the heavy elements, which are essential to the formation of stars, planets, living things, and most structure in the universe, and leaving behind a neutron star or a black hole. Such a short lead-time from discovery of a new event to making direct observations in wavelengths only observable above the atmosphere was possible within the balloon program. If observations had waited for the typical several-year lead-time for a spacecraft mission, the rapidly fading gamma-ray emission would have been undetectable.

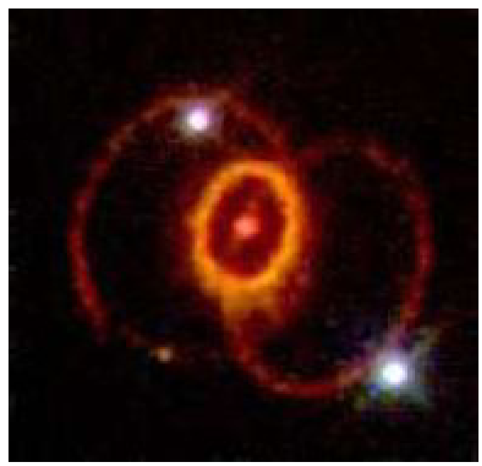
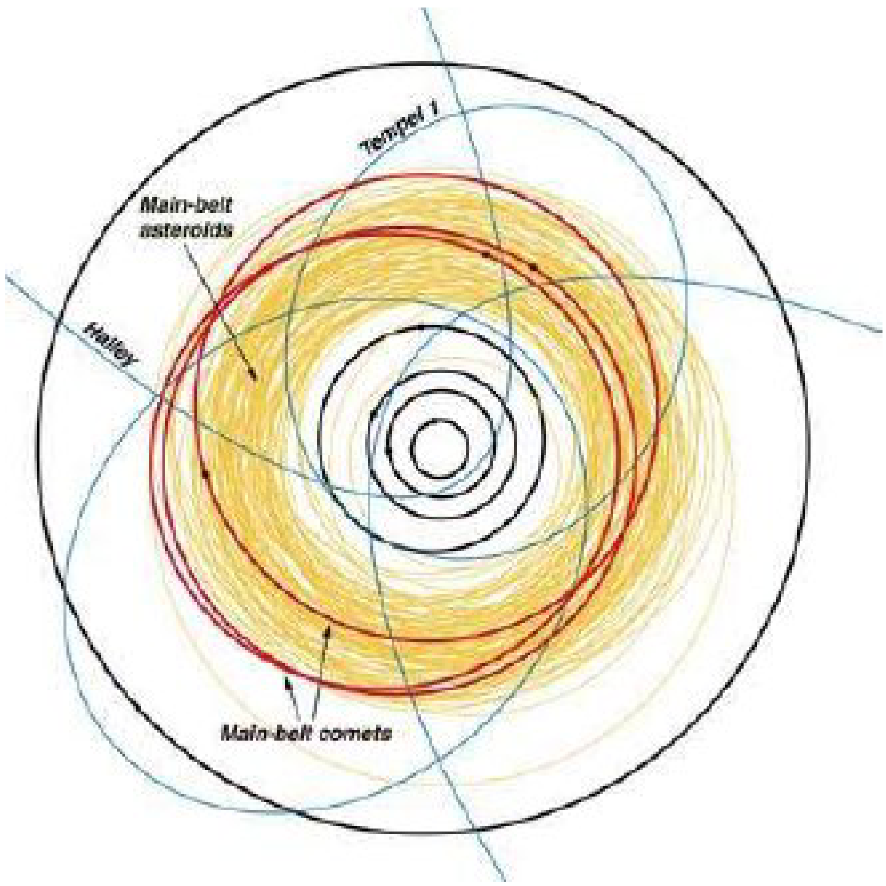


FIGURE 1.3.1 *Left:* ER-2 research aircraft. SOURCE: Courtesy of Jim Ross, NASA Dryden Flight Research Center. *Right:* Supernova SN 1987a as observed with the Hubble Space telescope. SOURCE: Courtesy of Dr. Christopher Burrows, ESA/STScI, and NASA.

BOX 1.4 Planetary Astronomy Program Discovers Main Belt Comets

In work using ground-based optical telescopes funded by the NASA planetary astronomy program, astronomers discovered comets orbiting in the main asteroid belt, a previously unknown class of solar system body. These bodies, referred to as “main-belt comets” (MBC), have caused a rethinking of the textbook categorization of comets and asteroids. The MBC are active (i.e., they eject substantial amounts of dust and gas) and have retained ice for the age of the solar system. At a distance of only 3 AU from the Sun they are exciting targets future comet missions. Their orbits and low level of activity benefit mission design and the presence of ice implies that they well preserved early solar bodies, unaltered by the internal heating experienced by many asteroids and all of the meteorite parent bodies. NASA funded R&A programs have also supported work at ground-based telescopes that has led to the discovery of other new classes of solar system bodies that will be targets for future missions. These include Kuiper Belt objects beyond the orbit of Neptune and Trojan “asteroids” in 1:1 orbital resonance with Neptune.



The family of main-belt comets (red orbits) shares the region of the solar system occupied by main-belt asteroids (orange orbits). The black ovals show the orbits of Mercury, Venus, Earth, Mars, and Jupiter. SOURCE: Courtesy of Pedro Lacerda, Queen's University Belfast.

BOX 1.5 Curation of Meteorites from Mars and the Moon

NASA's support for the laboratory analyses of meteorites led to the discovery of meteorites from Mars and also from the Moon. A very rare class of meteorites had elemental and mineralogical compositions suggestive of origin in a differentiated body of planetary size. Analysis of noble gases trapped in the meteorites matched Viking's *in-situ* analysis of the Martian atmosphere showing that these meteorites are liberated rocks from Mars. The growing collection of now 34 meteorites provides a unique sample-based information source on the geological chronology of Mars. The samples from various locales on Mars provide a wealth of information for planning future Mars missions and provide a broad base of sample information useful for data from missions. Similar studies have also identified 63 lunar meteorites and these also play a major role in understanding the geology and history of the Moon as well as planning future missions.

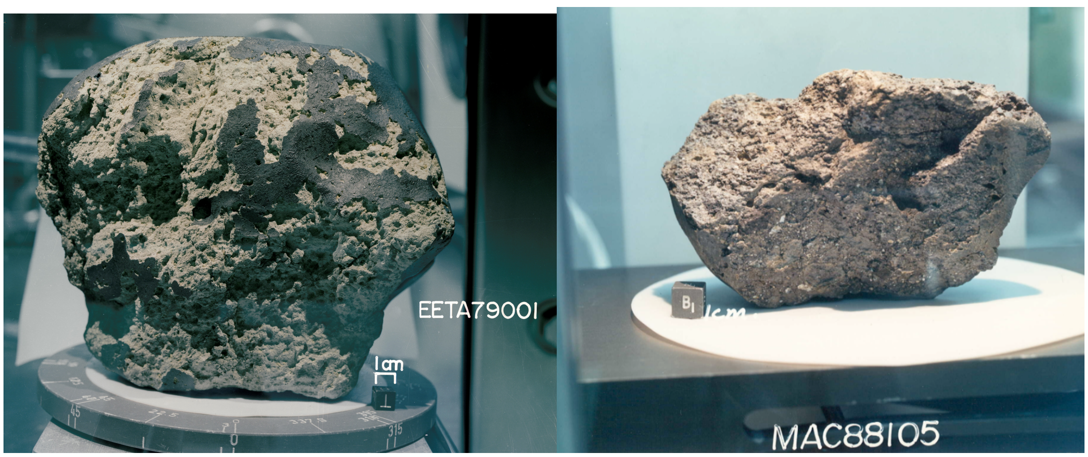


FIGURE 1.5.1 *Left:* The Martian meteorite, EETA79001, was collected in 1979 in the Elephant Moraine area of Antarctica. *Right:* The lunar meteorite, MAC88105, was collected in 1988 from the MacAlpine Hills area of Antarctica. SOURCE: NASA Astromaterials Acquisition and Curation Office.

Acquisition and Analysis of Supporting Data from Ground-based Facilities, Laboratories, Aircraft, Balloons, and Sounding Rockets

Many spacecraft missions require supporting observations, from the ground or from suborbital vehicles, to be able to plan their observations and interpret their data. Suborbital missions—balloons, sounding rockets and aircraft—have a number of essential functions in mission-enabling activities.[7] They are a training ground for both the current and next generation of scientists and engineers and are testing platforms for new instrumentation. In some cases the suborbital program provides the most cost-effective, and quickest, means to accomplish the science, more so than spacecraft observations. (For examples see Box 1.3.) In other cases, near-coincident ground-based telescope observations of a mission target provide information critical to interpreting the mission data.

For example, in Earth science ground truth or aircraft flights under the orbital tracks of spacecraft are essential for the calibration, validation, and interpretation of remote-sensing data. The suborbital

[7] For a comprehensive assessment of SMD suborbital programs see the forthcoming report of the NRC Committee on NASA's Suborbital Research Capabilities.

program also provides measurements with higher spatial and temporal resolution, and data for atmospheric species that cannot be observed from space. Satellite and suborbital data are used synergistically to investigate processes controlling atmospheric composition and to evaluate, improve, and constrain Earth system models. In planetary science and astrophysics, laboratory studies of chemical reactions under pressures and temperatures of different solar system and cosmic conditions, absorption coefficients and spectral line properties, and atomic and molecular transitions are often essential to the planning and interpretation of data from spaceflight missions. They feed into instrument design, identifying wavelength regimes and required resolution to study specific processes. Supporting ground-based telescopic observations have supported planetary and comet fly-by and entry missions, discovered a new class of comets in the asteroid belt (see Box 1.4), and mapped seasonal methane in the Martian atmosphere to indicate regions of the surface beneath which liquid water may exist today, possibly indicating life, thereby targeting future surface mission investigations on the planet. In astrophysics, a NASA-funded ground-based survey of the sky in the near-infrared (the Two-Micron All Sky Survey, or 2MASS) provided a highly sensitive sky census for use in planning the next-generation of infrared astronomy space missions.

Analysis of Mission Data

NASA science missions are often of limited duration. The spacecraft, however, will almost always return data for many years beyond the prime mission phase, the continued analysis of which generates important scientific results and directly contributes to the knowledgebase on which new missions are designed. For example, combined Mars data sets from missions extending back to Viking have built up the story of the evolution of water on the Martian surface, constraining optimum landing sites for Mars Science Laboratory. Survey data from the 1983 Infrared Astronomical Satellite mission provided maps of background sky brightness as well as interstellar cirrus structures integrated in observation planning tools for Spitzer Space Telescope, which was launched in 2003. The Heliophysics Great Observatory is a constellation of more than 15 spacecraft, strategically located throughout geospace and the heliosphere, which enables an unprecedented, coordinated study of the Sun and its influence on the heliosphere and Earth. These coordinated data analysis activities are conducted as a mission-enabling activity through a guest investigator program.

Establishment and/or Maintenance of Computational, Curatorial, and Other Ground-based Facilities

NASA science missions often require specialized and/or dedicated facilities to support analysis of their returned data and samples or to conduct studies to interpret data or run simulations. For example, the astromaterials curation facility at Johnson Space Center manages returned samples from Apollo, interplanetary dust collection experiments from aircraft, cometary samples returned from Stardust and more. (See Box 1.5) It is critical for current and future use, that these materials be kept in controlled environments and that all handling is tracked. A specialized laboratory for obtaining reflectance spectroscopy of wide ranges of terrestrial and extra-terrestrial materials at Brown University is necessary to explore the effects of parameters such as particle size and illumination and existence angles in order to properly interpret spectra of planetary and asteroidal surfaces returned from spacecraft. NASA maintains high-end computer systems and services at the Ames Research Center and the Goddard Space Flight Center (GSFC) that are used for data analysis and modeling in all four SMD science discipline areas.[8] For example, in 2008 these supercomputer systems supported over 130 principal-investigator-led projects in Earth sciences such as developing advanced data assimilation and visualization tools and modeling how

[8] See http://www.hec.nasa.gov/news/reports/HEC_2007-2008_web.pdf.

interactions of Earth's oceans and atmosphere affect climate change. Predictions of space weather, and how it will affect terrestrial systems, depend on advances in models of the various phenomena that control the impact of the Sun on Earth. The Community Coordinated Modeling Center at GSFC provides a readily accessible, community-developed model, as well as visualization and analysis tools and validation and metrics information.

Establishment and Maintenance of Data Archive Facilities

In the early years of NASA, the amount of data returned from missions was limited and generally thoroughly analyzed and made available through mission-related publications. Over time, data volumes have increased and continue to increase dramatically. Many missions today rely on years of post-mission analysis to extract most of the value from the data obtained. Also, as knowledge of the universe evolves, data can be reanalyzed and new information extracted from it. One example of this was re-analysis of Pioneer 10 and 11 dust impact data from the outer solar system, decades after its acquisition, showing evidence of dust spiraling in towards the sun from collisional production in the Kuiper Belt. At the time of the Pioneer mission, the Kuiper Belt had not been discovered. The primary product of all NASA missions is data. Its archiving, curation, and availability to the science community are critical to the derivation of value from those missions and hence are fundamental to the justification of continued data acquisition.

The NASA Planetary Data System (PDS) is the repository of all planetary digital data. All data in the PDS is peer-reviewed, curated at science discipline nodes, and accessible via the Internet. The challenge of the PDS is the extreme diversity of the nature and formats of its holdings, including mission data having different types of imaging systems and other remote sensing and in situ measurement instruments, as well as ground-based telescopic data, laboratory data, and derived data. The Earth Observing System Data and Information System manages and distributes data products through the Distributed Active Archive Centers. The centers process, archive, document, and distribute data from past and current research satellites and field programs. (See Box 1.6.) In heliophysics, the Virtual Solar Observatory unites access to space- and ground- based observations of the Sun, providing access to solar data through a variety of search engines.

NASA-supported archives have become fundamental to the infrastructure in astrophysics. The High Energy Astrophysics Science Archive Research Center, Multi-mission Archive at the Space Telescope Science Institute, and Infrared Processing and Analysis Center service thousands of requests per day from the community. NASA's shared support is also critical to other very large astrophysics archives such as SIMBAD (Set of Identifications, Measurements, and Bibliography for Astronomical Data) and the Sloan Digital Sky Survey. Although not precisely a data archive, most astronomers also use the journal access and bibliographical facilities of the Astrophysics Data System every day. NASA's shared support (with NSF) of the newly founded National Virtual Observatory promises to tie most astrophysics data bases together with 21st century technology.

Technology Development for Spaceflight Missions

Advances in technology facilitate advances in science. SMD missions operate in many different operating and radiation environments, such as Earth orbit, deep space, and planetary surfaces. Spacecraft systems and associated instrumentation must be designed and optimized to operate properly and make specific observations to address the intended mission science objectives. Past developments and adaptations in these areas have made the current SMD's missions possible just as on-going investments and development efforts will enable future missions.

For example, many instruments flown on NASA planetary science missions can trace their heritage to the Planetary Instrument Design and Development Program (PIDDP) and its counterparts dedicated to technologies for Mars missions and astrobiology. These technology development projects have impacted all mission size classes ranging from small and moderate-class Discovery missions to major flagship-class missions. In addition to contributions to instruments used for Mars missions, PIDDP has supported development of instruments or advanced instrument technologies that were subsequently used on the NASA-ESA Cassini mission to Saturn, Hubble Space Telescope, Messenger mission to Mercury, Near Earth Asteroid Rendezvous mission, ESA Rosetta comet mission, and ESA Beppi Colombo mission to Mercury, among others.

Suborbital programs provide a risk-tolerant pathway to support new instrument development, evaluation of innovative technologies, and flight operations experience while also carrying out important and often ground-breaking scientific research. (See Box 1.7.) These programs can be mounted quickly and inexpensively, and they bridge the gap between laboratory development of new technologies and flight-tested maturity.

For example, balloon missions provided development and test opportunities for the large silicon strip detector arrays now in orbit on the Fermi Gamma-ray Space Telescope. Spiderweb bolometers developed for balloon-borne measurements of the cosmic microwave background are now in space on the Plank and Herschel missions. In briefing the committee, the chair of NASA's Astrophysics Sounding Rocket Assessment Team reported that over its five-decade history the astrophysics sounding rocket program had contributed to development of dozens of new astronomical instrument technologies (e.g., aberration-corrected holographic gratings, far-ultraviolet optical coatings, and X-ray calorimeters) that subsequently played an enabling role on more than 20 different space astronomy missions. Similarly, balloon flights have provided development and test opportunities for prototype X-ray and gamma ray optics and detectors, cosmic microwave background bolometers, cosmic ray isotope spectrometers, Earth-atmosphere limb sounders, and many other instruments. These technologies have been incorporated into many past, currently operating, and planned future spaceflight missions.

Science and Engineering Workforce

Each of the four science disciplines within SMD requires a workforce of scientists, engineers, and other technical specialists to successfully accomplish its mission and associated research objectives. Because of the specialized state-of-the-art nature of the work undertaken by SMD, workforce maintenance is not only mission-enabling but is mission-essential. The engineering workforce is maintained primarily at NASA centers and industry plus university and non-university laboratories. The science workforce is maintained and developed primarily through a system of competitive grant programs that are subject-specific.[9]

Workforce stability, especially at universities and other non-government laboratories, is very sensitive to the stability of funding available through these programs and quickly responds negatively to sudden cuts. It is inelastic because workforce lost one year due to funding shortfalls will not be available when monies suddenly return. Specialists often depart for other career opportunities, and it takes a decade to train replacement scientists (including graduate school and post-doctoral experience). Some workforce specialties such as astronomy have significant sources of funding through other agencies (e.g., NSF) and private institutions. Other areas, such as planetary science, are largely creations of SMD and its progenitors and have little support beyond that provided via SMD-funded research activities.

[9] In briefing the committee, NASA officials reported that approximately 60 percent of SMD research grant funds goes to universities and other non-government laboratories, with about 33 percent going to NASA center researchers and the remainder going to other federal agencies.

BOX 1.6 Case Study: Ocean Color Science Advances via Mission-enabling Activities

Satellite remote sensing of ocean color has progressed significantly in the last three decades through a combination of new missions, mission-enabling data analysis, and technology development activities. For example, researchers have documented a significant decrease in ocean productivity through analysis of the multiple-satellite time series of ocean color measurements. Moreover, the technical capabilities of each mission have improved, which in turn have enabled more precise as well as more accurate measurements of the optical properties of the upper ocean. With the growing impacts of climate change on ocean ecosystems, the science issues have also evolved to include considerations of ecosystem function (e.g., nutrient cycles, organism resource production and consumption rates, and organism-environment feedback processes) and ecosystem structure(e.g., the numerical and physical distributions of species, nutrients, and natural resources in ecosystems and the configuration of these ecosystems' food webs). Of particular interest are studies of how climate-driven ocean acidification has led to decreased reef-building rates and declining populations of larval marine species like commercial fish and shell fish. To address these questions, mission-enabling activities have directly led to new technical requirements for future ocean color missions that rely on hyperspectral spectrometers rather than multi-band spectroradiometers, which have been flown for the past 30 years. Technical investments in airborne hyperspectral sensors have demonstrated that such sensors can be developed and flown with sufficient performance to meet the science requirements and at a cost to fit within an achievable budget profile.

The plots below, from satellite measurements of ocean color, show that global changes in annual average sea surface temperature (a) and net phytoplankton productivity (b) for the 1999 to 2004 warming period were inversely related (c).

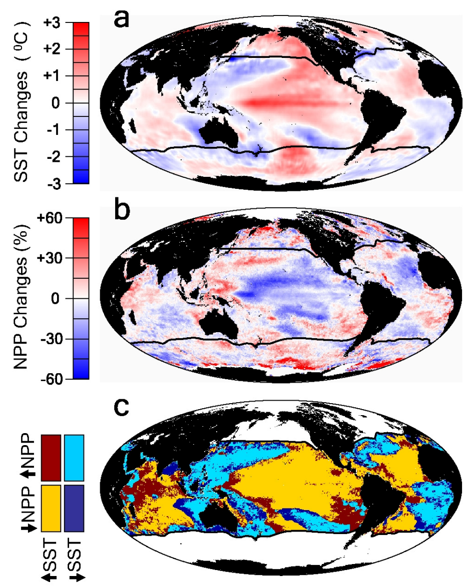


FIGURE 1.6.1 Reprinted by permission from Macmillan Publishers Ltd.: *Nature,* M.J. Behrenfeld, R.T. O'Malley, D.A. Siegel, C.R. McClain, J.L. Sarmiento, G.C. Feldman, A.J. Milligan, P.G. Falkowski, R.M. Letelier, and E.S. Boss, Climate-driven trends in contemporary ocean productivity, *Nature* 444:752-696, Copyright 2006.

BOX 1.7 Sounding Rocket Technology and Exploration Unveiled the X-ray Universe

In 1963 an Aerobee rocket was launched from White Sands, NM to detect X-rays from the Moon. With a flight to only 225 km altitude, onboard Geiger counters discovered Scorpio X-1, the first astronomical X-ray source other than the Sun, and detected the cosmic diffuse X-ray background radiation. This unexpected discovery on a single rocket flight opened up an entirely new field of science and a highly productive window on the universe. The mission-enabling discovery led to more rocket and balloon projects, and just 7 years later UHURU became the first Earth-orbiting mission dedicated entirely to celestial X-ray astronomy. This early sounding rocket work also was a factor leading to recognition of astrophysicist Riccardo Giacconi with the 2002 Nobel Prize in Physics. According to briefings to the committee, sounding rocket projects have contributed to new technologies for X-ray Geiger counters and proportional counters, modulation collimators, multi-anode detectors, polarimeters, grazing incidence mirrors, and quantum calorimeters, and those flight technology developments were subsequently used on nearly a dozen spaceflight missions.

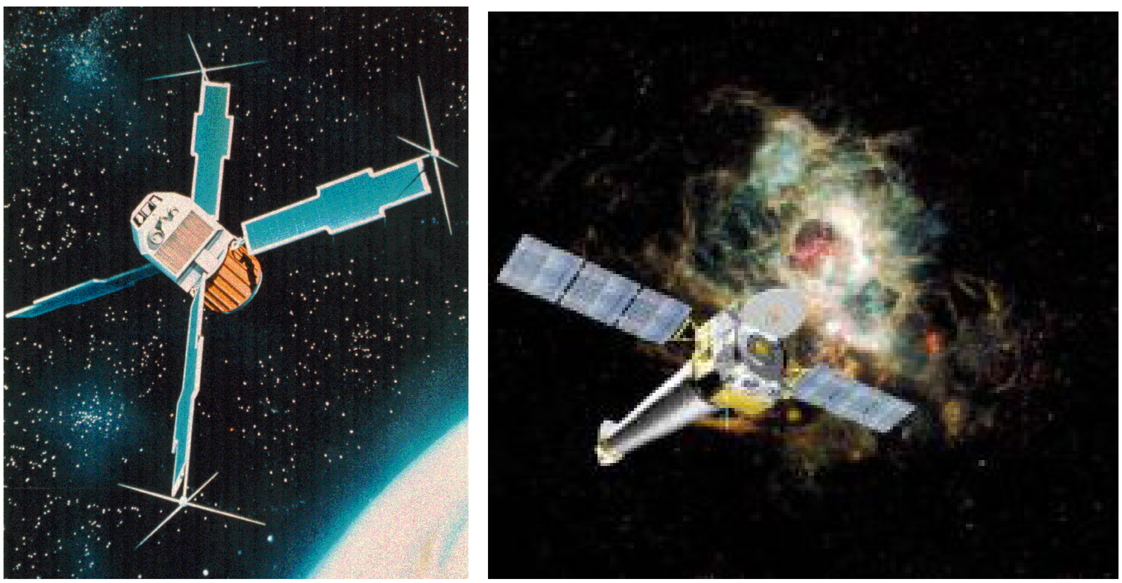


FIGURE 1.7.1 Artist's depictions of the UHURU *(left)* and Chandra *(right)* X-ray astronomy observatories. SOURCES: Courtesy of the Smithsonian Astrophysical Observatory (SAO) *(left)* and NASA Marshall Space Flight Center *(right).*

While research programs in general are not designed or contemplated with workforce maintenance in mind, they are the core of that maintenance and also the principal means by which training graduate students, post-docs, and early-career specialists in the discipline occurs. SMD also supports focused programs targeting students and younger researchers. The skills needed both inside and outside NASA in managing a scientific research project develop through years of experience. SMD-sponsored programs in advanced technology development and suborbital flight projects are especially relevant for providing hands-on hardware experience in engineering disciplines. Thus there is an important distinction between *training in specialized skills*, which is where mission-enabling activities have an important role, and *education*, which is the responsibility of the universities.

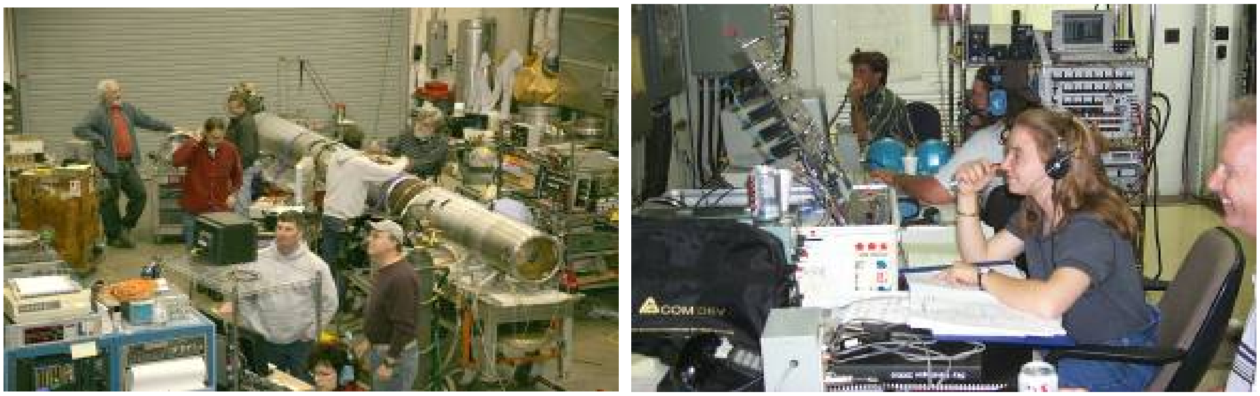


FIGURE 1.2 Participation in sounding rocket flight investigations gives science and engineering students soup-to-nuts, systems-wide exposure to the process of designing, building, integrating, testing, and flying a space research mission, all on a relatively short time scale, low cost, and high risk tolerance. SOURCES: *Left:* Courtesy of Stephan McCandliss, Johns Hopkins University. *Right:* Shown is Pennsylvania State University (PSU) graduate student Ann Hornschemeier; courtesy of David N. Burrows, PSU.

Examples of SMD training programs include the following:

- The NASA Earth and Space Science Fellowship program made awards to 87 graduate students in 2007 and 79 graduate students in 2008 across all four science discipline areas. (See Table 1.1 for discipline details.) The Earth Sciences division supports a New Investigator Program for junior scientists within 5 years of having received a terminal degree and is currently undertaking a new initiative to address the need for more young researchers having experience in building instruments within that community. The Planetary Sciences division supports a competitive Fellowship for Early Career Researchers Program providing additional salary and funding for equipment to researchers within 7 years of having received their Ph.D.[10]
- Research grants to researchers at universities often include support for students who participate in research projects under direction from a university faculty or research staff supervisor, and SMD-supported research projects frequently comprise the subjects of student thesis dissertations.
- The sounding rocket, balloon, and aircraft programs are important training venues, not only for scientists but also for engineers and engineering managers, in designing, building, and operating flight instrumentation and payloads. All three types of vehicles support university-based research teams, and the typical project durations of a few years or less are good matches to the duration of a graduate student thesis project. They are equally important for students, early-career technical professionals, and junior NASA engineers and managers as unique opportunities to gain hands-on experience and insight into the disciplines of systems engineering and operations. (See Figure 1.2.)

DIFFERENCES IN MISSION-ENABLING ACTIVITIES ACROSS SMD DISCIPLINE DIVISIONS

The elements of the mission-enabling programs in each of the SMD science divisions—astrophysics, heliophysics, planetary science, and Earth science—are very similar. Each division provides some support for technology development, data analysis and interpretation, theory and

[10] For more information on SMD student and post-doctoral opportunities see the SARA Web site at http://nasascience.nasa.gov/researchers/sara/student-programs.

modeling, workforce development, and so on. However, for each division, the balance among these various elements can differ depending how the science of the division is conducted, the extent to which other agencies support programs that complement or depend on NASA, and many other factors.

To highlight some of the differences, the committee considered how the SMD divisions' programs interact with the research programs of other agencies. In the case of planetary science, NASA is by far the principal sponsor of research, and thus programs supported by other agencies are not a major factor. In the case of astrophysics, the NSF, DOE, DOD, and even private foundations provide support for ground-based astronomical observations, and DOE also supports some spaceflight studies. In heliophysics, development of an operational capability in space weather modeling and forecasting is an important concern of DOD and NOAA; consequently both of those agencies and NSF provide complementary support for space weather research.[11] Earth science has the most extensive interagency relationships, because issues such as climate change and environmental monitoring are the concern of multiple agencies. Coordination of government climate change research receives particular attention from the White House, and global Earth observing systems are also an area of major international collaboration and coordination.

There are also differences among the SMD divisions in the importance of numerical modeling. Researchers connected to all divisions make use of numerical modeling because this is the means by which data are interpreted, theoretical calculations are grounded, and complex physical processes are simulated and understood. In divisions where there is a current or ultimate end-user who will depend on the predictive capability the models will provide, the modeling activity gets particular emphasis. In heliophysics models of the Sun-Earth system ultimately need to provide the capability to predict space weather hazards and effects. In Earth science, advances in modeling the global Earth system—i.e., the biosphere, atmosphere, oceans, land surface, and cryosphere—will improve weather forecasting and predictions of climate change that will serve as the basis for major environmental policy decisions.

Data analysis programs are often mission-specific, and in such cases they are not treated in this report as a broader mission-enabling activity. The part of data analysis programs that is considered to be mission-enabling is the analysis of data from past missions and programs that facilitate the synthesis and analysis of data from multiple missions. The level of emphasis on this mission-enabling activity depends on the suite of missions that is available in a particular field and the character of the scientific problems to be addressed. In heliophysics, many scientific problems require analysis of data from a suite of spacecraft, known collectively as the Heliospheric Great Observatory, launched during the last several decades. Analysis of current missions in astrophysics and planetary exploration are often done in the context of results from past missions. Earth science, which addresses the Earth as an integrated system, depends on the observations from multiple spacecraft and instruments, which need coordinated analysis and interpretation.

The importance of ground-based and suborbital observations also varies among the divisions. Earth science is heavily dependent on aircraft and ground-based observations for ground-truth and for calibration and validation of spaceflight data. Significant scientific observations in astrophysics can be conducted from high-altitude balloons and aircraft. Sounding rockets have a important role in technology development, workforce development, and science in both heliophysics and astrophysics. Missions in planetary science require ground-based observations, especially for mission planning and often also to provide data to complement the spacecraft data.

Technology development is a common need across the divisions, yet here too there are differences. In divisions that rely more on facility-class instruments, the technology advances need to feed into the major engineering organizations, especially NASA centers and industry, that will be responsible for the design and development of the facility instruments. When the instruments are developed by principal investigator-led teams, the technology advances may need to be available to university researchers. Theoretical research is also a common activity among the divisions, but there can

[11] NASA also has its own internal needs for operational space weather capabilities to understand and mediate space radiation risks to human spaceflight beyond low Earth orbit.

be differences in who depends most on the research results. In divisions with a strong numerical modeling emphasis—i.e., heliophysics and Earth science—advances in theoretical research need to be strongly coupled with and feed into the modeling effort.

As a consequence of the different roles mission-enabling activities have within each division, the committee believes that it is entirely appropriate for mission-enabling activities to be managed separately in each of the divisions and not consolidated in a single SMD mission-enabling program organization. The balance among different kinds of mission-enabling activity will surely differ substantially among the divisions, but it is to be expected that each division should include some level of support for each of the elements described in previously in this chapter.

2

Assessment of NASA's Mission-enabling Activities

The mission-enabling activities of NASA's Science Mission Directorate (SMD) have served as the essential foundation for the world's most diverse and successful space and Earth science program. NASA's spaceflight program has been highly successful, fundamentally altering our scientific understanding of the Earth, the solar system, and the universe beyond. The committee believes that for progress to continue, similarly visionary science and technology investments must continue and must be recognized as the essential foundation for all of SMD's activities.

BROAD CONCERNS AND OPPORTUNITIES FOR IMPROVEMENT

During briefings to the committee, NASA officials shared several concerns about mission-enabling programs. First, in a mission-oriented agency like NASA there is a natural tendency to give priority to targeted research investigations rather than to support more broadly based core activities. This preference also creates an inclination toward specific research projects rather than institutional or technical field needs. Second, there is a natural emphasis on spaceflight missions because budget allocation decisions that might lead to a decreasing flight rate are not viewed as consistent with a stable long-term strategy. Third, there are too many proposals being submitted relative to the total funding available to the research community and the resources to review them. More effort in proposal preparation and review means less time devoted to research and a less efficient process.

NASA officials also emphasized that the total research dollars available to the research community are not increasing at a time when the volume and complexity of mission data being returned and the depth and diversity of the science represented in flight missions are increasing rapidly. This leads to a growing gap between the money invested in NASA missions and NASA's capability to realize a full return on that investment. Indeed, several recent studies have concluded that the mismatch between NASA's assigned responsibilities and available budget is untenable.[1] Other participants in the committee's data-gathering meetings commented that the composition and balance between spaceflight missions and mission-enabling activities have evolved over time, but without quantification and explicit assessment inside or outside NASA.

The committee identified several basic practices for managing mission-enabling activities that do not appear to be widely employed or adequately applied in SMD.

Ensuring Traceability from Strategic Goals to Mission-enabling Objectives and Activities

The committee believes it is essential to identify those mission-enabling activities that are required to meet the unique strategic goals of each SMD scientific division with respect to past, imminent,

[1] National Research Council, *An Assessment of Balance in NASA's Science Programs*, The National Academies Press, Washington, D.C., 2006; National Research Council, *America's Future in Space: Aligning the Civil Space Program with National Needs*, The National Academies Press, Washington, D.C., 2009.

and still-to-be-identified future spaceflight missions. The lack of a well-defined process for selecting mission-enabling activities motivated by strategic program goals limits the ability of SMD to justify its mission-enabling activities to senior NASA management, OMB, and Congress. Lack of such a process also reduces the transparency of decision-making to the scientific community and fails to ensure that the goals of each division are adequately supported by mission-enabling activities.

Establishing Systematic Allocation of Resources and Metrics for Evaluation of Effectiveness

The SMD Strategic Plan discusses how spaceflight missions are assigned priorities within the context of the NRC decadal surveys[2] and a prioritized set of science questions, but aside from statements regarding the fundamental importance of mission-enabling activities to the scientific enterprise, the Strategic Plan does not discuss how relative funding allocation decisions are made within mission-enabling programs or between mission-enabling and spaceflight mission programs. Moreover, there is neither a set of criteria for determining the range of mission-enabling programs required to support SMD strategic goals nor an assessment process for determining the directions and effectiveness of the mission-enabling activities in the context of meeting the strategic goals of SMD or its divisions. This lack of strategic integration was noted in the first recommendation of the 1998 NRC report on research and data analysis (R&DA) activities.[3]

A 1999 NRC report[4] recommended ways to evaluate federally sponsored basic and applied research and drew several conclusions that are highly relevant to the committee's considerations of metrics of effectiveness. It emphasized the importance of using expert reviewers in assessing both types of research. One of the report's major recommendations was as follows:

> For applied research programs, agencies should measure progress toward practical outcomes. For basic research programs, agencies should measure quality, relevance, and leadership. In addition, agencies should conduct periodic reviews of the overall practical outcomes of an agency's overall past support of applied and basic research. The use of measurements needs to recognize what can and cannot be measured. Misuse of measurement can lead to strongly negative results; for example, measuring basic research on the basis of short-term relevance would be extremely destructive to quality work. (p. 38)

The following set of R&D metrics, which were developed by George Heilmeier,[5] former director of DARPA, is widely used by industry and government:

- What are you trying to do? Articulate your objectives using absolutely no jargon.
- How is it done today, and what are the limits of current practice?
- What's new in your approach and why do you think it will be successful?
- Who cares? If you're successful, what difference will it make?

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[2] The NRC decadal surveys have been widely used by the scientific community and by program decision makers because they (a) present explicit, consensus priorities for the most important, potentially revolutionary science that should be undertaken within the span of a decade; (b) develop priorities for future investments in research facilities, space missions, and/or supporting programs; (c) rank competing opportunities and ideas and clearly indicate which ones are of higher or lower priority in terms of the timing, risk, and cost of their implementation; and (d) make the difficult adverse decisions about other meritorious ideas that cannot be accommodated within realistically available resources.

[3] National Research Council, *Supporting Research and Data Analysis in NASA's Science Programs: Engines for Innovation and Synthesis*, National Academy Press, Washington, D.C., 1998.

[4] National Research Council, *Evaluating Federal Research Programs: Research and the Government Performance and Results Act*, National Academy Press, Washington, D.C., 1999.

[5] G. Heilmeier, Some reflections on innovation and invention, *The Bridge* 22(4):12-16, 1992.

- What are the risks and the payoffs?
- How much will it cost? How long will it take?
- What are the midterm and final "exams" to check for success?

Most often used for project selection, Heilmeier's criteria are also frequently used as the basis for reviews and evaluations of project progress. But these criteria can also be adapted at the strategic level—e.g., to measure linkages between customer needs, strategies to satisfy those needs, the objectives and goals associated with each strategy, and finally the projects and activities that enable the objectives and goals to be realized.

Obtaining Continual Advisory Input

For most of the history of NASA, SMD and its predecessor organizations had a highly effective internal advisory structure. Individual scientific disciplines had informal advisory committees, known as Management Operations Working Groups (MOWGs), which were not chartered under the Federal Advisory Committee Act (FACA). The chairs of these committees served on the advisory committees of the science divisions in SMD; the chairs of the divisional advisory committees served on the advisory committee of the associate administrator (AA) of SMD; and the chair of the AA's committee served on the NASA Advisory Council. This vertically integrated structure of advisory committees served to link all of the science activities of SMD and gave management at all levels access to expert advice. Conflicts of interest on the formal advisory committees were handled according to the procedures of the FACA. Conflicts of interest on the informal advisory committees were handled in the usual effective way of both revealing and balancing any potential conflict.

Despite the fact that this advisory structure served SMD and NASA very well for more than 40 years, it was effectively eliminated by NASA in 2004 without an adequate replacement. Some MOWGs still exist, but the linkage among advisory committees, and the flow of effective actionable scientific advice at the directorate level, is no longer possible. From the perspective of prioritization and management of SMD mission-enabling activities, this is a serious concern in that there is currently no mechanism in place whereby the scientific community can directly contribute to the design, assessment, or implementation of these programs.

A 2006 NRC report, *An Assessment of the Balance in NASA's Science Programs*, also noted the consequences of not having an effective internal advisory structure in SMD:

> A past strength of the NASA science programs, in both planning and their execution, has been the intimate involvement of the scientific community…[however] external scientific involvement was absent in the construction of the program that accompanied the FY2007 budget; had an advisory structure existed, it could have warned NASA of the outcry that would accompany cuts to the R&A budget and other decisions. (p. 33)

As a 2004 NRC report noted,[6] a scientific community that has some "ownership" in a program creates "constructive tension" that pushes the program to excel.

The effective management of the mission-enabling activities in SMD requires the continual interaction with and assessment by the science community. If it is not possible to reconstitute the advisory structure that previously performed the interaction and assessment functions, it will be necessary to create some equivalent advisory structure, even if it is only on an ad hoc basis and only devoted to mission-enabling activities.

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[6] National Research Council, *Issues and Opportunities Regarding the U.S. Space Program: A Summary Report of a Workshop on National Space Policy*, The National Academies Press, Washington, D.C., 2004.

Establishing Budget Transparency

SMD's funds for mission-enabling activities are carried in many different budget categories. They include, for example, lines for research and analysis, data analysis, data systems, technology development, suborbital programs, and guest investigator programs in some disciplines. Consequently, the structure of the SMD budget does not readily lend itself to identifying the total mission-enabling level of investment. SMD officials explained to the committee that "research is part of everything we do, and is part of every budget line" and that "isolating research into a single budget line gives the false impression to outside observers that research is separate from flight missions rather than being an integral part of the [nation's R&D efforts] benefiting from NASA's flight missions."[7] Thus, while some budget lines clearly relate to mission-enabling activities (e.g., research and analysis lines), other mission-enabling activities appear to be embedded in spaceflight mission budget lines. Without aggregating the total mission-enabling investment levels within SMD divisions and programs, it is difficult if not impossible to conduct analyses and evaluate trade-offs in the allocation of budgets for mission-enabling activities versus spaceflight missions.[8]

In contrast, the DOD has distinct and separate budgetary program elements for basic research (6.1), applied research (or exploratory development) (6.2), and advanced technology development (6.3).[9] Those funds must reside in their stand-alone program elements and cannot be mixed with one another nor embedded in non-research or non-technology budget lines. Thus, for instance, funding for basic research cannot be used for advanced technology development activities, and vice versa, and each of those budget elements must be separately identified and justified with their own respective rationales. Contrary to the idea that DOD research and technology funds should be placed in "one pot" for maximum flexibility and not differentiated from one another in terms of budget construction, such a practice might encourage misuse of basic research funds for advanced technology activities when these latter resource-intensive and highly visible activities run into budget overrun situations. Similarly, failure to clearly identify and differentiate the full magnitude of mission-enabling funds from spaceflight mission funds could lead to a similar situation within SMD. This full transparency of the research and technology budgets has motivated DOD organizations to develop and articulate the rationale for their research and technology budgets. It has also allowed various stakeholders (DOD agencies, Congress, others) to protect those budget elements when overall budgetary shortfalls would tempt some to divert funding away from mission-enabling activities within DOD to mission activities.

As an added consideration, experience within DOD has shown that actively managing basic research types of activities often requires different processes, metrics, and management techniques than those associated with managing advanced technology development and system prototyping activities. Thus, explicit identification and separation of basic research and advanced technology development funding can contribute to more effective portfolio management of the research and technology budget as a whole.

Sustaining a Capable Technical Workforce

In the past some mission-enabling programs have been vague or even inconsistent in their approach to workforce development. For example, the Long-Term Space Astrophysics Program was initially considered as a mechanism for encouraging junior investigators, but in the end supported a

[7] Briefing to the committee by SMD Chief Scientist, Paul Hertz, on January 22, 2009.

[8] The NRC report, *Supporting Research and Data Analysis in NASA's Science Programs: Engines for Innovation and Synthesis* (National Academy Press, Washington, D.C., 1998), made the same points.

[9] DOD R&D categories 6.1, 6.2, and 6.3 designate basic research, applied research, and advanced technology development, respectively. Higher categories cover stages of development ranging from technology demonstration and validation (6.4) through pre-production operational system development (6.7).

substantial number of senior ones.[10] The committee found that the lack of a clear definition of the role played by mission-enabling activities in workforce development has led to differences of opinion within SMD on what this role should be. Some divisions (e.g., Earth Science and Planetary Science) have specific programs for early career development, while others do not. All of the divisions have graduate student participation at some level, but the committee found no evidence that workforce development is being considered strategically in any of the divisions, beyond the usual counting of number of students supported. Specific selection criteria for proposals include "science merit (from peer review) and programmatic needs (future missions, unique opportunities, portfolio balance, high-risk research)."[11] Consideration of workforce development or training of young scientists and engineers is not currently part of the formal selection process. When interviewed, some SMD program managers indicated that workforce development was not a goal of their programs. Although they did find it to be an important side-benefit of SMD activities, they did not feel that it should be a consideration when selecting competing proposals. Other program managers did take it into consideration in an informal manner. The diversity in workforce goals among the different divisions is not necessarily undesirable, but the lack of public, clear articulation of the particular workforce goal for each group is a problem.

Providing for Adequate SMD Staffing in Support of Mission-enabling Activities

Over the last two decades there has been a substantial reduction in staff in SMD at NASA headquarters. (Counting support service contractors, the reduction is by a factor ~3). The result is that the research program staff no longer has the time to perform the tasks required of them, such as the management of mission-enabling activities, while still overseeing scientific aspects of flight programs, maintaining adequate contact with the scientific communities they serve, and in some instances participating in both interagency and international programs.

There are several root causes for the committee's concerns, not the least of which is the need for adequate scientific and support staff at NASA headquarters who have the skills, time, and opportunity to proactively manage the mission-enabling portfolios. The committee encountered program managers who are competent and dedicated but are overworked. Program managers who handle SMD's mission-enabling activities oversee the solicitation, evaluation, and award selection decisions for more than 4200 proposals annually. The committee heard, and saw, that program officers have heavy and complex workloads that leave them little time to focus on their mission-enabling program management responsibilities and still meet basic oversight requirements for tracking the progress of funding actions and program developments. For example, a typical SMD science program manager's responsibilities might now include the following roles:

- Program scientist for one or more future spaceflight missions and/or instruments in development or going through competitive selection
- Program scientist for several (e.g., 2-4) operating spaceflight missions
- Participation in biennial reviews of all operating missions in a discipline area
- Management of several (e.g., 2-5) different research and analysis grant programs (including oversight for preparation of the proposal solicitations, proposal peer reviews, award selection recommendations, and award paperwork)
- Program scientist for a suborbital flight program (or other major research facility)

[10] See National Research Council, *Astronomy and Astrophysics in the New Millennium* (National Academy Press, Washington, D.C., 2001, p. 199) and D. Helfand, Columbia University, "A Longitudinal Study of Selected Astronomers Based on Early Sources of Support," provided to the Panel on Astronomy Education and Policy of the Astronomy and Astrophysics Survey Committee, National Research Council, Washington, D.C.

[11] Briefing to the committee by SMD Chief Scientist, Paul Hertz, on January 22, 2009.

- Support of internal advisory committees and responses to requests from external advisory bodies (e.g., NRC committees)
- Participation in meetings of scientific societies to stay abreast of developments in relevant fields

The committee firmly believes that this diversity of roles in which SMD program officers maintain active insight into both mission-enabling and flight mission programs is a strength that should be preserved. Furthermore, responsibility for managing mission-enabling programs is properly a headquarters role; delegating this responsibility to NASA centers would create a conflict of interest because scientists at the centers compete with non-NASA scientists for funding in the programs. But with the current inadequate size of the SMD staff, program officers are not able to devote an appropriate amount of time to these tasks. The committee considers that the staffing shortfall at NASA headquarters is the most important impediment to being able to effectively implement its recommendations.

3

Principles and Metrics for Managing Effective Mission-Enabling Portfolios

The committee presents its recommendations for metrics for evaluating mission-enabling activities and criteria for making portfolio allocations in three steps: first, a set of guiding principles that should serve as the foundation for a successful mission-enabling program; second, complementary implementation principles to be considered in translating these principles into specific plans; and finally, a series of metrics that could be developed and applied to verify that the balance and distribution of mission-enabling activities is able to satisfy the guiding principles.

GUIDING PRINCIPLES

1. *First and most importantly, the mission-enabling program, taken in its entirety, should encompass the range and scope of activities needed to support SMD strategic goals, provide the broad knowledge base that is the context necessary to interpreting data from spaceflight missions and to defining new spaceflight missions, and maximize the scientific return from all spaceflight missions.*

Mission-enabling activities are essential to addressing SMD strategic goals, and they are the research foundation on which the success of the spaceflight program rests. They also provide—through theory, modeling, and coordinated research and data analysis—the linkages among the various flight missions, and they independently add to that data to form a cohesive space and Earth science program.

The scientific value of spaceflight missions depends on actions taken and investments made throughout the lifetime of a mission. Thus, many different components of the mission-enabling program are essential for achieving the maximum scientific return. New technologies have to be made available so that spaceflight missions can make forefront observations and measurements. New theoretical understandings need to be developed so that spaceflight missions can be designed to address the most pressing scientific questions and provide meaningful tests of new scientific ideas. The scientific results of one mission need to be compared with and analyzed in concert with results from other ongoing or past missions studying similar phenomena, to maximize the scientific return from the entire flight program.

2. *There should be a continuous flow of advanced technical capabilities and improved scientific understanding from mission-enabling activities into new spaceflight missions.*

New technologies at many steps in their development ultimately find their way into spaceflight programs. New technologies begin with an idea or concept, at a low technical readiness level (TRL),[1] and if successful undergo continuous refinement and improvement until they can be validated for flight. Ensuring a clear and predictable pathway from early technology development to mission-ready maturity is not always easy or straightforward. There are many opportunities to disrupt this flow and to fail to take

[1] NASA classifies the maturity of a technology according to seven technology readiness levels (TRLs), which start with TRL 1 (basic principles observed and reported), TRL 2 (technology concept and/or application formulated), TRL 3 (analytical and experimental critical function and/or characteristic proof of concept), TRL 4 (component and/or breadboard validation in laboratory environment), and so on, up to TRL 7 (system prototype demonstration in an operational environment).

advantage of a new capability that could achieve a scientific breakthrough. Active management of mission-enabling programs is thus required, to ensure that new technical concepts are being considered and that there are means by which the most promising new technologies can be brought to a sufficiently high TRL to be incorporated into or even serve as the basis for new spaceflight missions.

Theory and modeling follow a similar path. New scientific understanding begins with a concept—a new theory—often based on new observations. Such concepts then need to be incorporated into and improve comprehensive numerical models, which, when validated by observations, serve to provide increased scientific understanding. This portfolio of incubating ideas also needs to be actively managed, with theoretical research, modeling activities, and data interpretation all adequately supported, and linked so that observations drive new theoretical concepts, and new theoretical concepts are tested against observations.

3. *The mission-enabling program should enable a healthy scientific and technical workforce capable of conducting NASA's space and Earth science program.*

Success at NASA and within a scientific discipline requires a skilled, vibrant workforce. In scientific disciplines whose current practitioners entered the field decades ago, there is a need for early-career scientists and engineers. In other scientific disciplines the age distribution may be adequate, but the numbers or skills of scientists and engineers are insufficient to support the planned future program. There may be cases where it is necessary simply to rejuvenate a field with new researchers. It may also be the case that experienced scientists and engineers are being lost in an area due to temporary budget cuts and that the loss needs to be stemmed to be able to meet anticipated future demands.

It is in NASA's best interest to actively assess its internal workforce needs as well as required national capabilities in the scientific and engineering disciplines necessary to implement its programs. It is also appropriate that NASA take actions to deploy resources to facilitate and maintain a healthy workforce for those areas. The exciting programs of SMD should be widely known among students choosing careers, to encourage them to consider space and Earth science. Opportunities for undergraduate research and an adequate number of graduate fellowships should be available, as well as support for graduate students through NASA grants and contracts. Most importantly, the universities responsible for training undergraduate and graduate students, particularly experimentalists, should be supported to actively participate in flight programs, including the suborbital program, so that students receive essential hands-on experience that will make them valuable additions to the space and Earth science community.

IMPLEMENTATION PRINCIPLES

The first of the guiding principles above is applicable to each SMD science division. How the second and third principles are applied, and the priorities established among the elements of the mission-enabling program, will vary from division to division. However, each SMD science division needs a set of metrics that can be used to evaluate the completeness and efficacy of the components of its mission-enabling activities. Without such a set of metrics, it is difficult to know whether a particular resource allocation strategy is indeed appropriate, and if or when adjustments are needed to bring implementation back into alignment with the division's overall strategic framework. The committee identified the following cross-cutting issues or implementation principles that should be considered in applying a set of metrics.

1. *Investment needs will be different across SMD divisions.*

Each SMD science division has distinct strategic goals. Some division science plans require a higher level of integration across multiple spaceflight missions; some require longer-term observations relative to those of other divisions; and the nature and expense of spaceflight missions necessarily differ across divisions. The level of investment in mission-enabling activities will also differ and will depend on factors such as the amount of basic research required to allow cost-effective missions to be defined and the extent to which such research is supported external to NASA. Consequently, there should not be a rigid set of formulas for mission-enabling program funding across SMD, and investments should reflect this reality.

2. *Division-level mission statements should clearly articulate strategic priorities.*

SMD division goals are advanced directly (e.g., by addressing a science objective) as well as indirectly (e.g., by supporting necessary infrastructure) and are supported in both cases by the sum of its mission-enabling activities. Each division's mission statement for its mission-enabling activities should provide a rational framework for assessing how its portfolio ensures support for the full range of activities. Multiple possible components of a mission statement may include technology-readiness enhancement, development of a junior workforce, sustainment of a mid-career non-faculty workforce, and maintenance of critical physical infrastructure. In a constrained budget environment these multiple components are inevitably in significant tension with one another. Given these tensions and pressures, a mission statement that identifies these components allows for their overt prioritization and active management by each SMD division. There is an important role for the external science community in helping to identify these priorities.

3. *Balance between mission-enabling and spaceflight mission portfolios is never rigid.*

Balancing mission-enabling activities with spaceflight missions presents many challenges, the first of which is the meaning of the term "balance." The committee does not interpret balance to mean a fixed ratio. Rather, balance refers to finding the appropriate level and profile of funding for each activity within the resources available to NASA. This means that the ratio itself may not be constant over time.

In general, mission-enabling activities and spaceflight missions are programmatically very different. Spaceflight missions can take 10 years or more to design, develop, launch, and execute and have expense profiles that can vary substantially from one year to the next as a project moves through design, development, construction, and post-launch operation phases. Mission-enabling activities have objectives that are as broad and far-reaching as NASA strategic goals. They are executed by a large number of science teams undertaking individual research projects that overlap in time, run at a much lower funding level than spaceflight missions, and often achieve success within 2 to 3 years. Consequently, the mission-enabling programs cannot sustain significant swings in funding without suffering major disruptions.

4. *Programmatic relationships of mission-enabling activities to spaceflight programs should be clearly communicated.*

Although NASA is a spaceflight-mission-oriented agency and the mission-enabling activities must clearly relate to and support this responsibility, the connections of mission-enabling activities with flight missions are not always clearly appreciated. This relationship is on a general level and does not correspond one-to-one to specific flight missions or even specific flight programs. There may be a fear that some innovative, risky, or long-term mission-enabling activities will be particularly difficult to connect to the flight programs and thus be at financial risk in such a more open analysis. However, the committee believes that senior decision makers and the research community will be receptive to a broad range of mission-enabling activity when given the above context and when the rationale is openly articulated. Mission-enabling programs are actually more at risk when their role within SMD is not openly articulated and argued.

5. *Balance within portfolios requires active management.*

The distribution of resources among the various mission-enabling activities reflects whether such resources are appropriately balanced within schedule and budget constraints to achieve the intended goals and objectives. Too much research at the expense of too little technology could jeopardize the ability to conduct a mission; on the other hand, too little research at the expense of too much technology might result in a mission that is ill-conceived or ill-defined, even if it "flies on-time." Underinvestment in data analysis (relative to research and/or technology investments) could mean that even should a mission be successful in collecting the appropriate data, there is insufficient ability to analyze that data and turn it into knowledge—the end objective.

The characterization of a portfolio of projects from a near-term, mid-term, and far-term perspective determines whether the portfolio will be able to sustain the organizational mission in both the present and the future. Too much near-term investment at the expense of too little far-term investment could dry up the pipeline supporting next-generation missions even if near-term missions are successful. On the other hand, too much far-term investment at the expense of too little near-term investment could jeopardize the success of immediate missions.

In a budget-constrained environment (the norm), the probability of strategic success will be significantly enhanced by measuring whether there is an appropriate distribution of resources among mission-enabling elements in the context of supporting a given mission, and by measuring whether the resources within each element have an appropriate time perspective in supporting near-, mid-, and far-term activities. Likewise, traceability of projects linked to objectives, which in turn are linked to strategies, will enhance the probability that such projects are indeed relevant and will answer the question "so what" if a particular project is successful (or unsuccessful).

6. *Budget transparency facilitates active management.*

The current SMD budget structure does not readily lend itself to identifying the total mission-enabling investment within SMD divisions (or programs within those divisions). While some portions of the mission-enabling budget are in readily identifiable budget lines, other portions are embedded in spaceflight programs and other non-mission-enabling budget lines. The lack of transparency of the mission-enabling portion of the SMD budget makes it difficult for managers and outside parties as well to analyze, advocate, and proactively manage this critical activity.

Developing the ability to articulate the linkages between mission-enabling activities and the (planned and potential) missions they enable is in the best interests of an organization from a strategic perspective. More specifically, such articulation will result in the identification and continuation of more relevant mission-enabling activities and the reduction or elimination of less-relevant ones—the essence of strong and dynamic portfolio management.

Stability is a particularly critical aspect of mission-enabling budgets, not only for those programs themselves but also for the long-term viability of the research community and for the stability of spaceflight mission programs. Mission-enabling budgets cannot be treated as fungible sources of money to be tapped to solve problems in other parts of the SMD program. Doing so can have long-enduring impacts on the overall sustainability of space and Earth sciences.

METRICS

In the case of an SMD division, the metric for each of its mission-enabling activities should provide:

1. A simple statement of what the component of the mission-enabling activity is intended to accomplish and how it supports the strategic or tactical plans of the division.
2. A statement as to how the component is to accomplish its task.
3. An evaluation of the success of the activity relative to the stated mission, unexpected benefits, and lessons learned.
4. A justification for the resource allocation that is being applied to the component vis-à-vis other mission-enabling activities within the division.

One of the main purposes of establishing metrics for each component of mission-enabling activities is to inform the administration, the Congress, and the science community of the purpose of the component and the extent to which it is being successful. Such transparency, properly accomplished, provides justification for the essential roles of mission-enabling activities in the success of SMD. It also allows the broad national science community to engage with NASA in providing the most effective mission-enabling program. If what NASA intends to accomplish is clear, the science community can participate constructively.

The committee presents below a set of metrics for elements of an overall mission-enabling program. They are meant to be examples of what could be used and not necessarily a rigid prescription. The metrics reflect a common approach to evaluating R&D programs, and often they must be more qualitative than quantitative. The advisory committee process discussed in Chapter 2 will be an essential part of the process of implementing such metrics. It is important to remember that any set of metrics should be utilized in the context of managing a total portfolio of activities and not simply applied in isolation on an activity-by-activity basis. Active management requires that one always consider how applying metrics for one aspect of a program affects the rest of the program.

Metrics for Essential Components of a Broad-based Program to Advance Strategic Goals and Maximize Science Return

For Theoretical Research

To ensure the continuous flow of new scientific understanding, it is necessary that a component of the mission-enabling program be devoted to basic theoretical research that will serve as the basis for development of new scientific concepts, new interpretations of observations, and improved numerical models. This component is important for each SMD division, particularly those in which many new discoveries are being made.

The metric for the theoretical research component of mission-enabling activities should include the following:

(1) A statement of the importance of theoretical research to the SMD division.
(2) The means by which new theoretical concepts are to be sought, presumably through solicitations for research proposals that are open to all organizations with particular emphasis on universities, non-government laboratories, and NASA centers.
(3) An evaluation of how many new theoretical concepts are being introduced, and how many are ultimately validated through numerical modeling and data interpretation.
(4) An appropriate allocation of resources. Since this research is the foundation on which numerical models are to be built and data interpreted, a percentage, perhaps 5 to 10 percent, of all data analysis and modeling funding within the division seems appropriate.

For Numerical Modeling

Sophisticated numerical models are becoming increasingly important in some SMD science divisions. In general, the emphasis accorded to numerical modeling depends on whether there are multiple, comprehensive data sets to be assimilated and whether there is or will be an end-use (e.g., the prediction of space weather in the case of heliophysics or the prediction of global and regional climate change in the case of Earth science).

The metric for the numerical modeling component of mission-enabling activities should include the following:

(1) A statement of the importance of numerical modeling to the SMD division.
(2) The means by which the numerical modeling is to be supported, e.g., by the establishment of concentrated research centers or consortia at universities or national laboratories.
(3) An evaluation of the success of the numerical modeling activities in increasing scientific understanding and ultimately, where appropriate, serving as the basis for end-user predictive models.
(4) An appropriate allocation of resources. Since the purpose of the models is to assimilate, understand, and use data collections, the allocation of resources could be a percentage of the total funds expended for data analysis.

For Supporting Observations

Many spaceflight missions require supporting observations on the ground or from suborbital flights to be able to plan their observations and interpret their data. Examples include ground-truth or under-flights for calibration and interpretation of Earth remote-sensing data, and ground-based telescope observations for defining and planning planetary spacecraft missions.

The metric for the supporting observations component of the mission-enabling program should include the following:

(1) A statement of the importance of supporting observations to the SMD division.
(2) The means by which the supporting observations are to be obtained, presumably through solicitations that are open to all organizations with the required capabilities.
(3) A quantitative measure of the extent to which mission requirements for supporting observations are being met or to which supporting observations are providing the broad context for defining future missions and interpreting their data.
(4) An appropriate allocation of resources. Supporting observations are intended to satisfy specific mission requirements for ongoing missions as well as serve the much broader requirement to provide the baseline of knowledge needed to understand what missions are required to cost-effectively address open science issues. Thus, the measure of success and the allocation of resources should be determined by both mission requirements and strategic goals. NASA funding for supporting observations should not duplicate funding being provided by other agencies, but neither should funding by other agencies prevent NASA from ensuring that funding for supporting observations is at a net level adequate for it to achieve its goals.

For the Suborbital Program

The suborbital program, including sounding rockets and balloon and aircraft flights, is important to many different aspects of SMD mission-enabling activities. It provides opportunities for both workforce and technology development, means to collect complementary observations to support spaceflight programs, and cost-effective means to conduct scientific research for which spacecraft observations are not necessary.

The suborbital program should be included as a factor in metrics for other activities such as advanced technology and workforce development and supporting scientific observations. Despite the duplication, it is appropriate for each division to also establish a metric unique to its suborbital program.

The metric for the suborbital program component of mission-enabling activities should include the following:

(1) A statement of the importance of the suborbital program to the SMD division, based on the contributions that the suborbital program makes to other mission-enabling activities, as well as the unique scientific capabilities it can offer.
(2) The means by which the division intends to conduct its suborbital program, presumably through the solicitation of research proposals, and the establishment of national infrastructure that supports sounding rocket, balloon, and aircraft-based research.
(3) A quantitative measure of the extent to which the suborbital program is improving the workforce, introducing new technologies, or conducting unique science.
(4) An appropriate allocation of resources, based on the stated importance of the suborbital program, and the multiple contributions it has to make.

For Cross-Mission Research and Data Analysis Activities

Research and data analysis activities for a specific spaceflight mission, whether in its prime or extended mission phase, are not classified in this report as a mission-enabling activity. Data analysis activities involving multiple missions, and support for researchers who are not directly involved in a particular mission science team, are classified as mission-enabling and are essential for realizing the full scientific return from the portfolio of missions within SMD. This component of mission-enabling activities is particularly important for divisions in which the scientific questions are being addressed by multiple missions or where there is a need to involve researchers other than those selected as part of the mission development.

The metric for the research and data analysis component of mission-enabling activities should include the following:

(1) A statement of the importance of research and data analysis to the SMD division.
(2) The means by which cross-mission research and data analysis activities are to be sought, e.g., through a guest investigator program that is open to all organizations.
(3) An evaluation of the scientific questions that are being successfully addressed through multiple-mission data analysis and through involvement of the broader scientific community.
(4) An appropriate allocation of resources. The allocation is expected to vary among SMD divisions depending on the portfolio of missions, the scientific questions being addressed, and the need to involve a broader community of researchers.

Metric for Advanced Technology Development

To ensure the continuous flow of new technical capabilities (the second guiding principle outlined above), it is necessary that a component of the mission-enabling program be devoted to exploring new—low-TRL—technical concepts, which, if successful, could result in substantial improvements in planned—or even new—scientific space missions. This component is particularly important in divisions where advances in science will require new technical capabilities, but it is also important even in divisions where adequate technology appears to be available, because it is always possible that a serendipitous discovery will lead to an unanticipated breakthrough in capabilities.

The metric for the advanced technology development component of mission-enabling activities should include the following:

(1) A statement of the importance of advanced technology development to the long-term success of the SMD division.

(2) The means by which new technologies are to be sought, presumably through solicitations for research proposals that are open to all organizations with technical capabilities—universities, NASA centers, non-profit laboratories, and industry.
(3) A quantitative measure of how many new technologies are being introduced, and how many of these are sufficiently promising to undergo additional development.
(4) An allocation of resources as a percentage of all technology development activities within the division. A typical allocation for this activity for other organizations conducting R&D is 5 to 10 percent of the total technology development budget. (See Chapter 4.)

Metric for Workforce Development

The development of a capable workforce, both for NASA and for the outside space program community, is the third guiding principle articulated above and a singularly important task for the mission-enabling program. However, it is also one of the hardest for which to establish a metric. The metric should be based on the demographics of the scientific community and on a projection of workforce needs during future decades. Such an assessment will require considerable thought on the part of the science managers of NASA, in coordination with the science community. (See Chapter 4.)

The metric for the workforce development component of mission-enabling should include the following:

(1) A statement of the importance of workforce development to the SMD division, based on a realistic analysis of the demographics of the community, and expectations for future mission opportunities.
(2) The means by which the division intends to satisfy its workforce needs, including providing funding for graduate fellowships, ensuring that both undergraduate and graduate education can occur in universities that actively participate in SMD programs, and supporting hardware programs that will provide hands-on opportunities to train experimentalists.
(3) A quantitative measure of the extent to which the demographics and the scientific and technical competence of the science and engineering communities, including the relevant NASA workforce, are being improved and maintained.
(4) An appropriate allocation of resources, based on the stated workforce need and the means to satisfy the need.

4

Maximizing Program Effectiveness Through Strategic Management

This chapter discusses an approach that NASA officials should consider as they address concerns identified in the committee's assessment of the mission-enabling programs in Chapter 2 and as they apply the principles and metrics discussed in Chapter 3. The chapter also discusses specific management issues for three key areas that were singled out in the committee's charge—innovative research, interdisciplinary research, and workforce development.

TRACEABILITY OF MISSION-ENABLING ACTIVITIES FROM STRATEGIC GOALS

The committee believes that NASA mission-enabling program managers should have a clear and publicly stated set of strategic goals and priorities for each SMD mission-enabling program. Currently, these goals and priorities appear to be privately held rather than publicly stated. Each manager has a plan, but these plans are neither clear to outside researchers and policy makers nor openly articulated and advocated by SMD's senior management. Open, explicit articulation of mission-enabling priorities will lead to a more relevant SMD program that can also be more readily understood, adjusted in response to community input or new technical developments, and defended. The conclusion of the 1998 NRC report on NASA research and data analysis programs[1] that "[mission-enabling activities are] not always thoroughly and explicitly integrated into the NASA enterprise strategic plans and that not all decisions about the direction of [mission-enabling activities] are made with a view toward achieving the goals of the strategies" is still the case today.

However, it is not sufficient to determine that a mission-enabling activity supports a strategic goal of the agency. The committee provides an approach for using a traceability matrix as an example of how SMD could derive the range and scope of mission-enabling activities via a systematic flow-down analysis of all tasks and requirements needed to address SMD strategic goals. The level of detail can be taken to the program element level and even lower. Activities can be grouped together to define program elements. Each activity can be prioritized, budgeted, and related to assessment criteria. Because of differences in the strategic goals across SMD divisions, traceability matrices logically would be designed to the division level, and cross-discipline and cross-division activities can be identified by their multiple appearances. This traceability matrix provides a mechanism that allows balance to be determined among different activities by weighting costs by duration and priority. Mission-enabling activities can then be consolidated into higher-level tasks and into program elements through which activities are funded. The generation of such a traceability matrix can be an important tool for the active management of mission-enabling activities. It provides a means by which missing activities can be identified, optimal funding levels can be determined and compared with current budgets, and performance can be evaluated.

Because SMD strategic goals are fundamentally scientific and wide-ranging, it is appropriate for this traceability matrix to be generated with active input from and ongoing evaluation by the science community in conjunction with NASA management. The process is also a dynamic one such that tasks

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[1] National Research Council, *Supporting Research and Data Analysis in NASA's Science Program,* National Academy Press, Washington, D.C., 1998, p. 3.

and requirements in the mission-enabling portfolio flowing down from these goals will themselves be constantly refreshed by new information and understanding arising from the execution of mission-enabling activities and missions.

A traceability matrix begins with an articulation of individual strategic goals and then identifies the full range of high-level mission-enabling tasks required to address those goals. Each task is then further reduced to general subtasks. Each subtask is broken down into specific sub-subtasks as appropriate. Individual requirements are identified for the lowest-level subtasks to be executed. Mission-enabling activities are those needed to satisfy a requirement. Each activity can then be prioritized, budgeted over an anticipated duration or recurring period, and tagged for inclusion in (or across) specific program elements. Criteria by which the mission-enabling activity can be assessed can also be identified and used as part of management of the activity. These activities can then be rolled up within their subtasks and tasks for the purpose of understanding and tracking current and future efforts at different levels and their relative and total cost.

A detailed example, following a single hypothetical thread in the Planetary Science Division, is illustrated in Appendix C.

HIGH-RISK/HIGH-PAYOFF RESEARCH AND TECHNOLOGY DEVELOPMENT

The committee is convinced that, while most of the SMD mission-enabling research budget should be clearly directed at supporting specific goals of the various science divisions, NASA can benefit from separately funded and protected mission-enabling activities that pursue high-risk/high-payoff advanced technologies or other research activities that could produce game-changing results. This approach is consistent with the majority of successful R&D enterprises where some defendable fraction of resources is allocated to research activities for which there is not an immediate predictable benefit, but which can potentially be the basis for important solutions to future problems or which open up future opportunities.

In NASA's case, where mission development times can run as long as 7 to 10 years, such an approach is especially important because the phasing-in of new technologies can be 5 to 10 times longer than time to market in the commercial and university research sectors. Thus, one can envision progressively falling behind the state of the art in many technical areas unless technology is purposefully captured and utilized through an active mission-enabling research program.

Management of such research activities poses unique challenges because NASA technical development activities typically are structured to limit risk. This is especially true in mission-focused technology development activities where the fundamental objective is risk mitigation through the maturation of technologies to TRL-5 or TRL-6 prior to mission confirmation. As opposed to a *risk mitigation* strategy, game-changing research should be viewed as a *mission-enabling* strategy that is focused on the TRL-1 to TRL-4 elements with the objective of identifying and nurturing ideas and technologies that could serve SMD's future missions one to three generations ahead of existing technical approaches, system architectures, and design methods.

In general, successful outcomes in these types of activities are happy accidents often resulting from cross-cutting work in multiple disciplines. The key element to any incubation of new ideas is to ensure that a broad range of seeds are both protected and nurtured. Thus, funding stability and creative management capable of taking a 20- to 30-year perspective are essential components for a successful program. Benchmarking relevant practices in other organizations that perform R&D provides some insights for consideration by NASA.

Benchmarking Relevant Practices of Other Organizations

In industrial and military research organizations with which committee members are familiar, anywhere from 5 to 10 percent of their respective research and technology budgets are allocated to high-risk, high-payoff (i.e., potential break-through/game-changing) research activities. The DOD's Service research laboratories provide one example of a budget allocation philosophy that explicitly supports high-risk, high-payoff endeavors as defined above. More specifically, examining the science and technology (S&T) enterprises of DOD's three services—Army, Navy, and Air Force—indicated the following:

- Fifteen to 20 percent of the entire S&T budget for the Army and the Air Force (25 to 30 percent for the Navy) is devoted to basic research, whose purpose is to discover new phenomena and acquire fundamental knowledge that can enable new technologies and military capabilities. Within the basic research spectrum of activities, 33 percent (Navy) to 50 percent (Air Force) of the 6.1 budget is allocated for "high-risk research," which represents approximately 5 to 10 percent of the total S&T budget of each of these Services.
- The specific amount of the overall research budget, and that portion to be invested in "high-risk" research activities, is typically a top-down decision. This budget is fenced and protected even as the overall S&T budgets rise and fall, and it cannot be used for focused technology development to enable specific mission capabilities.
- Basic research programs are often managed by an organizational entity separate from those entities than manage the much larger technology-related budget elements (6.2 and 6.3) that collectively constitute the overall S&T budget. A separate organizational entity helps ensure that basic research funds do not migrate to nearer-term, higher-visibility projects. The assigned personnel are also uniquely qualified to understand the nuances of managing a portfolio of diverse, high-risk projects, which often do not lend themselves to precise definition or traditional project management methods.

A second approach for benchmarking comes from using the National Academies' report *Rising Above the Gathering Storm*.[2] A conclusion of that report is as follows:

> - Approximately eight percent of a government entity's S&T budget should be allocated to high-risk, high-payoff research.
> - Government agencies must take the lead in funding such research, since industry R&D is predominantly short-term in nature.
> - Additional government budget is probably not needed for high-risk research; rather, it is a matter of ensuring that about eight percent of the existing S&T budget is not committed to specific mission programs and is set aside for high-risk research, and that the barriers which discourage government program managers from pursuing high-risk research are eliminated for this portion of the S&T investment portfolio. Barriers to performing high-risk research include (1) a peer review system that tends to favor established investigators using well-known methods, (2) pressure from customers and management for short-term results, and (3) risk averseness, because high-risk projects are prone to failing and increased government and public scrutiny make "projects that fail" increasingly untenable.

Appendix D presents a more detailed discussion on benchmarking results with respect to allocation of resources for high-risk, high-payoff research endeavors.

[2] National Academy of Sciences-National Academy of Engineering-Institute of Medicine, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, The National Academies Press, Washington, D.C., 2005.

Organization and Management

In many cases, innovative research activities that are interdisciplinary may not fit clearly into one specific SMD science division. For example, game-changing research related to micro-thrusters, formation flying, micro-electro-mechanical-system valve devices, nano-materials, micro-instrumentation, radiation-hardened components, and many other technologies have applicability across all divisions such that there would be value to having a directorate-wide program for such activities. There are a number of possible options for SMD to consider for funding and incubating such very early technical developments.

1. *Programs within each science division*

a. High-risk/high-payoff projects could be supported within existing research and technology program elements. Program managers could allocate to activities of this type some fraction of the funds for individual programs and make awards on the basis of peer review of this aspect of the program in the context of the overall activity, or they could allocate some small fraction of program funds independent of the peer review of proposals for projects in the core program.

b. An alternative approach would be a program within each SMD division similar to the NSF Small Grants for Exploratory Research and Early Concept Grants for Exploratory Research (i.e., small, fast-track, pre-competitive projects). Small grants could be awarded at the discretion of the program manager to individuals whose proposals are not externally peer reviewed. The advantage of this approach is that all high-risk/high-payoff projects for a science division would be consolidated into a single program for the division, thereby providing for more efficient management, a critical-mass-size funding pool, and the opportunity to look more broadly across the division's activities for the most attractive opportunities for this kind of work.

2. *Cross-disciplinary programs managed centrally outside the science divisions*

a. As noted above, some high-risk/high-payoff research is inherently cross-disciplinary or will include technology developments that have the potential to benefit more than one SMD science division. An important consideration is whether critical mass on such research investments can be achieved with relatively limited funding in each discipline as opposed to an aggregated sum serving all disciplines under dedicated management through the SMD chief scientist or some other office. This approach was utilized by SMD's predecessor organizations for an innovative research program in the 1980s and for cross-cutting technology development projects in the late 1990s. Given the current national focus on innovative science and technology research, a clearly identified high-risk/high payoff research budget might also be more likely to attract new funding compared to smaller amounts partitioned between multiple discipline areas.

b. Several universities and other research centers throughout the country have a substantial number of scientists involved in a variety of NASA-funded research activities, not all funded by the same SMD division. These centers of excellence can be fertile grounds for innovative research and technical ideas. Typically such early-stage research and ideas require a modest amount of start-up money to bring them to a level where they can realistically compete for peer-reviewed funding from an R&A program of one of the SMD divisions. An option for providing this necessary seed money would be an innovative research block grant to such a university center or research institute, giving the center director discretion to allocate funds from this grant to several internal subgrants for early-stage technical developments. Internal grants would be awarded based on relatively simple internal proposals, typically not as detailed or well supported as a proposal to NASA.

Finally, the committee calls attention to a significant difference between the flexibility that some large entities such as industrial firms and federal laboratories have to self-fund some innovative research and the lack of that flexibility at universities. The former can include funding for innovative research in their overhead rates, e.g., via internal research and development funds from government contracts in industry and via directors' discretionary funds in the latter, and offer internally competed opportunities that satisfy this need. Although some universities return a fraction of their overhead to investigators to cover innovative research, in general such returns are very small because the overhead was collected to cover other legitimate university expenses.

INTERDISCIPLINARY RESEARCH

There are important opportunities to promote interdisciplinary research activities in space and Earth sciences. In some areas, such as the astrobiology program,[3] NASA deserves credit for having created an entirely new field of research and stimulated a vigorous new research community. SMD also has been active in fostering interdisciplinary programs within Earth science. Similarly, many areas of planetary science are intrinsically interdisciplinary. In other areas, such as Sun-climate studies, it is less clear that an adequate interdisciplinary program exists.

In a management structure based on discipline-oriented divisions with limited resources, it is not surprising that interdisciplinary activities may get inadequate attention. Program managers may look at cross-discipline efforts as diversions that are not appreciated or rewarded by their upper management. Thus, a change in strategic approach will be required before program management ownership will be encouraged and rewarded. The key problem with both cross-discipline and high-risk/high-payoff efforts is that the path to success can be unclear and the final result unknown. In fact, by some metrics the majority can be judged as failures even though there may be end-game spin-offs or spillovers that are extremely successful.

Real game-changing research breakthroughs are especially likely to come from cross-discipline activities, because the boundaries between disciplines are the most fertile place for important discoveries.[4] Therefore, program managers should be encouraged to "mine along the boundaries." Associated with the exploitation of disciplinary boundaries is the exploitation of generational boundaries. Teams that have an effective mix of both young and mature engineers and scientists are the most effective at making technological leaps or leaps in scientific understanding. Thus it is critical that early-career technologists be recruited and retained as part of the process.

The National Science Foundation is focused on basic research, and thus it is more straightforward for NSF to foster interdisciplinary research than for NASA SMD, which is organized around space missions. NSF often issues cross-division and even cross-directorate solicitations for proposals specifically for interdisciplinary research. For example, NSF's initiative in cyber-enabled discovery is specifically designed to bring together researchers from computer science and "domain" science (e.g., oceanography, biology, materials science, and so on).

However, except for these inherently interdisciplinary solicitations, interdisciplinary NSF proposals that are submitted in competition with traditional, discipline-based proposals do not necessarily fare well in the peer-review process. Such interdisciplinary proposals are often reviewed by two or more panels, thus increasing the likelihood of a less than favorable review. On the other hand, NSF leadership does encourage its program managers to move outside the discipline boundaries for innovative interdisciplinary proposals, and that does counterbalance the tendency for lower rankings by panels. Thus

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[3] See National Research Council, *Assessment of the NASA Astrobiology Institute*, The National Academies Press, Washington, D.C., 2008.

[4] For more on the motivation, character, and advantages of interdisciplinary research, see National Research Council, *Facilitating Interdisciplinary Research*, The National Academies Press, Washington, D.C., 2004.

the overall success of interdisciplinary proposals is not significantly lower than that of discipline-based proposals.

This only serves to emphasize the need for established goals for the mission-enabling activities of SMD, which are endorsed by the senior management of NASA, and for which there is adequate staff to initiate and manage new activities.

DEVELOPING AND SUSTAINING A HEALTHY TECHNICAL WORKFORCE

Every SMD division's research community, extramural and intramural, has some level of workforce deficiencies or rising demands. For example, there might be a lack of critical-mass expertise in spaceflight hardware design and development, or a need to shore up shortfalls in certain science skill areas, or to plan for succession in a field where the scientific or engineering leaders are all approaching retirement.[5] Supporting development and maintenance of a workforce able to execute the program is certainly an appropriate mission-enabling activity. In the committee's view, workforce development and maintenance should be a priority for mission-enabling activities, and efforts should be made to assess workforce status, define workforce needs, and manage the mission-enabling activities to meet these needs. Furthermore, awareness of the impact of funding volatility on the pool of capable researchers necessary to conduct SMD research activities and how this might vary from division to division are important issues. In areas where NASA is the principal source of funding, funding volatility may have a disproportionately negative impact on the corresponding workforce. Newly funded areas may not be able to tap a sufficient population of scientists and engineers to make progress. Sudden decreases in funding in another area may cause scientists to exit that area or new graduates to not enter it, disrupting the workforce for years to come. Workforce awareness and management are necessary components essential to the effective management of a science enterprise.

The committee envisions a three-part approach that can help SMD better utilize its mission-enabling activities to anticipate and address critical workforce issues. All three elements of this approach can benefit from participation by the outside scientific community via the involvement of advisory committees.

1. *Identification of workforce needs both in the short term and in the long term*

The first step should be to identify needs for key skill areas based on the current situation and the situation expected over the next decade. For instance, when mission-enabling activities are defined through a traceability exercise, there should be an assessment of the workforce required to execute those activities over the anticipated duration of the activity. The likely necessary distribution of skill areas (e.g., key areas in science, engineering, technical support, and technical management), age diversity (based on expected future needs), and location diversity (i.e., NASA centers, academia, industry) are all important factors. These factors can also constitute later workforce development effectiveness metrics.

Consideration should be given to the stability and sustainment of capabilities. For example, if fewer new missions are currently being developed, there is a risk of losing highly skilled engineers and technicians. Mission-enabling activities can help provide some continuity of funding to retain people. This can be achieved through technology development programs and, to some extent, suborbital programs. Likewise, any planning for significant increases in the volume and diversity of the data

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[5] The NRC report *Steps to Facilitate Principal-Investigator-Led Earth Science Missions* (The National Academies Press, Washington, D.C., 2004) concluded that "The Earth science community, particularly the university-based community, has historically produced only a small number of scientists with the in-depth space engineering and technical management experience that is required to lead a project in a PI mode of operation" (p. 29). The NRC report *Building a Better NASA Workforce: Meeting the Workforce Needs for the National Vision for Space Exploration* (The National Academies Press, Washington, D.C., 2007) discusses an acute NASA-wide and aerospace industry-wide need for experienced systems engineers and project managers.

obtained from missions must include an assessment of the sufficiency of scientists capable of generating benefit from the acquired data and whether to expand that workforce accordingly. Some stable level of the workforce also should be dedicated to working on fundamental research (both in technology and in basic science).

2. *Shaping programs and strategies for meeting workforce needs*

As opportunities and options are selected for applying mission-enabling programs to address workforce development needs, there are several factors to consider:

- Steady funding for specific types of programs including technology development, suborbital flights, and basic research (the "build it and they will come" approach),
- Programs specifically aimed at training and retention of early-career people—internships at NASA centers, graduate fellowships, early-career awards, Jet Propulsion Laboratory strategic partnerships, and support of the suborbital program,
- Strategies to enhance workforce diversity,
- Re-training programs,
- Selection criteria for proposals in some programs that could formally include workforce considerations (e.g., training of students), and
- Encouraging development of critical-mass research groups in NASA centers or universities and other research centers—in many cases, these groups will have unique capabilities (building spacecraft instrumentation, building numerical models). Incentives could include special programs or funding vehicles for research groups (e.g., block grants).

3. *Continued assessment*

The effectiveness of programs and approaches implemented in the step above must be assessed regularly (preferably every 2 or 3 years). Effectiveness should be determined by measuring against well-defined metrics, such as age distribution and evolution over time and the rate of students and young scientists being trained through the programs. The evaluation process could include a workforce review board or could be carried out by each division director. The needs and the effectiveness of programs should be considered at both the division and the agency level. The ability to forecast workforce needs is an important tool.

5

Consolidated Findings and Recommendations

The preceding chapters outline the committee's response to the study charge and offer perspectives on the roles and value of mission-enabling activities in NASA's space and Earth science programs; discuss concerns and opportunities for management improvement; delineate criteria for making portfolio allocations and metrics for evaluating program effectiveness; and suggest best practices for managing an effective mission-enabling program. In this chapter the committee consolidates those conclusions into a set of three principal findings and recommendations.

Finding 1. The mission-enabling activities in NASA's Science Mission Directorate (SMD)—including support for scientific research and research infrastructure, advanced technology development, and scientific and technical workforce development—are fundamentally important to NASA and to the nation.

NASA's mission-enabling activities constitute an integral part of the nation's overall R&D effort, and they play essential roles in maximizing the scientific return on investment in space and Earth science spaceflight missions and in providing a foundation for an effective and robust program for the future. Mission-enabling activities have had remarkable impacts over the history of NASA's space and Earth science programs, and there continue to be opportunities and needs to build on that record in the future.

Recommendation 1. NASA should ensure that SMD mission-enabling activities are linked to the strategic goals of the agency and of SMD and that they are structured so as to

- **Encompass the range and scope of activities needed to support those strategic goals,**
- **Provide the broad knowledge-base that is the context necessary to interpreting data from spaceflight missions and defining new spaceflight missions,**
- **Maximize the scientific return from all spaceflight missions,**
- **Supply a continuous flow of new technical capabilities and scientific understanding from mission-enabling activities into new spaceflight missions, and**
- **Enable the healthy scientific and technical workforce needed to conduct NASA's space and Earth science program.**

In recommending that SMD's mission-enabling activities be linked to agency and SMD goals the committee does not intend that the totality of the program be so constrained that innovative blue-sky ideas be frozen out. Instead the committee argues in Chapter 4 that some small fraction of resources should be set aside to support high-risk/high-payoff technology development and research projects.

Finding 2. Adoption of an active portfolio management approach is the key to providing an effective program of mission-enabling activities that will satisfy the intent of this committee's first finding and recommendation.

Recommendation 2. NASA's Science Mission Directorate should develop and implement an approach to actively managing its portfolio of mission-enabling activities.

Active portfolio management should include the following elements:

- **Clearly defined science division mission-enabling mission statements, objectives, strategies, and priorities that can be traced back to the overall strategic goals of NASA, SMD, and the division.**
- **Flexibility to accommodate differences in the scientific missions and programmatic options that are most appropriate to the different science discipline divisions.**
- **Clearly articulated relationships between mission-enabling activities and the ensemble of ongoing and future spaceflight missions that they support.**
- **Clear metrics that permit program managers to relate mission-enabling activities to strategic goals, evaluate the effectiveness of mission-enabling activities, and make informed decisions about priorities, programmatic needs, and portfolio balance.**
- **Provisions for integrating support for innovative high-risk/high-payoff research and technology, interdisciplinary research, and scientific and technical workforce development into mission-enabling program strategies.**
- **Active involvement of the scientific community via an open and robust advisory committee process.**
- **Transparent budgets that permit program managers to effectively manage mission-enabling activity portfolios and permit other decision makers and the research community to understand the content of mission-enabling activity programs.**

Finding 3. The NASA SMD headquarters scientific and technical staff is not adequately sized to manage mission-enabling activities effectively.

Recommendation 3. NASA should increase the number of scientifically and technically capable program officers so that they can devote an appropriate level of attention to the tasks of actively managing the portfolio of research and technology development that enables a world-class space and Earth science program.

The committee believes that action on Recommendation 3 is essential if NASA is to be able to respond properly to Recommendation 2. The committee is also convinced that having mission-enabling program managers divide their time between mission-enabling activities and duties related to spaceflight programs is desirable and that it improves their ability to be effective in both roles. Furthermore, because NASA center scientists and technologists compete with outside researchers for support for participation in mission-enabling programs, management of mission-enabling activities is properly a NASA headquarters, not a NASA field center, function.

The committee estimates that the size of the current SMD headquarters program manager staff falls short by between 35 and 75 percent. While some fraction of the shortfall can be remedied by the use of rotators and detailees, the committee believes that a workable solution will also need to include an increase in the SMD civil service ceiling.

Appendixes

A

Statement of Task

An ad-hoc committee will be organized under the auspices of the Space Studies Board to conduct a study of mission-enabling activities in NASA's space and Earth sciences program. The study will identify the appropriate roles for mission-enabling activities and metrics for assessing their effectiveness. It also will evaluate how, from a strategic perspective, decisions should be made about balance between mission-related and mission-enabling elements of the overall program as well as balance between various elements within the mission-enabling component. Among the topics to be considered are the following:

- Roles and objectives of mission-enabling activities in NASA as a mission-oriented agency;
- Necessary characteristics of an effective program of mission-enabling activities, including metrics by which effectiveness can be evaluated;
- Principles and metrics for determining the appropriate balance of investments between mission-enabling activities and space flight missions so as to best support the Agency's overall strategic objectives;
- Principles and metrics for determining the appropriate allocation of effort and resources between various mission-enabling program components, including scientific infrastructure (e.g., airplanes, computing) that enables R&A activity;
- The role and proper fraction of support that should be devoted to "innovative" (high risk, high payoff) research, and whether this might vary between science areas;
- The extent to which current R&A programs support cross-disciplinary and interdisciplinary science, especially across the divisions within NASA's Science Mission Directorate;
- The role of R&A programs in training the next generation of Earth and space scientists who will contribute to NASA's programs in the future; and
- Relevant benchmarks from industry or other public or private institutions where similar mission versus mission-enabling portfolio allocation assessments are made.

B

Presentations to the Committee

Joseph K. Alexander, NRC, "Summary of the SSB report Supporting Research and Data Analysis in NASA's Science Programs: Engines for Innovation and Synthesis (1998)" January 22, 2009.
Joseph K. Alexander, NRC, "Summary of the SSB interim assessment letter report (September 2000) on responses to the 1998 research and data analysis report" January 22, 2009.
Steven Battel, Battel Engineering, "A Business Perspective: Thoughts on NASA Research and Analysis Funding and Space Technology Development," January 23, 2009.
Max Bernstein, Jack Kaye, Mary Mellot, Michael New, and Wilton Sanders, NASA, "Program Managers' Perspectives on Mission-enabling Activities," March 12, 2009
Richard Chapas, Battelle Eastern Science and Technology Center, "Perspectives on Research Management," January 23, 2009.
Richard Fisher, NASA, "Strategies for the SMD Heliophysics Division, March 11, 2009
Michael H. Freilich, NASA, "Earth Observations Transitions from Research to Long-Term Data Acquisitions," March 11, 2009.
Michael H. Freilich, NASA, "Earth Science Division Strategies," March 11, 2009.
Paul Hertz, NASA, "Overview of SMD's Mission Enabling Activities in NASA's Earth and Space Science Missions," January 22, 2009.
Martin H. Israel, Washington University, St. Louis, "Report of the Scientific Ballooning Assessment Group," January 22, 2009.
Conilee G. Kirkpatrick, HRL Laboratories, LLC, "R&D portfolios, metrics, and transition at HRL Laboratories, LLC," January 23, 2009.
Christopher Martin, California Institute of Technology, "A Roadmap for Revitalizing the NASA Astrophysics Sounding Rocket Program," January 22, 2009.
Mike Meyers, NASA, "Planetary Science Division Goals," March 11, 2009.
Jon Morse, NASA, "Astrophysics Division Strategies," March 11, 2009.
Richard Paul, "Perspectives on Balance of R&T Budgets for a Federal Lab (AFRL) and an Industry (Boeing)," January 23, 2009.
Yvonne Pendleton, NASA Ames Research Center, "R&A: A View from the Inside," January 22, 2009.
Guenter Riegler, NASA retired, "NASA Senior Review of the R&A Program," January 22, 2009.
Robert Riemer, NRC, "Review of NASA Suborbital Mission Capabilities," January 23, 2009.
Andrew Roberts, NASA, "Airborne Science Program: Observing Platforms for Earth System Science Investigations," March 11, 2009.

C

Traceability of Mission-Enabling Activities from Strategic Goals

A detailed example, following a single hypothetical thread in the Planetary Science Division, is illustrated in Figure C.1. Each major division goal is broken down into scientific tasks and sub-tasks, and the requirements for particular scientific capabilities and activities are then identified for each sub-task. In that way, mission-enabling activities spanning the general scope of knowledge base, technology development and workforce maintenance are identified at the activity level. The process of translating top-level goals into more detailed objectives, requirements, and activities can benefit by drawing on research community input via the advisory committee process.

Once a mission-enabling traceability matrix is generated for each Science Mission Directorate (SMD) division, the resultant mission-enabling activities can be compared with those activities contained within the program elements identified in an inventory used to enhance budget transparency. Ultimately, these should converge. Initially, this exercise is likely to identify areas of necessary mission-enabling activities that are not currently supported within SMD.

Traceability obviates the practice of restoring overall mission-enabling funding cuts or expanding mission-enabling funding primarily through the creation of new programs. The committee heard that there is the perception within SMD that OMB will not approve the expansion of existing programs (even to restore a prior cut in funding). The result is program element proliferation and subject redundancy, which decreases efficiency in management and increases the need to write more proposals and subsequent multiple submissions of the same proposals by members of the science community. Appropriately sizing a mission-enabling activity within a single program element, instead of fragmenting its funding across several program elements, offers benefits to both managers and scientists.

Having identified firmly grounded funding levels for all mission-enabling activities and programs, all linked to and flowing from strategic goals, comparisons with existing budgets will likely reveal a range of disparate results from substantial funding to no funding at all. The worst response to such a scenario would be a sudden reallocation of resources across all programs to achieve a common level of under-funding.

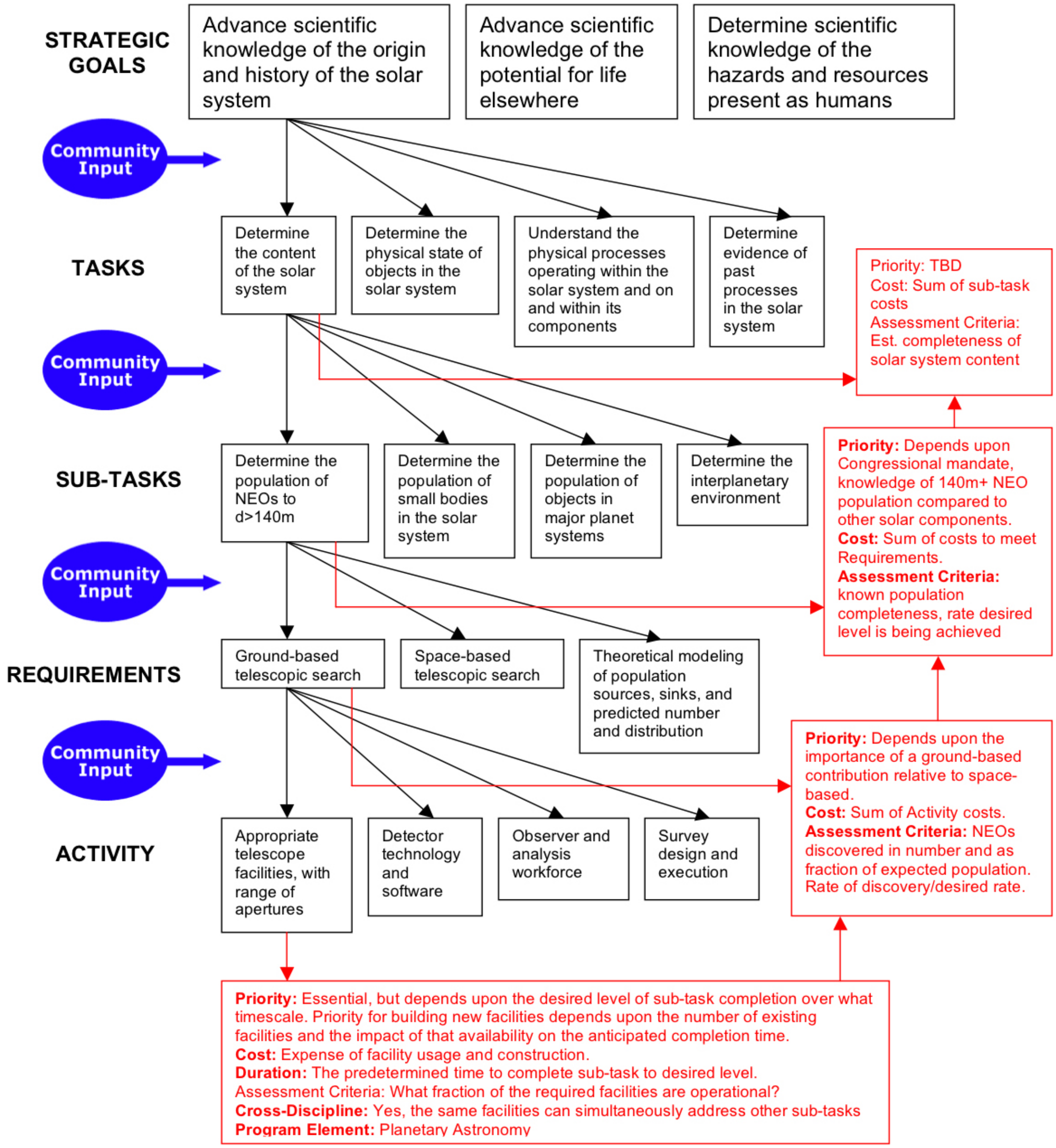

FIGURE C.1 Sample Science Mission Directorate Planetary Science Division traceability matrix (thread).

D

Benchmarking High-Risk/High-Payoff Research

DOD SERVICE LABORATORIES

While there is no precise organizational analogy to NASA SMD, examining how other aerospace-related agencies allocate resources for high risk/high payoff endeavors can be instructive. The three Service science and technology enterprises (Army, Navy, Air Force) under DOD provide one useful data point for addressing high risk/high payoff resource allocation.

To provide a context for discussing how the military services pursue high risk/high payoff research endeavors, it is important to begin with an understanding of the budget architecture for DOD science and technology as a whole. The budgetary architecture for science and technology (S&T, or the "R" in R&D) within the DOD consists of three budget categories:

- 6.1: Basic research, typically associated with TRL 1 and 2, in which new scientific phenomena are sought in an effort to discover and advance fundamental knowledge in fields important to national defense. Such research is generally broad in nature, and because of its low TRL, can be considered inherently "high risk."
- 6.2: Applied research (also called exploratory development), typically associated with TRL 3 and 4, in which technology is developed based on a newly discovered scientific phenomena, or by the application of scientific phenomena in a totally different manner than currently applied
- 6.3: Advanced technology development, typically associated with TRL 5 and 6, in which multiple technologies (often from cross disciplines) are integrated and demonstrated to enable the development of a new military capability to satisfy a military need.

Budget categories 6.1, 6.2, and 6.3, which collectively comprise S&T, can be envisioned as mission-enabling and represent the feedstock for the "D" in R&D (D is sometimes called engineering development; it is the engineering of advanced technology into an end item that can eventually be tested, manufactured, and delivered to the military war fighter). However, within the S&T spectrum, the 6.1 category (basic research) can most readily be labeled high risk/high payoff. That is because in examining basic scientific phenomena, there are limited expectations that such research will always yield usable results; however, when such discoveries are made, the accompanying expectation is that at least some will yield exceptionally high results, eventually enabling revolutionary military capabilities. A National Research Council report, *Assessment of Department of Defense Basic Research,*[1] discusses the basic research (6.1) element of S&T in terms of "unfettered exploration" and describes it as "farsighted, high-payoff research that provides the basis for technological progress." Past examples of game changing military capabilities enabled by discoveries from basic research projects include night vision; stealth technologies; near real-time delivery of battlefield information; navigation, communication, and weather satellites; and precise munitions. As noted in the study referenced in the follow-on benchmarking discussion, investments in basic research have led to revolutionary civilian capabilities as well. The

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[1] National Research Council, *Assessment of Department of Defense Basic Research,* The National Academies Press, Washington, D.C., 2005.

Internet, communications and weather satellites, global positioning technology, and even the search technologies used by Google all had origins in DOD basic research.

A 6.1 portfolio typically is comprised of numerous projects that are relatively small in terms of budget when compared to projects in the 6.2 budget category (fewer projects, bigger in scope and cost as compared to the average 6.1 project) and 6.3 budget category (even fewer projects, bigger in scope and cost as compared to the average 6.2 project budget). A large number of small 6.1 projects across the full spectrum of scientific disciplines maximize the opportunity of discovering scientific phenomena that can be game changing in nature if successfully implemented. As previously stated, if only a few such projects result in the discovery of phenomena that can subsequently be translated to technology in the 6.2 and 6.3 budget categories, that 6.1 investment portfolio would be considered as having achieved its purpose. The challenge: it can sometimes take years following discovery of a new phenomenon to know whether or not the technology it spawns has really enabled a useful new capability to the sponsoring agency.

Within the Service labs, overall 6.1 budgets are usually established by upper-management, such as by the Service Secretary or the senior-most executive responsible for the Service's overall R&D component. For the Army and Air Force, the 6.1 budget has varied between 15 to 20 percent of the overall S&T portion of the President's Budget request between FY98 and FY08. For the Navy, the 6.1 budget has varied between 25 to 30 percent of the overall S&T portion of the President's Budget request for the same 10-year period. While not every dollar of these basic research budgets can be definitively associated with high-risk research, the percentages represent an upper bound, and our committee would surmise in its collective experience that a significant portion of such budgets are aligned with high-risk, high-payoff research endeavors. To the committee's knowledge, there is no documented analytical basis for these specific 6.1 budget percentages. Rather, this allocation has developed over the years for each respective Service, has waxed and waned, and has ultimately been determined to be a reasonable level of investment for research of a broad and unfettered nature when traded off against budget needs for more specific S&T outcomes as pursued under the 6.2 and 6.3 budget categories. It should be noted that these 6.1 percentage allocations typically decrease when looking at the actual budget appropriated by Congress, since Congress often adds resources to the President's budget request, predominantly in the 6.2 and 6.3 program elements in support of specific projects or capabilities.

Debates often rage during annual budget formulations as to whether a specific top-down mandated 6.1 budget is over- or under-funded. Natural tensions tend to want to decrease 6.1 budgets to provide more resources for 6.2 and 6.3 (i.e., exploratory and advanced technology development), respectively, to meet more specific, shorter-term needs or desired capabilities. Yet, history has shown that fencing and protecting a basic research budget as a means of providing "seed corn" to the technology developers and encouraging the pursuit of high risk, very high payoff endeavors is critical to unimagined future capabilities. The protective fencing of an overall 6.1 budget for high-risk, high-payoff research does not imply that the portfolio of individual projects should not or cannot be actively managed. On the contrary, there will be more ideas for basic research projects than there are resources for pursuing them, and actively managing the basic research portfolio is necessary to ensure that the quality and relevance of the assigned projects is maximized. A basic research portfolio plants the seeds for future technologies, cultivates successful emerging capabilities, and eliminates less successful efforts.

The Services typically manage their basic research budgets through separate organizational entities vis-à-vis the organizations that manage the remainder (and much larger portion) of the S&T budget. For instance, the Air Force Research Laboratory has nine technology directorates, each of which manages the 6.2 and 6.3 budgets for its respective technology discipline (e.g., sensor technology, directed energy technology, information technology, propulsion technology, etc). But the 6.1 budget is managed separately by the AFRL Air Force Office of Scientific Research (AFOSR).

As the sole 6.1 budget manager for the Air Force, AFOSR is organized along scientific disciplines (e.g., chemistry and life sciences; aerospace and materials; physics and electronics; and math and geosciences), and its project managers seek discovery of new phenomena in these disciplines that could enable potential game changers when translated to a technology that can, in turn, provide a significantly improved military capability. AFOSR establishes the strategic objectives and investment strategy for the Air Force 6.1 budget, and AFOSR project managers then allocate that budget to universities (who are awarded the majority of the basic research portfolio), the AFRL technology directorates, or industry for execution. One rationale for a separate agency to manage this investment is the realization that managing basic research projects, with their unfettered and open approach where failure can occur as often as success, is different than managing technology development projects that often have performance and schedule milestones typically associated with more definitive and specific projects. Another rationale is that mixing the basic research budget with the technology budget in the same organization could lead to migration of the basic research budget into technology development activities, especially when technology projects (which have more definitive milestones because of their higher TRLs) encounter technical difficulties that lead to cost and schedule overruns.

Rising Above the Gathering Storm Report Recommendations

Another source regarding the amount that R&D-related government agencies should invest in high-risk, high-payoff endeavors can be found in the seminal report *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*.[2] The study's rationale was based on a widespread consensus among scientific and technological leaders throughout the United States that the nation's science and innovation enterprise was either stalled or in decline, with the consequence of jeopardizing future U.S. prosperity. Accordingly, the study committee was asked to identify the top 10 actions that federal policy makers could take to enhance the science and technology enterprise so that the United States can successfully compete, prosper, and be secure in the global community of the 21st century. Significantly, one of those actions concerned basic research, and the need for not only a higher level of investment, but also for additional emphasis on high-risk research endeavors. Specifically:

- Recommendation B of *Gathering Storm* says the following: "Sustain and strengthen the nation's traditional commitment to long-term basic research <u>that has the potential to be transformational</u> (emphasis added) to maintain the flow of new ideas that fuel the economy, provide security, and enhance the quality of life." The phrase "that has the potential to be transformational" can be equated to "high risk, high payoff" and thus tends to validate the premise from the earlier benchmarking discussion that long-term basic research is indeed the appropriate budget element to sponsor high-risk research.
- Of perhaps greater significance in the context of this particular benchmarking discussion, Action B-4, entitled "High-Risk Research", states the following: "At least 8 percent of the budgets of federal research agencies should be set aside for discretionary funding managed by technical program managers in those agencies to catalyze high-risk, high-payoff research." The discussion accompanying this recommended action points out that an important subset of basic research is the high-risk or transformative research involving new theories, methods, or tools that are often developed by new investigators—the group most likely to generate radical discoveries or new technologies.

The *Gathering Storm* report highlights two additional points relevant to an R&D entity's resource allocation for high-risk, high-payoff research:

1. It is not necessarily a matter of providing additional resources for high-risk research, but rather providing incentives for program managers to fund high-risk research out of a discretionary portion of the existing budget. Lack of incentives for (or barriers to) performing high-risk research include (1) a peer review system that tends to favor established investigators using well-known methods; (2) pressure from customers and management for short-term results; and (3) risk adverseness, since high-risk projects

[2] National Academy of Sciences-National Academy of Engineering-National Research Council, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, The National Academies Press, Washington, D.C., 2005.

are prone to failing and increased government and public scrutiny make "projects that fail" increasingly untenable. The study points out that partly because of these barriers, the percentage of efforts allocated to high-risk research is often quite small—1 to 3 percent being common. Individual committee members, based on their long-standing expertise in this area, believed that additional discretionary funding within existing budgets between 5 and 10 percent should be devoted to high-risk research. Thus, 8 percent seemed a reasonable compromise and is reflected in the committee's recommended Action B-4 discussed earlier. Significantly, the committee also pointed out that the degree to which a high-risk research program will be successful depends heavily on the quality of the program staff.

2. The study indicates the importance of government involvement in high-risk basic research. Specifically, while federal government spending in R&D has declined over the past several years, corporate R&D spending has dramatically increased, and in fact, has become the linchpin of the US R&D enterprise. However, corporate R&D funds relatively little basic research, since basic research does not typically offer immediate benefits to its sponsor. The study states that basic research, by its nature, is almost by definition risky (emphasis added), and shareholder pressure for short-term results discourages long-term, speculative investment by industry.

To summarize, the consensus of the *Gathering Storm* committee is as follows:

- Approximately 8 percent of a government entity's S&T budget should be allocated to high-risk, high-payoff research.
- Government agencies must take the lead in funding such research, since industry R&D is predominantly short-term in nature.
- Additional government budget is probably not needed; rather, it is a matter of insuring that 8 percent of the existing S&T budget is discretionary and fenced for high-risk research, and that the barriers which discourage government program managers to pursue high-risk research are eliminated for this portion of the S&T investment portfolio.

E

Committee and Staff Biographical Information

LENNARD A. FISK, *Chair*, is the Thomas M. Donahue Distinguished University Professor of Space Science in the Department of Atmospheric, Oceanic, and Space Sciences at the University of Michigan. He is an active researcher in both theoretical and experimental studies of the solar atmosphere and its expansion into space to form the heliosphere. He was the associate administrator for space science and applications and chief scientist at NASA (1987-1993), and from 1977 to 1987, he served as professor of physics and vice president for research and financial affairs at the University of New Hampshire. He is a member of the board of directors of the Orbital Sciences Corporation and co-founder of the Michigan Aerospace Corporation, and he is a former chair of the Board of Trustees of the University Corporation for Atmospheric Research. He is a member of the National Academy of Sciences (NAS). His prior NRC service includes chair of the Space Studies Board, co-vice chair of the Committee on the Rationale and Goals of the U.S. Civil Space Program, and membership on the Committee on Scientific Communication and National Security, the Committee on Fusion Science Assessment, the Committee on International Space Programs, Air Force Physics Research Committee, and the Committee on Solar and Space Physics.

BRUCE H. MARGON, *Vice Chair*, is vice chancellor of research and professor of astronomy and astrophysics at the University of California, Santa Cruz. He was associate director for science at the Space Telescope Science Institute and his own research has focused on high-energy astrophysics. He has been involved with the Hubble Space Telescope project for 30 years and has worked for more than a decade as the founding chair of the Board of Governors of the Astrophysical Research Consortium, a nonprofit consortium that builds and operates innovative ground-based telescopes, including the Sloan Digital Sky Survey. He served for many years on the board of directors of the Association of Universities for Research in Astronomy, including serving as chair (1995-1998). He has held faculty positions at the University of California at Los Angeles and the University of Washington, and he held an appointment as adjunct professor of physics and astronomy at Johns Hopkins University.

MARK R. ABBOTT is dean of the College of Oceanic and Atmospheric Sciences at Oregon State University. His research focuses on the interaction of biological and physical processes in the upper ocean and relies on both remote-sensing and field observations. He deployed the first array of bio-optical moorings in the Southern Ocean as part of the United States Joint Global Ocean Flux Study (U.S. JGOFS). Dr. Abbott chairs the U.S. JGOFS Science Steering Committee and he is also a member of the MODIS and SeaWiFS space remote sensing science teams. He is a member of the National Science Board and was a member of the NRC Space Studies Board and chaired its Committee on Earth Studies. He most recently served on the Committee on NOAA NESDIS Transition from Research to Operations and the Panel on Land-use Change, Ecosystem Dynamics, and Biodiversity of the Decadal Survey on Earth Science and Applications from Space.

STEVEN J. BATTEL, a private consultant, was an engineer, researcher and manager at the University of Michigan, Lockheed Palo Alto Research Laboratory, University of California at Berkeley (UC Berkeley), and the University of Arizona Lunar and Planetary Laboratory prior to becoming president of Battel Engineering. At UC Berkeley, he was project manager for the Extreme Ultraviolet Explorer Project. Since

1990 his company has provided engineering, development and review services to NASA, DOD, university, and industrial clients. Areas of specialization include program management, systems engineering, advanced technology, UV optics, RF communications, spacecraft avionics, power systems, high voltage systems, precision electronics and scientific instrument design. Battel was a member of the HST External Readiness Review Team for SM-2, SM-3A and SM-3B, the AXAF/Chandra Independent Assessment Team, the TDRS-H/I/J Independent Review Team and the Mars Polar Lander Failure Review Board. He is former member of the NSO Solar Observatory Council. He currently serves as a member of the NRC Space Studies Board and the Committee on Earth Studies.

YVONNE C. BRILL is an independent consultant whose primary focus is aerospace technology and policy issues. Her specific research interests include rocket motors, launch vehicles for space application, and spacecraft (on-board) propulsion systems. She began her career with Douglas Aircraft as a rocket-propellant chemist on a project to design and launch an unmanned, Earth-orbiting satellite. Later at RCA Astro-Electronics, she developed the concept for a new rocket engine—an electrothermal hydrazine thruster. Ms. Brill is a member of the National Academy of Engineering, an honorary fellow of the American Institute of Aeronautics and Astronautics, and a fellow of the Society of Women Engineers. She is a member of the SSB, and she has served on numerous NRC and NAE committees, including the Committee on Air Force/Department of Defense Aerospace Propulsion, the Committee on Strategic Assessment of Earth-to-Orbit Propulsion Options, and the Committee to Study the Advanced Solid Rocket Quality and Test Program.

DONALD E. BROWNLEE is a professor of astronomy at the University of Washington (UW) in Seattle. His primary research interests focus on the origin and evolution of planetary materials, planets, and planetary systems. He is extensively involved with the laboratory study of primitive materials from asteroids and comets, and he is the Principal Investigator of the NASA's Stardust comet sample return mission. He is also a member of the UW astrobiology program and has co-authored two books with UW paleontologist Peter Ward on the Earth's evolution to become a habitat for advanced life and on the remarkable aspects of the processes involved as viewed from the perspectives of space and time. He is a member of the NAS and served on the NRC Committee on Planetary on Planetary and Lunar Exploration, the Space Studies Board, and the Study Team on Primitive Bodies.

RICHARD CHAPAS is a senior marketing manager for environmental technologies at the Battelle Eastern Science and Technology Center. He was formerly director of industrial collaboration at the Pacific Northwest National Laboratory. Prior to joining Battelle, he ran his own consulting business and worked for the following companies: Rayonier, vice president of research and development; Kimberly-Clark, senior R&D manager; Johnson & Johnson, group leader; and Eastman Kodak, senior scientist. While operating his own business, he served as: COO for Cara Plastics, a University of Delaware start-up company producing bio-based materials; industrial liaison for the Particle Engineering Research Center at the University of Florida; technical consultant for Wellman which is a producer and recycler of polyester fiber; and strategic consultant for Lysac, a Canadian start-up producing bio-based superabsorbents. He is a member of the Industrial Research Institute, where he has served as chair for subcommittees on Knowledge Management and Research on Research, and he is also a board member for the Center for Sustainable Enterprise at the Kenan-Flagler Business School at the University of North Carolina.

MARTIN H. ISRAEL is a professor of physics at Washington University. He was principal investigator of the Heavy Nuclei Experiment on the HEAO-3 satellite, and a co-investigator on the Trans-Iron Galactic Element Recorder high-altitude balloon experiment, which had two successful flights. He also works on analysis of data from the Cosmic Ray Isotope Spectrometer on the Advanced Composition Explorer spacecraft. Dr. Israel is working on the Antarctic Impulsive Transient Antenna, a balloon-borne instrument that studies extremely high energy neutrinos. He is the recipient of NASA Exceptional Scientific Achievement Award (1980) and serves as chair of NASA Scientific Ballooning Roadmap

Team. Dr. Israel was a member of the NASA GSFC Space Science Visiting Committee, the Director's Visiting Committee, and the NASA Structure and Evolution of the Universe Subcommittee.

CONILEE G. KIRKPATRICK is vice president of HRL Laboratories, LLC (the former Hughes Research Laboratories) in Malibu, California. She is the senior technical executive at HRL where she guides a broad spectrum of research and development programs for HRL's members, government and commercial customers. Before joining HRL, Dr. Kirkpatrick was a senior scientist at Science Applications International Corporation. She has served as a member of the Defense Sciences Research Council in support of DARPA, a member of the NIST Visiting Industrial Scientist Committee, a member of the Main Group of the Advisory Group on Electron Devices to the Office of Undersecretary of Defense, Acquisition and Technology, a reviewer for the Naval Research Laboratory's Electronics program, and reviewer for the Office of Basic Research Review of 6.1 DOD programs. Other advisory roles have included membership on the Electrochemical Society Electronics Division Executive Council, the Device Research Conference committee, and the NRC National Materials Advisory Board Committee on Beam Technologies. She currently serves on the University of California Micro Policy Board and the Air Force Research Lab Electronics, EO and Optics Industrial Advisory Board.

JENNIFER A. LOGAN is a senior research fellow in the School of Engineering and Applied Sciences at Harvard University. Her research uses global models and analyses of atmospheric data to improve understanding of the processes affecting atmospheric composition, and hence climate, and the changes wrought by human activity. She has published extensively on trends in ozone. A particular focus of current research is analysis of tropospheric data from the Aura satellite. She is a member of the Tropospheric Emission Spectrometer science team and is on the steering committee of the Global Modeling Initiative. She is a fellow of the American Geophysical Union and the American Association for the Advancement of Science. Her prior NRC service includes membership on the Board of Atmospheric Sciences and Climate, the Committee to Assess the North American Research Strategy for the Tropospheric ozone Program, and the Committee on Atmospheric Chemistry.

ROBYN MILLAN is an assistant professor of physics and astronomy at Dartmouth College. Her research includes the use of high-altitude scientific balloon experiments to study the Earth's radiation belts, specifically the loss of relativistic electrons from the outer radiation belts into the Earth's atmosphere. She is principal investigator for the Balloon Array for RBSP Relativistic Electron Losses project, which is being planned for flight in association with the Radiation Belt Storm Probe mission. Her prior positions include research appointments at Dartmouth and at the UC Berkeley, where she received her Ph.D.

RICHARD R. PAUL served from 2000 to 2007 as vice president for Strategic Development and Analysis in Phantom Works at The Boeing Company. In 2006 and 2007, he concurrently served in the office of the Boeing chief technology officer. During his Air Force career, he served in three Air Force laboratories (AF Weapons Laboratory, Wright Laboratory, and the Air Force Research Laboratory), a product center (Electronic Systems Center), and two major command headquarters (HQ Strategic Air Command and HQ Air Force Materiel Command). Maj. Gen. Paul served as commander of Wright Laboratory and its predecessor organizations from 1988 to 1992. In his last assignment from 1997 to 2000, he served as the Air Force Technology executive officer and as the commander of AFRL. He is the past chair of the Industrial Research Institute and is currently a member of the Air Force Air University Board of Visitors, an advisor to the Sandia National Laboratories board of directors Missions Committee, and a member of the National Science Foundation SBIR Advisory Committee. He was a member of the NRC Air Force Studies Board and has been an ad hoc advisor to the Air Force Scientific Advisory Board.

GUENTER RIEGLER retired from NASA in 2005 after serving for 3 years as the director of science at the NASA Ames Research Center (ARC). His research experience is in X-ray astrophysics. Before joining ARC he was assistant associate administrator for space science at NASA headquarters where his responsibilities included oversight of the office's mission-enabling research programs and the mission and data operations for space flight missions. Prior positions included research appointments at the California Institute of Technology, Bendix Aerospace, and the Jet Propulsion Laboratory. He received his Ph.D. in x-ray astronomy from the University of Maryland.

MARK V. SYKES is CEO and director of the Planetary Science Institute in Tucson, AZ. His research interests include the origin and evolution of dust in the solar system, cometary dust trails and the collisional production of dust in the asteroid belt, and the compositional gradient in the early solar system and the heating and dynamical processes by which that gradient evolved. He is a member of the Dawn asteroid mission science team and is Chair of the NASA Small Bodies Assessment Group. He is a fellow of the American Association for the Advancement of Science, a former chair of the American Astronomical Society of the Pacific, a former chair of the Astronomy and Astrophysics Society Division for Planetary Sciences (AAS/DPS), and a former member of the NASA-NSF Astronomy and Astrophysics Advisory Committee. During his service in the AAS/DPS, he initiated statistical analyses of NASA planetary science R&A programs that are relevant to the tasks of this committee.

Staff

JOSEPH K. ALEXANDER, *Study Director,* served previously as director of the Space Studies Board (1998-2005), deputy assistant administrator for science in the Environmental Protection Agency's Office of Research and Development (1994-1998), associate director of space sciences at NASA Goddard Space Flight Center (1993-1994), and assistant associate administrator for space sciences and applications in the NASA Office of Space Science and Applications (1987-1993). Other positions have included deputy NASA chief scientist and senior policy analyst at the White House Office of Science and Technology Policy. Mr. Alexander's own research work has been in radio astronomy and space physics. He received B.S. and M.A. degrees in physics from the College of William and Mary.

CARMELA J. CHAMBERLAIN, administrative coordinator, has worked for the National Academies since 1974. She started as a senior project assistant at he Institute for Laboratory Animals for Research, which is now a board in the Division on Earth and Life Sciences, where she worked for 2 years, then transferred to the Space Science Board, which is now the SSB. She has previously served as a senior program assistant and as a program associate with the SSB.

CATHERINE A. GRUBER, editor, joined the SSB as a senior program assistant in 1995. Ms. Gruber first came to the NRC in 1988 as a senior secretary for the Computer Science and Telecommunications Board and also worked as an outreach assistant for the National Science Resources Center. She was a research assistant (chemist) in the National Institute of Mental Health's Laboratory of Cell Biology for 2 years. She has a B.A. in natural science from St. Mary's College of Maryland.

VICTORIA SWISHER, research associate, served with the SSB from 2006 until 2009. She supported studies and workshops on civil space policy, the Beyond Einstein program, NASA workforce, Mars research, research enabled by the lunar environment, ITAR, and other topics. Before joining the SSB, she performed research in x-ray astronomy and laboratory astrophysics, which included studying the x rays of plasma and culminated in her senior thesis, "Modeling UV and X-ray Spectra from the Swarthmore Spheromak Experiment." She graduated from Swarthmore College with a major in astronomy and minor in English literature.

LINDA M. WALKER is a senior program assistant with the SSB. She has been with the National Academies since September 2007. Before joining the SSB she worked with the National Academies Press. She has 28 years of administrative experience.