Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions

ISBN
978-0-309-16350-7

70 pages
8 1/2 x 11
PAPERBACK (2011)

Committee on Assessment of Impediments to Interagency Cooperation on Space and Earth Science Missions; National Research Council

THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

ASSESSMENT OF IMPEDIMENTS TO INTERAGENCY COLLABORATION ON SPACE AND EARTH SCIENCE MISSIONS

Committee on Assessment of Impediments to Interagency Cooperation
on 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

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

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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.

International Standard Book Number-13: 978-0-309-16350-7
International Standard Book Number-10: 0-309-16350-1

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Printed in the United States of America

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[1] Resigned from the committee on August 28, 2009.

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Preface

H.R. 6063, The National Aeronautics and Space Administration Authorization Act of 2008, was enacted into law on October 15, 2008. Included in the act is the following request to the NASA Administrator to initiate a National Academies study:[1]

> The [NASA] Administrator, in consultation with other agencies with space science programs, shall enter into an arrangement with the National Academies to assess impediments, including cost growth, to the successful conduct of interagency cooperation on space science missions, to provide lessons learned and best practices, and to recommend steps to help facilitate successful interagency collaborations on space science missions.
>
> As part of the same arrangement with the National Academies, the Administrator, in consultation with NOAA [the National Oceanic and Atmospheric Administration] and other agencies with civil Earth observation systems, shall have the National Academies assess impediments, including cost growth, to the successful conduct of interagency cooperation on Earth science missions, to provide lessons learned and best practices, and to recommend steps to help facilitate successful interagency collaborations on Earth science missions.

In mid-2009, NASA arranged with the National Academies to conduct the study described in this language. The committee's statement of task is reproduced as Appendix A. Specifically, the study should:

- Examine the rationale for interagency cooperation in Earth science and space science missions, including variations in motivation for interagency cooperation among agencies.
- Survey Earth science and space science missions, either in operation or under formulation or development, which involve a significant partnership in either mission execution or instrument development by NASA with one or more other federal agencies. . . .
- From these case studies, identify lessons learned and best practices. Areas include:

    —Acquisition strategies;
    —Program management and structure, including partnership models; and
    —Interagency issues related to the "research to operations transition."

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[1] Title V, section 507, "Assessment of Impediments to Interagency Cooperation on Space and Earth Science Missions." The full text of the act is available at http://legislative.nasa.gov/PL%20110-422.pdf.

Following approval by the National Research Council, the Space Studies Board appointed members to the Committee on Assessment of Impediments to Interagency Cooperation on Space and Earth Science Missions, which was tasked to carry out the study. Biographies of the committee members are given in Appendix F. Collectively, the committee was able to draw on significant personal experience involving senior agency leadership at NASA, NOAA, and the National Science Foundation; senior leadership at NASA and the Department of Energy (DOE) laboratories; space and Earth science mission scientific leadership, project management, and systems engineering; space program systems and cost analyses; aerospace industry program and project management; interagency and international program planning and execution; and research on complex organizations.

The committee met twice during the course of the study (Appendix E shows the agendas for these meetings). In addition, members of the committee met in informal splinter groups, and the committee also convened via teleconference on multiple occasions. Information in the report was current as of early 2010; however, the report was largely completed prior to the announcement on February 1, 2010, of the termination of the National Polar-orbiting Operational Environmental Satellite System program.[2]

The report is organized as follows: Chapter 1, "Introduction," provides the context for subsequent discussions on interagency collaboration. Included in this chapter is a brief discussion of the inherent challenges of executing space missions and the unique opportunities and challenges associated with collaborative missions. Chapter 2, "NASA Interagency Collaboration," reviews recent instrument and mission-level interagency collaborations for Earth and space science missions among NASA, NOAA, DOE, and the Department of Defense. The chapter also reviews the impact of collaboration on cost, schedule, and complexity. Chapter 3, "Lessons Learned and Best Practices," provides committee views on when collaboration should be undertaken and steps to increase the likelihood of its success.

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[2] Office of Science and Technology Policy, "Restructuring the National Polar-orbiting Operational Environmental Satellite System," February 1, 2010, Washington, D.C., available at http://www.whitehouse.gov/ administration/eop/ostp/rdbudgets/2011.

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 Report Review Committee of the National Research Council (NRC). 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 review of this report:

Mark Abbott, Oregon State University,
Susan Avery, Woods Hole Oceanographic Institution,
Vinton G. Cerf, Google, Inc.,
Paul G. Gaffney II, Monmouth University,
Charles G. Groat, University of Texas, Austin,
Molly Macauley, Resources for the Future,
Craig Thomas, University of Washington,
Michael Turner, University of Chicago, and
Carl Wunsch, Massachusetts Institute of Technology.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Byron D. Tapley, University of Texas, Austin. 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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APPENDIXES

Summary

Through an examination of case studies, agency briefings, and existing reports, and drawing on personal knowledge and direct experience, the Committee on Assessment of Impediments to Interagency Cooperation on Space and Earth Science Missions found that candidate projects for multiagency collaboration[1] in the development and implementation of Earth-observing or space science missions are often intrinsically complex and, therefore, costly, and that a multiagency approach to developing these missions typically results in additional complexity and cost. Advocates of collaboration have sometimes underestimated the difficulties and associated costs and risks of dividing responsibility and accountability between two or more partners; they also discount the possibility that collaboration will increase the risk in meeting performance objectives.

This committee's principal recommendation is that agencies should conduct Earth and space science projects independently unless:

- **It is judged that cooperation will result in significant added scientific (and possibly follow-on operational) value to the project over what could be achieved by a single agency alone; or**
- **Unique capabilities reside within one agency that are necessary for the mission success of a project managed by another agency; or**
- **The project is intended to transfer from research to operations necessitating a change in responsibility from one agency to another during the project; or**
- **There are other compelling reasons to pursue collaboration, for example, a desire to build capacity at one of the cooperating agencies.**

Even when the total project cost may increase, parties may still find collaboration attractive if their share of a mission is more affordable than funding it alone. In these cases, alternatives to interdependent reliance on another government agency should be considered. For example, agencies may find that buying services from another agency or pursuing interagency coordination of spaceflight data collection is preferable to fully interdependent cooperation.

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[1] In this report, "collaboration" is used as an overarching term that refers to more than one agency working together, and four types of collaboration are defined by the committee, based on the degrees of interdependency between collaborating entities. Although the committee's name refers to "cooperation," which is taken from the congressional call for this study, the committee treated "cooperation" as one of the four types of collaboration in which two or more agencies collaborate in a way that makes each agency dependent on the other for the project's success.

LESSONS FROM INTERNATIONAL COLLABORATION

Important lessons for national interagency collaboration efforts may also be learned from experiences with international collaboration (i.e., more than one country working together). In particular, the committee found that the U.S. experience in international collaborative projects is instructive with regard to the degree of upfront planning involved to define clear roles, responsibilities, and interfaces consistent with each entity's strategic plans.

Experience has shown that collaborative projects almost invariably lead to increased costs. When additional participants join a project, the basic costs remain, but the costs of duplicating management systems and of managing interactions must be added. It is also important to recognize that even though the overall cost of the program may increase, the cost to each partner is often decreased, thus making a program more affordable to each partner. With international cooperation, the cost of a program to the U.S. government can be decreased, since a foreign government is absorbing some of the basic costs. With interagency cooperation, the cost to the government inevitably rises, because the basic cost plus the additional costs must all be absorbed by the participating U.S. agencies.

A prerequisite for a successful international collaboration is that all parties believe the collaboration is of mutual benefit. Proposals for interagency collaboration within the United States should receive similar serious attention as part of each agency's strategic decision-making process *prior* to proceeding with technical commitments and procurements. As with international agreements, interagency agreements should not be entered into lightly and should be undertaken only with a full assessment of the inherent complexities and risks.

IMPEDIMENTS TO INTERAGENCY COLLABORATION

Impediments to interagency collaboration can result from sources both internal and external to the agencies themselves. Internal sources can include conflicts that result from differing agency goals, ambitions, cultures, and stakeholders, as well as agency-unique technical standards and processes. External sources can include the differing budget cycles for agencies—especially for the National Oceanic and Atmospheric Administration (NOAA), which must first submit its budget to the Department of Commerce—each of which has different congressional authorization and appropriation subcommittees, budget instability, and changes in policy direction from the administration and Congress. These impediments manifest themselves as impacts on mission success and as changes in cost, schedule, performance, and associated risks.

The most serious impediments to collaboration are external to the agencies. They are typically symptoms of conflicting policies that are often not made explicit at the beginning of proposed cooperative efforts. Such impediments manifest themselves as different budget priorities by agencies, the Office of Management and Budget (OMB), and the Congress toward the same collaborative activity. While there may be acknowledgment of the value of collaboration at a national level, at the implementation level decision makers can be unwilling to prioritize collaboration above other agency mission assignments and constraints.

As detailed in Chapter 3 of this report, many of the impediments to interagency collaboration, both internal and external, manifest themselves as impediments to good systems engineering. Good systems engineering and project management techniques[2] are important in any space mission, but especially when multiple organizations are involved. The inevitable creation of seams (i.e., divisions of responsibility and/or accountability between participants for planning, funding, decision making, and project execution) as a result of interagency collaboration is a source of technical and programmatic risks. Such risks could include failure to meet agreed-upon technical performance requirements, compromised system reliability, unacceptable schedule delays, or cost overruns, and mitigating such shortfalls requires proactive management and attention.

The committee identified a number of impediments that should be considered and addressed prior to the start of collaboration, and it outlines below a number of best practices to mitigate risk at various stages of mission devel-

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[2] By "systems engineering" the committee means the process by which the performance requirements, interfaces, and interactions of multiple elements of a complex system such as a spacecraft are analyzed, designed, integrated, and operated so as to meet the overall requirements of the total system within the physical constraints on and resources available to the system. By "project management" the committee means the overall management of the budget, schedule, performance requirements, and assignments of team member roles and responsibilities for the development of a complex system such as a scientific spacecraft.

opment. From its consideration of numerous case studies (see Appendix C), the committee found that interagency collaboration based on working-level collaborations among the agencies' technical staff is preferred to top-down direction to pursue collaboration (e.g., via policy edict), because top-down direction may be burdened from the beginning with a lack of working-level buy-in. Successful collaboration was also found to be more likely when each agency considers the partnership one of its highest priorities; such an understanding should be codified in signed agreements that also document the terms of the collaboration's management and operations.

GOVERNANCE AND INTERAGENCY COLLABORATION

To facilitate interagency collaborations, there is a need for coordinated oversight by the executive and legislative branches. Because the current roles of OMB and the Office of Science and Technology Policy (OSTP) are not suited to this kind of day-to-day operational oversight, some other governance mechanism may be needed to facilitate accountable decision making across multiple agencies while providing senior administration and congressional support for those decisions.

The committee recommends that if OSTP, OMB, or the Congress wishes to encourage a particular interagency research collaboration, then specific incentives and support for the interagency project should be provided. Such incentives and support could include facilitating cross-cutting budget submissions; protecting funding for interagency projects; providing freedom to move needed funds across appropriation accounts after approval of a cross-cutting budget; multiyear authorizations; lump-sum appropriations for validated independent cost estimates; minimization of external reviews that are not part of the project's approved implementation plans; and unified reporting to Congress and OMB, as opposed to separate agency submissions.

The committee also investigated the particular problems associated with NASA-NOAA collaboration in support of climate research. Ensuring the continuity of measurements of particular climate variables, sustaining measurements of the climate system, and developing and maintaining climate data records are long-standing problems rooted in the mismatch of agency charters and budgets. As noted in the 2007 National Research Council decadal survey, *Earth Science and Applications from Space*,[3] the nation's civil space institutions, including NASA and NOAA, have responsibilities that are in many cases mismatched with their authorities and resources: institutional mandates are inconsistent with agency charters, budgets are not well matched to emerging needs, and shared responsibilities are supported inconsistently by mechanisms for cooperation. This committee concurs with the decadal survey committee, which concluded that solutions to these issues will require action at a level of the federal government above that of the agencies.

FACILITATING SUCCESSFUL COLLABORATIONS

Successful interagency collaborations (i.e., those that have achieved their mission objectives and satisfied sponsor goals) share many common characteristics that are, in turn, the result of realistic assessment of agency self-interests and capabilities before and during the collaboration, and involve a disciplined attention to systems engineering and project management best practices.[4] **The committee recommends that the following key elements be incorporated in every interagency Earth and space science collaboration agreement:**

- **A small and achievable list of priorities.** Projects address a sharply focused set of priorities and have clear goals. Agreement is based on specific projects rather than general programs.
- **A clear process to make decisions and settle disputes.** Project decision making is driven by an intense focus on mission success. This is facilitated by formal agreement at the outset on explicitly defined agency roles and responsibilities and should involve agreed processes for making management decisions, single points of account-

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[3] National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, The National Academies Press, Washington, D.C., 2007, available at http://www.nap.edu/catalog.php?record_id=11820.

[4] The committee's views on best-practice approaches to systems engineering and project management are outlined in Chapter 3 in the section titled "Mitigating the Risks of Interagency Collaboration."

ability (i.e., not committees), and defined escalation paths to resolve disputes. Long-term planning, including the identification of exit strategies, is undertaken at the outset of the project and includes consideration of events that might trigger a reduction-in-scope or cancellation review and associated fallback options if there are unexpected technical difficulties or large cost overruns that make the collaboration untenable.

- **Clear lines of authority and responsibility for the project.** Technical and organizational interfaces are simple and aligned with the roles, responsibilities, and relative priorities of each collaborating entity. Project roles and responsibilities are consistent with agency strengths and capabilities. Expert and stable project management has both the time and the resources available to manage the collaboration. Specific points of contact for each agency are identified. Agency and project leadership provides firm resistance to changes in scope. When possible, one of the collaborating agencies should be designated as the lead agency with ultimate responsibility and accountability for executing the mission within the agreed set of roles and responsibilities, command structure, and dispute resolution process defined in a memorandum of understanding. In some cases the lead agency might change as a function of time, as for missions in which the lead agency differs between the implementation and operations phases.
- **Well-understood participation incentives for each agency and its primary stakeholders.** All parties share a common commitment to mission success and are confident in and rely on the relevant capabilities of each collaborating agency. Each agency understands how it benefits from the cooperation and recognizes that collaborative agreements may need to be revisited at regular intervals in response to budgetary and political changes. There is buy-in from political leadership (e.g., senior administration, Congress, and agency-level administrators), which can help projects move past the inevitable rough spots. There is a general spirit of intellectual and technical commitment from the agency workforce and contractors to help projects mitigate the disruptive effects of technical and programmatic problems that are likely to occur. Early and frequent stakeholder involvement throughout the mission keeps all stakeholders informed, manages expectations, and provides appropriate external input.
- **Single acquisition, funding, cost control, and review processes.** There is a single agency with acquisition authority, and each participating entity accepts financial responsibility for its own contributions to joint projects. Reliance on multiple appropriation committees for funding is avoided or reduced to the greatest possible extent. Cost control is ideally the responsibility of a single stakeholder or institution, because without a single point of cost accountability, shared costs tend to grow until the project is in crisis. Single, independent technical and management reviews occur at major milestones, including independent cost reviews at several stages in the project life cycle.
- **Adequate funding and stakeholder support to complete the task.** Funding adequacy is based on technically credible cost estimates with explicitly stated confidence levels.

In summary, engaging in collaboration carries significant cost and schedule risks that need to be actively mitigated. Agencies are especially likely to seek collaborators for complex missions so that expected costs can be shared. However, as the committee observed from historical experience and interviews, inefficiencies arise when collaborating agencies' goals, authorities, and responsibilities are not aligned. Thus, collaborations require higher levels of coordination, additional management layers, and greater attention to mechanisms for conflict resolution.

1

Introduction

THE INHERENT CHALLENGES OF SPACE MISSIONS

The allure of space is that it enables unique observations of Earth and the cosmos. However, underlying all that is said in this report is the empirical fact that access to space, with instruments capable of making measurements of either scientific or operational[1] utility, is both costly and complex. Even a comparatively simple Earth or space science mission developed in the streamlined "principal investigator"[2] (PI) management style may require several years of effort and incur costs measured in the hundreds of millions of dollars, while more complex multi-instrument "facility-class" or "flagship" missions such as the James Webb Space Telescope may require a decade or more of effort and incur costs measured in the billions of dollars. While the capability of space missions has increased over time—a reflection of technology evolution—overall mission costs have remained high. High mission costs are typically accompanied by a decreased tolerance for risk,[3] which in turn leads to additional layers of review and risk mitigation during mission development, producing a positive feedback cycle that results in both increased conservatism and mission cost.

Not surprisingly, much thought and effort have gone into investigating ways to reduce mission costs. NASA's experiment to deviate substantially from what had been viewed as overly conservative (and costly) acquisition practices with a "faster, better, cheaper" model of mission development led to both success (the 1996 Mars Path-

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[1] Here the committee defines an "operational" system as one that meets user needs for unbroken data streams. Familiar examples are the National Oceanic and Atmospheric Administration and U.S. Air Force meteorological satellite programs that provide data and imagery for use in numerical weather prediction and to support military operations.

[2] The "PI-mode" of mission management allows the scientist full authority and accountability for the success of the mission and puts NASA in the role of assisting—rather than directing. The PI picks the science question to be answered and the measurement approach to take, and has end-to-end mission management responsibility and authority. See two reports of the National Research Council, *Steps to Facilitate Principal-Investigator-Led Earth Science Missions* (2004) and *Principal-Investigator-Led Missions in the Space Sciences* (2006); both reports are published by The National Academies Press, Washington, D.C., and available at http://www.nap.edu/catalog.php?record _id=10949 and http://www.nap.edu/catalog.php?record_id=11530, respectively. Principle-investigator mode and facility-class missions are discussed in more detail in NASA NPR 7120.5D, NASA Space Flight Program and Project Management Requirements or the interim directive, NM 7120-81, as well as NASA NPR 8705.4—Risk Classification for NASA Payloads.

[3] There are a number of kinds of risks for a mission. For example, risks could include failure to meet agreed-upon technical performance requirements, compromised system reliability, unacceptable schedule delays, or cost overruns.

finder Mission) and failure (notably the losses in 1999 of the Mars Polar Lander and the Mars Climate Orbiter).[4] The appropriate balance for managing schedule, mission capability, and funding has thus proven elusive, leading to alternating calls for increased funding, less complex missions, schedule relief, or some combination of the three. Further, the continued search for an optimal and balanced solution has led many to call for increases in interagency collaboration.

In this report, "collaboration" is used as an overarching term that refers to more than one agency working together to plan and implement space missions in Earth and space science. The committee discusses different levels of collaboration below, which vary in the degree of interdependency between collaborating entities.

Mission collaboration can be undertaken by agency partners hoping to achieve a particular benefit or to avoid a particular difficulty. For example, agencies may collaborate when neither has the technical capabilities and resources to develop a program or execute a mission alone, or when a single measurement can provide for the needs of multiple agencies in a cost-effective way. In their briefings to the committee, there was agreement among the representatives from the study sponsor, NASA, the Office of Management and Budget, and the Office of Science and Technology Policy that multiagency missions would become more likely in the future and that such partnerships were to be encouraged. However, any collaboration effort needs to take into account differing styles of program management and different agency mandates, that is, NASA's role as primarily a research and development agency; the National Science Foundation's role as a supporter of basic research; and the principal roles of the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Geological Survey as operational, mission-oriented agencies.[5] The committee thus examined numerous examples of interagency collaborations to determine whether such joint endeavors served to reduce cost, complexity, or risk.[6]

PREVIOUS STUDIES OF INTERAGENCY COOPERATION

Although there has not been a single study that specifically examined issues related to interagency collaboration on Earth and space observations, the Government Accountability Office (GAO) conducted a study in 2005 that identified key practices that can help enhance and sustain agency collaboration in general.[7] As detailed in the chapters that follow, the present committee finds broad agreement with the principles enunciated in the GAO report. In particular, the GAO report states that:

> Collaboration can be broadly defined as any joint activity that is intended to produce more public value than could be produced when the organizations act alone. Agencies can enhance and sustain their collaborative efforts by engaging in the eight practices identified below. Running throughout these practices are a number of factors such as leadership, trust, and organizational culture that are necessary elements for a collaborative working relationship:
>
> - Define and articulate a common outcome;
> - Establish mutually reinforcing or joint strategies;
> - Identify and address needs by leveraging resources;

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[4] For example, see testimony of A. Thomas Young, chairman of the Mars Program Independent Assessment Team, before the House Science Committee, April 12, 2000, available at http://www.spaceref.com/news/ viewpr.html?pid=1444. Also see the Mars Climate Orbiter Mishap Investigation Board, *Report on Project Management in NASA by the Mars Climate Orbiter Mishap Investigation Board,* Jet Propulsion Laboratory, Pasadena, Calif., March 13, 2000, available at http://marsprogram.jpl.nasa.gov/msp98/news/reports.html; and, A successful strategy for satellite development and testing, in *Crosslink: The Aerospace Magazine of Advances in Aerospace Technology,* Volume 6, Number 3 (Fall 2005), available at http://www.aero.org/publications/crosslink/ fall2005/index.html.

[5] National Research Council, *Mission to Planet Earth: Space Science in the Twenty-First Century—Imperatives for the Decades 1995 to 2015*, National Academy Press, Washington, D.C., 1988, available at http://www.nap.edu/catalog.php?record_id=753, p. 107.

[6] The committee notes that although the emphasis of this report is on impediments to interagency collaboration, many of the same recommendations and best practices also apply to intra-agency collaboration situations, because even internal to a single agency there can be cultural and process differences that challenge mission implementation. See, for example, NASA, *The CALIPSO Mission: Project Management in the "PI Mode": Who's in Charge?,* NASA Case Study GSFC-1011C-1, NASA Goddard Space Flight Center, Greenbelt, Md., 2007, available at http://library.gsfc.nasa.gov/casestudies/public/GSFC-1011C-1-CALIPSO.pdf.

[7] Government Accountability Office, *Results-Oriented Government: Practices That Can Help Enhance and Sustain Collaboration among Federal Agencies,* GAO-06-15, Washington, D.C., October 2005.

- Agree on roles and responsibilities;
- Establish compatible policies, procedures, and other means to operate across agency boundaries;
- Develop mechanisms to monitor, evaluate, and report on results;
- Reinforce agency accountability for collaborative efforts through agency plans and reports; and
- Reinforce individual accountability for collaborative efforts through performance management systems.[8]

Box 1.1 summarizes conclusions from two reports on international space program cooperation that highlight similar conclusions. Similar general conclusions have been reached when considering partnerships outside the space sciences. A 1995 RAND report, *Pros and Cons of International Weapons Procurement Collaboration*,[9] used case study evidence to identify many of the same attributes that are associated with successful U.S.-European programs for co-development of weapons systems.

In a study commissioned by the Southern Area Consortium of Human Services (SACHS)[10] on the role of interagency collaboration[11] in producing information relevant to county directors as they address issues of service integration, the authors note that "the first and perhaps most compelling motivation to collaborate is that collaboration has come to enjoy broad acceptance in political and professional circles as a way to address a variety of problems in the human service system."[12] In addition, the study's authors note that "the policy environment, reflecting conventional wisdom on collaboration, is replete with exhortations, mandates, and other incentives for public agencies to work across agency boundaries."[13]

The external factors driving collaboration in human services are similar to the factors driving collaboration in Earth and space science missions; that is, the policy environment is encouraging, even pushing, collaborations. Also important to note is that the guidance offered by the present committee regarding conditions for successful collaboration is similar to that of SACHS study's four "prerequisites" to collaboration:[14]

- *Incentive*—mandated versus voluntary collaboration;
- *Willingness*—the level of trust among participants, shared values, open communication, and a commitment to making it work;
- *Ability*—relevant knowledge and skills; and
- *Capacity*—the existence of relevant rules, regulations, norms, communication systems, etc. that can enable collaboration.

These factors map well with the committee's findings, described in Chapter 3, regarding the impact of top-down versus bottom-up imperatives to collaborate and the anecdotal reports the committee received regarding the importance of a shared vision for a multiagency effort, good communications, and acceptance at all levels of the collaborating organizations.

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[8] Ibid.; see detailed discussion on pp. 10-25.

[9] M.A. Lorell and J.F. Lowell, *Pros and Cons of International Weapons Procurement Collaboration,* RAND Monograph/Report Series, MR-565-OSD, RAND Corporation, Santa Monica, Calif., 1995.

[10] The Southern Area Consortium of Human Services (SACHS), a county/university partnership, is a forum for County Human Services Agency directors in southern California and School of Social Work deans to explore and exchange ideas and information on issues facing public human services, and to develop strategies for addressing these needs.

[11] In the SACHS-commissioned study, "collaboration" is defined as "a broad concept that encompasses relationships, formal and informal, between programs in an agency or across agencies in which the parties share or exchange resources in order to achieve common goals."

[12] Southern Area Consortium of Human Services (SACHS), *Seeking Better Performance Through Interagency Collaboration: Prospects and Challenges,* prepared by R. Patti, T. Packard, D. Daly, J. Tucker-Tatlow, and K. Prosek, with the assistance of A. Potter and C. Gibson, SACHS, San Diego, Calif., February 2003, available at http://theacademy.sdsu.edu/programs/SACHS/research.htm, p. vii.

[13] SACHS, *Seeking Better Performance Through Interagency Collaboration: Prospects and Challenges,* 2003, p. vii.

[14] P. Robertson, Interorganizational relationships: Key issues for integrated services, pp. 67-78 in *Universities and Communities: Remaking Professional and Interprofessional Education for the Next Century* (J. McCroskey and S. Einbinder, eds.), Praeger Publishers, Westport, Conn., 1998.

BOX 1.1
Lessons Learned from International Space Program Cooperation

Two independent studies of international space program collaboration—one focused on space science missions and the other on the International Space Station (ISS)—also provide potentially relevant insights for assessing interagency collaboration. Some of their key findings are summarized here.

In a 1998 report,[1] a joint committee of the Space Studies Board and the European Space Science Committee identified the following as elements essential to successful international cooperation in space research missions:

1. *Scientific support*—compelling scientific justification of a mission and strong support from the scientific community. All partners need to recognize that international cooperative efforts should not be entered into solely because they are international in scope.
2. *Historical foundation*—partners have a common scientific heritage that provides a basis of cooperation and a context within which a mission fits.
3. *Shared goals and objectives* for international cooperation that go beyond the objectives of scientists to include those of the engineers and others involved in a joint mission.
4. *Clearly defined responsibilities* and a clear understanding of how they are to be shared among the partners, a clear management scheme with a well-defined interface between the parties, and efficient communication.
5. *Sound plan for data access and distribution*—a well-organized and agreed-upon process for data calibration, validation, access, and distribution.
6. *Sense of partnership* that nurtures mutual respect and confidence among participants.
7. *Beneficial characteristics*—successful missions have had at least one (but usually more) of the following characteristics:
    - Unique and complementary capabilities offered by each international partner;
    - Contributions made by each partner that are considered vital for the mission;
    - Significant net cost reductions for each partner, which can be documented rigorously, leading to favorable cost-benefit ratios;
    - International scientific and political context and impetus; and
    - Synergistic effects and cross-fertilization or benefit.
8. *Recognition of importance of reviews*—periodic monitoring of mission goals and execution to ensure that missions are timely, efficient, and prepared to respond to unforeseen problems.

THE SPECTRUM OF INTERAGENCY COLLABORATION

Interagency or multiagency collaboration may occur under a variety of arrangements and govern a wide range of engineering, technology, and acquisition elements in mission development and subsequent operations. Yet calls for “increased collaboration” rarely specify the level of collaboration being called for. The committee has thus defined four categories that span the spectrum of examined interagency collaborations to allow for a more complete discussion of the associated risks and to encourage advocates to be more specific about the expected degree of interagency collaboration.

The committee employed a three-part approach to analyzing interagency collaborations. First, the committee had briefings and discussions with many current and former government officials and others about their experiences and insights regarding interagency collaboration in space missions. (See Appendix E for meeting agendas.) Second, as called for in the study charge (Appendix A), the committee selected a set of projects as case studies that could illuminate similarities in and distinctions between different kinds of collaborations. (See Appendix C

In 2009 the senior representatives of the five ISS international partner agencies summarized lessons[2] from collaborations to design, develop, construct, and operate the ISS. The lessons were intended for use by future international space projects, but many, such as those listed below, may also have relevance to interagency activities:

1. *Accommodate partner's objectives*—Recognizing the importance of a partner's agenda can help to mitigate conflicts and aid in fostering the realization of common goals.
2. *Establish realistic expectations*—The purpose of collaboration requires clear, thorough definition, ensuring that the goals are commensurate with available resources.
3. *Use clear mission objectives to drive support*—Ambitious, attractive, and achievable mission objectives can help to ensure stable support of a mission. Achievements must be timely and comprehensively reported, with continuous progress toward achieving mission objectives.
4. *Ensure that all mission objectives are well integrated*—Roles, responsibilities, and the scope of activities must be established throughout the mission at a high level.
5. *Carefully balance specificity and flexibility in program agreements*—Explicit partnership agreements are important but need to allow flexibility in order for each partner to contribute to the resolution of unforeseen circumstances. Defining the roles, duties, and commitments of each partner can provide an overarching framework for achieving objectives.
6. *Use a consensus approach to decision making*—Governance by consensus provides assurance that partners are invested in decisions, management, and other issues. Consensus can be built by identifying the interests of each partner. Provision should be maintained establishing one partner that has the ability to make a decision for the rare case that consensus cannot be reached in order to ensure the continuation of the program.
7. *Accommodate partner budget cycles*—Each partner must be aware of the policy generation and budget process of other partners. Understanding differences in these processes is critical to planning program milestones.

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[1] National Research Council, *U.S.-European Collaboration in Space Science,* National Academy Press, Washington, D.C., 1998, available at http://www.nap.edu/catalog.php?record_id=5981.

[2] National Aeronautics and Space Administration, *International Space Station Lessons Learned as Applied to Exploration*, International Space Station Multilateral Coordination Board, NASA Kennedy Space Center, Fla., July 22, 2009.

for the list of case studies and the projects' principal characteristics.) While the committee does not assert that the case studies are necessarily so broadly generalizable as to cover every likely collaboration, the cases do illustrate a relevant range of levels of collaboration, their histories, and their outcomes. Third, the committee drew on an analysis by the Aerospace Corporation of the impact of collaboration on mission cost, complexity, and schedule. The Aerospace Corporation analysis is presented in Chapter 2.

In this report, "collaboration" is used as an overarching term that refers to more than one agency working together, and several other terms are reserved to describe the details of the collaborative arrangement:

- *Use of resources.* One agency uses a resource from another agency without the exchange of funds or the consumption/destruction of the resource.
- *Procurement of services or products.* One agency procures a service or product from another agency in a contract-like manner.

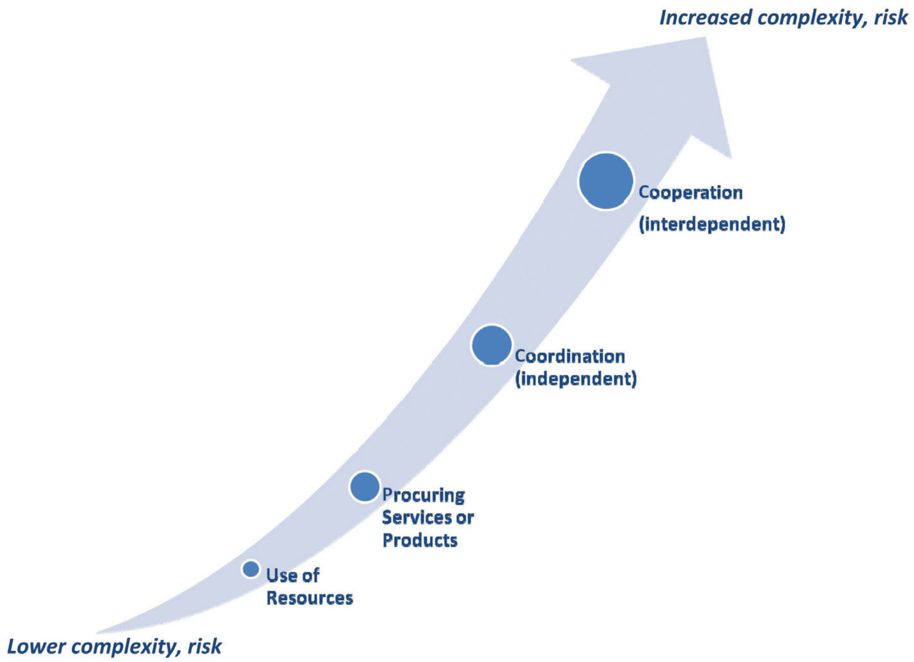

FIGURE 1.1 As the degree of interdependency increases between multiagency participants in a collaborative mission, so also do the mission complexity and performance risks.

- *Coordination.* Two agencies work together on a project in a way that makes them not dependent on each other for the project's success.
- *Cooperation.* Two or more agencies work together on a project in a way that makes each agency dependent on the other for the project's success.

As Figure 1.1 indicates, the committee finds that these collaboration arrangements are also associated with increasing levels of complexity and risk.

Use of Resources Example: Space Weather Data from the Advanced Composition Explorer

The least complex and least risky arrangement is "use of resources," illustrated here by NOAA's use of space weather data acquired by the NASA Advanced Composition Explorer (ACE) spacecraft launched on August 25, 1997[15] (Figure 1.2). Among the instruments on ACE are particle detectors, spectrometers, and a magnetometer that provide near-real-time continuous measurements of solar wind parameters and solar energetic particle intensities, which are used to monitor and forecast Earth's space weather environment. The committee views the ongoing arrangement for NOAA's use of NASA's ACE data as a prototypical example of the lowest level of complexity and risk whereby one agency uses a resource from another agency without the exchange of funds or the consumption/destruction of the resource.

From its halo orbit around the Sun-Earth libration point, L1, ACE provides approximately 1-hour advance warning of geomagnetic storms, which can overload power grids, disrupt civilian and military space- and ground-

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[15] The ACE mission development was managed by the NASA Goddard Space Flight Center Explorer Projects Office of the Flight Projects Directorate. The spacecraft was developed by the Johns Hopkins University Applied Physics Laboratory. Instrument development was the responsibility of the California Institute of Technology under contract to NASA.

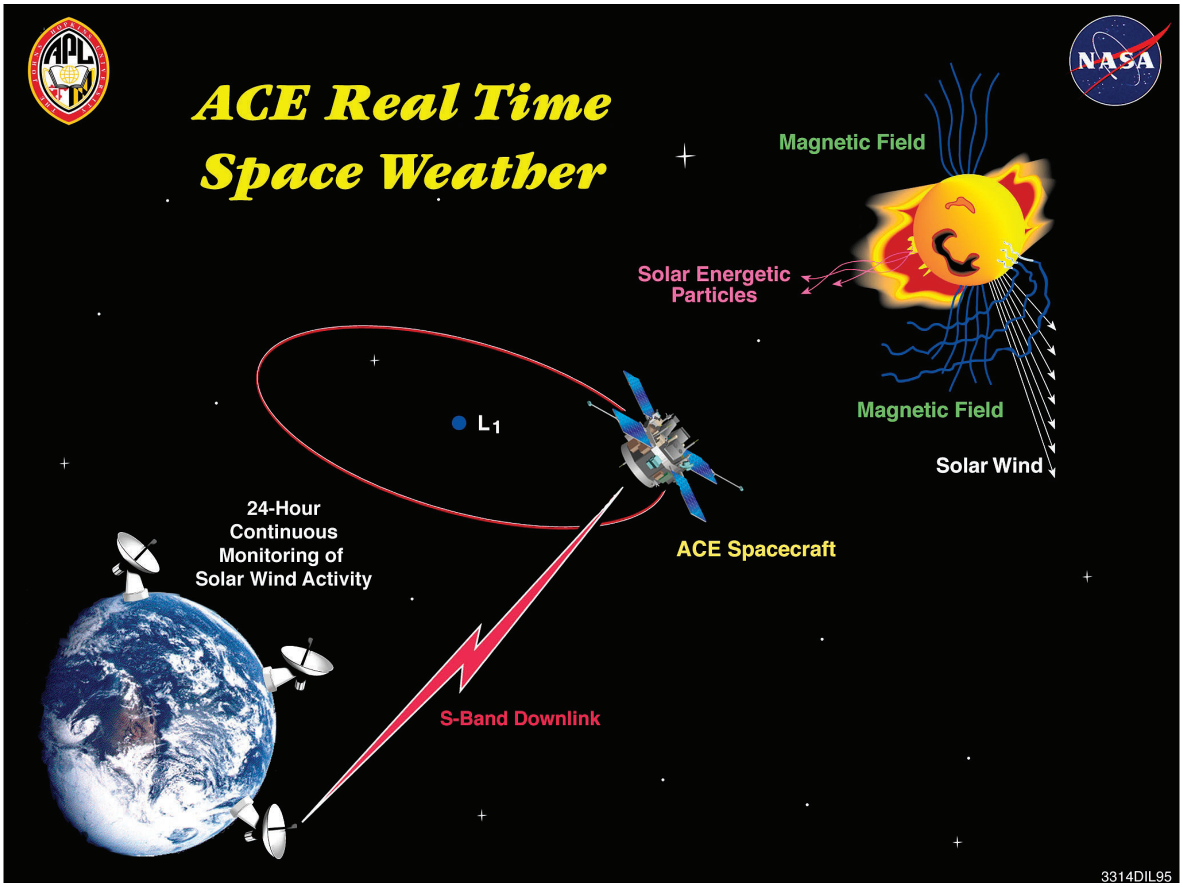

FIGURE 1.2 Use of resources: Space weather data collected by NASA's Advanced Composition Explorer (ACE) mission are provided in real time to NOAA. SOURCE: Courtesy of NASA/JHUAPL.

based communications, and result in disruptions to the ionosphere that affect the commerce and safety-related uses of the Global Positioning Satellite system. Timely and accurate geomagnetic storm warnings provide emergency managers, government officials, and space-weather-sensitive businesses with the information necessary to develop preparedness plans to mitigate property damage and operational impacts.[16]

Prior to launch, NOAA provided $680,000 to modify the ACE spacecraft and enable 24-hour continuous transmission of real-time data on the solar wind. (Specifically, the NOAA-funded changes allowed for the transmission of a subset of data from four ACE instruments during times when ACE is not transmitting its full telemetry.) ACE data and forecast products are relayed to a broad user community by NOAA's Space Weather Prediction Center in Boulder, Colorado.

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[16] Though ACE is the nation's sole real-time upstream solar wind monitor (located directly between Earth and the Sun) and thus is critical to operational solar activity forecasts, the spacecraft is 12 years old and well beyond its design lifetime of 2 years. Difficulties in ensuring the availability of real-time solar wind data beyond the mission lifetime of ACE are illustrative of a problem more frequently associated with the Earth observation programs of NASA and NOAA: failure to manage a timely transition from research to operations. Although recognition of this issue is long-standing, budget pressures and disputes about agency roles and responsibilities have worked against the development of timely solutions. See National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., 2003, available at http://www.nap.edu/catalog.php?record_id=10477; Office of the Federal Coordinator for Meteorological Services and Supporting Research, *Report of the Assessment Committee for the National Space Weather Program*, FCM-R24-2006, June 2006, available at http://www.ofcm.gov/r24/fcm-r24.htm.

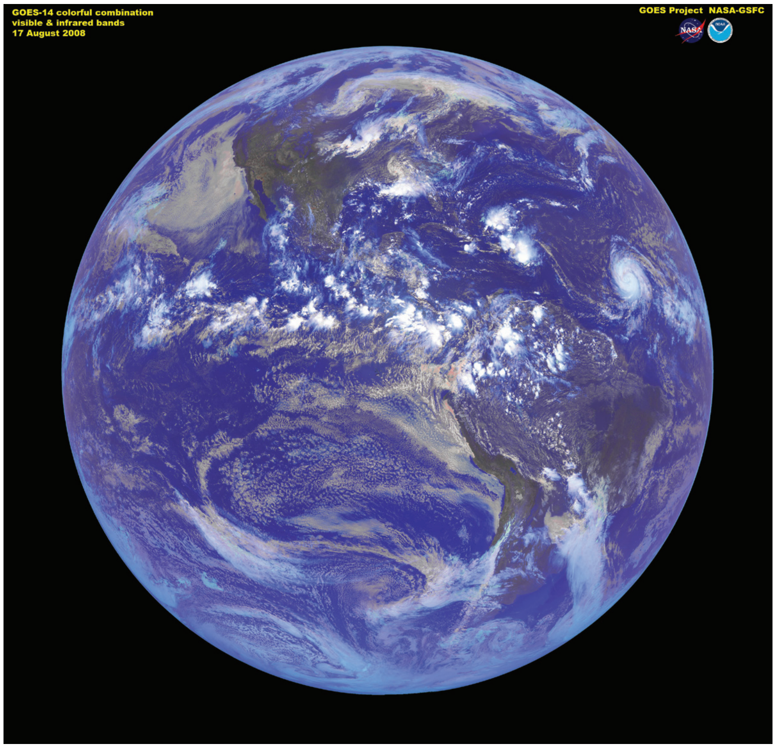

FIGURE 1.3 Procuring services or products: NOAA contracts with NASA to obtain polar and geostationary environmental satellites, such as GOES-14, which produced this 4-km-resolution color composite of the visible and the 4- and 11-micron channels. SOURCE: NASA Goddard Space Flight Center, data from NOAA GOES.

Procurement of Services or Products Example: Polar and Geostationary Environmental Satellites

NOAA's procurement from NASA of launch services and acquisition of instruments and spacecraft for the NOAA polar (Polar Operational Environmental Satellite, POES) and geostationary (Geostationary Operational Environmental Satellite, GOES) programs is an example of "procurement of services or products," the next level in complexity and risk (satellite image example given in Figure 1.3). The committee views these arrangements as prototypical examples of the next-to-lowest level of complexity and risk whereby one agency procures a service or product from another agency in a contract-like manner.

In 1960, the nation's first weather satellite, TIROS 1, was built and launched by NASA. Since that time, the U.S. civilian environmental satellite program has consisted of a succession of experimental and research satellites followed by operational systems. NASA has overseen the development of experimental and research-oriented programs, while the Department of Commerce (DOC), through NOAA and its predecessor organizations, has overseen the routine operation of the operational environmental systems.

The 1998 memorandums of understanding between NASA and NOAA for cooperation in the POES and GOES programs describe the multiagency process used to design and develop the operational POES and GOES systems, in which NOAA procures NASA spacecraft, instruments, and launch services to accomplish its operational objectives.[17] Specifically, NOAA establishes requirements, provides all funding, and distributes the environmental

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[17] The 1998 memorandums of understanding for POES and GOES can be found at http://science.nasa.gov/about-us/science-strategy/interagency-agreements/partnerships-table/.

FIGURE 1.4 OSTM/Jason-2: An example of interagency coordination. SOURCE: NASA/JPL-California Institute of Technology.

satellite data for the United States,[18] while NASA manages the procurement, design, development, and launch of the spacecraft and its instruments.

Coordination Example: Ocean Surface Topography Mission/Jason-2

The committee defines "coordination" as a still higher level of involvement between agencies, but one whereby overall mission success can still be achieved by an individual partner agency. The Ocean Surface Topography Mission (OSTM) is a successful interagency and international collaboration to measure sea surface height by using a radar altimeter mounted on a low-Earth-orbiting satellite called Jason-2 (Figure 1.4). The collaborating organizations are NASA, NOAA, the French space agency Centre National d'Etudes Spatiales (CNES), and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT).[19] The NASA-NOAA relationship for OSTM was one of coordination because NOAA's role in operations did not present a dependent relationship; that is, NASA could have continued post-launch operations to still achieve mission success if the partnership had failed.

Launched by NASA on a Delta-II rocket on June 20, 2008, OSTM/Jason-2 is extending the continuous climate record of sea surface height measurements begun in 1992 by the joint NASA/CNES TOPEX/Poseidon mission and continued by the NASA/CNES Jason-1 mission launched in 2001. High-precision ocean altimetry measures the distance between a satellite and the ocean surface to within a few centimeters. Jason-2's accurate observations of sea surface height variations track global variations in sea level and yield information about the speed and direction of ocean currents and heat stored in the ocean. Jason-2 data are also used operationally and are assimilated into

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[18] Responsibility for the ground systems resides with NOAA, though NASA may provide ground station components.

[19] NASA's Jet Propulsion Laboratory manages the mission for NASA.

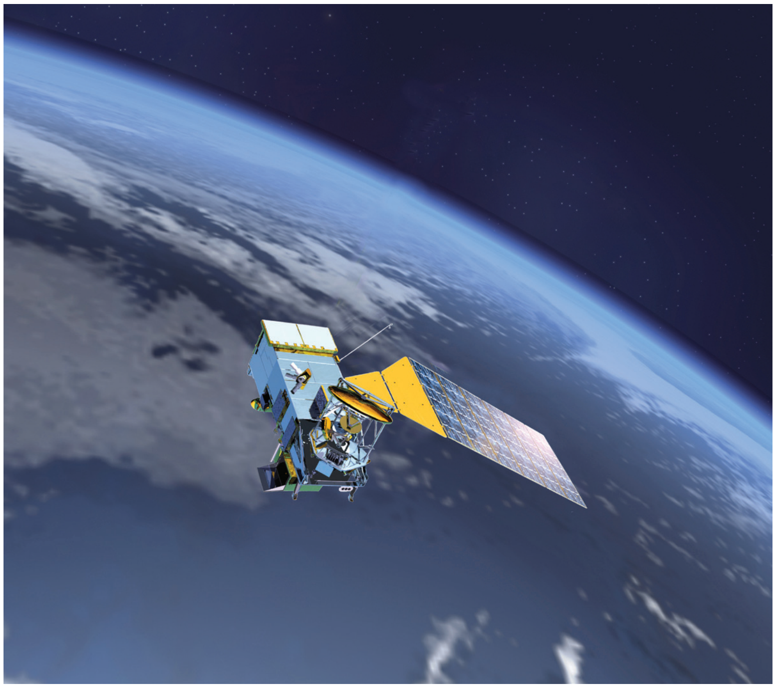

FIGURE 1.5 Artist's conception of NPOESS satellite, which is an example of multiagency cooperation. SOURCE: NOAA.

global ocean circulation, sea state, and coupled numerical models that are used to support a variety of applications, including marine meteorology, hurricane forecasting and tracking, fisheries management, and ship routing.[20]

CNES provided the spacecraft for OSTM, and NASA and CNES jointly provided the payload instruments. In October 2008, following completion of 4 months of post-launch tests and qualification of the entire satellite and the ground system by CNES and NASA, command and control operations for Jason-2 were handed over to NOAA and EUMETSAT.[21]

Although NOAA's primary contribution to the collaborative mission occurs during the operational phase of the mission, the committee notes that the expectation that NOAA would assume post-launch operational responsibility for the mission was also beneficial to gaining support for the mission by NASA, the administration, and Congress during the early stages of mission development. This is an example of how unstated strategic objectives (e.g., increasing the number of stakeholders and supporters) can also serve to motivate collaboration.

Cooperation Example: National Polar-orbiting Operational Environmental Satellite System

The complex multiagency governance and acquisition arrangements for the National Polar-orbiting Operational Environmental Satellite System (NPOESS—Figure 1.5) are an example of "cooperation," whereby two or more agencies work together on a project in a way that makes each agency dependent on the other for the project's success. The committee considers this type of partnership, characterized by the NOAA-Department of Defense (DOD) governance of NPOESS, as having the highest level of complexity and risk of failure.

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[20] See, for example, links on EUMETSAT's Web page for Jason-2/OSTM at http://www.eumetsat.int/Home/Main/Satellites/Jason-2/index.htm.

[21] EUMETSAT receives data from Jason-2 using its ground station in Usingen, Germany, which is remotely accessed and commanded from NOAA's Suitland, Maryland, operation center. Both NOAA and EUMETSAT generate near-real-time data products and distribute them to users; both agencies also maintain archives of scientific data products from the mission.

The model used for procurement of POES and GOES, described in the coordination example above, was not used in the 1994 merger ("convergence") of separate civilian and military meteorological programs that created NPOESS.[22] NPOESS was conceived as a single next-generation successor to the NOAA POES and U.S. Air Force DMSP (Defense Meteorological Satellite Program) programs. As planning evolved, a number of other Earth-observing and space-environment sensors and capabilities were incorporated into the basic program, making NPOESS (as envisioned at that time) a key component for operational weather forecasting and for research on climate, oceans, and space weather. NPOESS is widely viewed as the most complex environmental satellite system ever attempted.

As specified in a memorandum of agreement (MOA),[23] the NPOESS program was to be managed by a tri-agency (NASA, NOAA, DOD) integrated program office (IPO). Within the IPO:

- NOAA had the lead responsibility for satellite and ground segment operations and for interfacing with national and international civil user communities.
- DOD had the lead responsibility for component acquisitions that were necessary to execute the acquisition program baseline.
- NASA had the lead responsibility for improving the remote sensing capabilities of the operational system through the insertion of new technologies.

The MOA also specified that the DOC (NOAA) and the DOD (Air Force) were to share equally in the funding for NPOESS at the program level, with part of the Air Force share residing in the launch vehicle. These program and funding arrangements were unique within the federal government. Furthermore, there were significant differences in the risks and costs for each partner, because the Air Force share was not required until later in the program and NOAA assumed the early cost risks. This illustrates another level of complication that can become an impediment to collaboration.

In 2000, the NPOESS program anticipated purchasing six satellites for $6.5 billion, with a first launch in 2008. By November 2005, it became apparent that NPOESS would overrun its cost estimates by at least 25 percent, triggering a Nunn-McCurdy termination review[24] by the DOD. In June 2006, a certified NPOESS program emerged from review. The certified program reduced the planned acquisition of six spacecraft to four, delayed the launch of the first spacecraft until 2013,[25] and refocused the program on core requirements related to the acquisition of data to support numerical weather prediction. As a result, several sensors were canceled or descoped in capability, and secondary sensors designed to provide crucial continuity to long-term climate records were not funded.[26]

The president's fiscal year 2011 budget, which was released to the public on February 1, 2010, as this report was entering final preparation, terminated the NPOESS program and instead directed a return to the historical model that had the Air Force and NOAA managing separate acquisition programs for polar-orbiting satellites to serve military and civilian users.[27]

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[22] Presidential Decision Directive/NSTC-2, "Convergence of U.S.-Polar-Orbiting Operation Environmental Satellite Systems," May 5, 1994, available at http://www.ipo.noaa.gov/About/NSTC-2.html.

[23] See 1995 "MOA between NASA, DOC, and DOD for the NPOESS," available at http://science.nasa.gov/about-us/science-strategy/interagency-agreements/partnerships-table/.

[24] Language in the Nunn-McCurdy amendment to the Defense Authorization Act of 1982 calls for congressional notifications when programs exceed their original estimated costs by 15 percent and termination when growth is in excess of 25 percent. Provisions in the amendment allow for the continued funding of programs that have exceeded the 25 percent limit only if the secretary of defense deems the program as essential to national security and certifies that the management structure is adequate to control total program acquisition unit cost or procurement unit cost. See http://www.cdi.org/missile-defense/s815-conf-rpt.cfm.

[25] In late 2009, the date for launch of C1 was March 2014. See http://fpd.gsfc.nasa.gov/launches.html.

[26] National Research Council, *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement Capabilities Lost in Program Restructuring*, The National Academies Press, Washington, D.C., 2008, available at http://www.nap.edu/catalog.php?record_id=12254.

[27] Office of Science and Technology Policy, "Restructuring the National Polar-orbiting Operational Environmental Satellite System," February 1, 2010, Washington, D.C., available at http://www.whitehouse.gov/ administration/eop/ostp/rdbudgets/2011.

2

NASA Interagency Collaboration

The NASA Act of 1958, also known as the "Space Act," was part of President Eisenhower's and the U.S. Congress's response to the technology and national security threats that were perceived following the Soviet Union's launch of Sputnik in October 1957. The act created a new agency, the National Aeronautics and Space Administration, to conduct the nation's *civil* space activities.[1] Subsequent national space policies have reaffirmed NASA's responsibility for the development of advanced civil space technologies.[2]

The Space Act also provided NASA with the authority to enter into agreements with other U.S. government agencies, commercial entities, academic institutions, and other organizations. In particular, the Space Act authorizes and encourages NASA to enter into partnerships that help fulfill its mission. NASA has engaged in a wide variety of interagency collaborations to develop and operate space missions. These efforts have involved civil and military agencies, both domestic and international.[3]

Examples of NASA-USGS-NOAA-DOD, NASA-DOD, NASA-DOE, and NASA-NOAA collaborations are provided in this chapter as well as lessons learned from the U.S. Global Change Research Program, an 11-agency collaboration to coordinate global change research. (An example of NOAA-DOD collaboration, NPOESS, is provided in Chapter 1.) This chapter also briefly reviews lessons that may be derived from international collaborations.

NASA-USGS-NOAA-DOD COLLABORATION

NASA initiated what has now become the Landsat program as a research activity. Over the years, the program has assumed an operational character with a diverse set of users reliant on the continuing availability of Landsat imagery and derived data products. However, responsibility for funding, management, development, and operations of the Landsat series has changed hands numerous times, with shifting responsibilities among government agencies and private sector entities (Figure 2.1). Landsat also continued to be beset by enormous pressures from its

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[1] The Space Act of 1958 mandated that NASA direct and control all U.S. space activities except those "peculiar to or primarily associated with the development of weapons systems, military operations, or the defense of the United States" (the DOD was given responsibility for these activities).

[2] NASA, National Space Policy Directives and Executive Charter NSPD-1, November 2, 1989, and White House National Science and Technology Council, National Space Policy Fact Sheet, September 19, 1996, are available at http://history.nasa.gov/printFriendly/spdocs.html.

[3] NASA maintains a Web site that contains full text of its interagency agreements since 1972 at http://science.nasa.gov/about-us/science-strategy/interagency-agreements/partnerships-table/.

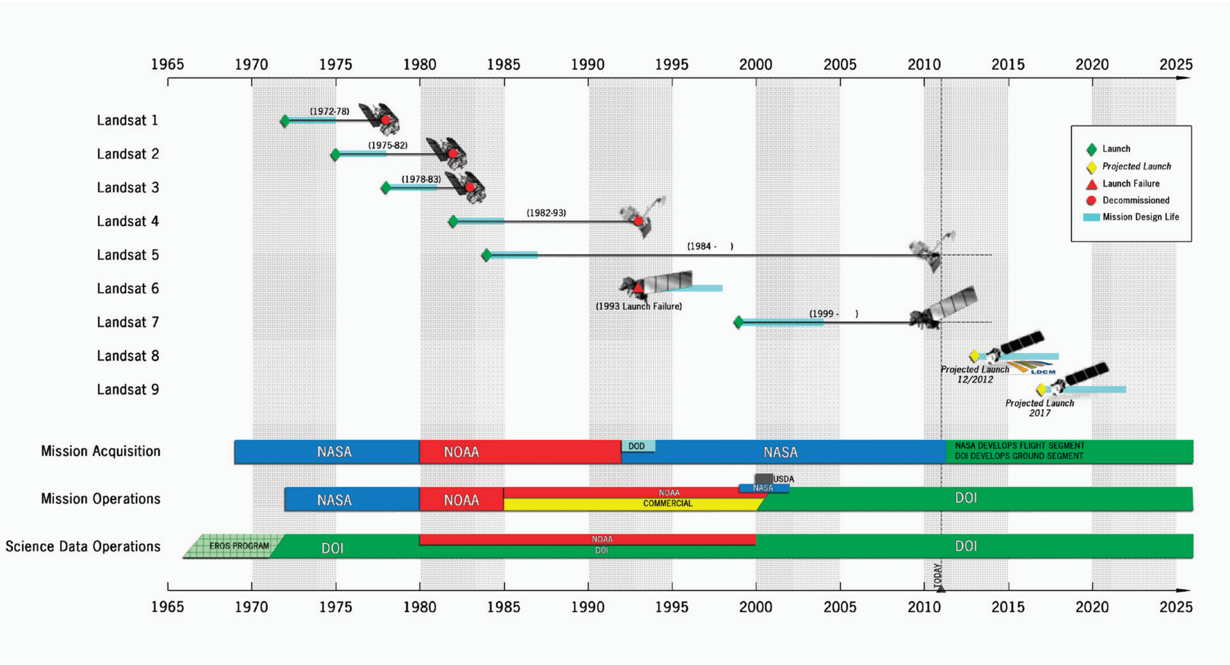

FIGURE 2.1 Landsat timeline and management, 1965-2025. The responsibility for oversight of the Landsat program has shifted from NASA, to NOAA, to NOAA/private industry, to DOD/NASA (overlapping with NOAA/private industry), to NASA/NOAA, to NASA/NOAA/USGS, and to NASA/USGS. SOURCE: Courtesy of the U.S. Geological Survey.

user base which further complicated the establishment and implementation of interagency collaboration. Landsat is an example of how the needs of external stakeholders, when not explicitly acknowledged and accommodated at the outset of a collaboration, can result in impediments to interagency collaboration. A brief history below of the Landsat program highlights the challenges of maintaining the nation's longest continuous space-based data record in the midst of uncertain interagency collaborations.

The Landsat Program

The Landsat series of satellites began with the launch of ERTS-1 (Earth Resources Technology Satellite, later renamed Landsat 1) in 1972 and continues to this day, providing the world's longest continuously acquired collection of space-based land remote sensing data. Data from Landsat are used widely in the United States and worldwide in support of a range of applications in areas including agriculture, forestry and range resources, land use and mapping, geology, hydrology, coastal resources, and environmental monitoring.[4] Imagery that combines moderate spatial resolution with a multispectral capability is suited to diverse applications ranging from modeling of population dynamics of disease vectors in association with habitat features to support for emergency response and disaster relief and predictions. Landsat data also support a variety of national security applications. Despite its demonstrated utility, the Landsat program has been beset since its inception with shifting agency and public/private roles and responsibilities, which in turn have reflected uncertainty in the political, commercial, and scientific sectors about how to develop and manage a new technology and provide civilian Earth-remote-sensing data.

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[4] See, for example, National Research Council, "On Research Uses of LANDSAT: Letter Report," National Academy Press, Washington, D.C, 1991, available at http://books.nap.edu/catalog.php?record_id=12326. Also see National Research Council, *Transforming Remote Sensing Data into Information and Applications*, National Academy Press, Washington, D.C., 2001, available at http://books.nap.edu/catalog.php?record_id=10257. NASA also maintains several Web sites devoted to Landsat; see, e.g., http://landsat.gsfc.nasa.gov/.

Although it was initiated as a research activity, data from the Landsat system soon proved capable of serving a wide variety of government and private sector needs for spatial information about the land surface and coastal areas. NASA designed, built, and operated Landsats 1 through 3. The perceived potential economic value of Landsat imagery led to a plan to transfer control of Landsat operations and data distribution from NASA to the private sector. The first step in the transition gave operational control of the Landsat system to NOAA in 1981 because of NOAA's extensive experience in operating remote sensing satellites for weather observations. Landsat 4 was launched in 1982, and Landsat 5 became operational in 1984. In late 1983, the Reagan administration took steps to speed the transfer of operation of Landsat 4 and 5 to private hands, because it did not want to continue public funding for the system.[5]

Proponents of commercialization expected that industry could soon build a sufficient data market to support a land remote sensing system. This view proved incorrect, and the Landsat program underwent additional management changes in the late-1980s during a failed transition to private industry. A decade of attempts to commercialize Landsat and changes in program management ensued, ending with the Land Remote Sensing Policy Act of 1992, which returned program management to the federal government under joint management of the Department of Defense (specifically the USAF) and NASA and created the legislative mandate for the National Satellite Land Remote Sensing Data Archive, assigning this responsibility to the Department of the Interior. The act effectively ended the government's experiment to privatize the Landsat program.

Management of the Landsat program changed frequently from 1992 through 1998, with responsibility moving from NASA-USAF-USGS to NASA-NOAA-USGS to NASA-USGS. The USGS assumed operational responsibility for the Landsat program in 1999, but NASA continued flight operations for Landsat 7 until 2000, when the USGS implemented a new flight operations contract. In mid-2001, the USGS also assumed responsibility for Landsat 4 and 5 flight operations. This turmoil in agency management of Landsat was also reflected in, indeed caused by, the erratic budgetary support for Landsat in Congress.

Problems with the Landsat program's attempt to collaborate with DOD in the development of Landsat 7 illustrate many of the complications of multiagency partnerships. The end of the experiment begun in the mid-1980s to privatize Landsat has been attributed to the recognition of Landsat's importance to global change research and, most importantly, to U.S. national security. In particular, during the Desert Shield/Desert Storm operations in the early 1990s, the DOD made heavy use of Landsat for mapping and operations.[6] This experience led DOD to pursue a role in the Landsat program; indeed, for a brief period, DOD carried in its budget a significant portion of the funding for Landsat 7 development. However, the agency withdrew from the program at the end of 1993 (i.e., DOD did not request funding for Landsat in its fiscal year (FY) 1995 budget submission to Congress) following a dispute with NASA over funding issues.

In presidential decision directive (PDD)/NSTC-3, dated May 5, 1994, President Clinton issued a new Landsat policy that reorganized agency responsibilities for operating Landsat 7. The policy followed the earlier recommendations of the National Science and Technology Council. In accordance with the PDD, on May 20, 1994, the management responsibility for the satellite development contract was transferred from DOD to NASA.

Landsat-7 was successfully launched in April 1999. However, in May 2003, the Landsat 7 Enhanced Thematic Mapper Plus, ETM+, sensor experienced a partial, but permanent, failure of its scan line corrector (SLC), resulting in a loss of approximately 25 percent of each scene. Although NASA and USGS have developed methods for piecing together scenes from multiple dates to fill the gaps, the resulting product is insufficient for some applica-

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[5] The Land Remote Sensing Commercialization Act of 1984 was intended to provide legislative authority for the transfer process. During deliberations over the Landsat Act, the administration issued a request for proposals for industry to operate Landsat and any follow-on satellite system. Public Law 98-365 was signed on July 17, 1984. After competitive bidding, NOAA transferred control of operations and marketing of data to the Earth Observation Satellite Company, now Space Imaging, in 1985. Space Imaging continued to operate Landsats 4 and 5 until mid-2001, when it returned responsibility to the U.S. government. Throughout these changes, the USGS retained primary responsibility for long-term preservation as the U.S. government archive of Landsat data.

[6] United States Space Command, United States Space Command Operations Desert Shield and Desert Storm, January 1992. Declassified, pp. 39-46. Available at http://www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB39/. See also Three decades of Landsat instruments, *Photogrammetric Engineering and Remote Sensing* 63(7):839-852, July 1997, available at http://www.asprs.org/publications/pers/97journal/july/1997_jul_839-852.pdf; and C.E. Behrens, *Landsat and the Data Continuity Mission,* Report to Congress 7-5700, R40594, Congressional Research Service, Washington, D.C., 2009.

tions.[7] In September of 2003 (3 months after the Landsat 7 ETM+ SLC failure), NASA canceled the request for proposals for the Landsat 7 follow-on mission, called the Landsat Data Continuity Mission (LDCM), leaving the future continuity of Landsat data in question.

In August 2004, the Office of Science and Technology Policy (OSTP) issued a memorandum that directed USGS and NASA to initiate a partnership with the NPOESS Integrated Program Office for the inclusion of an LDCM sensor on NPOESS.[8] However, the NPOESS program continued to suffer from budget overruns and technical problems with several key sensors. On December 23, 2005, OSTP issued a second memo calling for NPOESS to proceed without Landsat and for NASA to build and launch a Landsat follow-on mission to be operated by USGS.[9] As of March 2010, plans called for the launch of LDCM in December 2012.

Landsat is emblematic of the problems that can arise in multiagency programs. In summary:

- The Land Remote Sensing Act of 1992 defines a need but does not assign responsibility or provide funding.[10]
- Despite Landsat's success both for the United States and globally, an acceptable and fully funded management arrangement has never been agreed to.
- The USGS has a basic need for Landsat capabilities; however, the expertise to implement the space component is at NASA.
- Various forms of collaboration have been tried over the years, but the agency with operational responsibility continues to lack resources and technical capability.
- The practice of satisfying one agency's mandate using another agency's budget has resulted in program volatility.

NASA-DOD INTERAGENCY COLLABORATION

Although NASA was created to lead the nation's civil space efforts, NASA's origins also fostered very strong ties to DOD, especially in the area of propulsion. Over the years, the two agencies have collaborated on several scientific missions that also had value to DOD. Most recently, this includes the Advanced Composition Explorer (described earlier in the Chapter 1 section entitled "Use of Resources Example: Space Weather Data from the Advanced Composition Explorer") and the Communication/Navigation Outage Forecasting System (C/NOFS; described below) space weather missions.

Through discussions with individuals involved in NASA-DOD interagency collaborations, the committee found that civil-military interagency relationships differ significantly from civil-civil interagency relationships. In particular:

- Conflicting aspirations are less significant than is often found in civil-civil collaborations,
- Cultural differences and differences in priorities and process are more dramatic in civil-military collaborations, and
- Budget pressures appear to sharpen the conflicts that can appear in civil-military collaborations.

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[7] K. Green, Landsat in context: The land remote sensing business model, *Photogrammetric Engineering and Remote Sensing* 72(10):1147-1153, 2006.

[8] J. Marburger, Landsat Data Continuity Policy, Executive Office of the President, Office of Science and Technology Policy, Washington, D.C., August 13, 2004.

[9] J. Marburger, Landsat Data Continuity Strategy Adjustment, Executive Office of the President, Office of Science and Technology Policy, December 23, 2005.

[10] The full text of the Land Remote Sensing Policy Act of 1992 is available at http://thomas.loc.gov/cgi-bin/query/z?c102:H.R.6133.ENR. Reference to agency roles and responsibilities is made in Section 5631, entitled "Continued Federal Research and Development."

CINDI and C/NOFS

The Coupled Ion-Neutral Dynamics Investigation (CINDI) on the C/NOFS satellite is an example of NASA-DOD coordination. CINDI is a NASA-sponsored mission of opportunity conducted by the University of Texas at Dallas (UTD). The instruments comprised by CINDI are critical parts of C/NOFS undertaken by the Air Force Research Laboratory and the Space and Missile Command Test and Evaluation Directorate. CINDI consists of two instruments on board the satellite, the Ion Velocity Meter and the Neutral Wind Meter, which separately measure the ionized (electrically charged) and neutral particles that exist in the ionosphere. C/NOFS was successfully launched on April 16, 2008, and the CINDI instruments were turned on in early May 2008.

Although CINDI is an example of a multiagency scientific success according to the principal investigator,[11] there was a lack of communication between the agencies (NASA and DOD) after the initial startup agreement. As a result, UTD often had to negotiate requirements, reviews, and specifications with each agency independently, often resulting in the need for separate (often duplicative) design reviews and status reports for each agency. This example illustrates the need for all agencies and third parties to have a clear agreement on project management roles and responsibilities from the outset, supported by clean, well-defined management interfaces and single points of contact to resolve conflicts during implementation. In addition, conflicting mission objectives impacted the mission design, for example by requiring a higher orbit to meet USAF requirements at the expense of a science mission preference for a lower orbit.

NASA-DOE INTERAGENCY COLLABORATION

As detailed below, NASA and the Department of Energy (DOE) have collaborated to pursue research in high-energy astrophysics. Although NASA and DOE also have interests that align in areas related to climate research, advanced computational capabilities, and characterization of the near-Earth space environment, NASA-DOE collaborations in the Earth sciences typically have focused more on specific activities than on space and Earth science missions. For example, a July 9, 1992, NASA-DOE memorandum of understanding (MOU) for energy-related civil space activities covered joint nuclear propulsion activities as well as joint efforts on atmospheric and environmental phenomena, radiation effects on humans, and advanced computing research.[12]

Perhaps the most significant NASA-DOE collaboration in the space and Earth sciences was on the Gamma-ray Large Area Space Telescope (GLAST; renamed Fermi in February 2008) mission. In recent years, there have also been attempts, led by OSTP, to reach agreement on a new collaboration for the Joint Dark Energy Mission (JDEM), which has had a particularly contentious history. Agency officials and mission representatives who briefed the committee noted that, in pursuing these collaborations, NASA and DOE have had to overcome challenges that derived from significant differences in agency practices (cultures), especially with respect to:

- Management styles;
- Differing definitions of "peer review" and "independent review," including different levels of competitiveness associated with each; and
- Approaches to developing instruments and hardware, which reflect DOE's historical experience in developing ground-based accelerators and detectors versus NASA's historical experience in developing space-qualified instruments and hardware.

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[11] As part of this study, the committee interviewed the principal investigator for CINDI, Roderick Heelis, who is also the director of the William B. Hanson Center for Space Sciences at UTD.

[12] "Memorandum of Understanding Between National Aeronautics and Space Administration and U.S. Department of Energy Regarding Energy-Related Civil Space Activities," available at http://nasascience.nasa.gov/about-us/science-strategy/interagency-agreements/partnerships-table/DOE-NASA-MOU-Energy-related-Civil-Space-Activities-920709.pdf.

The Gamma-ray Large Area Space Telescope Mission (Renamed Fermi)

In the 1990s, a group led out of Stanford University and the Stanford Linear Accelerator Center (SLAC)[13] developed a concept for a space instrument to follow up on the discoveries made by NASA's Energetic Gamma Ray Experiment Telescope instrument on the Compton Gamma Ray Observatory. GLAST was selected by NASA as a mission concept study in 1994, endorsed by NASA's Gamma-Ray Astronomy Program Working Group as the highest priority in gamma-ray astronomy in 1996, and chosen in 1997 by NASA's Structure and Evolution of the Universe Subcommittee as the top priority (with Constellation-X). Plans for the GLAST mission collaboration were presented to the DOE-NSF High Energy Physics Advisory Panel[14] (HEPAP) in January 1997. In January 1998, NASA issued an open call for proposals for instrument technology development for a potential GLAST mission; DOE funded its own internal team. At about the same time, in February 1998, a proposal to begin to fund Stanford's Large Area Telescope (LAT) instrument development was submitted to DOE and was reviewed by the DOE-NSF Scientific Assessment Group for Experiments in Non-Accelerator Physics[15] (SAGENAP) in April 1998.

In June 1998, NASA competitively selected two proposals for funding for GLAST instrument technology development, one of which effectively covered the U.S. part of DOE/Stanford/SLAC's proposal. To obtain advice on the mission, NASA and DOE formed the GLAST Council, which had its first meeting in January 1999. In March 1999, NASA issued an announcement of opportunity (AO) for flight investigations for the GLAST mission. Although the call for proposals was open and invited submissions from any qualified party, the significant funding[16] for and sponsorship by DOE of the Stanford/SLAC team's proposal were, the committee was told, viewed by some in the community as making it unlikely that an unsponsored collaboration could compete effectively for the opportunity. In February 2000, NASA selected the Stanford/SLAC proposal for the GLAST flight investigation, as well as the LAT instrument, reinforcing that view.

NASA and DOE negotiations on an implementation agreement for GLAST that would establish the two agencies' roles and responsibilities became a highly contentious process, and the agreement went through approximately 25 draft versions. The final agreement established a collaboration under the 1992 MOU on energy-related civil space activities and assigned NASA overall responsibility for the mission.[17] NASA was not, however, an exclusive stakeholder with authority to unilaterally set the mission requirements. A separate NASA-DOE MOU established the Joint Oversight Group (JOG), co-chaired by NASA's Structure and Evolution of the Universe director and DOE's director of High-Energy Physics, to set jointly accepted requirements for GLAST, oversee LAT management and execution, and coordinate DOE and NASA procedures for the LAT project. The JOG made decisions that otherwise would have been specified in a signed implementation agreement.

The interdependency between NASA and DOE for GLAST mission implementation makes the collaboration on GLAST/Fermi an example of what the committee terms "cooperation" between agencies. Cultural differences between the NASA and DOE communities complicated many aspects of the collaboration. Further, when the LAT team ran into financial trouble,[18] there was no clear prior agreement to implement as to whether DOE or NASA

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[13] On October 15, 2008, the U.S. Department of Energy renamed the Stanford Linear Accelerator Center, calling it the SLAC National Accelerator Laboratory.

[14] HEPAP provides advice to DOE and NSF in the area of high-energy physics. Its members are appointed on a rotating basis by the two agencies.

[15] SAGENAP is commissioned by NSF and DOE to provide advice on high-energy physics proposals submitted to the two agencies.

[16] The proposal was endorsed by the SLAC director, who committed $35 million in DOE funds for the fabrication of LAT.

[17] NASA assigned GLAST mission management and mission systems engineering to the NASA Goddard Space Flight Center (GSFC). GSFC also managed and built the anticoincidence detector. The Mission Operations Center and the GLAST Science Support Center are located at GSFC. SLAC hosts the Instrument Science Operations Center, where the LAT raw data is processed and prepared for scientific data analysis. The data is sent to the GLAST Science Support Center at GSFC, which then distributes it to the scientific community.

[18] The LAT team originally had foreign team members and associated funding from agencies in France, Italy, Japan, and Sweden, each of which endorsed the proposal and was assigned specific mission roles. Early in development, before formal agreements with NASA were concluded, one of the foreign agencies (CNES in France) pulled out, creating a significant financial shortfall that threatened development of the instrument. However, the remainder of the international LAT collaboration remained intact and the Stanford principal investigator and Stanford/SLAC management worked to adjust the instrument fabrication responsibilities to cover the shortfall caused by CNES's action. DOE and NASA shared the associated financial shortfall in the LAT instrument funding. [Editor's note—Following release of the prepublication version of this report, this footnote was expanded to clarify the nature of the financial shortfall and how the parties worked to resolve it.]

would pay for the cost overrun. Each party expected the other to pay. Despite the many interagency tensions, however, NASA and DOE worked to make GLAST/Fermi a major scientific success.[19]

The Joint Dark Energy Mission

Like GLAST/Fermi before it, JDEM has been constructed to be an interdependent interagency cooperation, with neither NASA nor DOE in full control of the mission, its requirements, or its implementation.

The discovery of the accelerated expansion of the universe in 1998 relied on Type 1a supernovae as "standard candles" by which distances could be derived. In 1999 a group centered at the DOE Lawrence Berkeley National Laboratory (LBNL) proposed a space mission called the SuperNova Acceleration Probe (SNAP) to collect more measurements using supernovae. In response to the 2003 NRC report *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*, NASA formed the Beyond Einstein program, which included concepts for two flagship missions and three lower-cost probe-class missions. One of the probe-class missions was the Dark Energy Probe. In 2004, NASA and DOE formed a JDEM science definition team (SDT) to lay out the requirements for a dark energy mission sponsored by DOE and NASA. All of the SDT members had significant interest in the dark energy problem, but there was considerable disagreement as to the best measurement approach. Although supernovae were used to discover the accelerated expansion of the universe attributed to dark energy, new techniques for characterizing the dark energy were becoming prominent. At the same time, the approach using supernovae was encountering systematic measurement errors. The SDT initiated calculations to elucidate the merits of the different approaches.

In 2005, NASA issued an open competitive call for mission concept study proposals. Of the many teams that submitted proposals, three were given grants for further investigations of specific mission concepts. The SNAP team proposed adding a method called weak gravitational lensing to its mission concept. Another team with a concept called DESTINY had previously received a NASA study grant, and the new grant provided an opportunity to continue the team's work. DESTINY used the same two techniques (supernovae and weak gravitational lensing) as SNAP but aimed at a lower-cost mission. Also selected was a newly formed team with a mission concept called ADEPT (Advanced Dark Energy Physics Telescope). ADEPT put primary emphasis on a newly developed technique involving baryon acoustic oscillations.

In February 2005 the NSF-NASA-DOE National Astronomy and Astrophysics Advisory Committee and the NSF-DOE High Energy Physics Advisory Panel established the Dark Energy Task Force as a joint subcommittee to advise NSF, NASA, and DOE on the future of dark energy research from the ground and from space. That subcommittee recommended funding of SNAP. However, all related missions were delayed in the president's FY 2005 budget request.

In May 2006, ongoing congressional support for a dark energy mission was expressed in H.R. 5427.[20] In the end, this bill never became law, but it helped to advance the steps that were eventually taken to resolve significant interagency controversies that were playing out in the legislative and executive branches of government. In August 2006 the OSTP director, together with the NASA administrator and the DOE science undersecretary, requested that the NRC Space Studies Board and Board on Physics and Astronomy convene a panel to recommend which of the Beyond Einstein missions should fly first. Additional prioritizations would await the subsequent 2010 NRC decadal survey, which would prioritize the remaining Beyond Einstein missions, along with the entire Astrophysics Division mission suite.

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[19] For example, *Science* magazine named GLAST the runner-up for the 2009 "Breakthrough of the Year" for its role in opening up gamma-ray astronomy.

[20] Both the House and the Senate appropriations committees voiced strong support for JDEM but recognized that the multiagency aspect of the mission was insurmountably flawed. In H.R. 5427 DOE was directed to continue investigating the launching of the SNAP mission on its own, and the Senate (in S. Rpt. 110-127) provided "$7 million above the combined requests for JDEM, SNAP, and other dark energy programs" to encourage the research program competition and to ramp up activities toward a launch in 2014. The JDEM mission had become an item of contention between agencies and their respective congressional committees. Funding reductions for NASA in the FY 2007 presidential budget placed LISA and Con-X, the flagship missions of the Beyond Einstein program, on a low level of technology development with a funding wedge opening for only one new Beyond Einstein start in 2009. See H.R. 5427/H. Rpt. 109-474.

The NRC Beyond Einstein Program Assessment Committee (BEPAC) met in November 2006 to consider 11 mission candidates in five mission areas. The BEPAC final report was issued in 2007.[21] Although BEPAC favored the science of the LISA (Laser Interferometer Space Antenna) mission,[22] in the end it recommended JDEM as the first start, based on science and technological readiness. BEPAC had also indicated (in Table 3.32 of its report) that the cost of SNAP and other missions had been significantly underestimated and their technological readiness overestimated. Because Congress had repeatedly emphasized the need for a full and open competition,[23] it had been anticipated that the three teams with approved mission concept study grants from NASA (DESTINY, ADEPT, and SNAP) would compete in response to an AO for JDEM. However, in September 2008 DOE and NASA announced that they would establish a JDEM science coordination group to set mission requirements so that NASA and DOE could build the mission with no hardware solicited from outside the government and, thus, without the standard competitive NASA AO process.

In October 2009, DOE and NASA announced an intention to form a JDEM interim science working group (ISWG) to provide the JDEM project offices at NASA and DOE with scientific assistance during pre-Phase A (mission formulation) activities. As is the case for members of the JDEM SDT, JDEM Figure of Merit Science Working Group, and JDEM Science Coordination Group, NASA generally provides no financial support for ISWG members, ensuring that funds appropriated for JDEM stay within the agencies, while the critical but uncompensated expertise is provided by the university community.

Two mission concepts—JDEM/Omega and an international version called IDECS—were submitted as mission candidates for consideration in the astronomy and astrophysics (Astro2010) decadal survey. The NRC Astro2010 report[24] recommended mission priorities for the upcoming decade, and its highest-priority large-scale space mission was a dark energy mission—the Wide-Field Infrared Survey Telescope (WFIRST), which uses the JDEM/Omega hardware design approach but has a broader science focus. The survey report noted that the European Space Agency's (ESA's) candidate mission called Euclid, which would have many of the same scientific goals as WFIRST, was in its definition phase and competing with two other European mission candidates for selection for a launch opportunity in 2017-2018. The survey report acknowledged that there had been NASA-ESA discussions about collaborating on a possible joint mission, and the report indicated that international collaboration would be attractive if "it leads to timely execution of a program that fully supports all of the key science goals of WFIRST… and leads to savings overall," and also meets expectations "that the United States will play a leading role."[25]

Although JDEM resembles GLAST/Fermi in the sense that it has been constructed as an interdependent interagency cooperation with neither agency in full control of the mission, its requirements, or its implementation, there are important differences. Unlike GLAST/Fermi, the JDEM mission was not founded as a bottom-up NASA-DOE scientific collaboration. Further, in contrast to its comparatively limited experience in the development of the high-energy detectors required for GLAST/Fermi, NASA has considerable experience (as do some university laboratories) relevant to the development of the JDEM spaceborne infrared detectors, some of that experience having been acquired in work on the detectors for the James Webb Space Telescope.[26]

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[21] National Research Council, *NASA's Beyond Einstein Program: An Architecture for Implementation*, The National Academies Press, Washington, D.C., 2007.

[22] LISA is a joint NASA-ESA mission to observe astrophysical and cosmological sources of gravitational waves of low frequencies. See http://lisa.nasa.gov/.

[23] Following the release of the BEPAC report, U.S. Senate Report 110-124 stated, "Joint Dark Energy Mission—The National Academy of Sciences has recommended that NASA and the Department of Energy work together to develop a Joint Dark Energy Mission [JDEM]. The Committee provides the budget request of $2,300,000 for JDEM, and strongly supports development of the JDEM through full and open competition with project management residing at the appropriate NASA center." The Senate Appropriations Committee text for the FY 2009 Appropriations Bill for the Commerce, Justice, Science, and Related Agencies stated, "The Committee also provides the full budget request of $8,500,000 for the Joint Dark Energy Mission [JDEM] and continues to support development of the JDEM through full and open competition with project management residing at the appropriate NASA center."

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

[25] National Research Council, *New Worlds, New Horizons in Astronomy and Astrophysics*, 2010, p. 208.

[26] Editor's note: Following release of the prepublication version of this report, this paragraph was revised somewhat to emphasize NASA's capability for building a JDEM detector.

The 2008 DOE-NASA decision to build JDEM without a competition open to non-government institutions raises an important issue that was not explored in depth in this study. Namely, what is the extent to which interagency missions might lead to more missions executed at NASA centers versus development of missions with significant university involvement? The JDEM experience would suggest that when agencies split project roles, university roles are diminished, with a concomitant loss of intellectual capital, innovation, and opportunity to benefit from the project as a training ground for future scientific and technical workforce.

NASA-NOAA INTERAGENCY COLLABORATION[27]

NASA's history of collaboration with NOAA dates to the start of the space age. For example, NASA developed the first TIROS polar-orbiting satellite in 1960 and the precursor to NOAA's current Polar Operational Environmental Satellite system, and in 1974 it launched SMS-GOES (Synchronous Meteorological Satellites-Geostationary Operational Environmental Satellite), the precursor to NOAA's current GOES system (the latter collaboration is described more fully in a Chapter 1). Generally, NOAA has relied on NASA to fund and develop new sensors, several of which NOAA has subsequently adopted for its environmental satellites. A 1973 agreement between NASA and NOAA resulted in the Operational Satellite Improvement Program (OSIP) within NASA, which provided funding at the rate of some $15 million per year to support development of new sensors and other technologies to improve NOAA's operational satellites. Partnerships under OSIP subsequently contributed to the development of sensors, including the Advanced Very High Resolution Radiometer and the Total Ozone Mapping Spectrometer. In the context of the present report, what is particularly noteworthy about the OSIP model is that each agency operated within roles consistent with their cultures and neither was reliant on the other for funding.

Research to Operations

NASA and NOAA are charged to fulfill distinct but complementary missions related to space-based observations relevant to Earth science. NASA is a mission-based agency whose program is strongly focused on research, development, and launching of space-based instruments; NOAA is an operational and regulatory agency that draws on the results of research and that serves external user communities and internal entities such as the National Weather Service. An important theme of NASA-NOAA collaboration is the transfer of research to operations. NASA and NOAA have collaborated in the development of operational spacecraft from the early years of the space program, perhaps best exemplified by NASA's Nimbus series of satellites that began in 1964 with testing instruments for later transfer to NOAA.[28] However, with respect to the development of operational spacecraft for weather-related observations, this model, while successful, proved short-lived.

Although NASA remained the procurement agency for NOAA spacecraft, budget constraints resulted in the termination of its OSIP partnership with NOAA in 1981. The elimination of OSIP impacted NOAA's ability to access the requisite engineering support and expertise to design, develop, and test new spacecraft and instrument technologies before incorporating them into the agency's operational satellite systems. Indeed, termination of OSIP is cited in a 1997 Government Accountability Office (GAO) report[29] as an important contributing factor in the technical problems, cost overruns, and schedule delays that beset NOAA as it developed GOES-Next, the second generation of operational geostationary satellites in the 1980s. The GAO report further suggests that many

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[27] Material in this section is adapted from U.S. Congress, Office of Technology Assessment, *The Future of Remote Sensing from Space: Civilian Satellite Systems and Applications,* OTA-ISC-558, U.S. Government Printing Office, Washington, D.C., 1993.

[28] See, for example, G. Davis, History of the NOAA satellite program, *Journal of Applied Remote Sensing* 1:012504, 2007, available at http://www.osd.noaa.gov/download/JRS012504-GD.pdf; *and NASA, Nimbus Program History, NASA Goddard Space Flight Center, Greenbelt, Md., 2004, available at* http://atmospheres.gsfc.nasa.gov/ uploads/files/Nimbus_History.pdf.

[29] Government Accountability Office, *Weather Satellites: Planning for the Geostationary Satellite Program Needs More Attention,* GAO/AIMD-97-37, Washington, D.C., March 1997, available at http://goes.gsfc.nasa.gov/text/gao97.goes.pdf, p. 41.

of the technical problems that plagued GOES-Next development could have been addressed and resolved more efficiently and less expensively within the context of a smaller, experimental precursor program, such as OSIP.[30]

Today, NOAA uses many NASA research data and model products in carrying out its operational responsibilities. NASA's practice of providing many of those products online and in near real time further enhances their operational value to NOAA and other operational agencies. Yet the issue of the technology transfer from research to operations is still a thorny one that bears heavily on interagency collaboration. For example, when a NASA-funded research satellite that has provided valuable data for operational applications reaches its end of life, NASA has no research requirement (and consequently no funding) to continue collecting the same type of data, even though a need for this valuable data still exists (as seen, for example, in the fire detection data products produced by MODIS, the harmful algal bloom detection by MODIS and SeaWiFS, and the precipitation data from the Tropical Rainfall Measuring Mission, TRMM). The same is true when NASA develops a new data set that can improve a current operational product (e.g., QuikSCAT ocean vector winds to improve severe storm/hurricane forecasts or AIRS atmospheric temperature and water vapor profiles to significantly improve weather forecasts).

Problems in executing the transition to operations, in extending the lifetime of Earth-observing missions,[31] and in sustaining measurements over long time periods in support of climate research (see Appendix B) are all examples of a misalignment between NASA and NOAA roles and responsibilities and their budgets. This issue was discussed at length in a 2003 NRC report on the transition of research to operations;[32] it also is informed by the analysis and key recommendation that were offered in the 2007 decadal survey, *Earth Science and Applications from Space*.[33] In that report, it is stated that:

> The [survey] committee is concerned that the nation's institutions involved in civil Earth science and applications from space (including NASA, NOAA, and USGS) are not adequately prepared to meet society's rapidly evolving Earth information needs. Those institutions have responsibilities that are in many cases mismatched with their authorities and resources: institutional mandates are inconsistent with agency charters, budgets are not well matched to emerging needs, and shared responsibilities are supported inconsistently by mechanisms for cooperation. These are issues whose solutions will require action at high levels of the federal government. Thus, the committee makes the following recommendation:
>
> Recommendation: The Office of Science and Technology Policy, in collaboration with the relevant agencies and in consultation with the scientific community, should develop and implement a plan for achieving and sustaining global Earth observations. This plan should recognize the complexity of differing agency roles, responsibilities, and capabilities as well as the lessons from implementation of the Landsat, EOS [Earth Observing System], and NPOESS programs.

The present committee finds it particularly noteworthy that several NASA-NOAA collaborations have succeeded when they focused on specific goals with very clear roles for each agency (e.g., GOES and Ocean Surface Topography Mission (OSTM)/Jason-2). These agreements generally grow from the bottom upward; they are not top-down mandates and thus inherently have buy-in at the working level. In general, however, lack of effective collaboration between these agencies and lack of resources (time, personnel, funding, infrastructure, expertise,

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[30] However, the GAO report also noted that even without OSIP, NASA had several avenues within its existing programmatic structure for undertaking research and demonstration projects related to advanced weather satellites.

[31] See National Research Council, *Extending the Effective Lifetimes of Earth Observing Research Missions*, The National Academies Press, Washington, D.C., 2005, available at http://www.nap.edu/catalog.php?record_id=11485. It is noteworthy that some of the recommendations in that report have been adopted by NASA. In particular, during the latest NASA Senior Review for Continuation of Earth Science Missions, one of the criteria was how science data were used by operational agencies—evidence that despite differences in culture and interest, NASA is well aware of the immediate societal benefits of its research data products.

[32] National Research Council, *Satellite Observations of the Earth's Environment: Accelerating the Transitions of Research to Operations*, The National Academies Press, Washington, D.C., 2003, available at http://www.nap.edu/catalog.php?record_id=10658.

[33] National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, The National Academies Press, Washington, D.C., 2007, available at http://www.nap.edu/catalog.php?record_id=11820, p. 66.

and so on) to incorporate the new data sets into their operations affect the agencies' capability to execute efficient transition to operations.

Finally, the committee notes that problems in executing the transition to operations are not confined to Earth science missions. The importance of ensuring critical measurements of the solar wind upstream from Earth is noted in Chapter 1 (see the section entitled "Use of Resources Example: Space Weather Data from the Advanced Composition Explorer"). A similar problem in the development of operational capabilities for space weather prediction is evident in the failure to develop an operational coronagraph, which is required to provide advanced warning of the effects of a coronal mass ejection (a powerful eruption of the Sun's atmosphere).

MULTIAGENCY COLLABORATION

The history of the U.S. Global Change Research Program (USGCRP) is instructive for interagency collaboration because it shows how a partnership between OSTP and the Office of Management and Budget (OMB) can facilitate interagency collaboration. The lessons learned—both opportunities and challenges—from this facilitation can be usefully applied to interagency collaboration on space missions, and therefore the committee has included a short summary of USGCRP here.

Begun as a presidential initiative in 1989 to integrate the research programs from 11 agencies through the Federal Coordinating Council for Science, Education, and Technology, USGCRP supports research on the interactions of natural and human-induced changes in the global environment and their implications for society. Congress codified the program in the Global Change Research Act of 1990 (P.L. 101-606),[34] which mandates development of a coordinated interagency research program.

The success of USGCRP in its early years is attributed to the creative use of a budget cross-cut process and the active leadership of and effective participation by OSTP and OMB. The budget cross-cut was described in a 1993 report from the congressional Office of Technology Assessment as follows:[35]

> Internal budget negotiations culminate with the presentation of a single budget for global change research that spells out individual agency responsibilities in detail. By evaluating agency proposals as part of an integrated program, CEES [the OSTP Committee on Earth and Environmental Sciences] and OMB attempt to avoid duplication of effort and make optimal use of agency expertise. An agreement that had been in effect between OMB and agencies during the first 3 years of the USGCRP required agencies to fence off monies for global change research in return for an OMB commitment to an overall funding envelope over 5 years. In effect, agency heads agreed to their global change research budgets once the process of negotiation with OMB and CEES was complete. Thus, an agency could not reprogram global change funds if it later suffered an unexpected cut in its overall budget.

The prohibition on reprogramming global change funds ended in FY 1993 with detrimental effects on the program, according to participants interviewed by this committee. In particular, one lesson learned from the implementation of the USGCRP is that the senior interagency project leadership budget must be sufficient to influence the direction of the various agency contributions. In a letter to the committee, Jack Fellows, chief of the Science and Space Program Branch of OMB from 1984 to 1997, suggested that senior leadership should control a central pool of funds totaling roughly 10 to 15 percent of the overall interagency budget to effectively influence the direction of individual agency investments. Other factors cited by Fellows for successful interagency projects include ensuring that OMB and its budget examiners are assigned responsibility for, and are active partners in, the effort; having clear objectives and small and achievable priorities; managing in a way that is perceived as transparent and fair; and, of critical importance, providing incentives to the agencies for their participation.

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[34] See http://www.gcrio.org/gcact1990.html. The Climate Change Science Program, which was established in 2002, incorporated the USGRCP with the U.S. Climate Change Research Initiative of President George W. Bush. See *Our Changing Planet: The U.S. Climate Change Science Program for Fiscal Year 2009,* a Report by the Climate Change Science Program and the Subcommittee on Global Change Research, a Supplement to the President's Fiscal Year 2009 Budget, available at http://www.usgcrp.gov/usgcrp/Library/ ocp2009.

[35] U.S. Congress, Office of Technology Assessment, *Global Change Research and NASA's Earth Observing System,* OTA-BP-ISC-122, U.S. Government Printing Office, Washington, D.C., November 1993. A scanned version of this report is available at http://www.fas.org/ota/reports/9324.pdf.

INTERNATIONAL COLLABORATIONS: NASA'S APPROACH TO INTERNATIONAL COLLABORATION AS A "BEST PRACTICE"

The historical record from international collaborations in Earth and space science missions also offers insight into the challenges of multiagency U.S. missions. International collaboration on instrument development, satellite operations, data exchange, and data analysis can spread the cost burden internationally, mitigate risks of gaps in the delivery of data sets or the generation of particular data products, encourage technical innovation by broadening the engineering expertise base, and increase the number of science users. NASA and its international partners have enjoyed such benefits through numerous programs. There are many parallels between working with foreign partners and working with partners from other U.S. agencies. Given the success of international collaboration in the space arena since the earliest days of the space program, it is instructive to look at international activity as a "best practice."

The potential advantages of international collaborations are numerous, but realizing these advantages can be complicated by a number of factors. Instruments built by one partner may not be designed to the exact requirements of another partner, and technology-transfer restrictions may prevent the exchange of technical details about the instruments which are needed to facilitate mission development. Restrictions on access to data and software vary from country to country, as do approaches to calibration and validation. Issues with data cost, availability, and distribution can ensue when one or more collaborating space agencies has commercial partners.

Over the years, the vast majority of U.S. space programs in space and Earth science have been undertaken with other countries. This is not because international collaboration is an end in itself, although it can support U.S. foreign policy objectives, but rather because of the potential benefits that result from having partners, which include economic leverage on U.S. investments, enhanced scientific productivity, and access to foreign technology.[36]

Each negotiated agreement between participants is different depending on the specifics of the project, what each brings to the table, and what each needs to gain from the cooperation. A lopsided agreement bringing great benefit to one side and taking advantage of another is not only hard to negotiate, but also hard to implement and inadvisable if future cooperation is desired. Thus, as a bottom line, *mutual* benefit has been viewed as a mandatory requirement—all participants must feel that their benefits outweigh their costs and risks.

Many advantages can flow from international collaboration. Collaboration may permit a program to be more affordable to a participating nation, even though the overall program may turn out to be more expensive than if conducted by one nation alone. In addition, engaging with partners often creates a critical mass that enables a program by leveraging each government's investment off that of others. Collaborating also expands the scope of a program beyond individual participants' capabilities by tapping into an extended base of scientific and technical expertise and industrial capability. Additional benefits to international collaboration include the elimination of gaps and overlaps via coordination of individual efforts (e.g., the Global Earth Observation System of Systems, GEOSS[37]) and also the enhancement of operational robustness and redundancy (e.g., launchers, launch facilities, and ground networks). International collaboration has been known to generate political support for an initiative and to provide greater stability, and it is especially effective in insulating programs from drastic budgetary and political changes (as seen, for example, in development of the International Space Station). International collaboration has also been used to reap foreign policy benefits.[38]

International collaboration brings complications to programs as well. Communications problems can arise, ranging from the obvious—such as budget cycle and time zone differences—to the more subtle, such as cultural differences in management styles, decision-making approaches, and design practices and documentation. Collaboration is further complicated because each nation will have established unique management structures between its

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[36] See National Research Council, *Approaches to Future Space Cooperation and Competition in a Globalizing World: Summary of a Workshop*, The National Academies Press, Washington, D.C., 2009, available at http://www.nap.edu/catalog.php?record_id=12694.

[37] For a detailed up-to-date discussion of accomplishments from GEOSS, see I. McCallum, S. Fritz, N. Khabarov, S. Fuss, J. Szolgayova, F. Rydzak, P. Havlik, F. Kraxner, M. Obersteiner, K. Aoki, C. Schill, et al., Identifying and quantifying the benefits of GEOSS, posted on July 12, 2010, to *Earthzine,* available at http://www.earthzine.org/2010/07/12/identifying-and-quantifying-the-benefits-of-geoss/.

[38] Indeed, the title of an opinion piece published on June 26, 1993, in the *New York Times* by Michael Nacht, a scholar at the University of Maryland, and Roald Sagdeev, an émigré from the former Soviet Union and former science adviser to then Soviet leader Mikhail Gorbachev, was titled, "Space Policy Is Foreign Policy."

space agencies and industrial contractors. Technical and programmatic risks are greater as more interdependencies are created, and failures and delays on one partner's part can greatly impact other partners' costs and schedules. Furthermore, international programs can be held hostage to domestic politics, especially during administration or regime changes.

Beginning with the first collaborative efforts with the United Kingdom in 1962, U.S. international civil space collaboration has followed a few stable principles:[39]

- Designation by each participating government of a central agency for the negotiation and supervision of joint efforts,
- Each country's acceptance of financial responsibility for its own contributions to joint projects,
- Agreements on specific projects rather than generalized programs,
- Projects of mutual scientific interest, and
- General publication of scientific results.

The second item above, which requires that there be no exchange of funds, is an especially important constraint in that it decouples U.S. and foreign budgetary processes and focuses on the delivery of hardware, services, or other capabilities needed by the mission. Similarly, technical and managerial expertise is not exchanged. Foreign contributions, insofar as possible, take the form of discrete hardware packages that lend themselves to clean interfaces, thus facilitating management and minimizing technology transfer.

These rules were originally followed quite strictly by NASA, and over the years they have lent stability to the cooperative projects themselves and generated general enthusiasm for international collaboration in the agency. The rules are less rigidly adhered to today but still form the basis for assessing international activities.[40]

Recent and notable examples of joint ventures in Earth sciences include EOS, a series of space-based precision altimetry missions (TOPEX/Poseidon, 1992; Jason-1, 2001; and Jason-2, 2008), RADARSAT-1, and TRMM.[41] Moreover, it is now relatively common for space agencies to offer announcements of opportunity to the international science community as the agencies attempt to maximize the payoff of each flight project.

Lessons learned from international collaborative projects are applicable to national interagency collaborative efforts, particularly with regard to the degree of upfront planning involved to define clear roles, responsibilities, and interfaces consistent with each entity's strategic plans and with a sense of mutual benefit being a prerequisite. Proposals for interagency collaboration within the United States should receive similar serious attention as part of each agency's strategic decision-making process *prior* to proceeding with technical commitments and procurements.

THE IMPACT OF COLLABORATION ON MISSION COST, COMPLEXITY, AND SCHEDULE

A significant data set exists for the examination of relationships between space system cost and schedule and the implications of various collaboration approaches. To examine the relationship among multiagency and foreign collaborations, cost and schedule data were assembled for numerous (>100) missions launched over the past two decades (1989 to 2009) using a database developed by the Aerospace Corporation of technical specifications, costs, development time, and cost/schedule growth during development.[42] These data include NASA planetary, near-Earth, and Earth-orbiting spacecraft, as well as other U.S. government satellite systems.

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[39] Division of International Affairs, NASA, *26 Years of NASA International Programs*, NASA, Washington, D.C., January 1, 1984, p. 2.

[40] The agreement covering the Russian participation in the International Space Station is an exception to the no-exchange-of-funds rule that has created its own problems as a result.

[41] See http://eospso.gsfc.nasa.gov/ for information about EOS; references to the other missions mentioned above can be found via links at the NASA Web site, http://www.nasa.gov/missions/index.html.

[42] Although much of the information in the database is based on publicly available information, cost and other sensitive data are made available by industry to Aerospace, a federally funded research and development center, with the understanding that they are to be considered proprietary. In its publications and in the present report, the Aerospace data are used only to derive information depicted in a generalized manner. See D. Bearden, Small-satellite costs, in *Crosslink: The Aerospace Magazine of Advances in Aerospace Technology,* Volume 2, Number 1 (Winter 2000/2001), available at http://www.aero.org/publications/crosslink/winter2001/04.html.

In addition to single U.S. agency missions, two classes of collaborations were considered: (1) collaborations between multiple U.S. agencies and (2) collaborations with foreign participants. U.S. multiagency partnerships include cases where multiple agencies sponsored development of the system and systems with multiple-agency operators. Only cases with significant payloads that drove system design or operational requirements were included. Cases where multiple agencies were users of the system but did not interact significantly during development or jointly levy design or operational requirements were not categorized as U.S. multiagency. Collaborations with foreign participants included missions whose participants contributed specific systems such as one or more payload instruments, a spacecraft bus, or one or more significant subsystems (e.g., solar panels, propulsion, avionics). Cases where a foreign participant contributed only a ground station for downlink of data, spacecraft components (e.g., star tracker, momentum wheel, etc.), or launch vehicle/services were not included as foreign collaborations.

Figures 2.2 and 2.3 show the average cost growth and schedule growth for U.S. multiagency, foreign, and single-agency developed space systems. Cost and schedule growth is most pronounced for foreign collaborations; however, U.S. multiagency developments experienced significantly larger cost and schedule growth compared with those developed by a single agency (i.e., "No Collaboration"). Note that while cost and schedule growth is larger for multiagency developments, the system may still be considered more affordable due to cost sharing among the partners. Similarly, although international collaborations may experience the highest-percentage cost growth, cost sharing may still make the system more affordable to the United States.

To understand how technical complexity relates to budget and schedule, a complexity index may be derived based on performance, mass, power, and technology choices to arrive at a broad representation of the system for the purposes of comparison (Figure 2.4).[43]

The complexity index uses a matrix of technical factors (on the order of 30 to 40) to place, in rank order, the complexity of a particular spacecraft relative to all the other spacecraft in the data set. Complexity drivers are demonstrable objective technical parameters (e.g., number of instruments, mass, power, performance, subsystem characteristics, pointing accuracy, downlink data rate, technology choices, etc.). The strength of using a number of parameters is that peculiarities associated with any given implementation are averaged out. These descriptive parameters are normalized based on the applicable range as designated by the programs in the database; i.e., they are given as percentile values for the data set.[44,45]

The total flight system development cost (payload instruments and spacecraft bus, excluding launch and operations) is the independent variable against which the complexity is compared. Missions were grouped according to level of foreign participation and U.S. multiagency involvement. Figure 2.4 shows complexity versus cost for the data set, with collaboration approach noted. Several of the case studies shown in Appendix C and discussed in this report are represented in Figure 2.4. A positive correlation between complexity and cost based on actual program experience is apparent. Foreign collaborations and multiagency missions are generally more complex and costly. This trend is underscored in Figure 2.5, which shows the average complexity for U.S. multiagency, foreign, and single-agency developed space systems.

A recent NRC study on controlling the costs of Earth and space science missions[46] indicated that the most commonly identified factors that contribute to mission cost and schedule growth are (1) overly optimistic and unrealistic initial cost estimates, (2) project instability and funding issues, (3) problems with development of instruments and other spacecraft technology, and (4) launch service issues. Collaborative missions can be vulnerable to all four factors, and especially factors 1 and 2. Mission complexity also can be particularly important for factors 1 and 3.

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[43] D.A. Bearden, A complexity-based risk assessment of low-cost planetary missions: When is a mission too fast and too cheap?, presented to the Fourth IAA International Conference on Low-Cost Planetary Missions, JHU/APL, Laurel, Md., May 2-5, 2000.

[44] D.A. Bearden, Perspectives on NASA robotic mission success with a cost and schedule-constrained environment, presented at the Aerospace Risk Symposium, Manhattan Beach, Calif., August 2005.

[45] Only robotic spacecraft missions that meet certain criteria and constraints were considered (i.e., shuttle science experiments and university-developed spacecraft were not considered). Large (e.g., Flagship/Great Observatory-class), medium (e.g., New Frontiers-class) and small missions (e.g., Discovery-class or smaller) were included. Landed systems (e.g., Mars landers) are included with the caveat that when a larger data set becomes available, the technical drivers used to assess these missions may differ from those used for orbiting systems. Missions yet to complete a portion of their development are included; however, it is noted that final cost is yet to be determined.

[46] National Research Council, *Controlling Cost Growth of NASA Earth and Space Science Missions,* The National Academies Press, Washington, D.C., 2010, available at http://www.nap.edu/catalog.php?record_id=12946.

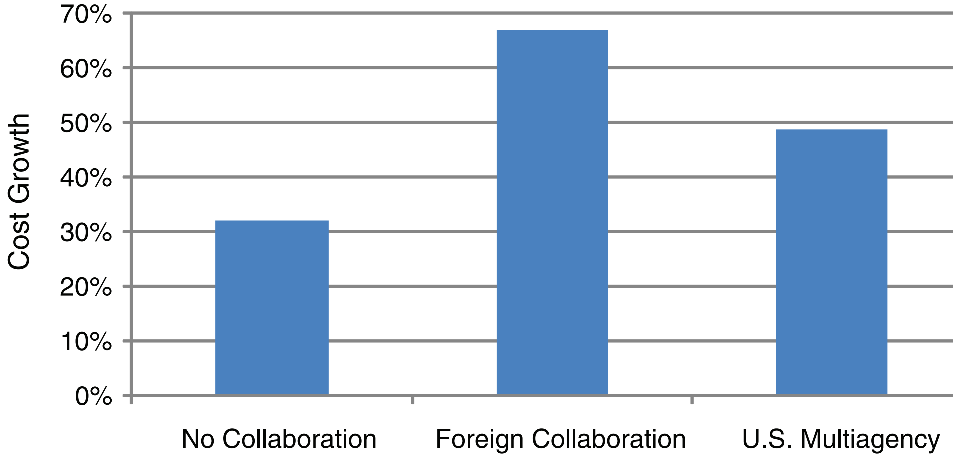

FIGURE 2.2 Cost growth during development (phases B through D) for U.S. multiagency developments and foreign collaborations compared with U.S. single-agency developments (no collaboration).

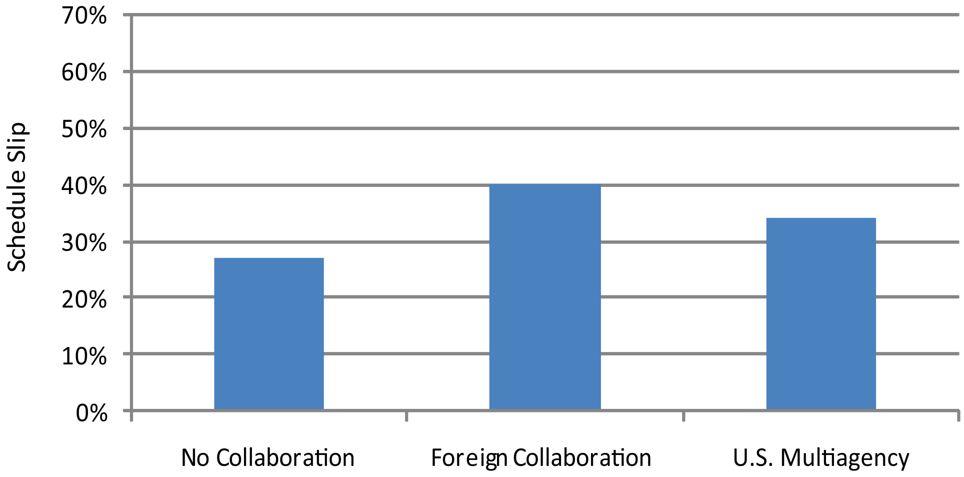

FIGURE 2.3 Schedule growth (delay) during development (phases B through D) for U.S. multiagency developments and foreign collaborations compared with U.S. single-agency developments (no collaboration).

In summary, engaging in collaboration carries significant cost and schedule risks that need to be actively mitigated. Agencies are especially likely to seek collaborators for complex missions so that expected costs can be shared. However, as the committee observed from historical experience and interviews, inefficiencies arise when collaborating agencies' goals, authorities, and responsibilities are not aligned. Thus, collaborations require higher levels of coordination, additional management layers, and greater attention to mechanisms for conflict resolution—as is discussed in Chapter 3.

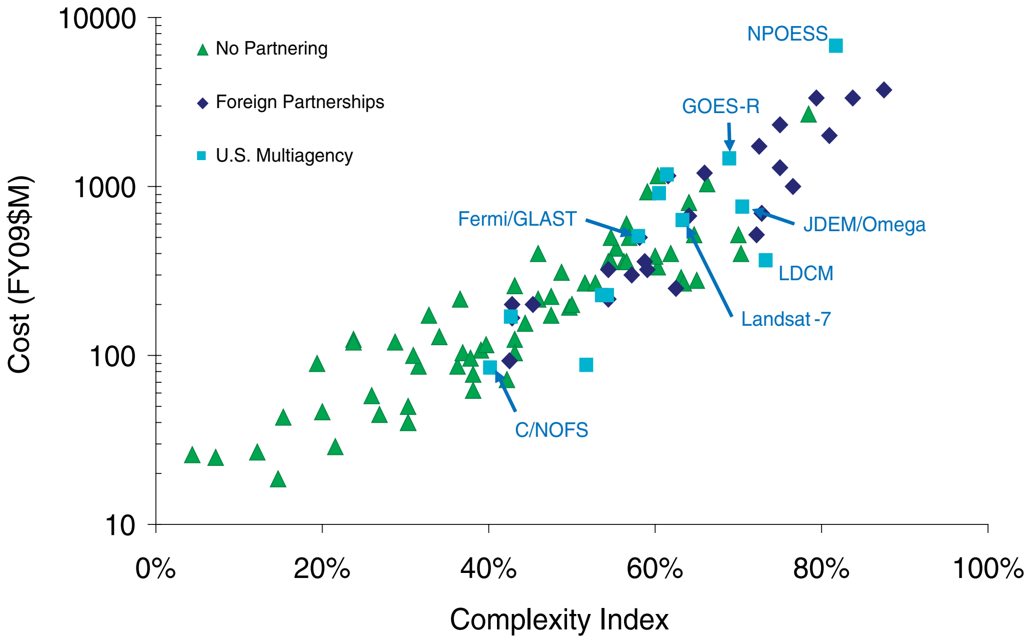

FIGURE 2.4 Complexity of U.S. multiagency developments, foreign collaborations, and U.S. single-agency developments (no collaboration) versus development cost (phases B through D).

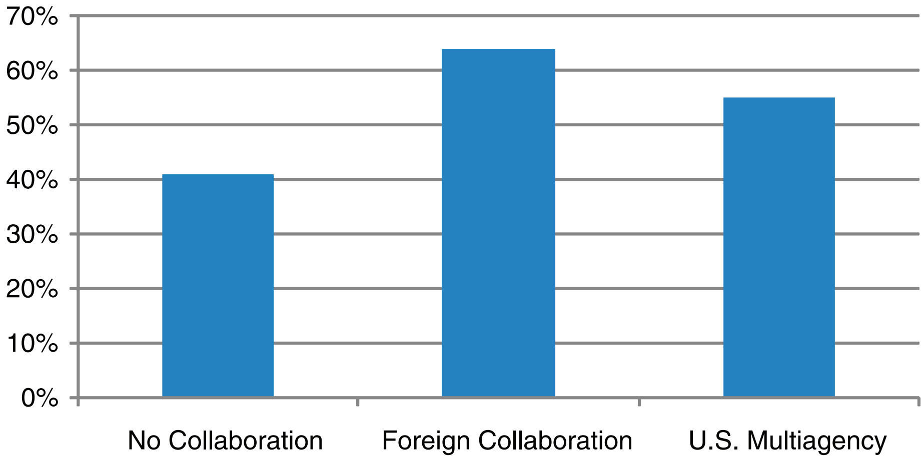

FIGURE 2.5 Complexity of U.S. multiagency developments and foreign collaborations compared with U.S. single-agency developments (no collaboration).

3

Lessons Learned and Best Practices

As discussed in prior chapters, interagency or multiagency collaboration may occur under a variety of arrangements and govern a wide range of engineering, technology, and acquisition elements in mission development and subsequent operations. Recall that, for the purposes of this report, the term "interagency" refers to multiple agencies of the U.S. federal government and the term "collaboration" is an overarching term that refers to more than one agency working together.

REASONS FOR INTERAGENCY COOPERATION

The most interdependent and highest-risk form of collaboration, interagency cooperation, occurs when multiple agencies are on the critical path to mission success. Such cooperation can result when multiple agencies are involved in funding or providing mission-critical hardware. Whether interdependence is stated explicitly or not, and whether it is intended or not, interagency cooperation exists in any space mission when the loss of the contribution from any agency would cause the mission to fail or would require drastic changes in mission scope or structure. The failure can be technical, cost-, schedule-, or risk-related and might occur during any phase of the project, from initial development through mission operations.

Although interagency cooperation is the riskiest form of collaboration, there are reasons that it might be considered for a particular mission. For example, cooperation might be considered when scientific opportunities organically emerge, when technical capabilities exist in one agency that address a mission need in another, or when a new mission need emerges that cuts across existing agency responsibilities. However, the committee found that cooperation is ill-advised if it is motivated by factors not directly related to mission performance. These include, for example, an imposed merger of technical requirements for political reasons, external hopes for cost savings, the addition of unfunded mandates, or directed interagency collaboration for the sake of collaboration. Interagency cooperation on a particular space mission can be encouraged or even mandated to address budgetary, political, or industrial base objectives that are in tension with the ostensible technical objectives of the mission. Advocates of cooperation can underestimate the difficulties and associated transaction costs while assuming no increase in risk to performance.

If external political pressure for more interagency cooperation continues without appropriate attention to mitigating the inevitable associated risks with such agency interdependence, it should be expected that costs to the nation would rise as well as would the chances for mission failure. *Although cooperation should be encouraged when good reasons support it, interagency cooperation should be treated as an exception rather than a norm.*

Agencies considering collaboration should engage in a formal decision process to assess whether the coordination of multiple agency activities is preferable to formal cooperation and at what level collaboration should occur (e.g., mission, spacecraft, subsystem, component, data standard), if at all. Such strategic decisions should be made by the agencies prior to consideration of the more tactical aspects of a proposed collaboration.

IMPEDIMENTS TO INTERAGENCY COLLABORATION

Impediments to interagency collaboration can result from sources both internal and external to the agencies themselves. Internal sources can include agency goals and ambitions, culture, stakeholders, and agency-unique technical standards and processes. External sources can include the different budget cycles for each agency, different authorization and appropriation subcommittees, budget instability, and changes in policy direction from the administration and Congress. These impediments manifest themselves as impacts to mission success and as changes in cost, schedule, performance, and associated risks.

The most serious impediments are external to the agencies. They are typically symptoms of conflicting policies that are often not made explicit at the beginning of proposed cooperative efforts. Such impediments manifest themselves as different budget priorities by agencies, the Office of Management and Budget (OMB), and the Congress toward the same collaborative activity. While there may be acknowledgment of the value of collaboration at a national level, decision makers at the implementation level can be unwilling to prioritize collaboration above other agency mission assignments and constraints.

Many of the impediments to interagency collaboration appear as impediments to good systems engineering and project management.[1] A general tenet of systems engineering is that risks tend to occur at the "seams" between major system elements.[2] Thus the more organizations that are involved, the more interfaces there are to manage, and the greater the risk of something being missed or of miscommunication.

The increased number of stakeholders also serves to complicate the requirements development process, as a number of technical, programmatic, and political requirements are typically implied by the decision to collaborate that may not be explicitly stated at the outset.[3] Yet, collaborative requirements development and prioritization constitute one of the most important elements of successful collaboration. The challenge then becomes to understand the similarities *and differences* between the agencies' requirements *prior* to a commitment to work together on a collaborative mission. Of course, a prerequisite is that the agencies need to fully understand their own requirements (and the traceability thereof) to manage partner and stakeholder expectations for meeting those requirements.

MITIGATING THE RISKS OF INTERAGENCY COLLABORATION

Given a decision to pursue a collaborative space mission with interdependence greater than "the use of resources" level, there are several dimensions and distinct modalities in which risks need to be mitigated. The most important ones include:

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[1] By "systems engineering" the committee means the process by which the performance requirements, interfaces, and interactions of multiple elements of a complex system such as a spacecraft are analyzed, designed, integrated, and operated so as to meet the overall requirements of the total system within the physical constraints on and resources available to the system. Thus, for example, managing the effective integration and operation of a spacecraft requires that the physical, electrical, and thermal interfaces between different spacecraft subsystems, as well as their performance requirements and characteristics, be clearly defined and that responsibility for each side of an interface be well understood and as simple as possible. When organizational responsibilities for such systems interfaces are ambiguous or unnecessarily complex, the situation often leads to a less effective systems engineering process. By "project management" the committee means the overall management of the budget, schedule, performance requirements, and assignments of team member roles and responsibilities for the development of a complex system such as a scientific spacecraft.

[2] See, for example, E. Bardach, Turf barriers to interagency collaboration, pp. 168-192 in *The State of Public Management* (D.F. Kettl and H.B. Milward, eds.), Johns Hopkins University Press, Baltimore, Md., 1996.

[3] Agencies have both internal and external stakeholders for their space missions, and so they can be simultaneously both developers and consumers. One agency can also, at times, be a stakeholder of another (e.g., NASA is a stakeholder for long-term NOAA observations; NOAA has an interest in NASA's research observations). These interdependencies, which evolve over time, can make relationships more complex than one might infer from examination of the publicly stated agency missions.

- *Policy.* There should be a single, clear memorandum of understanding (MOU) or similar agreement between participating agencies. The MOU should define the project's chain of command and dispute resolution mechanism. There should be an explicit treatment of how requirements are to be decided and budget disputes are to be resolved. Since OMB acceptance is crucial to resolving budgetary issues and taking a unified executive branch approach to Congress, it is highly preferable that the MOU be endorsed at a policy level that covers all participating agencies, e.g., OMB program associate director(s) or higher.
- *Management.* One of the collaborating agencies should be designated as the lead agency. Ultimate responsibility and accountability for executing the mission—within the agreed set of roles and responsibilities, command structure, and dispute resolution process defined by the MOU—should rest with the lead agency. For missions for which there is expected to be a transition of major responsibility at a point in time—for example, the transition between acquiring a new sensor, putting it on orbit, and receiving its data stream for research to ensuring follow-on sensors and long time-series of data—the single lead agency might also change. If so, then the mission budget could shift as well from the first lead agency to the later lead agency.
- *Systems engineering.* There should be a single, well-defined, established systems engineering process with a single chief systems engineer. There should be no duplicate milestone reviews or redundant appeals processes.
- *Acquisition.* A single acquisition authority should be used by the lead agency. Different authorities might be used for clearly separable components that are not on the critical path, but they should be used only sparingly and should be entirely separable. For industry, the transaction costs involved for interagency collaboration should be tracked and treated as explicitly allowable costs under contract.
- *Operations.* Interagency collaboration does not end with a successful launch but extends into the operational phase. As such there should be a common, agreed-upon concept of operations. This can evolve with time and experience, but it is preferable to have an explicit agreement on an operational approach at the outset.

QUESTIONS TO ADDRESS BEFORE COLLABORATING

Interagency collaborations do not start with a blank sheet of paper. Agencies and their overseers need to ensure that they are organized, trained, and equipped to implement collaborative efforts at all levels (policy, acquisition, systems engineering, and operations), whether they have existing internal capabilities, or whether precursor, confidence-building engagements are needed. After the decision to involve Russia in the space station, for example, there was an extensive Shuttle-Mir effort to build a foundation for what would later become routine operational cooperation with Russia on the International Space Station.[4] Similarly, agencies engaging in collaboration need to realistically judge their readiness for collaboration and adjust their expectations and resources accordingly.

Taking into consideration the mixed results of interagency collaboration, the committee compiled a series of questions, organized into topical categories that should be carefully considered before committing to a collaborative Earth or space mission. These questions do not have simple yes or no answers but, rather, address the multiple layers of collaboration that must succeed for the overall mission to succeed. In some cases, variants of the same question appear in multiple categories to ensure consideration from multiple points of view. As might be expected, the most important questions, with the greatest potential impact for mission success, are those asked before agencies commit to collaboration.

Evaluation—Deciding Whether to Collaborate

- Why is the collaboration being contemplated? What are the arguments for and against separate missions?
- How real are potential synergies? What assumptions, if changed, would cause significant increases in cost and complexity?
- What kind of collaboration is being contemplated? (See specific types defined Chapter 1.)

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[4] The history of Shuttle-Mir operations is available in NASA, *Phase 1 Program Joint Report* (G.C. Nield and P.M. Vorobiev, eds.), NASA SP-1999-6108, January 1999, available at http://spaceflight.nasa.gov/history/shuttle-mir/welcome/goals.htm.

- Who is advocating collaboration? Options may include agency leaders, OMB, the Office of Science and Technology Policy (OSTP), Congress, agency workforces, scientific users, industry contractors, and others. Are all or just some of the stakeholders supportive?
- What does each agency bring to the table? Examples include expertise in acquisition, insight/oversight capability, and technical skills.
- What happens if one partner leaves the collaboration? What can be done to minimize the impact of one agency's default?
- What is the level of support from the agency's workforce or from the scientific community for the collaboration?
- To what extent will the proposed collaboration encourage or preclude involvement of third parties in mission implementation (e.g., universities, agencies, international partners)?
- How will agreement (e.g., on the scope and funding of a proposed collaboration) be secured among administration, legislative, and agency stakeholders?
- Who will be tasked with building and maintaining consensus?

Policy—Setting Priorities and Resolving Disputes

- How high does the cooperative project rank on each agency's priority list?
- What level of leadership support is available for the project at each agency?
- How will project decisions be made?
- Are there clear lines of authority, responsibility, and accountability?
- Is there an agreed-upon decision-making process that includes an effective dispute resolution approach?
- Are the respective organizations adequately defined and structured in accordance with agreed-upon roles and responsibilities?
- How will funding be provided to and from each agency?
- How will cost overruns be paid for?
- What is the process to resolve disputes at the project, program, and agency levels?
- What are the criteria for terminating the project?

Systems Engineering—Achieving Mission Success

- Is there an agreement on a single process for systems engineering? If so, what is the process?
- Is there an agreement on a single process for requirements definition, and what is the process?
- How will project decisions be made, and who is empowered to make them?
- How will the interfaces and work breakdown between agencies be determined?
- To what extent are the mission systems defined at all levels so that each participating agency understands how its roles and responsibilities translate into work and products?
- To what extent does each participant understand what it needs to provide to the other team members and when? Is there a written plan (e.g., project plan) including this level of detail?
- To what extent do good open communications between all parties occur, and what provisions can be made to ensure good future communications?
- To what extent do the participants trust and respect each other, and can appropriate commitment be demonstrated?

Acquisition—Achieving Technical and Programmatic Success

- Which agency's acquisition process will be used?
- Are there independent cost estimates at each major milestone, and is there a process for reconciling differences between the project office's estimates and independent estimates?
- Which agency's quality assurance process will be used?

TABLE 3.1 Leadership Responsibility for Interagency Cooperative Missions

	Evaluation—Deciding Whether to Collaborate	Policy—Setting Priorities and Resolving Disputes	Systems Engineering—Achieving Mission Success	Acquisition—Technical and Programmatic Success	Operations—Successful Mission Execution
Executive Branch Leaders	*	*			
Agency Leaders	*	*	*	*	
Project Leaders			*	*	*

- Which agency's spaceflight project and/or flight instrument selection process will be used?
- What evidence suggests that good open communication between all parties happens?
- What evidence suggests that the participants trust and respect each other and are committed?

Operations—Successful Mission Execution

- Is there an agreement on a single operational concept, and if so, what is it?
- To what extent do good, open communications exist between all parties?
- To what extent do the parties trust and respect each other, and are they committed?

Different levels of government will have different roles and responsibilities for answering these questions. As a collaborative endeavor progresses from policy decision and strategic planning phases into tactical planning and execution phases, the level at which officials need to be responsible for decision making and program direction also change. Senior agency leadership and the executive branch (notably OMB) need to take ownership of the strategic acquisition and policy aspects of interagency collaboration. If interagency cooperation, requiring a significant level of interdependency between participants, is intended, primary responsibility for systems engineering and acquisition will need to be clearly assigned, preferably to one agency or organization. The collaborating agencies may increasingly share responsibilities as the mission enters an operational phase, but this, too, requires a clear mechanism for setting priorities and quickly elevating any disputes for resolution. Table 3.1 shows how responsibility for addressing the categories of questions listed above might be allocated.

CHARACTERISTICS OF SUCCESSFUL INTERAGENCY COLLABORATIONS

Despite the numerous impediments and potential pitfalls of interagency collaboration in Earth and space science missions, it is nonetheless possible to have successful outcomes. As discussed in previous chapters, and as drawn from the committee's examination of case studies, agency briefings, existing reports, and members' own personal knowledge and direct experience, successful interagency collaborations share many common characteristics.[5] Those characteristics are, in turn, the result of realistic assessments of agency self-interest and capabilities and a disciplined attention to systems engineering and management "best practices." The committee finds that successful interagency space mission collaborations are characterized by:

- **A small and achievable list of priorities.** Projects address a sharply focused set of priorities and have clear goals. Agreement is based on specific projects rather than general programs.
- **A clear process to make decisions and settle disputes.** Project decision making is driven by an intense focus on mission success. This is facilitated by formal agreement at the outset on explicitly defined agency roles

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[5] Those same characteristics, and others related to them and mentioned earlier in this report, were also identified in a document prepared by the senior representatives of the five International Space Station international partner agencies. See "International Space Station Lessons Learned as Applied to Exploration," International Space Station Multilateral Coordination Board, Kennedy Space Center, Fla., July 22, 2009.

and responsibilities and should involve agreed-upon processes for making management decisions, single points of accountability (i.e., not committees), and defined escalation paths to resolve disputes. Long-term planning, including the identification of exit strategies, is undertaken at the outset of the project and includes consideration of events that might trigger a descope or cancellation review and associated fallback options if there are unexpected technical difficulties or large cost overruns that make the collaboration untenable.

- **Clear lines of authority and responsibility for the project.** Technical and organizational interfaces are simple and aligned with the roles, responsibilities, and relative priorities of each cooperating entity. Project roles and responsibilities are consistent with agency strengths and capabilities. Expert and stable project management has both the time and the resources available to manage the collaboration. Specific points of contact for each agency are identified. Agency and project leadership provides firm resistance to changes in scope. When possible, one of the collaborating agencies should be designated as the lead agency with ultimate responsibility and accountability for executing the mission within the agreed set of roles and responsibilities, command structure, and dispute resolution process defined by the MOU. In some cases the lead agency might change as a function of time, as for missions in which the lead agency differs between the implementation and operations phases.
- **Well-understood participation incentives for each agency and its primary stakeholders.** There is a shared common commitment to mission success, and there is confidence in and reliance upon the relevant capabilities of each partner agency. Each agency understands how it benefits from the collaboration, and recognizes that collaborative agreements may need to be revisited at regular intervals in response to budgetary and political changes. There is buy-in from political leadership (e.g., executive branch, Congress, and agency-level administrators), which can help projects move past rough spots that will inevitably occur in funding and support. There is a general spirit of intellectual and technical commitment from the agency workforce and contractors to help projects mitigate the disruptive effects of technical and programmatic problems that will also inevitably occur. Early and frequent stakeholder involvement throughout the mission keeps all stakeholders informed, manages expectations, and provides appropriate external input.
- **Single acquisition, funding, cost control, and review processes.** There is a single agency with acquisition authority, and each participating entity accepts financial responsibility for its own contributions to joint projects. Reliance on multiple appropriation committees for funding is avoided or reduced to the greatest possible extent. Cost control is ideally the responsibility of a single stakeholder or institution, because without a single point of cost accountability, shared costs tend to grow until the project is in crisis. Single, independent technical and management reviews occur at major milestones, including independent cost reviews at several stages in the project life cycle.
- **Adequate funding and stakeholder support to complete the task.** Funding adequacy is based on technically credible cost estimates with explicitly stated confidence levels.

The committee recommends that all of the above characteristics be incorporated in every interagency Earth and space science collaboration agreement. Beyond the formal interagency MOU creating an interagency collaborative space mission, there should be a joint (signed) implementation plan. The committee found that while such documents are commonplace in international collaborations, they are equally crucial for interagency collaborations. The implementation plan establishes management authority, organizational responsibilities, integrated review plans, budgets, schedule, and priorities at the outset and explicitly spells out how conflicts over scarce resources are to be handled. This implementation plan should be responsive to each agency's needs for involvement and oversight.

Once agreed to, the implementation plan supersedes individual agency policies when there is conflict and remains invariant throughout the project life cycle regardless of any participating agencies' internal changes in policies and procedures. This prevents the phenomenon of "moving the goalposts" during implementation, which can create dramatic disruptions to project budgets and schedules. A prerequisite for the implementation plan is the existence of a well-formed requirements document that allows explicit trade-offs between priorities that may become necessary and provides a foundation for resisting changes in mission scale and scope once underway.

Finally, the committee notes the critical importance of open, honest, effective, and complete communications. This encompasses all types of communication—written, oral, formal, and informal—from program and project plans, schedules, requirements, and contracts, to technical interchange meetings, interface control documents, MOUs, and configuration control boards, including telephone calls, e-mail, and on-site visits. Communication is important in any space mission, but even more important when organizations with different cultures, procedures, vocabularies, and roles come together to achieve a common goal.

Differences of culture, language, and procedures are expected in international space cooperation but are often underestimated in interagency collaborations until problems become quite obvious. As part of having good documentation and open communication, a collaborative project should strenuously avoid having separate agency project plans covering the same work content. Aside from the duplication of effort, separate plans tend to perpetuate areas of project team miscommunication that should be resolved early and quickly.

SUMMARY OF LESSONS LEARNED

As evidenced by the case studies discussed in Chapter 2, interagency collaboration is both difficult and expensive. It should never be pursued solely for political expediency or in hopes of reducing total costs. As with other types of collaborations, including international ones, the costs of collaboration (i.e., the additional administrative burdens and management complexity, and the real financial costs to deal with those) can be significant. Although parties may still find collaboration attractive if their share of a mission is more affordable than it would be if they were going it alone, they may nonetheless want to consider alternatives to interdependent reliance on another government agency. For example, agencies might consider buying services and/or coordinating observations preferable to fully interdependent cooperation.

Because of increased costs and complexity when space projects are conducted on a cooperative[6] multiagency basis, as opposed to under the auspices of a single agency, **the committee recommends that agencies should conduct Earth and space science projects independently unless:**

- **It is judged that cooperation will result in significant added scientific (and possibly follow-on operational) value to the project over what could be achieved by a single agency alone; or**
- **Unique capabilities reside within one agency that are necessary for the mission success of a project managed by another agency; or**
- **The project is intended to transfer from research to operations necessitating a change in responsibility from one agency to another during the project; or**
- **There are other compelling reasons to pursue collaboration, for example, a desire to build capacity at one of the cooperating agencies.**

Good systems engineering and project management techniques are important in any space mission, but especially where multiple organizations are involved. As has already been noted, the seams that characterize the interface between collaborating organizations are a source of technical and programmatic risk that requires proactive management and attention. In the event of a decision to proceed with collaboration, conscious steps to mitigate risk are required at every stage of development—from identification of the potential partner agencies and assignment of their respective roles; through project definition, management, and acquisition; to working with the administration and Congress to ensure mission success.

Interagency collaboration is not the norm for federal agencies pursuing Earth or space science missions. However, when agencies do collaborate, grassroots collaboration is preferred because it is based on technical necessity and a desire to work together. The committee understands that there may be national policy reasons to require collaboration in certain situations, but top-down collaboration will be burdened from the beginning with a lack of working-level buy-in. Teams that want to work together far outperform those that are forced together, and they also facilitate the application of the tools and techniques associated with good program and project management. Successful collaboration is more likely when each agency considers the partnership one of its highest priorities;

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[6] This means a relationship that has multiple agencies on the critical path to mission success. Necessary funding and/or mission-critical hardware may come from multiple agencies. If one agency leaves the program, the program falls apart unless that agency's elements are replaced.

such an understanding should be codified in signed agreements that also document the terms of the collaboration's management and operations.

Interagency collaborations for Earth and space science missions will occur over the development period of instruments and spacecraft, a time that will typically be measured in years and extend over multiple congressional budget cycles. During this period, agency priorities or external events may result in one of the partners wishing to terminate the collaboration. It is important to recognize the potential for breakdowns in collaboration to impact the likelihood of future collaborations. Not all collaborations will be of critical priority for an agency or group of agencies. If, for example, the collaboration consists of procuring services or using another agency's resources, then a formal high-level agreement may not be necessary. The level of criticality depends on the impacts of one party or another pulling out. As with international agreements, *interagency agreements should not be entered into lightly, and even then, entered into only when alternatives are considered and discarded*.

Numerous impediments challenge the successful implementation of collaborative missions, requiring numerous parties to mitigate these challenges. At the policy level, the projects may have to deal with multiple appropriations committees, and at the engineering level there may be overlapping review processes and conflicting acquisition rules. The commitment necessitated by interagency collaborations means there is a need for coordinated oversight by the executive and legislative branches of these special projects. The success that the U.S. Global Change Research Program enjoyed in its early years illustrates the value of an OMB-led budget cross-cut process as well as the active leadership and effective partnership of OSTP and OMB. However, the current oversight roles of OMB and OSTP are not suited to the kind of day-to-day operational oversight needed to facilitate interagency cooperative efforts, and so some other governance mechanism may be needed to facilitate decisions across multiple agencies and to provide accountability and support for those decisions by the administration and Congress.[7]

The committee recommends that if OSTP, OMB, or the Congress wishes to encourage a particular interagency research collaboration, then specific incentives and support for the interagency project should be provided. Such incentives and support could include cross-cutting budget submissions; protection of funding for interagency projects; freedom to move needed funds across appropriation accounts after approval of a cross-cutting budget; multiyear authorizations; lump-sum appropriations for validated independent cost estimates; minimization of external reviews that are not part of the project's approved implementation plans; and unified reporting to Congress and OMB, as opposed to separate agency submissions.

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[7] National Research Council, *Earth Science and Applications from Space—National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007, pp. 13-14.

Appendixes

A

Statement of Task

BACKGROUND

On October 15, 2008, the president signed into law H.R. 6063, the National Aeronautics and Space Administration Authorization Act of 2008, which authorized appropriations to NASA for Fiscal Year 2009. Section 507 of the act, "Assessment of Impediments to Interagency Cooperation on Space and Earth Science Missions," directed NASA to engage the National Research Council to carry out the following assessment:

> (a) Assessments- The Administrator, in consultation with other agencies with space science programs, shall enter into an arrangement with the National Academies to assess impediments, including cost growth, to the successful conduct of interagency cooperation on space science missions, to provide lessons learned and best practices, and to recommend steps to help facilitate successful interagency collaborations on space science missions. As part of the same arrangement with the National Academies, the Administrator, in consultation with NOAA and other agencies with civil Earth observation systems, shall have the National Academies assess impediments, including cost growth, to the successful conduct of interagency cooperation on Earth science missions, to provide lessons learned and best practices, and to recommend steps to help facilitate successful interagency collaborations on Earth science missions.
>
> (b) Report- The report of the assessments carried out under subsection (a) shall be transmitted to the Committee on Science and Technology of the House of Representatives and the Committee on Commerce, Science, and Transportation of the Senate not later than 15 months after the date of enactment of this Act.

ACTIVITY

The Space Studies Board will establish an ad hoc study committee to prepare a report that will:

- Assess impediments, including cost growth, to the successful conduct of interagency cooperation on Earth science and space science missions;
- Identify lessons learned and best practices from past interagency Earth science and space science missions; and
- Recommend steps to help facilitate successful interagency collaborations on Earth science and space science missions.

Specifically, the study shall:

- Examine the rationale for interagency cooperation in Earth science and space science missions, including variations in motivation for interagency cooperation among agencies.
- Survey Earth science and space science missions, either in operation or under formulation or development, which involve a significant partnership in either mission execution or instrument development by NASA with one or more other federal agencies. Such missions might include:

  —Fermi (formerly the Gamma-ray Large Aperture Space Telescope, GLAST), a NASA-DOE astrophysics mission;
  —Joint Dark Energy Mission (JDEM), a NASA-DOE astrophysics mission;
  —OSTM/Jason-2, developed by NASA and CNES and handed off for operation to NOAA and EUMETSAT;
  —ACE, developed and operated by NASA for research purposes, but provides data for operational use to NOAA and DOD;
  —GOES-R, being developed by NASA for NOAA under a reimbursable arrangement and originally included development of an advanced instrument suite (the Hyperspectral Environmental Suite);
  —National Polar-Orbiting Environmental Satellite System (NPOESS), a tri-agency (NOAA, DOD, and NASA) program; also the NPOESS Preparatory Program (NPP), a joint program of NASA and the NPOESS Integrated Program Office (IPO);
  —The operational Landsat system, which has involved combinations of NASA, NOAA, and USGS; include also the Landsat Data Continuity Mission (LDCM); and
  —C/NOFS, a DOD-NASA program to enable forecasting and nowcasting of ionospheric irregularities.

- From these case studies, identify lessons learned and best practices. Areas include:
  —Acquisition strategies;
  —Program management and structure, including partnership models; and
  —Interagency issues related to the “research to operations transition.”

B

Long-Term Sustained Observations for Climate

An important additional theme in NASA-NOAA collaboration arises from the need for long-term sustained observations of climate. A climate data record may be defined as "a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change."[1] Notably, climate records require support beyond provision of the observations themselves through careful attention to prelaunch sensor characterization, calibration, archiving, and reprocessing (Box B.1). Climate data are revised, reprocessed, and improved based on incremental understanding of the sensors and their space environment, improved calibrations, and development of new algorithms.

By their very nature, climate data records require continual active stewardship by the research community. In contrast, data used in operational settings typically have a short shelf life, highlighting an inherent peril in any proposal to collect climate data records in the context of an operational activity. Providing the climate records that are necessary for documenting, understanding, and dealing with policy issues thus requires interagency collaboration whereby both NASA and NOAA (and other agencies with climate interest) continue to remain closely involved. Thus interagency collaboration here goes beyond a transfer of research to operations and, instead, requires continuing close collaboration.

The situation was well stated in a 2008 report from the National Research Council (NRC), *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement Capabilities Lost in Program Restructuring*:[2]

> Much of climate science depends on long-term, sustained measurement records. Yet, as noted in many previous NRC and agency reports, the nation lacks a clear policy to address these known national and international needs. A coherent, integrated, and viable long-term climate observation strategy should explicitly seek to balance the myriad science and applications objectives basic to serving the variety of climate data stakeholders. The program should, for example, consider the appropriate balance between (1) new sensors for technological innovation, (2) new observations for emerging science needs, (3) long-term sustainable science-grade environmental observations, and (4) measurements that improve support for decision making to enable more effective climate mitigation and adaptation regulations. The various agencies have differing levels of expertise associated with each of these programmatic elements, and a long-term strategy should seek to capitalize on inherent organizational strengths where appropriate.

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[1] National Research Council, *Climate Data Records from Environmental Satellites: Interim Report*, The National Academies Press, Washington, D.C., 2004, p. 1.

[2] National Research Council, *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement Capabilities Lost in Program Restructuring*, The National Academies Press, Washington, D.C., 2008, p. 73.

BOX B.1
What Is a Climate Data Record?

Climate research and monitoring often require the detection of very small changes against a naturally noisy background. For example, sea surface temperatures can change by several kelvin (K) between daytime and nighttime or from year to year, whereas the climate signal of interest may change only 0.1 K over a decade. Moreover, changes in sensor performance or data processing algorithms often introduce changes greater than the climate signal. In addition to noise, spatial, temporal, and instrumental biases in the measurements confound climate researchers.

A climate data record (CDR) is a time series that tries to account for these sources of error and noise, producing a stable, high-quality data record with quantified error characteristics. A CDR is suitable for studying interannual to decadal variability. A CDR requires considerable refinement of the raw data, generally the blending of multiple data streams. These streams may come from multiple copies of the same sensor, or they may be ancillary data fields that are used to correct the primary data stream. Thorough analysis of sensor performance and improved processing algorithms are also required, as are quantitative estimates of spatial and temporal errors.

SOURCE: National Research Council, *Ensuring the Climate Record from the NPP and NPOESS Meteorological Satellites*, National Academy Press, Washington, D.C., 2000, available at http://www.nap.edu/catalog/12263.html, pp. 23-24.™

From the point of view of this report on interagency collaboration, it is clear that the elements of a strategy such as that proposed in *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft* must include clear agency roles and responsibilities, international coordination, an integrated approach across in situ and space-based observations, a systems design of the architecture for sustained climate observations, and community involvement in the development of climate data records. Due to the complexity of the systems and the multiple communities involved, some level of redundancy between agencies must be included. The establishment of clear roles for one agency should not be interpreted to preclude the other agency from pursuing activities that complement its mission.

There is recognition by the management of both NASA's Earth Science Division and NOAA's National Environmental Satellite Data and Information Service (NESDIS) that sustained and improved measurements are required to answer fundamental science and policy questions. This is reflected in NASA's practice of extending missions (e.g., TOPEX/Poseidon) past their performance period if they are providing scientific data and in NOAA's support of long-term observations relevant to climate and the production of climate data records. However, NASA's lack of funding and institutional interest to launch new instruments to continue existing measurement records and the lack of funding and expertise within NOAA to take on this responsibility are already affecting the continuity of climate data. NOAA, NASA, and other involved agencies have not yet come to agreement on how both operational and sustained climate data are to be provided. In the committee's view, a more systematic and sustained approach is warranted to facilitate NASA-NOAA collaborations. This might be achieved through a natural extension of the collaboration mechanisms already created under Section 306 of the 2005 NASA Authorization Act.[3]

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[3] Section 306, titled "Coordination with the National Oceanic and Atmospheric Administration," of the NASA Authorization Act of 2005 provides that the NASA and NOAA Administrators "review and monitor missions of the two agencies to ensure maximum coordination in the design, operation, and transition of missions where appropriate." In addition, section 306 calls for an evaluation of relevant NASA science missions for their potential operational capabilities and asks NASA and NOAA to "prepare transition plans for the existing and future Earth observing systems found to have potential operational capabilities." The full bill, which became Public Law 109-155 on December 30, 2005, is available at http://www.gpo.gov/fdsys/pkg/PLAW-109publ155/pdf/PLAW-109publ155.pdf.

Earth observations in support of climate and global change research are an emerging national imperative that engages a number of federal agencies. However, high-level policy direction appears to be necessary to ensure that the high-precision measurements required by the climate research community are sustained along with the routine (operational) observations of weather-related variables. Drawing on a decade of previous NRC studies[4] as well as its own experience, the committee found that:

- This is a governance problem, not an issue of basic expertise. It is further challenged by conflicting agency aspirations, especially regarding new funding for specific research areas like climate studies.
- A higher-level policy structure could prevent situations where agencies or contractors seek legislation to secure desired responsibilities and their associated funding.
- There is a current lack of sufficient in-house expertise within NOAA/NESDIS to address the full range of issues required for sustained space-based climate monitoring as distinct from satellite observations to support the National Weather Program.
- An efficient, long-term spaceborne environmental data acquisition system that has the ability to integrate new measurements could provide a framework for interagency collaboration.

  Such a data acquisition system currently does not exist, and no steps are being taken to develop it.
- It may not be necessary or even desirable to have all the expertise in one agency; however, operational agencies should be aggressively involved from the outset in the technologies they need to have implemented and tested and should be responsible for providing resources that are commensurate with their needs.

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[4] *Issues in the Integration of Research and Operational Satellite Systems for Climate Research: Part I. Science and Design* (2000); *From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death* (2000); *Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations* (2003); *Extending the Effective Lifetimes of Earth Observing Research Missions* (2005); *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation* (2005); *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (2007); and *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement Capabilities Lost in Program Restructuring* (2008). Each NRC report was published by the National Academy Press (after mid-2002, The National Academies Press), Washington, D.C., in the year indicated.

C

Characteristics of NASA's Recent Interagency Collaborations

Table C.1 shows a side-by-side comparison of some of the key attributes of selected recent interagency collaborative efforts that were reviewed by the committee. In addition to the type of collaboration and governance structure, the committee noted whether the collaboration was directed by Congress or the administration or whether it emerged in a more spontaneous fashion from the agencies and scientists themselves.

TABLE C.1 Selected Recent Interagency Collaborative Efforts

	NPOESS[a]	OSTM/Jason-2	Fermi/GLAST	JDEM/Omega
Nation(s) Involved	United States	United States, France	United States	United States
Type of Collaboration	Cooperation Cost-sharing (NOAA, DOD) Technology infusion (NASA)	Coordination (NASA-NOAA) CNES: bus, 2 instruments, launch and early orbit phase (LEOP), and checkout NASA: 3 instruments, launch services NOAA/EUMETSAT: ground segment	Cooperation	Cooperation NASA: telescope, main science instrument, spacecraft bus DOE: fabrication of major science instrument, development of science operations center
Agencies Involved	NOAA, DOD, NASA	NASA, NOAA, EUMETSAT, CNES	NASA, DOE	NASA, DOE
Governance Structure	Integrated Program Office (IPO) for NPOESS	Developed by NASA, CNES and operated by NOAA, EUMETSAT	NASA: project office, instruments DOE: instruments	NASA: lead agency responsible for overall success of the mission DOE: science and operations contribution
Project/ Program	Program—multiple spacecraft	Single project	Single project	Single project
Directed/ Organic[b]	Directed (executive order)	Organic	Organic	Directed

GOES-R	Landsat 7	LDCM	C/NOFS	ACE
United States	United States	United States	United States	United States
Procurement of services NOAA: provides direct oversight for the GOES-R program, flight and ground segment NASA: procurement, management, and execution of the flight project in accordance with overall NOAA guidance	Coordination NASA: development and launch of the spacecraft; development of the ground system USGS: operates the satellite and captures, processes, and distributes the data and is responsible for maintaining the data archive	Coordination NASA: development and launch of the spacecraft; development of the ground system USGS: operation of the satellite and responsible for a ground system to receive, ingest, archive, calibrate, process, validate, and distribute LDCM science data	Coordination	Use of resources NASA: spacecraft and instruments NOAA: small ($680,000) contribution to modify the ACE spacecraft and enable 24-hour continuous transmission of real-time data on the solar wind DOD: Air Force ground stations
NASA, NOAA	Development: NASA, NOAA, USGS Operations: NASA, USGS	NASA, USGS	Joint USAF Space Test Program (STP) and Air Force Research Laboratory (AFRL); participation by NASA, NRL, universities, federally funded research and development centers	NASA, NOAA, DOD
Developed by NASA for NOAA on a cost-reimbursable basis	NASA: spacecraft, instrument, and ground system NOAA: spacecraft and ground systems operations and functions USGS: Landsat data distribution and archiving	NASA: development of spacecraft USGS: development and operation of the ground system	STP: spacecraft, launch vehicle, launch and first year of on-orbit operations AFRL: payload, payload integration and test, model development, data center operations, and product generation and distribution NASA: CINDI instrument	Managed by NASA
Single project	Single project	Single project	Single project	Single project
Organic	Directed	Directed	Organic	Organic

(continued)

TABLE C.1 Continued

	NPOESS[a]	OSTM/Jason-2	Fermi/GLAST	JDEM/Omega
Year Started	2006 (spacecraft development)	2002	September 2000 (SRR)	2010 (Phase A)
Launch (or Launch Readiness Date)	2014 (C-1)	June 2008	2006 (ICRR, 2001) June 2008 (actual)	2017
Number of Spacecraft	Originally 6, now 4 (not including NPP)	1	1	1
Number of Instruments	7 (C-1), 8 (FOC)	5	2	1
Initial Budget		$76 million (no LV, NASA only, March 2006) $76 million (no LV, NASA only, at launch)	$454 million FY 2006 (ICRR, 2001)	~$900 million (FY 2009)
Budgetary Outcome	Significant overrun; program descoped: $6.8 billion through C1, $8 billion through C2	Met launch date on budget	$508 million FY 2006 (at launch)	Not yet selected
Motivation for Collaboration at the Outset	Cost: "eliminate the financial redundancy of acquiring and operating polar-orbiting environmental satellite systems, while continuing to satisfy U.S. operational requirement for data from these systems"	Third in partnership; continue measurement record	Similar science goals: GLAST draws on the interest of both the high-energy particle physics and high-energy astrophysics communities and is the highest ranked initiative in its category in the NRC 2000 decadal survey report[d]	Science goals are high priority to both organizations; leverage each agency's expertise

GOES-R	Landsat 7	LDCM	C/NOFS	ACE
September 2004 (instrument development) October 2005 (preliminary spacecraft design)	1993 (SRR)	2007	At least 2000	1991
April 2015 (GAO, 2009)[c]	1998 (1993) instrument power supply failures during thermal/vacuum testing; 1999 (actual)	2011 (ICR, 2008) 2012 (PDR, 2009)	2003 (2001) February 2006 (October 2005) solar panel (18-month delay) and EMI probes; rebuilt harness April 2008 (actual)	1997
2	1	1	1	1
4	1	Originally 1, now 2	6	9
$6.6 billion		$652 million (ICR, 2008)		Total cost for Phase C/D through launch plus 30 days of checkout not to exceed $141.1 million (in real-year dollars)
$7.67 billion (GAO, 2009)[c] significant overrun; program descoped from 4 satellites/5 sensors to 2 satellites/4 sensors	$718 million (at launch, includes $212 million DOD, $6.5 million USGS)	Still in development, has overrun; USGS funding shortfalls have impacted ground system	Combined cost of satellite development and construction, the Pegasus rocket, and the 13 months of in-space operations total about $135 million (at launch); solar panel design issues slowed the program; instrument RF sensitivities created technical challenges	Final project cost $106.8 million, a $34.3 million under-run
NOAA: procurement of next-generation GOES spacecraft NASA: Possible transition of GIFTS instrument to advanced sounder for GOES-R	Latest partnership to continue decades-long record of moderate-resolution measurements of the land surface (see text for details)	NSTC directed collaboration to maintain continuity of Landsat-type data for civil, commercial, and national security interests	NASA: science payload access to space as mission of opportunity DOD: means to expand scope of mission through hosting NASA-funded payload; support operational users of space weather information	Merging of NASA research interests with NOAA and Air Force operational needs for real-time data on the upstream solar wind and forecast and warning of severe space weather events

(continued)

TABLE C.1 Continued

	NPOESS[a]	OSTM/Jason-2	Fermi/GLAST	JDEM/Omega
Primary Sources for the Committee's Analysis[e]	See in the main text references cited in the section "NASA-NOAA Interagency Collaboration."	See in the main text references cited in the section "Coordination Example: Ocean Surface Topography Mission/Jason-2."	See in the main text references cited in the section "The Gamma-ray Large Area Space Telescope Mission."	See in the main text references cited in the section "The Joint Dark Energy Mission."

[a] As noted in the text, on February 1, 2010, it was announced that the NPOESS program would be restructured into two separate lines of polar-orbiting satellites to serve military and civilian users. Information in this table refers to the NPOESS program prior to the restructuring.

[b] "Organic" and "directed" are used here to distinguish between agency collaborations that arise mostly from the normal self-interests of the agencies and in which efforts are made to align the structure with normal agency practices and culture (partnerships arise from the bottom up) versus collaborations that arise from external demands, for example, to meet a political objective beyond the agency's own self-interests or to meet a mission requirement that is externally imposed (partnerships arise from the top down).

[c] Government Accountability Office (GAO), "Geostationary Operational Environmental Satellites, GAO Testimony Before the Subcommittee on Energy and Environment, Committee on Science and Technology, House of Representatives, Statement of David A. Powner, Director, Information Technology Management Issues," GAO-09-596T, April 23, 2009.

[d] National Research Council, *Astronomy and Astrophysics in the New Millennium,* The National Academies Press, Washington, D.C., 2010.

[e] For all missions and especially for NPOESS, Fermi/GLAST, and JDEM/Omega, the committee also drew on the substantive knowledge and first-hand experiences of its members.

[f] National Research Council, *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement Capabilities Lost in Program Restructuring,* The National Academies Press, Washington, D.C., 2008, available at http://www.nap.edu/catalog.php?record_id=12254.

GOES-R	Landsat 7	LDCM	C/NOFS	ACE
NRC (2008)[f]	See in the main text references cited in the section "The Landsat Program."	See in the main text references cited in the section "The Landsat Program."	Interview with Roderick Heelis, principal investigator for CINDI	See in the main text references cited in the section "Use of Resources Example: Space Weather Data from the Advanced Composition Explorer."

D

Acronyms

AAAC	Astronomy and Astrophysics Advisory Committee
ACE	Advanced Composition Explorer (spacecraft)
ADEPT	Advanced Dark Energy Physics Telescope
AFRI	
AIRS	Atmospheric Infrared Sounder
AMS	Alpha Magnetic Spectrometer
AO	announcement of opportunity
BEPAC	Beyond Einstein Program Assessment Committee
CDR	climate data record
CEES	Committee on Earth and Environmental Sciences (under OSTP)
CINDI	Coupled Ion-Neutral Dynamics Investigation
CNES	Centre National d'Etudes Spatiales (French National Space Agency)
C/NOFS	Communication/Navigation Outage Forecasting System
DESTINY	mission concept for the NASA-DOE Joint Dark Energy Mission (JDEM)
DMSP	Defense Meteorological Satellite Program
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DSN	Deep Space Network
EMI	electromagnetic interference
EOS	Earth Observing System
ERTS-1	Earth Resources Technology Satellite; renamed Landsat 1
ETM+	Enhanced Thematic Mapper Plus; an instrument on Landsat 7
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites

Fermi	Fermi Gamma-ray Space Telescope; formerly known as GLAST
FOC	full operating capability
GAO	Government Accountability Office
GLAST	Gamma-ray Large Area Space Telescope; now Fermi Gamma-ray Space Telescope
GOES	Geostationary Operational Environmental Satellite
GOESS	Global Earth Observation System of Systems
GSFC	Goddard Space Flight Center
HEPAP	High Energy Physics Advisory Panel
ICR	initial confirmation review
ICRR	initial confirmation readiness review
IPO	integrated program office
ISOC	Instrument Science Operations Center
ISS	International Space Station
ISWG	Interim Science Working Group
Jason	series of Earth observation satellites for oceanic measurements; also known as OSTM, the Ocean Surface Topography Mission
JDEM	Joint Dark Energy Mission
JHU	Johns Hopkins University
JOG	Joint Oversight Group
JPL	Jet Propulsion Laboratory
L1	Earth-Sun Lagrangian Point 1; a gravitationally stable point approximately 1.5 million km from Earth in the direction of the Sun
Landsat	series of Earth-imaging satellites
LAT	Large Area Telescope; main instrument of the Fermi Gamma-ray Space Telescope
LBNL	Lawrence Berkeley National Laboratory
LDCM	Landsat Data Continuity Mission
LISA	Laser Interferometer Space Antenna
LV	launch vehicle
Mir	decommissioned Russian space station
MODIS	Moderate-resolution Imaging Spectroradiometer
MOU	memorandum of understanding
NASA	National Aeronautics and Space Administration
Nimbus	Series of satellites for meteorological research and development
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NPR	NASA Procedural Requirement
NRC	National Research Council
NRL	Naval Research Laboratory
NSF	National Science Foundation
NSTC	National Science and Technology Council
OFCM	Office of the Federal Coordinator for Meteorology

OMB	Office of Management and Budget
OSIP	Operational Satellite Improvement Program
OSTM	Ocean Surface Topography Mission
OSTP	Office of Science and Technology Policy
PDD	Presidential Decision Directive
PDD/NSTC-2	Convergence of NPOESS
PDD/NSTC-3	Landsat Remote Sensing Strategy
PDR	preliminary design review
PI	principal investigator
POES	Polar Operational Environmental Satellite
QuikSCAT	Quick Scatterometer; Earth-observing satellite measuring wind data over oceans
RADARSAT-1	Canadian Earth-observation satellite equipped with synthetic aperture radar
RF	radio frequency
SACHS	Southern Area Consortium of Human Services
SAGENAP	Scientific Assessment Group for Experiments in Non-Accelerator Physics
SDT	Science Definition Team
SeaWiFS	Sea-viewing Wide Field-of-View Sensor; instrument on OrbView-2 (aka SeaStar)
SLAC	Stanford Linear Accelerator Center; renamed SLAC National Accelerator Laboratory
SLC	Stanford Linear Collider
SNAP	Supernovae Acceleration Probe
SPIRES	Stanford Physics Information Retrieval System
SRR	systems requirements review
STP	Space Test Program
TIROS	Television Infrared Observation Satellite
TOPEX/Poseidon	Joint NASA/CNES ocean surface topography mapping mission; succeeded by Jason-1 and Jason-2/OSTM
TRMM	Tropical Rainfall Measuring Mission
USAF	United States Air Force
USGCRP	United States Global Change Research Program
USGS	United States Geological Survey
UTD	University of Texas at Dallas
WFIRST	Wide-Field Infrared Survey Telescope
WMAP	Wilkinson Microwave Anisotropy Probe

E

Meeting Agendas

JULY 30-31, 2009
KECK CENTER, 500 FIFTH STREET, NW
WASHINGTON, D.C.

July 30, 2009

Open Sessions

11:00 a.m.	Videoconference with Mike Freilich, Earth Science Division Director, NASA HQ
12:00 p.m.	Continue Discussions/Lunch
1:00	Discussion with A. Thomas Young, Executive Vice President, Lockheed Martin Corp. (retired) and member of the committee
1:45	Discussion with Tom Karl, Director NOAA NCDC (via videoconference) and Jeff Privette, NOAA NCDC
2:45	Discussion with Bob Winokur, Technical Director, Oceanographer of the Navy
3:15	Panel on NASA-DOE Cooperation • Anne Kinney, Director, Solar System Exploration Division, NASA GSFC • Paul Hertz, Chief Scientist, Science Mission Directorate, NASA HQ • Robin Staffin, Director for Basic Research, OSD • Kathy Turner, Office of High Energy Physics, DOE • Persis Drell, Director, SLAC National Accelerator Laboratory (via teleconference)

July 31, 2009

Open Sessions

9:30 a.m. Discussion with Pam Whitney, Space and Aeronautics Subcommittee, House S&T Committee
9:50 Discussions with Staff from OMB and OSTP

- Amy Kaminski, OMB
- Robie Samanta-Roy, OSTP
- Damon Wells, OSTP
- Phil DeCola, OSTP

10:50 Lessons from the Landsat Program
Darrel Williams and Jim Irons, NASA GSFC

11:30 Discussion with Paul Menzel, University of Wisconsin (via videoconference)

12:00 p.m. Continue Discussions/Lunch

1:00 Discussion with Colleen Hartman, George Washington University

1:30 "Policy Issues and Challenges for Interagency Space Systems Acquisition"
Dana Johnson, Northrop

2:15 Discussion with Ron Sega, Colorado State University (invited)

SEPTEMBER 30-OCTOBER 1, 2009
KECK CENTER, 500 FIFTH STREET, NW
WASHINGTON, D.C.

September 30, 2009

Not Open to the Public Session

9:00 a.m. Meeting Objectives
Jim Baker and Dan Baker, Committee Co-chairs

Open Session

10:00 Discussions with Dick Obermann, Staff Director, House Science and Technology Committee, Subcommittee on Space and Aeronautics

Not Open to the Public Session

11:00 Committee Discussions
Mission Cost, Schedule, and Complexity Impacts from Multi-Agency and Foreign Partner Contributions

Open Sessions

12:00 p.m.	Continue Discussions/Lunch
1:00	The Senior Review Process at NASA's Earth Science Division Mike Freilich, NASA (tentative)
2:00	Discussion with Mary Kicza, NOAA Assistant Administrator for Satellite and Information Services

Not Open to the Public Session

3:15	Committee Discussions Finalize report outline Assign writing teams Discussion of presentations and related materials from meeting 1
6:30	Working Dinner for the Committee

October 1, 2009

Not Open to the Public Session

9:00 a.m.	Committee Discussions

Open Session

9:30	Discussion with Geoff Pendleton, Dynetics Corporation
10:30	Discussions among Committee and Guests
11:00	Teleconference with Alan Stern, SWRI (tentative)
12:00 p.m.	Working Lunch/Committee Discussions

Not Open to the Public Session

1:00	Committee Discussions/Begin Writing Assignments
4:00	Meeting Adjourns

F

Biographies of Committee Members and Staff

D. JAMES BAKER, *Co-Chair,* is the director of the Global Carbon Measurement Program of the William J. Clinton Foundation, where he currently focuses on the use of forestry programs to reduce carbon dioxide emissions and to alleviate poverty in developing countries. He is also a science and management consultant with the Intergovernmental Oceanographic Commission of UNESCO (Paris) and the H. John Heinz III Center for Science, Economics and the Environment (Washington, D.C.). During the 1990s, Dr. Baker was administrator of the National Oceanic and Atmospheric Administration (NOAA) and under secretary of commerce for oceans and atmosphere, where he guided the completion of the modernization of the National Weather Service, initiated new climate forecasting services, and merged civil and military environmental satellite systems. Dr. Baker was educated as a physicist, practiced as an oceanographer, and has held science and management positions in academia, not-for-profit organizations, and government institutions. Dr. Baker has served on more than 30 National Research Council (NRC) committees, most recently the Panel on Oceans (Physical) of the Committee on Climate, Energy, and National Security.

DANIEL N. BAKER, *Co-Chair,* is director of the Laboratory for Atmospheric and Space Physics at the University of Colorado, Boulder, and is a professor of astrophysical and planetary sciences and a professor of physics there. His primary research interest is the study of plasma physical and energetic particle phenomena in planetary magnetospheres and in Earth's vicinity. He conducts research in space instrument design, space physics data analysis, and magnetospheric modeling. He currently is an investigator on several NASA space missions, including the MESSENGER mission to Mercury, the Magnetospheric MultiScale (MMS) mission, and the Radiation Belt Storm Probes (RBSP) mission. Dr. Baker has published more than 750 papers in the refereed literature and has edited six books on topics in space physics. He is a fellow of the American Geophysical Union, the International Academy of Astronautics (IAA), and the American Association for the Advancement of Science (AAAS). He has won numerous awards for his research efforts and for his management activities, including recognition by the Institute for Scientific Information, where he is "highly cited" in space research. Dr. Baker was chosen as a 2007 winner of the University of Colorado's Robert L. Stearns Award for outstanding research, service, and teaching. Dr. Baker was the 2010 winner of the American Institute of Astronautics and Aeronautics (AIAA) James A. Van Allen Space Environments Medal and was the recipient of the 2010 Distinguished Research Lecturer Award—the highest honor bestowed on a University of Colorado faculty member by fellow faculty. Professor Baker is an associate of the National Academy of Sciences (2004) and was recently elected a member of the National Academy of Engineering (NAE). He currently serves on several national and international scientific and advisory committees, including committees of the NRC, the U.S. Air Force, and other federal agencies. He was a member of the NRC's Space Studies Board, the Solar and Space Physics Survey Committee (2001-2003), and the 2006 Assessment Committee for the National Space Weather Program. Professor Baker has been selected to chair the next decadal survey (2013-2022) in solar and space physics.

DAVID A. BEARDEN is the general manager of the Aerospace Corporation's NASA Programs Office, where he manages and provides technical direction to staff supporting various NASA human exploration and science programs, including the Constellation program, the Mars program, the Astrophysics program, the Discovery/New Frontiers programs, and other missions at NASA headquarters and field centers. His expertise lies in project management and space systems architectural assessment, including conceptual design, simulation, and programmatic analysis of space systems. He led the Hubble Space Telescope Servicing Analysis of Alternatives, which earned him the 2006 Aerospace Corporation's President's Award. He has also led various mission studies, including the Lunar Robotic Exploration Architecture study and the Mars Sample Return studies. He served on the NRC Beyond Einstein Program Assessment Committee in 2008. Dr. Bearden has served on a number of standing review boards and led development of the Small Satellite Cost and Complexity-based Risk Assessment (CoBRA) models and their application to NASA independent reviews. He also led deployment of the Concurrent Engineering Methodology at the Jet Propulsion Laboratory's Project Design Center. He has authored chapters in *Space Mission Analysis and Design* and *Reducing the Cost of Space Systems*. He was the recipient of the *Aviation Week & Space Technology* Annual Aerospace Laurels in 2000 for conducting "the first quantitative assessment of NASA's faster-better-cheaper initiative in space exploration." He holds a Ph.D. and an M.S. in aerospace engineering from the University of Southern California and a B.S. in mechanical engineering/computer science from the University of Utah.

CHARLES L. BENNETT is a professor of physics and astronomy at Johns Hopkins University. Dr. Bennett's research interests include experimental cosmology and astronomical instrumentation. He is the principal investigator (PI) for the Wilkinson Microwave Anisotropy Probe (WMAP) mission, which quantitatively specified the age, content, history, and other key properties of the universe with unprecedented precision. Previous to his work on WMAP, Dr. Bennett was the deputy PI of the Cosmic Background Explorer (COBE) Differential Microwave Radiometers instrument. Dr. Bennett received the 2009 Comstock Prize in Physics, the 2006 Harvey Prize, and the 2005 Henry Draper Medal. He also shared the 2006 Gruber Prize in Cosmology. From 1984 to 2005, Dr. Bennett was an astrophysicist at the NASA Goddard Space Flight Center, where he won the NASA Outstanding Leadership Medal and twice won the NASA Exceptional Scientific Achievement Medal. Dr. Bennett is a member of the NAS and the American Academy of Arts and Sciences. He is also a fellow of the American Association of Arts and Sciences and of the American Physical Society. Dr. Bennett served on the NRC's Committee on Astronomy and Astrophysics and the Space Studies Board.

STACEY W. BOLAND is a senior systems engineer at the Jet Propulsion Laboratory working in Earth mission concepts. Dr. Boland is the observatory system engineer for the Orbiting Carbon Observatory-2 (OCO-2) Earth System Science Pathfinder mission. She is also a cross-disciplinary generalist specializing in Earth-mission concept development and systems engineering and mission architecture development for advanced (future) Earth observing mission concepts, which involves a variety of remote sensing instruments applicable to a number of scientific fields, particularly atmospheric science. Dr. Boland received her B.S. in physics from the University of Texas, Dallas, and her M.S. and Ph.D. in mechanical engineering from California Institute of Technology. Dr. Boland was awarded NASA's Exceptional Achievement Medal in 2009. She has served as a consultant to the NRC Earth Science and Applications from Space: A Community Assessment and Strategy for the Future study; the Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft; and the Committee on a Strategy to Mitigate the Impact of Sensor Descopes and Demanifests on the NPOESS and GOES-R Spacecraft.

ANTONIO J. BUSALACCHI, JR., is director of the Earth System Science Interdisciplinary Center (ESSIC) and a professor in the Department of Atmospheric and Oceanic Science at the University of Maryland. Dr. Busalacchi joined ESSIC in 2000 after serving as chief of the NASA GSFC Laboratory for Hydrospheric Processes. In 1999, he was appointed co-chair of the Scientific Steering Group for the World Climate Research Programme on Climate Variability and Predictability (CLIVAR). Dr. Busalacchi's ongoing area of research is the role of tropical ocean circulation in the coupled climate system. He has a doctorate in oceanography from Florida State University. Dr. Busalacchi's NRC service includes membership on the Board on Atmospheric Sciences and Climate and serving as chair of the Climate Research Committee. He is currently a member of the Committee on Earth Studies.

CARLOS E. DEL CASTILLO is a member of the senior professional staff with the Space Department of the Johns Hopkins University Applied Physics Laboratory and the William S. Parsons Professor in the Department of Earth and Planetary Sciences. Dr. Del Castillo started his career at the University of Puerto Rico studying the effects of oil pollution in tropical marine environments. Later, at the University of South Florida, his interest in organic carbon biogeochemistry and the carbon cycle led him to the use of remote sensing to study biogeochemical and physical processes in the oceans through a combination of remote sensing and field and laboratory experiments. While working at NASA as a researcher, Dr. Del Castillo also served as project manager at Stennis Space Center and as a program scientist at NASA headquarters. He served on several interagency working groups, chaired NASA and NSF workshops, and is now a member of NASA's Carbon Cycle and Ecosystem Management and Operations Working Group. Dr. Del Castillo received the William Sackett Prize for Innovation and Excellence in Research from the University of South Florida (1999), the NASA Presidential Early Career Award for Scientists and Engineers (2004), and the Emerald Honors Trailblazer Award (2007), among others. He received his B.S. in biology and M.S. in marine chemistry from the University of Puerto Rico and his Ph.D. in oceanography from the University of South Florida.

ANTONIO L. ELIAS is executive vice president and general manager for advanced programs at Orbital Sciences Corporation. Previously, he served as Orbital's chief technical officer (1996-1997), corporate senior vice president (1992-1996), and Orbital's first vice president for engineering (1989-1992). From 1987 to 1997, he led the technical team that designed and built the Pegasus air-launched booster, flying as a launch vehicle operator on the carrier aircraft for the rocket's first and fourth flights. He also led the design teams of Orbital's APEX and Sea Star satellites and the X-34 hypersonic research vehicle. Dr. Elias came to Orbital from the Massachusetts Institute of Technology (MIT), where he held various teaching and research positions, including the Boeing Chair in the Department of Aeronautics and Astronautics. Dr. Elias is a member of the NAE and a fellow of the AIAA, the American Astronautical Society (AAS), and IAA. His awards include the 1991 AIAA Engineer of the Year, the AIAA Aircraft Design Award, and the AAS Brouwer Award. He is also a co-recipient of the National Medal of Technology and the National Air and Space Museum Trophy.

MARGARET FINARELLI is currently a senior fellow at the Center for Aerospace Policy Research of George Mason University. Her prior career with NASA and other federal government agencies focused on interagency policy development and international space cooperation. Ms. Finarelli joined NASA's International Affairs Division in 1981 and undertook the conceptual development and negotiation of numerous international space science, Earth science, and space infrastructure projects. She has served as NASA's deputy associate administrator for external relations and was appointed associate administrator for policy coordination and international relations. She serves as the vice president for public policy for AAS, is a member of the International Activities Committee of the AIAA, and is on the board of advisers for Students for the Exploration and Development of Space-USA. Ms. Finarelli received NASA's Exceptional Service Medal (1985) and NASA's Exceptional Achievement Medal (1991). She was elected to the IAA in 2003. In 2004, she was awarded the AIAA's International Cooperation Award and was elected as a fellow of the AAS. In 2005, she was elected an associate fellow of the AIAA. Ms. Finarelli has a master of science degree in physical chemistry from Drexel University.

TODD R. LaPORTE is a professor of political science at the University of California, Berkeley. Previously, he was also associate director of the Institute of Governmental Studies and held faculty posts at the University of Southern California and Stanford University. Dr. LaPorte teaches and publishes in the areas of organization theory, technology, and politics and the organizational and decision-making dynamics of large, complex, technologically intensive organizations, as well as public attitudes toward advanced technologies and the challenges of governance in a technological society. At Los Alamos National Laboratory (LANL) he examined the institutional challenges of multi-generation nuclear missions. In a parallel effort, he is examining the institutional evolution of the National Polar-orbiter Operational Environmental Satellite System (NPOESS). In 1985, Dr. LaPorte was elected to the National Academy of Public Administration. He has served on the Secretary of Energy Advisory Board of the Department of Energy and chaired its Task Force on Radioactive Waste Management, which examined questions of institutional trustworthiness. Dr. LaPorte was also on the Technical Review Committee of LANL's Nuclear Materials Technology Division. He received his Ph.D. from Stanford University.

MARGARET S. LEINEN is the associate provost of marine and environmental initiatives and the executive director of Harbor Branch Oceanographic Institute, Florida Atlantic University. She was formerly the head of the Climate Response Fund, a nonprofit organization created to provide funding and support other activities needed to explore innovative solutions to the climate crisis facing the world. Previously she was the chief science officer of Climos, Inc., a start-up company leveraging natural processes to mitigate climate change. Before joining Climos in 2006, Dr. Leinen served for 7 years as the assistant director for geosciences at NSF. While at NSF, she served as the vice chair of the Interagency Climate Change Science Program of the federal government and as the co-chair of the Joint Subcommittee on Ocean Science and Technology, which developed the first interagency assessment of national priorities for ocean research. She was the U.S. representative to the International Group of Funding Agencies for Global Change Research and the Inter-American Institute for Global Change Research. Dr. Leinen also served as the first cross-agency coordinator of the NSF portfolio of activities in environmental research and education. She was responsible for the biocomplexity in the environment priority area of the NSF and initiated NSF-wide activities in cyberinfrastructure for the environment and in observing systems for the environment. At the University of Rhode Island, Dr. Leinen served as dean of the Graduate School of Oceanography and dean of the College of Environment and Life Sciences and was the vice provost for marine and environmental programs. She is a well-known researcher in the areas of paleoceanography, paleoclimatology, and biogeochemical cycling in the ocean and is a fellow of the AAAS and the Geological Society of America. Dr. Leinen received her B.S. in geology from the University of Illinois, her M.S. in geological oceanography from Oregon State University, and her Ph.D. in geological oceanography from the University of Rhode Island. Dr. Leinen's most recent NRC service was as a member of the Committee on Global Change Research (1995-1998).

SCOTT N. PACE is the director of the Space Policy Institute and professor of the practice of international affairs at the George Washington University's Elliott School of International Affairs. His research interests include civil, commercial, and national security space policy and the management of technical innovation. He has served as the associate administrator for program analysis and evaluation at NASA, where he was responsible for providing objective studies and analyses in support of policy, program, and budget decisions by the NASA administrator. He previously served as chief technologist for space communications in NASA's Office of Space Operations, where he was responsible for issues related to space-based information systems. Dr. Pace also previously served as the deputy chief of staff to NASA administrator Sean O'Keefe. Prior to joining NASA, Dr. Pace was the assistant director for space and aeronautics in the White House Office of Science and Technology Policy (OSTP), where he was responsible for space- and aviation-related issues and coordination of civil and commercial space issues through the Space Policy Coordinating Committee of the National Security Council. Dr. Pace received a B.S. degree in physics from Harvey Mudd College and a master's degree in aeronautics and astronautics and technology and policy from the Massachusetts Institute of Technology (MIT), and a doctorate in policy analysis from the RAND Graduate School. He was a member of the NRC Committee on Earth Studies but resigned in the first year of his appointment in order to take a position at NASA headquarters.

GRAEME L. STEPHENS is a professor in the Department of Atmospheric Sciences at Colorado State University. His research activities focus on atmospheric radiation and on the application of remote sensing in climate research, with particular emphasis on understanding the role of hydrological processes in climate change. His other activities include the development of Doppler lidar for measurement of boundary layer winds and studies in atmospheric visibility. Dr. Stephens is the principal investigator of NASA's Cloudsat Mission. He is the author of *Remote Sensing of the Lower Atmosphere: An Introduction*. His most recent NRC service includes membership on the Committee on a Strategy to Mitigate the Impact of Sensor De-Scopes and De-Manifests on the NPOESS and GOES-R Spacecraft, the Committee on the Future of Rainfall Measuring Missions, the Panel on Climate Change Feedbacks, and the Committee on Earth Studies.

ANNALISA L. WEIGEL is the Jerome C. Hunsacker Assistant Professor of Aeronautics and Astronautics and Engineering Systems at Massachusetts Institute of Technology. Dr. Weigel's research interests include aerospace policy and economics, aerospace systems architecting and design, innovation and change dynamics in the aerospace industry, and systems engineering. She began her professional career as an engineer at Adroit Systems, first supporting the Defense Airborne Reconnaissance Office as an analyst for manned and unmanned platforms. Later, she worked in support of the DOD Space Architect Office during its stand-up and initial space system architecture design studies in the areas of satellite communications, satellite operations, and launch on demand. Dr. Weigel was elected as an AIAA associate fellow in 2007. She received an S.B. and an S.M. in aeronautics and astronautics and a Ph.D. in technology, management, and policy from MIT. She also received a second S.B. in science, technology, and society from MIT and an M.A. in international relations from George Washington University.

MICHAEL S. WITHERELL is vice chancellor for research at the University of California, Santa Barbara (UCSB). Dr. Witherell also holds a University of California Presidential Chair in the UCSB Physics Department. Dr. Witherell served as director of Fermi National Accelerator Laboratory (Fermilab), the largest particle physics laboratory in the country, from 1999 to 2005. From 1981 to 1999, he was a faculty member in the UCSB Physics Department. Dr. Witherell has done research in particle physics with accelerators at Brookhaven National Laboratory, Stanford Linear Accelerator Center, and Cornell Laboratory for Elementary Particle Physics, in addition to Fermilab. In 1990, his work at Fermilab studying charm quarks brought him the prestigious W.K.H. Panofsky Prize in Experimental Particle Physics, awarded annually by the American Physical Society (APS). Dr. Witherell was elected to membership in the National Academy of Sciences in 1998 for his work in the application of new technologies that "profoundly influenced all subsequent experiments aimed at the study of heavy-quark states." In 2004, he received the U.S. secretary of energy's Gold Award, the highest honorary award of the Department of Energy. He is a fellow of the AAAS and the APS. Dr. Witherell's most recent NRC service was as a member of the Committee on NASA's Beyond Einstein Program.

A. THOMAS YOUNG is a retired executive vice president of Lockheed Martin Corporation. Mr. Young previously was president and chief operating officer of Martin Marietta Corporation. Prior to joining industry, Mr. Young worked for 21 years at NASA, where he directed the Goddard Space Flight Center, was deputy director of the Ames Research Center, and directed the Planetary Program in the Office of Space Science. Mr. Young received high acclaim for his technical leadership in organizing and directing national space and defense programs, especially the Viking program. Mr. Young is a member of the National Academy of Engineering. He currently serves as the vice chair of the NRC Space Studies Board and formerly served on the Committee on the Scientific Context for Space Exploration (2004-2005), the Committee on Systems Integration for Project Constellation (2004), and the Committee on a New Science Strategy for Solar System Exploration (2001-2002), and he previously chaired the Committee for Technological Literacy.

Staff

ARTHUR A. CHARO, *Study Director*, joined the Space Studies Board (SSB) as a senior program officer in 1995. He has directed studies that have resulted in some 30 reports, notably the first National Research Council (NRC) decadal survey in solar and space physics (2002) and in Earth science and applications from space (2007). Dr. Charo received his Ph.D. in physics from Duke University in 1981 and was a postdoctoral fellow in chemical physics at Harvard University from 1982 to 1985. He then pursued his interests in national security and arms control at Harvard University's Center for Science and International Affairs, where he was a research fellow from 1985 to 1988. From 1988 to 1995, he worked as a senior analyst and study director in the International Security and Space Program in the U.S. Congress's Office of Technology Assessment. Dr. Charo is a recipient of a MacArthur Foundation Fellowship in International Security (1985-1987) and a Harvard-Sloan Foundation Fellowship (1987-1988). He was the 1988-1989 American Institute of Physics AAAS Congressional Science Fellow. In addition to NRC reports, he is the author of research papers in molecular spectroscopy, reports on arms control and space policy, and the monograph "Continental Air Defense: A Neglected Dimension of Strategic Defense" (University Press of America, 1990).

JOSEPH K. ALEXANDER served previously as director of the SSB (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.

ABIGAIL A. SHEFFER is an associate program officer with the SSB. She first came to the SSB in the fall of 2009 as a Christine Mirzayan Science and Technology Policy Graduate Fellow working with Dr. David Smith. Dr. Sheffer received her Ph.D. in planetary science from the University of Arizona and her A.B. in geosciences from Princeton University. She has assisted with several NRC reports including *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies.*

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.

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

TERRI BAKER is a senior program assistant. She comes to SSB from the National Academies' Center for Education. Mrs. Baker has held numerous managerial, administrative, and coordinative positions.

MICHAEL H. MOLONEY is the director of the SSB and the Aeronautics and Space Engineering Board at the NRC. Since joining the NRC in 2001, Dr. Moloney has served as a study director at the National Materials Advisory Board, the Board on Physics and Astronomy (BPA), the Board on Manufacturing and Engineering Design, and the Center for Economic, Governance, and International Studies. Before joining the SSB and ASEB in April 2010, he was associate director of the BPA and study director for the Astro2010 decadal survey for astronomy and astrophysics. In addition to his professional experience at the NRC, Dr. Moloney has more than 7 years' experience as a foreign-service officer for the Irish government and served in that capacity at the Embassy of Ireland in Washington, D.C., the Mission of Ireland to the United Nations in New York, and the Department of Foreign Affairs in Dublin, Ireland. A physicist, Dr. Moloney did his graduate Ph.D. work at Trinity College Dublin in Ireland. He received his undergraduate degree in experimental physics at University College Dublin, where he was awarded the Nevin Medal for Physics.