**Steps to Facilitate Principal-Investigator-Led Earth Science Missions**

Committee on Earth Studies, National Research Council
ISBN: 0-309-09185-3, 94 pages, 8 1/2 x 11, (2004)

# STEPS TO FACILITATE PRINCIPAL-INVESTIGATOR-LED EARTH SCIENCE MISSIONS

Committee on Earth Studies

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**

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by Contract NASW-01001 between the National Academy of Sciences and the National Aeronautics and Space Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the agency that provided support for the project.

*Cover:* Image courtesy of Graeme Stephens, Colorado State University, from his painting *Useful Pursuit of Shadows,* 2003.

International Standard Book Number 0-309-09185-3 (Book)
International Standard Book Number 0-309-53137-3 (PDF)

Copies of this report are available free of charge from:

Space Studies Board
National Research Council
500 Fifth Street, N.W.
Washington, DC 20001

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.



Printed in the United States of America.

# THE NATIONAL ACADEMIES

*Advisers to the Nation on Science, Engineering, and Medicine*

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Wm. A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. Wm. A. Wulf are chair and vice chair, respectively, of the National Research Council.

**www.national-academies.org**

**OTHER REPORTS OF THE SPACE STUDIES BOARD**

Issues and Opportunities Regarding the U.S. Space Program: A Summary Report of a Workshop on National Space Policy (2004)

"Assessment of NASA's Draft 2003 Earth Science Enterprise Strategy" (2003)
"Assessment of NASA's Draft 2003 Space Science Enterprise Strategy" (2003)
Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations (2003)
The Sun to the Earth—and Beyond: Panel Reports (2003)

Assessment of Directions in Microgravity and Physical Sciences Research at NASA (2002)
Assessment of the Usefulness and Availability of NASA's Earth and Space Science Mission Data (2002)
Factors Affecting the Utilization of the International Space Station for Research in the Biological and Physical Sciences (2002)
Life in the Universe: An Assessment of U.S. and International Programs in Astrobiology (2002)
New Frontiers in the Solar System: An Integrated Exploration Strategy (2002)
Review of NASA's Earth Science Enterprise Applications Program Plan (2002)
"Review of the Redesigned Space Interferometry Mission (SIM)" (2002)
Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface (2002)
The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics (2002)
Toward New Partnerships in Remote Sensing: Government, the Private Sector, and Earth Science Research (2002)
Using Remote Sensing in State and Local Government: Information for Management and Decision Making (2002)

Assessment of Mars Science and Mission Priorities (2001)
The Mission of Microgravity and Physical Sciences Research at NASA (2001)
The Quarantine and Certification of Martian Samples (2001)
Readiness Issues Related to Research in the Biological and Physical Sciences on the International Space Station (2001)
"Scientific Assessment of the Descoped Mission Concept for the Next Generation Space Telescope (NGST)" (2001)
Signs of Life: A Report Based on the April 2000 Workshop on Life Detection Techniques (2001)
Transforming Remote Sensing Data into Information and Applications (2001)
U.S. Astronomy and Astrophysics: Managing an Integrated Program (2001)

Limited copies of these reports are available free of charge from:
Space Studies Board
The National Academies
500 Fifth Street, NW, Washington, DC 20001
(202) 334-3477
ssb@nas.edu
www.nationalacademies.org/ssb/ssb.html

NOTE: Listed according to year of approval for release.

## COMMITTEE ON EARTH STUDIES

MICHAEL H. FREILICH, Oregon State University, *Chair*
ANTONIO J. BUSALACCHI, JR., University of Maryland
JOHN R. CHRISTY,* University of Alabama in Huntsville
CAROL ANNE CLAYSON, Florida State University
WILLIAM B. GAIL, Ball Aerospace and Technologies Corp.
CATHERINE GAUTIER,* University of California, Santa Barbara
WILLIAM C. GIBSON, Southwest Research Institute
SARAH T. GILLE, University of California, San Diego
ROSS N. HOFFMAN, Atmospheric and Environmental Research, Inc.
BRUCE D. MARCUS, TRW, Inc. (retired)
RALPH F. MILLIFF,† Colorado Research Associates
MICHAEL J. PRATHER,† University of California, Irvine
R. KEITH RANEY,* Johns Hopkins University
STEVEN W. RUNNING, University of Montana
LAWRENCE C. SCHOLZ,* Lockheed Martin (retired)
CARL F. SCHUELER, Raytheon Santa Barbara Remote Sensing
ROBERT A. SHUCHMAN, Altarum, Inc.
ROY W. SPENCER, University of Alabama
WILLIAM STONEY, Mitretek Corporation
JAN SVEJKOVSKY, Ocean Imaging, Inc.
KURT THOME, University of Arizona
JOHN R.G. TOWNSHEND, University of Maryland

*Staff*

ARTHUR CHARO, Study Director
THERESA M. FISHER, Senior Program Assistant

* Member through June 2001.
† Member through December 2002.

# Foreword

Principal-investigator (PI)-led missions are an important component of NASA's Earth Science Enterprise, as they are also for space science in general. They provide an opportunity to conduct focused scientific investigation of a size that can be managed by a scientist and his/her team, often as an integral part of a university-led research effort. They offer the opportunity to engage the best scientific talent of the nation, to introduce innovative instrumentation and mission concepts, and to make advances in selected scientific problems that ultimately may be addressed by larger missions.

PI-led missions, however, have not been free of difficulties. Despite their limited size, PI-led missions can stress particularly the development and management capabilities of a university-based scientist and can strain the limited budgets allotted to them. Difficulties can have their roots in many different aspects of the project: from the experience and capabilities of the PI team, to the initial definition of the mission, to how missions are selected, to how they are ultimately executed.

This report is intended to provide NASA with practical advice for improving all aspects of PI-led missions, and thus to preserve and enhance this essential component of the Earth Science Enterprise.

Lennard A. Fisk, *Chair*
Space Studies Board

# Preface

In a principal-investigator (PI)-led mission, the PI has responsibilities that range from defining the original concept to implementing it and then generating the final science results. In general, PI-led missions are associated with comparatively small spacecraft whose complement of sensors is smaller than that of the more traditional multisensor, facility-class missions. Among the advantages usually associated with small, PI-led missions is the flexibility to accommodate new technology or to make trade-offs among science and engineering goals. Typically, PI-led missions are executed to meet relatively short-term, well-focused science objectives.

NASA's Earth Science Enterprise (ESE) is placing increased emphasis on the use of smaller space missions through programs such as the Earth System Science Pathfinder, which organizes missions with small PI-led teams that are in some cases based at universities. This strategy is designed in part to enhance scientific and technical innovation in ESE programs by, for example, reducing mission development times and increasing the overall launch frequency. However, the development of small space missions poses technical and management challenges that are beyond the capabilities of most universities and university-based scientists. Indeed, part of the motivation for the current study can be traced to the failures in 1999 of the PI-led small space science missions TERRIERS and WIRE and to concerns regarding the cost and schedule of several small Earth science missions that were then in early development. The failures in 1999 of the Mars Climate Observer and the Mars Polar Lander, although they were not PI-class missions, also highlighted the need for increased attention to management structures and processes both inside and outside NASA.

At the request of NASA's Office of Earth Science, the National Research Council's Committee on Earth Studies began in the fall of 2000 to analyze a variety of issues thought to be relevant to the success of university-based PI-led Earth observation missions (see Appendix A for the statement of task). Because the Earth science community did not have the same breadth of experience as that developed over the years in the space sciences, both NASA and the committee viewed examination of the capacity of universities to manage complete space missions in the Earth sciences as particularly worthy of attention.

In addition to its own expertise, the committee drew on background information acquired at meetings with numerous scientists and engineers who had firsthand experience in leading or managing small, university-based space and Earth science missions (see Appendix B for the agendas of the two principal data-gathering meetings). The committee also met with representatives from companies that partner with PIs in conducting NASA-sponsored missions, and it benefited greatly from discussions with NASA officials in the Office of Space Science, the Office of Earth Science, and at NASA centers, especially the Earth Explorers Program Office at NASA Goddard

Spaceflight Center. The committee also thanks Daniel Baker, director of the University of Colorado's Laboratory for Atmospheric and Space Physics (LASP), for his assistance in organizing one of the data-gathering meetings and for making the facilities at LASP available to the committee, and it acknowledges the assistance of Jonathan Osgood, then an intern at Raytheon Santa Barbara Remote Sensing, in the preparation of Appendix C.

# Acknowledgment of Reviewers

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

Lew Allen, Jr., Jet Propulsion Laboratory (retired),
Christopher Justice, University of Maryland,
Gary Rottman, University of Colorado,
Mark Saunders, NASA Langley Research Center,
Joseph Veverka, Cornell University, and
Steven Wofsy, Harvard University.

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 Thomas Donahue, University of Michigan. Appointed by the National Research Council, 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.

# Contents

# Executive Summary

Over the last decade, NASA has increasingly emphasized small, focused principal-investigator (PI)-led science missions as an important element of its space and Earth science programs. NASA has chosen to implement many of these projects by soliciting mission ideas from the scientific community and giving the selected PI responsibility for both the scientific and the programmatic success of the entire project. With the first of these missions now launched and producing valuable scientific results, PI-led missions have established their importance as part of a balanced scientific observing program.

NASA's Earth Science Enterprise (ESE) initiated the Earth System Science Pathfinder (ESSP), its first program for PI-led missions, in 1996.[1] ESSP supports "low-cost, quick turnaround spaceborne missions" intended to provide "exploratory measurements which can yield new scientific breakthroughs and can deliver conclusive scientific results addressing a focused set of scientific questions."[2] Six missions have since been selected in three rounds of ESSP proposals, with one mission successfully launched and four in development for launch in 2004 and beyond (the sixth mission—Vegetation Canopy Lidar—was descoped to a technology development program and has now been canceled).

PI-led missions represent one of several programmatic approaches that ESE takes to obtain scientific data from space, including multi-instrument facility-class missions, data buys, dedicated observatories, and others. The Earth Explorers Program,[3] within which PI-led mission projects are executed, has proven to be a valuable and complementary component in this portfolio of mission approaches for obtaining the data required to support the

---

[1]According to the *NPG 7120.5B*, a *program* is "an activity within an Enterprise having defined goals, objectives, requirements, funding, and consisting of one or more projects, reporting to the NASA Program Management Council, unless delegated to a Governing Program Management Council"; a *project* is "an activity designated by a program and characterized as having defined goals, objectives, requirements, life cycle costs, a beginning, and an end." See *NASA Procedures and Guidelines 7120.5B: NASA Program and Project Management Processes and Requirements.* Available online at <http://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_7120_005B_&page_name=main>.

[2]ESSP-3 Announcement of Opportunity (AO), 2001. This and other reference documents for the ESSP program can be found in the ESSP AO library online at <http://centauri.larc.nasa.gov/essp/essplib.html>.

[3]NASA's Earth Explorers Program is "the component of Earth Science Enterprise that investigates specific, highly focused areas of Earth science research. It is comprised of flight projects that provide pathfinder exploratory and process driven measurements, answering innovative and unique Earth science questions." Currently, the components of the Earth Explorers Program are the Earth System Science Pathfinder; the Rapid Spacecraft Development Office; the Solar Radiation and Climate Experiment (SORCE), which is in orbit; and Triana, which has been placed in storage indefinitely. See the Earth Explorers Program home page at <http://earthexplorers.gsfc.nasa.gov/index.html>.

ESE objective of developing an understanding of the total Earth system and of the effects of natural and human-induced changes on the global environment.[4]

The explicit objectives of PI-led missions are usually stated clearly in the solicitation,[5] but such projects have also historically promoted additional ESE goals. In particular, PI-led missions have been viewed as a means to help develop the capacity of university-based research, building on the potential for leadership by university-based PIs and for the substantial involvement of educational institutions.

The experiences with the first six selected ESSP projects underscore the challenges that PI-led missions face. All spaceborne missions are subject to the risks associated with pursuing difficult objectives in the harsh environment of space. PI-led ESSP missions face further challenges that are closely associated with the ambitious objectives of the ESSP program, the limited resources available to satisfy those objectives, the uneven record of the solicitation and selection process in choosing viable missions, and the varying maturity of the processes for executing these missions.

The purpose of this study is to identify and evaluate opportunities for enhancing all aspects of PI-led missions and to recommend whether (and if so, how) they should be used to build the capacity of university-based research. The committee concluded that ESE should focus on enhancements for PI-led missions in three areas: the conceptualization of the programs, the institutional investments that support them, and the implementation of the projects themselves. Its findings and recommendations address potential enhancements aligned with these three areas.

***Finding:*** The PI-led mission paradigm represents a valuable approach to soliciting and executing missions involving focused science objectives, with demonstrated success in both the Earth and space sciences. PI-led missions provide an important element of the overall ESE observing strategy, complementing other elements such as facility-class missions and data buys.

***Recommendation:*** **NASA's Earth Science Enterprise should continue to employ PI-led missions as one element of the ESE observation system. It should ensure regular review and improvement of the programs that employ or are associated with PI-led missions to increase their effectiveness and value to ESE and the science community.**

## PROGRAM CONCEPTUALIZATION: MATCHING OBJECTIVES TO CONSTRAINTS

By design, the PI-led missions that are selected by NASA's ESE are ambitious in their expected science return and frugal in their demands on fiscal and other resources. In the committee's view, a mismatch between objectives and constraints has been the root cause of many difficulties encountered in the execution of PI-led missions.

***Finding:*** The scientific and programmatic objectives of ESE are ambitious compared with the constraints under which PI-led missions are implemented, particularly the capped funding and tight schedule.

***Recommendation:*** **NASA's Earth Science Enterprise should focus its programmatic objectives for PI-led missions to better match the available resources and constraints, with achievement of high-quality science measurements being the highest-priority objective.**

***Finding:*** Universities can derive considerable benefit by participating in an ESE mission; however, using PI-led missions to build the capacity of university-based research is not readily achievable within the structure and resources of current ESE PI-led programs.

---

[4]See the ESE home page at <www.earth.nasa.gov>.

[5]The primary stated objectives in the ESSP-3 AO (2001) solicitation included frequent low-cost missions, high-priority focused exploratory science, and innovative project implementation.

***Recommendation:*** **NASA's Earth Science Enterprise should not include building the capacity of university-based research as an explicit objective of PI-led missions unless fundamental changes are made to program structure and resources.**

## INSTITUTIONAL INVESTMENTS: ESTABLISHING THE FOUNDATIONS

Success in PI-led missions correlates with direction of the projects by experienced PI-led teams, the use of mature technologies,[6] and the existence of adequate project management tools at the time of mission selection. Ensuring an adequate number of potential proposers requires that opportunities exist to develop these tools and capabilities.

***Finding:*** The rigorous and ambitious cost and schedule constraints imposed on PI-led missions preclude all but minimal technology development prior to launch.

***Recommendation:*** **NASA's Earth Science Enterprise should explicitly nurture and coordinate technology feeder programs—such as the Instrument Incubator Program and the Office of Aerospace Technology's Mission and Science Measurement Technology Program—that develop technologies with potential application to PI-led missions. A quantitative assessment of the anticipated flow of technology through the technology readiness level chain would help guide this effort.**

***Finding:*** Proposers of non-selected PI-led missions found to have high scientific priority but known technical risk have limited access to funding for reducing the project's level of risk prior to the next proposal round. Both ESE and the scientific community would benefit from improved opportunities to reduce the technical risk of recognized high-priority science missions and then re-propose them.

***Recommendation:*** **NASA's Earth Science Enterprise should include within the solicitation for PI-led missions a component, following the Solar System Exploration Discovery model, that provides limited technology funding for high-priority non-selected PI-led mission proposals to increase their technology readiness for the next proposal round.**

***Finding:*** The Earth science community, particularly the university-based community, has historically produced only a small number of scientists with the in-depth space engineering and technical management experience that is required to lead a project in a PI mode of operation.

***Recommendation:*** **NASA's Earth Science Enterprise should formally identify and promote activities that develop PIs qualified to propose and lead small, focused science missions.**

## PROJECT IMPLEMENTATION: IMPROVING LIFE-CYCLE PROCESSES

The three fundamental elements of the PI-led mission life cycle—solicitation, selection, and execution—are part of a system of checks and balances. The system functions properly when the solicitation process establishes an achievable balance of objectives and resources, the selection process ensures that the chosen missions reflect that balance, and the execution process rigorously maintains the balance throughout mission development. Some of the problems encountered with current ESE PI-led missions could have been avoided if this system had worked more effectively. The committee's recommendations for enhancing project implementation focus on improving the checks and balances in each of these three life-cycle processes.

[6] NASA assesses the maturity of a technology according to technology readiness levels (TRLs). For an explanation of TRLs, see John C. Mankins, "Technology Readiness Levels: A White Paper," available at <www.ngst.nasa.gov/public/unconfigured/doc_0375/rev_02/technology_readiness.doc>. See also Table 4.1 in Chapter 4.

***Finding:*** Existing NASA guidelines (e.g., *NPG 7120.5B*) establish a management system relevant to PI-led missions, including an essential checks-and-balances formalism for the three PI-led mission project life-cycle processes of solicitation, selection, and execution.

***Recommendation:*** **NASA's Earth Science Enterprise should emphasize formal and regular reviews of the life-cycle system of checks and balances as applied to PI-led missions and should continuously strengthen the processes on which the system is based.**

***Finding:*** Many of the issues arising throughout a mission's lifetime are rooted in decisions made by the PI and project team during the formulation phase—early in the project—as the mission concept is developed, team roles and responsibilities (including NASA's) are defined, and the management approach is established. Ultimate mission success requires that major technical and programmatic issues be identified and jointly addressed by both the PI team and the NASA program office during the formulation phase. While extending competition between PI teams through the entire formulation phase provides NASA with additional insight into the effectiveness of the PI teams and the maturity of the mission designs, it delays the integration of the PI and NASA teams and motivates the PI teams to emphasize strengths and minimize weaknesses.

***Recommendation:*** **NASA's Earth Science Enterprise should avoid extensive overlap between competition and execution activities during the formulation phase of PI-led missions, thus providing an adequate schedule for the PI team and NASA to perform critical formulation tasks after the competitive selection is completed.**

## Solicitation

The objectives and constraints that drive a PI-led project are determined largely by the first element of the life cycle, solicitation. A carefully constructed solicitation can provide for a more achievable balance between objectives and constraints, thus increasing the probability of receiving viable proposals.

***Finding:*** The threat of project cancellation has not proved effective either in motivating the submission of PI-led proposals with adequate reserves or in constraining costs to meet the cost cap.

***Recommendation:*** **NASA's Earth Science Enterprise should redefine cost caps from a threshold that triggers an automatic termination review to a threshold for a remedial review that includes an examination of how the division of responsibility and authority between the PI and ESE might be revised to better control costs. Cost caps should be established only when the project has reached a sufficient level of maturity that the proposed cost is credible, such as at mission design review. ESE should also consider the use of a science floor, a PI-proposed minimum scientific achievement needed to justify the mission, in setting and managing within cost caps.**

***Finding:*** Domestic and international partners have increasingly been included on PI-led mission teams to enhance the quality of science achievable within the available ESE project budget. Despite the many benefits of such collaborations, more complex and diverse teams increase risk and add costs to pay for team interfaces.

***Recommendation:*** **NASA's Earth Science Enterprise should recognize not only the benefits but also the risks of having domestic and international partners in a PI-led mission program. The mission solicitation should identify the need for processes by which both the PI team and the relevant NASA office ensure that partnering agreements are completed early in the formulation phase, that definition of an interface is given high priority, and that the management decision chain is clear and is understood by all parties.**

***Finding:*** A properly constructed solicitation balances the need for proposals detailed enough to permit thorough evaluation against the time required both to prepare and to evaluate proposals. The two-step proposal process, in particular the use of short Step 1 proposals within ESSP, has provided a workable balance. However, the lack of NASA-funded support for proposals, particularly during Step 2, is increasingly limiting the ability of smaller organizations and universities to participate.

*Recommendation:* **NASA's Earth Science Enterprise should maintain the current two-step proposal process for PI-led missions but should provide funding to proposers for Step 2.**

***Finding:*** Scientific results are the primary objective in PI-led missions, but postlaunch science funding commitments are not adequately identified in mission solicitations.

*Recommendation:* **NASA's Earth Science Enterprise should clearly specify within the solicitation for a PI-led mission the extent to which scientific investigation and data analysis are expected to be included in the initial mission project budget, as well as the anticipated plans and budget for additional postlaunch science investigations. The science funded for the mission should address a PI-proposed science floor.**

***Finding:*** Effective communication and the transfer of lessons learned between the Earth Explorers Program Office, current flight projects, and potential PI proposers can both increase the number of qualified proposers and reduce the risk associated with proposed projects.

*Recommendation:* **NASA's Earth Science Enterprise should continue to emphasize and promote communication and the transfer of lessons learned between the Earth Explorers Program Office, current flight projects, and potential PI proposers.**

## Selection

Even a well-designed solicitation fails if the second element in the life cycle, the selection process, cannot reliably identify and select PI-led missions that both satisfy the solicitation and can be implemented within cost and schedule constraints.

***Finding:*** The quality of the selection process determines whether viable projects proceed to execution and thus greatly influences the overall success of PI-led missions. Selection criteria for PI-led missions, particularly those employed in Step 2, must adequately consider the ability of the project team to successfully implement a project; the ESE associate administrator must be provided sufficient information to determine the likely success of a project; and the selection decision must reflect an objective evaluation of the likelihood of success.

*Recommendation:* **NASA's Earth Science Enterprise should carefully review the selection criteria for PI-led missions to ensure that they adequately identify and promote missions that can succeed.**

***Finding:*** The number of qualified reviewers for ESE PI-led missions is small, particularly after elimination of scientists with conflicts of interest because of relationships with proposing teams.

*Recommendation:* **NASA's Earth Science Enterprise should consider enlarging the pool of possible reviewers of PI-led missions by adding qualified international scientists (if feasible, given current International Traffic in Arms Regulations constraints) and scientists from the space science community. ESE should also consider requiring as part of the contract for selected PI-led projects that the PI serve subsequently as a reviewer.**

***Finding:*** The number of proposals selected for consideration in Step 2 represents a critical compromise between the desire for a large pool of evaluated PI-led mission proposals from which to make the final selection and the need for a pool small enough that available reviewers can perform detailed reviews. Selection for Step 2 of proposals that have a lower probability of final selection results in inefficient use of proposers' resources.

***Recommendation:*** **The proposals supported in Step 2 of the selection process for PI-led missions should include only those that have sufficiently high scientific merit and an acceptable initial evaluation of technical, management, and cost risk so as to be fully competitive with all other Step 2 proposals. As an informal guideline, a minimum of two Step 2 proposals should be selected for evaluation for each flight opportunity to be awarded, and the maximum number considered should be one-third of the total proposals submitted in Step 1.**

***Finding:*** Maintaining and improving the credibility of checks and balances is the highest priority for enhancing the selection process for PI-led missions. An effective and credible proposal review process requires a balanced effort among proposers, reviewers, and the selection official. Proposers are motivated to avoid overly optimistic costing if they respect the cost-review process; reviewers are more diligent when their recommendations are likely to be accepted by the selection official; and the selection official relies more readily on reviewer recommendations when the proposal and review process is effective at identifying the best mission candidates.

***Recommendation:*** **NASA's Earth Science Enterprise should strengthen the complementary roles of proposers, reviewers, and the selection official in the selection process for PI-led missions, improving the critical balance between the three roles and focusing on clear traceability of the selection process to independent reviews and established ESE priorities.**

***Finding:*** The availability of accurate cost estimates is a very important element of the mission selection process, but establishing accurate estimates of project cost has historically provided one of the largest challenges to both proposers and reviewers of PI-led missions.

***Recommendation*****:** **NASA's Earth Science Enterprise should enhance its cost evaluation capabilities to improve the accuracy of mission selection decisions and to motivate improved fidelity of cost proposals.**

### Execution

Finally, selected PI-led missions will not succeed if the execution processes are inadequate.

***Finding:*** Although some of the difficulties with recent PI-led missions are unique, many of the problems encountered have root causes in common with non-PI-led missions. In particular, the transition to smaller cost-constrained projects during the 1990s and the contraction and aging of the space industry workforce have affected project success. These problems should not be attributed to flaws in the PI-mode process, but rather applied as general lessons for all small-mission projects.

***Recommendation:*** **NASA's Earth Science Enterprise should establish management processes for PI-led missions that emphasize understanding all PI-led and non-PI-led mission issues and the inclusion of appropriate lessons learned from both types of missions.**

***Finding:*** Mission success is appropriately viewed as the combined responsibility of the PI-led team and NASA. Split as opposed to shared authority is appropriate for achieving mission success and is healthy for the PI community; split authority and the resulting allocation of responsibility should be explicitly recognized in the project plan and should also reflect the philosophy inherent in PI-led missions that the mission is to be defined and developed by the science community itself.

***Recommendation:*** **NASA's Earth Science Enterprise should explicitly recognize that mission success is a combined responsibility of the PI team and NASA and should establish project management plans, organizations, and processes that reflect an appropriate split, not a sharing, of authority, with the PI taking the lead in defining and maintaining overall mission integrity.**

***Finding:*** While it may be appropriate for PI-led missions to use management processes that differ from NASA standards, NASA-defined minimum management standards are desirable to reduce programmatic risk to acceptable levels.

***Recommendation:*** **NASA's Earth Science Enterprise should establish and enforce a comprehensive set of minimum standards for program management to be applied to all PI-led missions, while accepting that such missions may employ management processes that differ from those of NASA. These minimum management standards must invoke the rigor that experience has shown is required for success.**

# 1

# Introduction

NASA's Earth Science Enterprise (ESE) uses remotely sensed observations to develop scientific understanding of the total Earth system and the effects of natural and anthropogenic changes on the global environment. ESE-supported research combines observations and modeling to characterize forcing and response, understand internal variability in Earth's systems, and ultimately increase the accuracy of a variety of predictions. ESE pursues vigorous research on climate interactions, atmospheric phenomena, terrestrial and oceanic processes and ecosystems, and solid earth processes with the goal of determining their impacts on natural resource availability, resource management, and food production.[1]

The acquisition of accurate and adequately sampled measurements from space is crucial to ESE objectives, and so ESE sponsors research to develop new measurement approaches and to expand the scope and accuracy of data analyses. A substantial fraction of ESE's resources is devoted to developing, launching, and operating satellite missions and generating, validating, and distributing scientifically useful products. These products in turn provide crucial input to a variety of scientific, operational, and applications endeavors.

ESE employs four basic types of space mission programs to provide data in support of ESE scientific objectives:

- *Facility-class missions at the observatory level* acquire simultaneous, colocated measurements from many instruments; recent examples include the Upper Atmosphere Research Satellite (UARS), Terra, Aqua, and Aura. This class of missions formed the foundation of the Earth Observing System (EOS) program.
- *Facility-class missions and instruments at the dedicated measurement level* provide platforms focused on a single measurement set with previously identified value to generate long-duration, accurate data useful for focused scientific investigations and modeling studies; recent examples include Landsat-7, TOPEX/Poseidon, QuikSCAT, TRMM, TOMS, and SAGE.
- *Exploratory missions* provide platforms intended to investigate new processes or phenomena or to evaluate innovative measurement approaches; recent examples include GRACE, CALIPSO, CloudSat, and Triana.[2] ESE

[1]The 2001 ESE strategic plan, *Exploring Our Home Planet: Earth Science Enterprise Strategic Plan*, can be found at <http://www.earth.nasa.gov/visions/stratplan/index.html>. A newer version of the plan was in preparation at the time this report went to press. See <http://www.earth.nasa.gov/visions/index.html>.

[2]Mission descriptions are available at <http://earthexplorers.gsfc.nasa.gov/project.html> and at the link to ESSP missions, <http://essp.gsfc.nasa.gov/esspmissions.html>. Also see Appendix C, Tables C.3 and C.4, of this report.

has chosen to implement many of the missions in this class through competitive selection of a principal investigator (PI) who is given responsibility for the programmatic and/or scientific leadership of the mission.

• *Data purchase agreements* provide an alternative means of obtaining Earth science data when the data are available from the private sector as commercial products; the best recent example is NASA's purchase of SeaWiFS data from the private SeaStar mission.[3] In data purchase agreements, ESE coordinates data product quality (including formats, accuracy, and overall coverage and usage timelines) with private-sector suppliers based on requirements and assessments provided by NASA-appointed science panels. The private company owns and operates the spaceborne hardware and retains commercial rights to the data, which NASA makes available at no cost to scientists for noncommercial research use under terms previously agreed to by NASA and the private-sector suppliers.[4]

## PI-LED MISSIONS AND CHALLENGES

Over the last decade, NASA has increasingly solicited proposals for exploratory missions through Announcements of Opportunity (AOs) and implemented them as PI-led projects. In this study, the committee defines a PI-led mission as one with the following characteristics. A single PI, working with his/her team, is responsible for the leadership and successful performance of the mission/investigation. The PI has a large degree of freedom with which to accomplish the proposed objectives with appropriate NASA oversight, which includes reporting requirements at a level that will ensure mission success and agreed upon science return in compliance with the committed cost, schedule, performance, quality, reliability, and safety requirements. The level of NASA's oversight involvement may vary from mission to mission, depending on the implementing organization and other programmatic considerations.[5]

Within ESE, PI-led missions have been aggregated into a program called Earth Explorers,[6] which is managed for ESE by the Goddard Space Flight Center. The Earth Explorers Program was established by ESE to provide unique, focused, and rapid remotely sensed measurements that address high-priority Earth science questions.[7] Measurements acquired by Earth Explorer missions are intended to be complementary to, and not duplicative of, data available from any existing or approved national, international, or commercial satellites. PI-led Earth Explorer missions are competitively selected from proposals submitted in response to an open AO and are managed by a single PI with formal control over, and responsibility for, all aspects of the mission in cooperation with NASA.

The selection, implementation, management, and flight of these types of missions present challenges to both ESE and the Earth science community similar to those in other relatively small, rapid, and cost-constrained space missions.[8] In addition, however, PI-led Earth Explorer missions, especially those for which the PI is affiliated with a university, face particular difficulties that arise from factors such as a typical lack of mission- and project-management expertise among PIs, weak institutional support bases, management ambiguities resulting from

---

[3]C.R. McClain, M.L. Cleave, G.C. Feldman, W.W. Greg, S.B. Hooker, and N. Kuring, 1998, Science quality SeaWiFS data for global biosphere research, *Sea Technology*, Sept., pp. 10-16; see also National Research Council (NRC), Space Studies Board, 2000, *The Role of Small Satellites in NASA and NOAA Earth Observation Programs,* National Academy Press, Washington, D.C., pp. 84-87 (the NRC *Small Satellite*s report).

[4]See discussion of SeaWiFS in Appendix D of the NRC *Small Satellite*s report, pp. 84-87.

[5]See AO-01-OSS-03, Medium-Class Explorer and Missions of Opportunity: Announcement of Opportunity, Section 3.1.

[6]NASA's Earth Explorers Program is composed of "flight projects that provide pathfinder exploratory and process driven measurements, answering innovative and unique Earth science questions. The program has the flexibility to take advantage of unique opportunities offered through technical innovation by domestic or international cooperative efforts. It provides the ability to investigate processes having unique measurement requirements and which call for quick turnaround and reaction." See Earth Explorers mission statement at <http://earthexplorers.gsfc.nasa.gov/>. Currently, the components of the Earth Explorers Program are ESSP; the Rapid Spacecraft Development Office; SORCE, which is in orbit; and Triana, which has been placed in storage indefinitely.

[7]See note 6. Also from N. Chrissotimos, NASA Goddard Space Flight Center, presentation to the Committee on Earth Studies, April 25, 2001, p. 3.

[8]See NRC, *The Role of Small Satellites in NASA and NOAA Earth Observation Programs*, 2000.

shared responsibilities between the PI and ESE for the ultimate success of the mission, and the need to balance cutting-edge science with training of the next generation of Earth scientists, engineers, managers, and entrepreneurs.

Implementation experiences for Earth Explorer missions to date have been decidedly mixed. Several missions has been successfully launched, others are proceeding well toward near-term launch dates, and a few have suffered significant cost and schedule growth, resulting in long delays and ESE-mandated changes in management and/or flight status. These diverse experiences led NASA to ask the Committee on Earth Studies to examine the challenges associated with Earth Explorer missions led by academic PIs, and to evaluate a series of evolutionary programmatic changes in the Earth Explorers Program that have been made by ESE over the last 7 years (see the statement of task, Appendix A).

## ORGANIZATION OF THIS REPORT

This report discusses issues and improvements in three fundamental areas identified by the committee as having high leverage for enhancing PI-led missions: improving the *conceptualization* of programs under which PI-led missions are executed, enhancing the *institutional investments* that support these programs, and improving *project implementation* processes. These areas are discussed in Chapters 3, 4, and 5, respectively. Chapter 6 provides an overall study summary and conclusion. Additional supporting information is contained in the appendixes.

# 2

# Background: PI-Led Missions in the Earth Science Enterprise

This chapter outlines the scientific and programmatic objectives of PI-led missions in ESE and summarizes NASA's experience with PI-led missions in both Earth and space sciences over the last several decades.

## THE ROLE OF EARTH EXPLORER MISSIONS

Through the 1980s and 1990s, NASA's Earth science program built the foundation of its observing system on facility-class missions, including core Earth Observing System projects that have evolved into the current Terra, Aqua, and Aura missions. Facility-class missions have been generally successful in providing an unprecedented quantity of unique, high-quality data for Earth science investigations. However, since each facility-class mission is required to serve many different user communities, individual science objectives and instrument capabilities have sometimes been compromised because of limitations in overall mission resources and spacecraft accommodation.

In addition, facility-class mission costs have been high and development times long, in part because steps must be taken to mitigate significant scientific and programmatic risks associated with the launch or on-orbit failure of large satellites. But the pace of advances in scientific understanding and measurement technology have often resulted in considerable changes in scientific priorities or instrument capabilities during the decade or more that typically has passed between selection of the instrument complement for a facility-class mission and its eventual launch.

ESE established the Earth Explorers Program to address these issues by providing frequent, flexible opportunities for rapid-development flight missions focused on specific Earth science investigations. Earth Explorer missions thus fill a well-defined and focused role in ESE, complementing facility-class missions to achieve ESE's overall scientific objectives.

### Objectives of the Earth Explorers Program

The Earth Explorers Program is explicitly designed to support Earth remote sensing missions that contribute directly to:

- Acquiring key additional measurements in response to new scientific understanding, including exploiting scientific discoveries from facility-class missions;
- Proving the concept and scientific utility of new data sets and measurement approaches; and/or
- Ensuring the continuity of critical measurement time series (i.e., "gap filler" missions for critical data sets).

Although the following are not always stated as explicit goals, the program appears also to have been designed to:

- Provide frequent, predictable opportunities for training new investigators and ensuring the continued broad involvement of the scientific community in the overall development of ESE satellite projects;
- Encourage direct involvement of university faculty and students in all aspects of ESE flight mission planning and implementation, and expand the base of academic institutions that have the capability (through experienced faculty) to manage satellite-related technical projects; and
- Foster development of innovative teaming arrangements that optimize the contributions and minimize the costs of industry, university, and government partners.

### Constraints Within the Earth Explorers Program

The Earth Explorers Program also has a wide-ranging set of explicit constraints that greatly influence all aspects of its sponsored missions.[1] These constraints fall generally into the areas of (1) mission scope and capabilities, and (2) mission selection and management.

- *Mission Scope and Capability Constraints*
  - — Acquisition of measurements from space must be central to each mission, with each mission acquiring all unique measurements and producing all fundamental new products needed to solve the defined scientific problem.
  - — Prelaunch development time must be less than 36 months.
  - — All data required to make substantial progress on the defined scientific problem must be acquired within 3 to 4 years after launch.
  - — Mission success must not require a sustained, long-term commitment on the part of the responsible institution or PI beyond the expected on-orbit mission lifetime.
  - — NASA costs are capped, although collaborations with domestic and international partners are allowed in order to increase scientific return without requiring additional direct NASA funding.
  - — NASA funding for launch vehicles is separately limited and can only be applied to a specific list of launch vehicle options.
- *Mission Selection and Management Constraints*
  - — All missions are selected competitively in response to open AO solicitations.
  - — Missions are led by a principal investigator.

## EARTH EXPLORERS PROGRAM COMPONENTS

Until FY2002, the Earth Explorers Program included two primary PI-led mission components with related but distinct goals and scope: the Earth System Science Pathfinder (ESSP) and the University Earth System Science (UnESS) components.[2] Although UnESS was not funded by Congress in FY2002 and is not part of the approved FY2003 budget, the committee believes that its objectives were unique, important, and contributed directly to the development of end-to-end remote sensing expertise in the academic community. Thus, while this report focuses

[1]Richard Zurek, Jet Propulsion Laboratory, "PI-Mode Management: Response to ESE Biennial Review Action BR-2, May 26, 2000," presentation made to the Committee on Earth Studies, December 12, 2000.
[2]NASA maintains a home page for UnESS at <http://www.wff.nasa.gov/~code850/pages/uness.html>.

on ESSP as the primary remaining PI-led mission component of the Earth Explorers Program, descriptions and analyses of UnESS are included where appropriate.

## Earth System Science Pathfinder

ESSP AOs solicit proposals for focused, unique PI-led satellite missions that support any of the ESE Earth science objectives.[3] ESSP missions are selected to provide new space-based observations that are complementary to, and not duplicative of, existing and planned data sets. Although ESSP missions may demonstrate the utility of new measurement types and approaches, the conduct and substantial solution of a specific, well-defined geophysical investigation using 3 to 4 years of on-orbit data is a paramount programmatic requirement.

The most recent ESSP AO explicitly requires that the proposed science be considered high priority and clearly beyond the scope of that possible from existing or approved missions in order for the proposed mission to be accepted.[4] Successful ESSP proposals are supported over the total mission life cycle from concept formulation and refinement through integration, test, and launch, followed by production and dissemination of validated geophysical data sets. Proposed missions must include payload, spacecraft, and launch components in addition to data production and validation activities—they cannot be restricted to provision of a limited suite of instruments to fly as a partial, or secondary, payload in association with another mission.

The NASA cost for each ESSP mission is capped at a level defined in the AO. To maximize the scientific value and minimize NASA's cost, PIs are encouraged to collaborate in a cost-sharing mode with non-NASA organizations, including foreign organizations and agencies.[5]

Table 2.1 summarizes the ESSP selections to date. The first ESSP AO was issued in 1996 and resulted in the selection of the Vegetation Canopy Lidar (VCL) and GRACE missions. CloudSat and what is now called CALIPSO were chosen from the second ESSP AO in 1998; Aquarius and the Orbiting Carbon Observatory (OCO) were selected during the third AO in 2001.

The life cycle of a PI-led ESSP mission begins with a science-oriented Step 1 proposal effort. Selection at the end of Step 1 leads to a recommendation for submission and evaluation of a competitive Step 2 proposal, which must include the technical aspects of mission development as well as the science. Selection after a Step 2 proposal results in a funded mission project, which leads to a mission confirmation review. After passing mission confirmation, the project moves on to implementation and launch. Following launch and after up to 3 to 4 years of on-orbit data acquisition, the baseline PI mission is regarded as complete. Figure 2.1 provides an overview of the selection process and other mission stages.

## University Earth System Science

UnESS sought to develop PI-led spaceflight missions in which all aspects of the scientific formulation, mission design, implementation, and data analysis would be performed substantially by students. Like ESSP, UnESS missions were to involve the use of space-based data to address geophysical problems related to the ESE science strategy and complementary to other ESE investigations and missions. However, in contrast with other ESE flight programs, UnESS objectives and mission selection criteria gave equal weight to science and to the training and education of researchers, engineers, managers, educators, and entrepreneurs through extensive hands-on involvement throughout the mission.

UnESS missions were designed to be smaller than ESSP missions and to be developed at lower cost and on a faster schedule. Mission scope was not expected to be as encompassing as for an ESSP mission. NASA costs were capped at $15 million; typically, missions were intended to have a 9-month concept study followed by 24 months for definition, approval, design, and development. Unlike ESSP missions, UnESS investigations also did not have

[3]The science objectives for NASA's ESE can be found on the ESE home page at <http://www.earth.nasa.gov>.
[4]ESSP-3 AO, p. 12.
[5]ESSP-3 AO.

TABLE 2.1 History of Earth System Science Pathfinder Selections

| | No. of Step 1 Proposals | No. of Step 2 Proposals | No. of Candidates at Mission Confirmation Review | Cost Cap ($ million) | Selected Mission[a] | Status[b] |
|---|---|---|---|---|---|---|
| ESSP-1 (1996) | 44 | 12 | 2 + alternate | 60 | VCL | No longer an active mission |
| | | | | 90 | GRACE | On-orbit, launched May 2002 |
| | | | | | CCOSM | Alternate; not selected for flight development |
| ESSP-2 (1998) | 20 | 10 | 2 + alternate | 120 | CloudSat | Launch April 2004 |
| | | | | 120 | CALIPSO | Scheduled for launch in 2004 |
| | | | | 120 | VOLCAM | Alternate; not selected for flight development |
| ESSP-3 (2001) | 18 | 6 | 2 + alternate | 125 + launch vehicle | Aquarius | Missions selected July 2002 and now in study phase |
| | | | | 125 + launch vehicle | OCO | In formulation phase; scheduled for launch in August 2007 |
| | | | | 125 + launch vehicle | HYDROS | In formulation phase; scheduled for launch in December 2009 |

[a]For additional data on these missions, see Appendix C, Table C.4.
[b]See <http://essp.gsfc.nasa.gov/esspmissions.html>.

to be complete flight missions in which the proposed instrument (or instrument suite) was the primary payload on the spacecraft and launch vehicle. Instead, UnESS proposals could address partial missions, in which the instrument was a secondary payload on the spacecraft.

As originally designed, UnESS was to release biennial solicitations, from each of which two missions would eventually be selected for flight, leading to a flight rate of about one UnESS mission per year. The first (and only) UnESS AO was released in late 1999; of the 24 proposals submitted, 4 were selected for further concept definition (a fifth effort, resulting from combining two separate proposals, was also supported in the concept definition phase). But UnESS was not funded by Congress in the FY2002 budget, precluding advancement of any of the missions to development or flight.

## DISTINGUISHING CHARACTERISTICS OF PI-LED MISSIONS

Distinctions in scientific focus and mission management differentiate Earth Explorer missions from the larger and longer-duration facility-class missions.

### Scientific Characteristics

Facility-class missions are justified based on the breadth of the science enabled by the data they collect and the contributions of the measurements they make to the generation of multidecadal time series of key quantities. To ensure widespread exploitation of the data, ESE selects interdisciplinary science teams for the facility-class

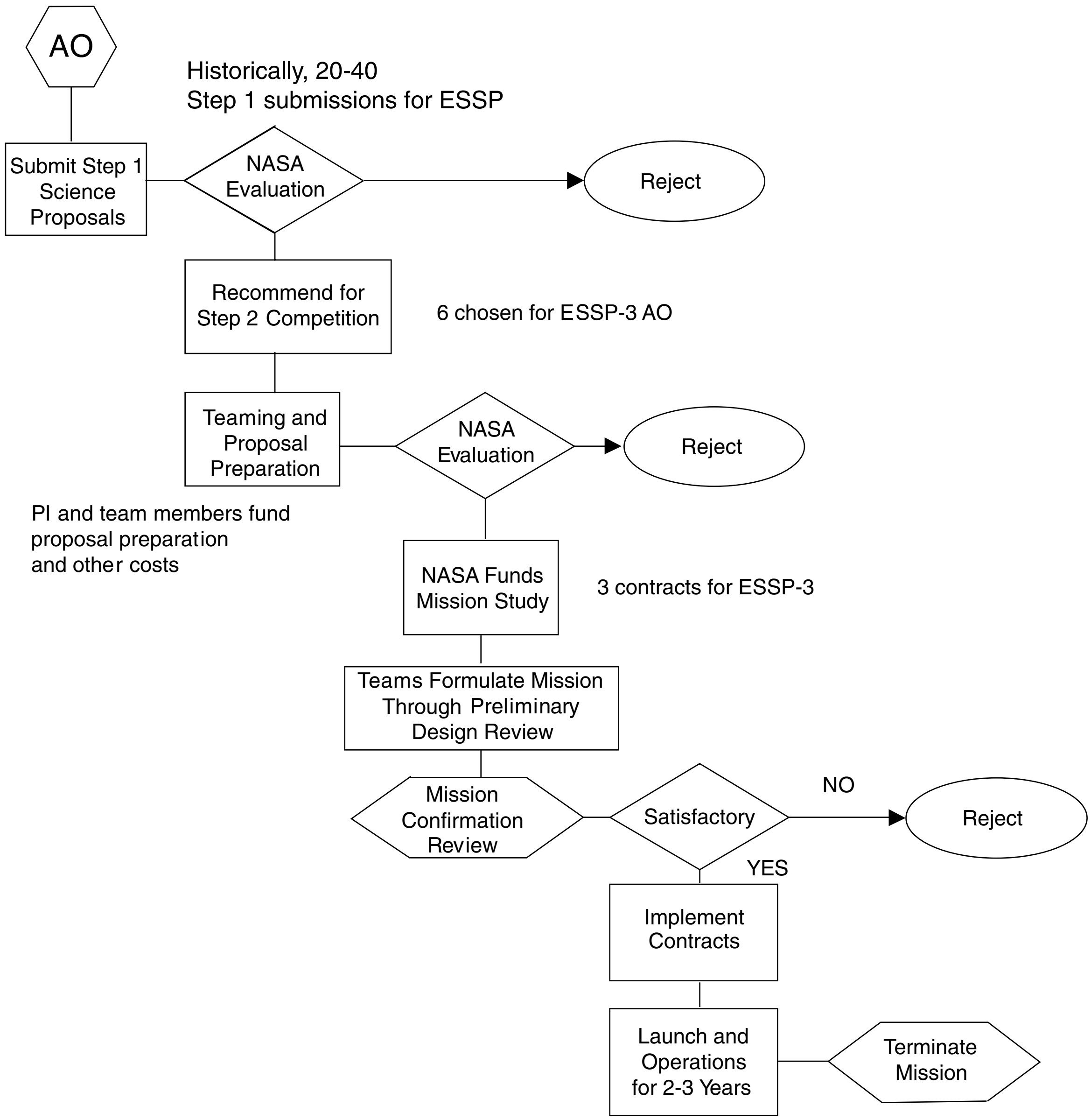


FIGURE 2.1 Steps in the development and execution of an ESE PI-led mission.

missions through competitive research announcements. During the prelaunch phases of the missions, competing and evolving requirements of different scientific users can influence the design of the instruments, data products, and calibration/validation activities in the quest for broad scientific utility. Facility-class missions thus fulfill an ESE commitment to acquire data for many segments of the Earth science community; however, this commitment can result in the degradation of the measurements' utility for specific investigations in exchange for their contributions to a wide range of multidisciplinary studies.

In contrast, PI-led Earth Explorer missions are distinguished by their focus on well-defined, important geophysical problems that are amenable to substantial progress using 3 to 4 years of on-orbit measurements; indeed, the ranking of the proposed investigation's contemporary scientific importance is a primary selection criterion for Earth Explorer (and especially ESSP) missions. The focus on addressing a small set of specific scientific problems ensures that trade-offs made during the development stages (for example, to accommodate mission constraints) directly support the particular scientific goals that were the basis for the mission's initial acceptance; at least in principle, design and implementation trade-offs do not require balancing the needs and desires of diverse research communities addressing a wide range of geophysical investigations. All of the Earth Explorer AOs to date have limited the funding of the science team to the design, production, and validation of new geophysical data products, rather than the solution of an identified problem or the conduct of the specific investigation(s) that formed the basis for the mission's selection and justification. Funding for the latter is awarded competitively as the mission approaches operational status through a separate Science Data Analysis Program (SDAP) NASA Research Announcement (NRA).

### Programmatic Characteristics

The NASA-mandated PI-led mission management approach is fundamental to the Earth Explorers Program and is a significant differentiator between Earth Explorer missions and facility-class missions. There is, however, no unique definition of a "PI-led management approach." As articulated in presentations to the committee by NASA program and NASA center officials, as well as in the most recent ESSP AO,[6] the intention of the PI-led management approach is to vest end-to-end mission responsibility (from original concept, through implementation, to generation and distribution of validated data sets and products derived from remotely sensed measurements) in a single, identified PI, working with a team of his or her choice.[7] The PI is accountable to NASA for overall mission success, including maintenance of the scientific/applications integrity and success of the mission.[8] To achieve these ends, the PI is formally empowered to manage cost and schedule milestones at every stage of the mission;[9] in particular, the PI is responsible for making key science trade-offs, including those required by resource limitations (e.g., funding, mass, power, accommodation).[10]

## VIABILITY OF THE PI-LED MISSION APPROACH

Over the last decade, PI-led missions have been used increasingly as a fundamental building block of NASA's ESE and Space Science Enterprise (SSE). PI-led missions represent a trade-off between two important but potentially conflicting objectives: *innovation* derived from direct ownership of mission success by PIs in the science community, and *mission success* based on the long heritage of successful projects performed in the NASA centers. Both ESE and SSE have begun to recognize that a balanced scientific program includes elements that accept some increased risk to mission success in return for enhanced scientific and programmatic innovation.

The PI-led mission paradigm has indeed led to innovative science that has been successfully executed. Within SSE, these projects include the NEAR mission, which achieved the first rendezvous with an asteroid, and the MAP mission, which is redefining our understanding of the cosmic background radiation and the early universe. Within ESE, projects include the GRACE mission, which is providing profound insights into Earth's structure, and the recently launched SORCE mission, which is investigating the role of solar variability in climate change.

The committee believes that the PI-led approach to implementing missions is fundamentally valuable, subject to acceptance of the trade-off between innovation and risk. As one element of an overall scientific program, PI-led missions provide an important complement to facility-class missions and other means for obtaining scientific data.

[6] The ESSP-3 AO can be found at <http://centauri.larc.nasa.gov/essp/>.
[7] Richard Zurek, Jet Propulsion Laboratory, presentation to the Committee on Earth Studies, December 12, 2000.
[8] ESSP-3 AO, p. 27; N. Chrissotimos, NASA Goddard Space Flight Center, presentation to the Committee on Earth Studies, April 25, 2001, p. 9.
[9] ESSP-3 AO, p. 25.
[10] Richard Zurek, Jet Propulsion Laboratory, presentation to the Committee on Earth Studies, and ESSP-3 AO, p. 18.

**BOX 2.1**
**Findings from**
***Assessment of Mission Size Trade-Offs for NASA's Earth and Space Science Missions***

- A mixed portfolio of mission sizes is crucial in virtually all Earth and space science disciplines to accomplish the various research objectives. The FBC [faster, better, cheaper] approach has produced useful improvements across the spectrum of programs regardless of absolute mission size or cost.
- Shorter development cycles have enhanced scientific responsiveness, lowered costs, involved a larger community, and enabled the use of the best available technologies.
- The increased frequency of missions has broadened research opportunities for the Earth and space sciences.
- Scientific objectives can be met with greater flexibility by spreading the program over several missions.

Nonetheless, some problems exist in the practical application of the FBC approach, including the following:

- The heavy emphasis on cost and schedule has too often compromised scientific outcomes (scope of the mission, data return, and analysis of results).
- Technology development is a cornerstone of the FBC approach for science missions but is often not aligned with the science-based mission objectives.
- The cost and schedule constraints for some missions may lead to choosing designs, management practices, and technologies that introduce additional risks.
- The nation's launch infrastructure is limited in its ability to accommodate smaller spacecraft in a timely, reliable, and cost-effective way.

SOURCE: Space Studies Board, National Research Council. 2000. *Assessment of Mission Size Trade-Offs for NASA's Earth and Space Science Missions.* National Academy Press, Washington, D.C., p. 3.

A mixed portfolio of mission sizes was endorsed in a previous National Research Council report,[11] which also provides insight into many issues associated with PI-led missions, as summarized in Box 2.1.

***Finding:*** The PI-led mission paradigm represents a valuable approach to soliciting and executing missions involving focused science objectives, with demonstrated success in both the Earth and space sciences. PI-led missions provide an important element of the overall ESE observing strategy, complementing other elements such as facility-class missions and data buys.

***Recommendation:*** **NASA's Earth Science Enterprise should continue to employ PI-led missions as one element of the ESE observation system. It should ensure regular review and improvement of the programs that employ or are associated with PI-led missions to increase their effectiveness and value to ESE and the science community.**

[11]National Research Council, Space Studies Board, 2000, *Assessment of Mission Size Trade-offs for NASA's Earth and Space Science Missions,* National Academy Press, Washington, D.C. See Box 2.1.

# 3

# Program Conceptualization: Matching Objectives to Constraints

Successful programs start with proper conceptualization, including the identification of well-defined and widely understood objectives and the establishment of resources sufficient to achieve those objectives. This chapter identifies several areas in which it has proved difficult to match objectives and resources for existing PI-led missions and investigates how the issue is addressed in several non-PI-led programs.

## STATED OBJECTIVES AND CONSTRAINTS

Table 3.1 summarizes ESE's stated ESSP objectives and constraints, which are representative of all ESE PI-led missions and are appropriate as guidelines for PI-led missions when considered individually. Nevertheless, the combination of ambitious scientific and programmatic objectives, coupled with tight schedules, capped costs, and (to a lesser extent) management and implementation constraints, makes PI-led missions very challenging, even in comparison to larger, more typical NASA projects.

## UNSTATED OBJECTIVES AND CONSTRAINTS

In addition to the stated objectives listed in Table 3.1, there are a number of unstated objectives that PI-led missions are expected to satisfy, including the desire to increase the capacity of university-based research (which is an explicit objective of UnESS). Potential mismatches between unstated objectives and existing constraints are often more difficult to identify than those associated with stated objectives, but they can be equally important in the success of a mission. The following four examples illustrate the impact of mismatches that can arise between unstated objectives and constraints in PI-led Earth science missions.

### Example 1: The Limited Capacity of Universities

*Objective:* Enhance university-based Earth science research through participation in PI-led missions.

*Constraints:* For Earth science, universities generally have limited technical and programmatic experience with spaceborne missions, and relatively few universities have the capacity to lead or support PI-led Earth science missions at acceptable risk levels.

TABLE 3.1 Stated Objectives and Constraints Within the Earth System Science Pathfinder Program

| | Text from ESSP-3 AO[a] |
|---|---|
| **Objectives** | |
| Frequent low-cost missions | "launch rate of at least one mission per year"<br>"low-cost, quick turnaround spaceborne missions"<br>"NASA encourages and favors low-cost missions" |
| High-priority, focused, exploratory science | "the philosophy behind ESSP embraces small satellite missions addressing high priority Earth System Science objectives"<br>"ESSP . . . is intended to address exploratory measurements which can yield new scientific breakthroughs . . . addressing a focused set of scientific questions" |
| Innovative project implementation | "creativity in all aspects of mission development"<br>"innovation in instrumentation and strategies for acquiring and distributing new data products"<br>"the PI's team will have a large degree of freedom in accomplishing mission objectives within the stated constraints" |
| **Constraints** | |
| Available funding | "NASA encourages but does not require contributions from sources other than NASA"<br>"the NASA ESE cost ceiling is $125M" |
| Mission readiness | "every aspect of the mission shall reflect a commitment to mission success"<br>"all proposed missions shall be of sufficient technical maturity to achieve launch readiness within a goal of 36 months"<br>"to ensure mission success, there will be appropriate Government oversight and insight" |

[a]ESSP-3 Announcement of Opportunity (AO), 2001. This and other reference documents for the ESSP program can be found in the ESSP AO library online at <http://centauri.larc.nasa.gov/essp/essplib.html>.

The space science community has long required technically advanced remote sensing systems because many critical space science measurements cannot be made with the necessary accuracy or precision from the ground through the intervening atmosphere. Thus, university researchers in the space sciences have of necessity acquired the appropriate management skills and established strategic collaborations with engineering organizations (including university engineering departments) to enable the development, construction, and testing of remote sensing instruments and even entire spacecraft and missions.

In contrast, much of the university-based Earth science community has focused on and made significant progress to date using in situ data, given that certain critical subsurface oceanic and land measurements and atmospheric profile measurements cannot be obtained even from space-based platforms. Most Earth science researchers and their academic institutions have thus developed the unique skills and support infrastructures required for the different, and in many cases less demanding, tasks of constructing, testing, and deploying in situ instrumentation. For example, nine academic institutions currently operate the 14 major oceanographic research vessels that make up the nation's University-National Oceanographic Laboratory System (UNOLS) fleet, but none of these institutions has developed a spaceborne remote sensing instrument, let alone a spacecraft or an entire mission.

The development of spaceborne Earth observation measurement techniques, instruments, and remote sensing missions has therefore taken place largely in industry and government (principally at Goddard Space Flight Center (GSFC), the Jet Propulsion Laboratory (JPL), and the Naval Research Laboratory), while the academic focus has been on measurement validation using classic in situ data and the interpretation and utilization of the data once acquired.[1] Consequently, the university-based Earth science community has neither the tradition nor a large number of PIs trained and experienced in managing advanced space-based technical projects.

Few universities have sufficiently strong space system and Earth remote sensing instrumentation development programs to complement and support geophysical research efforts sponsored by NASA and other agencies. Furthermore, few senior Earth science faculty can serve as space mission PI role models for younger scientists, and (as noted throughout this report) the stringent cost and schedule constraints of ESSP missions do not make them suitable for initial PI training of junior faculty.

### Example 2: Risk Tolerance—Theory Versus Practice

*Objective:* Accept relaxed risk tolerance to support innovative approaches to measurement techniques, technical innovation, and novel management approaches.
*Constraints:* NASA is unwilling in practice to accept mission failure, the risk of which might be increased with more innovative approaches.

The Earth Explorers Program identifies several objectives—including "pathfinder exploratory measurements," "technical innovation," and innovative management approaches—that imply a greater tolerance of risk than would be acceptable for facility-class missions. However, increased risk tolerance in theory does not translate in practice to NASA's being more willing to accept failures in the program. Congress, the public, and the research community all hold NASA responsible for mission success or failure.[2] ESE cannot therefore divest itself of the ultimate programmatic responsibility for the success of any of its space missions.

Furthermore, Earth Explorer missions must succeed scientifically if they are to play a vital role in the overall ESE and national Earth science programs as claimed by NASA. Because these missions are used to address unique and high-priority science, they are critically important to the overall ESE science strategy.

Another aspect of risk is the introduction of a new and untried technology or methodology in a cost schedule-constrained program. NASA has been explicit about avoiding technology development within the Earth Explorer missions, but there is still some general indication in the AO statement that innovative management techniques should be considered. As is discussed in more detail below, the schedule and cost constraints for Earth Explorer missions, coupled with NASA's responsibilities for the missions' scientific success, substantially diminish the likelihood that innovative management approaches could be used successfully. Any attempt to force the introduction of a new technology or methodology into the program makes it far more difficult for inexperienced academic scientists and their institutions to participate fully as mission management leaders.

### Example 3: NASA Acceptance of Innovative PI Management Approaches

*Objective:* Allow the PI to define and implement the management approach.
*Constraints:* NASA depends on its own management practices to ensure success.

The decision to promote management leadership of Earth Explorer missions outside NASA centers was intended partly to provide incentives for the development of innovative management practices. In practice, however, NASA's stake in ensuring mission success inhibits management practices proposed by a PI that NASA believes could be inconsistent with mission success.

The ESSP office at GSFC is tasked with ensuring the effectiveness of a PI's management approach. The history of successful flight projects at GSFC, and the reliance on proven management approaches to achieve those

[1]The Applied Physics Laboratory of Johns Hopkins University, with significant spaceborne instrument and spacecraft development expertise and strong ties to Earth science researchers, represents a notable exception.

[2]William B. Gail, Ball Aerospace and Technologies Corporation and a member of the Committee on Earth Studies, "Perspectives on the PI-led AO Mission and the CES PI-Mode Study," presentation to the Committee on Earth Studies, April 25, 2001, p. 15.

successes, suggest the potential for conflict with management approaches that differ from GSFC processes. The committee recognizes that various organizations, such as GSFC, JPL, the Department of Defense, and industry, all have proven but differing management approaches. In many cases, GSFC may be justified in promoting its processes over those proposed by a PI, but it is not clear that there are viable criteria for distinguishing between effective nontraditional management approaches and approaches that are inherently less effective than proven GSFC techniques.

The involvement of academic institutions in mission management introduces other issues as well. The mandated PI-led management mode is consistent with NASA's aims of building university mission capability and fostering innovative teaming arrangements between government and nongovernmental (e.g., industry and/or university) partners. But the time scale of ESSP Earth Explorer missions, with a maximum of 3 years for prelaunch development and 6 to 7 years total from inception to the end of the baseline mission, is inconsistent with academic career objectives and the tenure of undergraduate or graduate students. Furthermore, a university academic department is not always the best place for hardware development and testing. ESE therefore expects the PI to contract out these tasks to the appropriate development organizations (private industry or NASA laboratories), leaving the PI and the students to concentrate on the research tasks.

Thus PI control and leadership do not necessarily mean that the PI is fully the project manager, with the day-to-day concerns for schedule, cost, and work completion. Such responsibilities may be delegated to a professional manager with space mission experience and preferably an understanding of the technology or science, so that the PI is free to be the primary arbiter of the science and the final decision maker when compromises must be made. PI-led management also contributes directly to ensuring that the necessary trade-offs during the mission design and implementation stages preserve the scientific integrity of the mission. During the development phase, the PI-led science team is the only recognized user of the mission's measurement capabilities.

In contrast, the government/private-sector relationships and interactions as practiced by the NASA field centers are conservative and hierarchical. This is appropriate for large observatory- and facility-class missions where NASA has responsibilities to sizable segments of the research community and the overall goal is to meet the requirements of the largest number of users with minimal risk. But it is difficult to introduce innovative changes in such programs. The long time scale of development, greater cost, and significant penalty for failure reduce the incentive for certain kinds of innovation. (Of course, because of the longer time scale, these programs are the ones that could afford to try new management techniques and develop new technology.)

In principle, empowered "outsiders" such as selected PIs can be efficient agents of innovation—a principle substantiated in the automotive industry by, for example, the General Motors Saturn enterprise and in portions of the Japanese manufacturing sector.[3] But although truly innovative management approaches have been demonstrated in industry (such as the integration of multigroup and multi-institution product teams and end-to-end manufacturing processes), the time, expense, and technical management expertise devoted to these efforts in the private sector have been far larger than can reasonably be expected from a small program like an Earth Explorer mission. Furthermore, there is no basis to expect that a typical inexperienced science-oriented PI at an academic institution, operating under the tight schedule and cost constraints of an Earth Explorer mission, would have the desire or the skills necessary to implement such innovative management approaches.

**Example 4: Erosion of Cost and Schedule Objectives**

*Objective:* Maintain a fixed and regular program launch schedule.
*Constraints:* Unanticipated management rigor and reviews can impose programmatic burdens.

The stringent Earth Explorers Program cost and schedule constraints and the mandated PI-mode of management may deprive NASA of many of its standard management tools for ensuring mission success. The classical

[3]National Research Council, Space Studies Board, 2000, *The Role of Small Satellites in NASA and NOAA Earth Observation Programs*, National Academy Press, Washington, D.C., p. 52.

approach to minimizing failures usually involves a combination of active oversight and consistent management of the contractor—an approach that conflicts with the Earth Explorers Program's PI management approach, increases both NASA and contractor costs, and generally lengthens schedules when unanticipated reviews or additional analysis and review tasks are imposed, thus violating the cost and schedule constraints basic to the original mission proposal solicitation and evaluation and essential to the long-term vitality of a flight program intended to have a fixed, regular launch schedule.

Thus, lacking flexibility to change the schedule and cost once a mission is under way, NASA has a greater responsibility to plan, schedule, and obtain agreement on risk monitoring and risk-reduction activities in the mission's initial phase. These risk management tasks are paramount throughout the lifetime of an Earth Explorer mission, from solicitation and selection through implementation and launch.

## COMPARISON WITH NON-PI-LED PROGRAMS

Comparing PI-led missions with non-PI-led programs can be valuable for understanding how to resolve conflicting objectives and constrained resources. Several small non-PI-led NASA programs that were very successful should be considered in the context of their development by industry or government laboratories. The Clementine program, for example, is often held up as a very successful small satellite program and has been compared to several of the less successful planetary programs. In testimony before the House Science Committee, Pedro Rustan, Clementine's mission director and later the director of the National Reconnaissance Office's Small Satellites Program, gave his views on managing these advanced programs according to 10 management practices that he believed were key to the success of the Clementine program.[4] Although most of the 10 practices are applicable to all programs, points 1 and 5 can be directly contrasted with the requirements of PI-led missions:

> 1. Empower a single program manager who is a seasoned leader and make that person responsible and accountable for all aspects of the mission during the entire duration of the program.

This approach is in keeping with the stated philosophy of PI-led missions but introduces the challenge of finding strong scientists who are also good program managers. Such a program management practice, which is

---

[4]In his testimony, Dr. Rustan stated, "The ten most important management practices used in the Clementine Program that are relevant to the recent Mars Mission can be summarized as follows:

1. Empower a single PM who is a seasoned manager and a top leader and hold him/her fully responsible and accountable for all aspects (technical, managerial, and financial) of the mission during the entire duration of the program (cradle to grave).
2. Nurture a group of government and industry personnel with a successful legacy for problem solving who are willing to do whatever it takes to guarantee mission success.
3. Select and collocate a team of experienced managers to direct the development and integration of the various systems and subsystems throughout the mission.
4. Remain steadfast without making any significant changes in the requirements (scientific, operational, or technical) of the mission after final design completion.
5. Use the most advanced technologies readily available that can increase mission capabilities and reduce cost.
6. Depend on extensive testing throughout the entire mission and minimize dependence on analysis and simulation.
7. Perform only four major reviews at the program transition points, but be ready to perform an in-depth review whenever there is a problem or discrepancy.
8. Use Integrated Product Teams (IPTs) to maintain online communication with all the stakeholders.
9. Ensure that only one person can make changes in the Interface Control Document (ICD).
10. Complete all new technology developments before the Critical Design Review (CDR).

See Testimony of Pedro L. Rustan, PhD, United States House of Representatives Committee on Science hearing, "NASA's Mars Program After the Young Report, Part II," May 11, 2000. Available at <http://www.house.gov/science/rustan_062000.htm>.

Pedro L. Rustan, adapted from May 11, 2000, testimony to the House Science Committee and published in *Space News*, August 28, 2000, p. 25.

universally supported but not always evenly applied, is specifically designed for an industry or government laboratory. The academic PI, on the other hand, will probably have to share control with an experienced program manager:

5. Use the most advanced technologies available to increase mission capabilities and reduce cost.

Rustan is a strong supporter of the use of advanced technology, which was used in the Clementine program. While all Earth Explorer missions incorporate advanced technologies in the instruments and the science payload, the committee does not recommend trying to develop advanced technology during these missions. Clementine benefited from a dedicated team of spacecraft systems developers, and considerable effort went into the development and testing of new hardware, much of which was being developed for other programs and was made available to the Clementine program. The Earth Explorers Program does not enjoy these advantages.[5]

As stated in Rustan's seventh principle, he is also a proponent of a small number of essential reviews at program transition points and has observed that NASA programs have too many reviews that take critical time from the program.

## FINDINGS AND RECOMMENDATIONS

As currently conceptualized, ESE PI-led missions include a wide variety of explicit and implicit objectives while maintaining very tight limitations on resources. Mismatches between objectives and constraints have been the root cause of many difficulties faced by PI-led missions.

***Finding:*** The scientific and programmatic objectives of ESE are ambitious compared with the constraints under which PI-led missions are implemented, particularly the capped funding and tight schedule.

***Recommendation:*** **NASA's Earth Science Enterprise should focus its programmatic objectives for PI-led missions to better match the available resources and constraints, with achievement of high-quality science measurements being the highest-priority objective.**

***Finding:*** Universities can derive considerable benefit by participating in an ESE mission; however, using PI-led missions to build the capacity of university-based research is not readily achievable within the structure and resources of current ESE PI-led programs.

***Recommendation:*** **NASA's Earth Science Enterprise should not include building the capacity of university-based research as an explicit objective of PI-led missions unless fundamental changes are made to program structure and resources.**

[5]In his analysis of small satellite programs, Sarsfield also suggests that technology is the key to lower costs and, obviously, better performance, although he recognizes some of the disadvantages of introducing technology too early. See Liam P. Sarsfield, 1998, The Cosmos on a Shoestring: Small Spacecraft for Space and Earth Science, Document Number MR-864-OSTP, RAND Corporation, Santa Monica, Calif.

# 4

# Institutional Investments: Establishing the Foundations

ESE programs and projects are commonly designed to build on each other, as exemplified by component technology studies that feed into instrument development projects and ultimately support research missions. This chapter discusses two institutional investments that are particularly critical to laying the groundwork for resource-constrained PI-led missions.

The first important institutional investment is technology development. A hallmark of successful missions has been a technology base, built up over the course of a decade or longer, that reduces the risks associated with the short development schedule of PI-led missions. The second critical institutional investment is the nurturing of a community of PIs with the skills and experience required to lead a project with the scope of a PI-led mission. The number of qualified PIs is currently small, and there are limited opportunities in ESE to develop both the system engineering and project management expertise necessary to lead a mission.

## DEVELOPMENT OF REQUIRED TECHNOLOGIES

New scientific measurements generally require the development of new technology or new applications of existing technology. However, the desire for PI-led missions to provide fast turnaround conflicts with the time and testing required to adequately reduce the risks of new technologies during the development phase. Although this conflict has been recognized,[1] NASA's Earth and Space Science Enterprises (ESE and SSE, respectively) have devised only limited solutions to address it.

NASA's recent shift toward more frequent, faster, and cheaper missions, which began after Daniel Goldin was appointed as administrator in 1992, took advantage of a fairly large "reservoir" of new technologies developed under previous observatory- and facility-class missions and technology programs. A concern was raised, however, that early PI-led missions would exploit this reservoir and that future mission concepts would be limited as the backlog of previously developed technology was exhausted without concurrently developing new technologies.

The committee heard from numerous presenters, including several small-mission PIs, that cost- and schedule-constrained missions are not well suited for undertaking significant technology development. In most cases the

[1]The ESSP-3 AO summarizes the dilemma with regard to technology development: "NASA is committed to successfully infusing new technologies that will lower mission costs in its programs. However, the short definition and development time available for ESSP missions generally will not allow for significant technology development after mission selection."

TABLE 4.1 NASA Technology Readiness Levels (TRLs)

| Technology Phase | TRL Level | TRL Level Description |
|---|---|---|
| Basic Research | Level 1 | Basic principles observed and reported |
| Research to Prove Feasibility | Level 2 | Technology concept and/or application formulated |
| Technology Development | Level 3 | Analytical and experimental critical function and/or characteristic proof-of-concept |
| Technology Development | Level 4 | Component and/or breadboard validation in laboratory environment |
| Technology Demonstration | Level 5 | Component and/or breadboard validation in relevant environment |
| Technology Demonstration | Level 6 | System/subsystem model or prototype demonstration in relevant environment (ground or space) |
| System/Subsystem Development | Level 7 | System prototype demonstration in a space environment |
| System/Subsystem Development | Level 8 | Actual system completed and “flight qualified” through test and demonstration (ground or space) |
| System Test, Launch, and Operations | Level 9 | Actual system “flight proven” through successful mission operations |

payload and spacecraft bus of such missions benefited from substantial design and hardware heritage at the start. In a few cases where significant technology advancements were required, development difficulties led to substantial cost increases and schedule delays that have jeopardized the missions.

As a result of these experiences NASA has recognized the need for further limiting the risks associated with new technology development. ESSP officials told the committee that under prior solicitations, proposal reviews paid inadequate attention to implementation capability and technology maturity.[2] In future solicitations, however, new technology infusion will be encouraged where it enables new measurement capabilities and/or promises reduced costs, while development risk will be more closely controlled by ensuring sufficient technology maturity at the start. NASA describes technology maturity in terms of technology readiness levels (TRLs), as described in Table 4.1. Although the ESSP-3 AO does not appear to identify a specific TRL requirement, it was suggested to the committee that the TRL should be at least TRL 6.[3]

### Existing Technology Development Resources

ESSP expects proposed mission technologies to have sufficient maturity to achieve launch readiness within 36 months (nominally TRL 6 or higher); therefore, the community must look to other programs for new technology development at lower TRLs. NASA has several programs that currently address these needs for the Earth sciences. Under the Earth Science Technology Program (ESTP), the Earth Science Technology Office (ESTO) sponsors four such programs: Advanced Component Technologies (ACT), Computational Technologies (CT), Advanced Information Systems Technology (AIST), and the Instrument Incubator Program (IIP). Under the Office of Space Science, the New Millennium Program (NMP) supports spaceflight proof-of-concept demonstrations. The Office of Aerospace Technology’s Mission and Science Measurement Technology (MSMT) theme sponsors the Enabling Concepts and Technologies Program (EC&TP, which incorporates the former Cross-Enterprise Technology Development Program (CETDP)) that provides a vehicle for more basic research leading to laboratory demonstration. Finally, the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs support R&D efforts at small companies and nonprofit research institutions. Table 4.2 summarizes the key characteristics of these programs; more detailed descriptions of the programs are in Appendix D.

The combination of NASA programs available to support new technology development appears to address the entire range of technology readiness needed for support of and inclusion in new Earth science missions. Indeed,

[2] N. Chrissotimos, Earth System Science Pathfinder, presentation to the Committee on Earth Studies, April 25, 2001.
[3] N. Chrissotimos; see note 2.

TABLE 4.2 NASA Programs for New Technology Development

| Program | Key Characteristics | Technology Readiness |
|---|---|---|
| Mission and Science Measurement Technology/ Enabling Concepts and Technologies Program | Concept development through laboratory demonstration | TRL 2-4 |
| Advanced Component Technologies and Advanced Information Systems Technology | Component and information systems technology development | TRL 2-5 |
| Instrument Incubator Program | Instrument system technology development | TRL 3-6 |
| New Millennium Program | Flight validation | TRL 5-8 |
| Small Business Innovation Research/ Small Business Technology Transfer | Small company R&D support | N.A. |
| Computational Technologies | Massive parallel computing applications | N.A. |

ESSP AO-01-OES-01 states that NASA expects that the technology-driven activities such as the NMP and the IIP "will serve as the primary technology 'engines' for future Earth Science Enterprise missions." The committee agrees that this may be a reasonable expectation if the MSMT/EC&TP, ACT, and AIST programs can provide adequate low-TRL research and development on new concepts to fuel the IIP and NMP programs.

## Coordination, Continuity, and Balance of Technology Resources

With adequate funding, NASA's existing programs have the potential to provide the new technologies and instruments needed to support a robust Earth science program. However, funding is always an issue, and NASA should seek maximum cost-effectiveness by striving for coordination, continuity, and balance among its programs. There is a clear need to coordinate programs between enterprises to ensure needed coverage and to avoid redundancy. This is particularly important for Earth science since both the NMP and MSMT/EC&TP are managed outside ESE.

Continuity is a key to effective planning and efficient operations. Over the past several years, ESE has revolutionized its approach to technology development, as reflected in its strategic plans. As a result, most of the ESTO programs—ACT, AIST, and IIP—are new and have experienced only one or two acquisition cycles; the NMP has recently been restructured to focus on technology and to broaden participation; and, with the move from the SSE to the Office of Aerospace Technology and its incorporation into the MSMT Enabling Concepts and Technologies Program, the continuity and future direction of the former CETDP are uncertain.

Although the MSMT/EC&TP, ACT, AIST, CT, IIP, and NMP together address all elements of the technology development process, there arises a question of balance. Will funding allocated among these programs yield a continuous flow of new instruments and spacecraft technologies as needed, or will some activity be underfunded and result in a TRL gap? As indicated below, the committee recommends that a quantitative assessment of the anticipated flow of technology through the TRL chain compared with the projected needs of future ESE missions be performed.

## Potential for Enhancing Technology Development

NASA's SSE has recently begun to consider ways to enhance technology development by providing limited technology funding to highly rated Discovery missions that were not selected because of technology readiness concerns.[4] Other projects, including ESE's CALIPSO, have taken the initiative after nonselection to perform technology risk reduction, using team funding, in preparation for subsequent AO submissions.

It is clear that even limited technology funding prior to an AO can provide substantial risk reduction leverage by eliminating one or several "tall poles" that would otherwise impede approval for flight. Such support is particularly effective with risk reduction tasks that require limited funding but have schedule needs inconsistent with accomplishing the task during formulation. The Discovery model, based on identifying funding candidates from the pool of nonselected proposals, provides a good approach to limited technology development within the control of the PI-led mission programs.

***Finding:*** The rigorous and ambitious cost and schedule constraints imposed on PI-led missions preclude all but minimal technology development prior to launch.

***Recommendation:*** **NASA's Earth Science Enterprise should explicitly nurture and coordinate technology feeder programs—such as the Instrument Incubator Program and the Office of Aerospace Technology's Mission and Science Measurement Technology Program—that develop technologies with potential application to PI-led missions. A quantitative assessment of the anticipated flow of technology through the technology readiness level chain would help guide this effort.**

***Finding:*** Proposers of non-selected PI-led missions found to have high scientific priority but known technical risk have limited access to funding for reducing the project's level of risk prior to the next proposal round. Both ESE and the scientific community would benefit from improved opportunities to reduce the technical risk of recognized high-priority science missions and then re-propose them.

***Recommendation:*** **NASA's Earth Science Enterprise should include within the solicitation for PI-led missions a component, following the Solar System Exploration Discovery model, that provides limited technology funding for high-priority non-selected PI-led mission proposals to increase their technology readiness for the next proposal round.**

## DEVELOPMENT OF QUALIFIED PRINCIPAL INVESTIGATORS

Experience and institutional capabilities vary greatly among scientists who may be PI candidates for PI-led missions. A purported advantage of such missions is that they are driven by science rather than technology. However, in order for PIs to succeed in their mission management they must have adequate institutional infrastructure and program management support, as well as a working understanding of the trade-offs between science requirements, technology development requirements, schedule constraints, and costs. To increase and strengthen the field of potential PIs it is therefore necessary to provide more scientists with opportunities to develop these capabilities. Scientists' involvement in technology development projects can familiarize them with the scope of activity required to successfully lead projects and ultimately missions, help them establish relationships with industry representatives and NASA program managers, and help build and sustain the university infrastructure needed to support such activities.

The experience and capability both needed and acquired increase substantially with the scope of the project. Thus, scientists should compete for opportunities consistent with their capabilities and advance to progressively greater challenges. ESE can facilitate this process by encouraging university participation in programs like ACT, AIST, IIP, NMP, and ESSP, which offer PIs opportunities to develop their skills and institutional capabilities over the entire range of technical readiness levels for components, instruments, and entire missions. Experience to date

[4]Kepler was provided limited technology funding following the Discovery-3 selection despite not being selected for flight. This funding was used to mitigate the risk associated with a prominent "tall pole" in its technology readiness, and Kepler was selected for flight in Discovery-4.

is mixed. The first ACT (formerly known as the ATIP [Advanced Technology Initiative Program]) awards were skewed heavily toward NASA centers and federally funded research and development centers (FFRDCs; only 2 of 23 went to universities), whereas the first CEDTP awards went mostly to universities (56 of 111) and industry. Further up the technical maturity chain, 8 of the first 27 IIP awards but only 2 of the next 11 have gone to universities.

Balloon, aircraft, sounding rocket, and shuttle flight opportunities can also increase the number of experienced PIs.[5] ESE may wish to encourage the growth of intermediate-scale Earth observation programs that can fill the PI-training gap between instrument development and full ESSP mission leadership. In addition, ESE may wish to consider a more proactive stance in encouraging university participation in its technology development programs, perhaps along the lines of the recent NMP AOs, which indicated NASA would reject FFRDC, government, or national laboratory proposals that are substantially the same as those submitted by universities or industry.

Successful PI-led programs tend to be mature mission designs under the leadership of highly experienced PIs. In SSE as well as ESE, experienced PIs are those who are intimately familiar with standard technical, cost, and schedule management techniques, or they team closely with industry managers or NASA centers that know how to manage missions. Much of the technical work required to build and launch a satellite experiment is incompatible with career advancement expectations for university-based PIs (because the process of building an instrument does not produce a steady stream of peer-reviewed publications), and it is of limited pedagogical value for their PhD students (who need to produce original work rather than reconstructing reliable well-tested systems).[6] The teaming of PIs with experienced project managers can create sufficiently strong teams even if the PI has limited project experience.

Even if PIs work with experienced engineering teams, the long-term success of PI-led missions requires that NASA ensure the availability of qualified PIs. To date, there has been no evidence of any shortage of scientific ideas or of PI candidates who are scientifically qualified to promote them. There is, however, substantial concern about the limited number of scientists who also have project management experience and who can make the time commitment to lead a mission program. The scientific community needs to be nurtured so that potential PIs have a path in ESE to gain the experience needed to lead a mission. ESE should, for example, explicitly recognize that a properly structured AO provides a learning experience for nonselected PI candidates so that they are able to submit stronger proposals for subsequent solicitations. Information exchange is critical to building the community of qualified PIs. Thus posting documentation such as "lessons learned" on the Web, organizing town meeting workshops (at major conferences or in Washington, D.C.), or planning other informational activities to educate prospective PIs and project managers are all useful. Additional steps that can be taken to nurture PIs include:

- Emphasizing the objective of high flight rate to increase the number of opportunities available for PIs;
- Creating a multitiered AO structure that allows PIs to gain experience on smaller projects before moving to larger ones;
- Establishing a publicly recognized process that helps potential PIs access the experience of current PIs and the AO program and project offices;
- Making ESE and SSE mission AOs and evaluation processes as similar as possible, thus increasing the number of PIs and potential PIs who can share experience; and
- Providing extensive face-to-face feedback for nonselected teams to enable them to become more effective proposers in subsequent AO proposal rounds.

---

[5]The importance of balloon and sounding rocket programs to both the advancement of space science and the training of future PIs is discussed in Chapter 7 of National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics,* National Academies Press, Washington, D.C., 2003, and in Chapter 3, "Report of the Panel on Atmosphere-Ionosphere-Magnetosphere Interactions" in National Research Council, *The Sun to the Earth—and Beyond: Panel Reports,* National Academies Press, Washington, D.C., 2003.

[6]G. Stephens, Colorado State University, presentation to the Committee on Earth Studies, April 26, 2001.

***Finding:*** The Earth science community, particularly the university-based community, has historically produced only a small number of scientists with the in-depth space engineering and technical management experience that is required to lead a project in a PI mode of operation.

***Recommendation:*** **NASA's Earth Science Enterprise should formally identify and promote activities that develop PIs qualified to propose and lead small, focused science missions.**

# 5

# Project Implementation: Improving Life-Cycle Processes

The processes by which a program and its constituent projects are implemented are critical to the success of the program as a whole. Within PI-led programs such as the Earth System Science Pathfinder and Discovery (in NASA's SSE), individual missions are solicited, selected, and executed as distinct projects whose activities are guided by processes developed over many years with the goal of producing missions characterized by both excellent science and a high likelihood of success. The effectiveness of these processes is a significant factor in achieving success in PI-led missions.

This chapter discusses the life cycle of PI-led projects and provides specific recommendations for enhancing the solicitation, selection, and execution of PI-led missions. Background on existing and previous PI-led programs in both ESE and SSE is provided in Appendix D.

## LIFE-CYCLE OVERVIEW

NASA projects, including PI-led missions, are guided by procedures in the NASA project management handbook *NPG 7120.5B,*[1] which identifies the general process structure to be used in both programs and projects[2] and establishes the project life cycle. The PI-led mission project life cycle includes the three fundamental processes of solicitation, selection, and execution. Solicitation is used to define the objectives of a program and to establish the guidelines for project selection and execution. Projects are chosen during selection; execution is the activity of accomplishing projects.

NASA has established checks-and-balances mechanisms for each of these processes based on three functions: perform/manage, oversee/evaluate, and approve/select. Figure 5.1 shows how these three functions are applied to solicitation, selection, and execution and who has responsibility for each function. During solicitation, the NASA program office writes the AO solicitation (perform/manage), drafts of the AO are reviewed internally and by the

[1]*NASA Procedures and Guidelines 7120.5B: NASA Program and Project Management Processes and Requirements.* Available online at <http://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_7120_005B_&page_name=main>.

[2]According to the *NPG 7120.5B*, a *program* is "an activity within an Enterprise having defined goals, objectives, requirements, funding, and consisting of one or more projects, reporting to the NASA Program Management Council, unless delegated to a Governing Program Management Council"; a *project* is "an activity designated by a program and characterized as having defined goals, objectives, requirements, life cycle costs, a beginning, and an end."

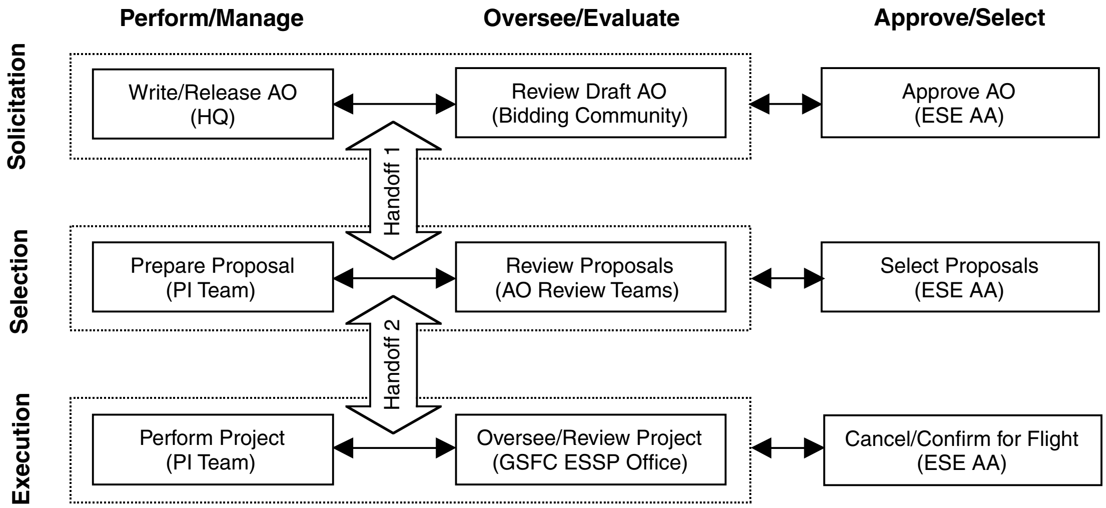


FIGURE 5.1 The checks-and-balances process used for the three project life-cycle activities of solicitation, selection, and execution.

community of potential proposers (oversee/evaluate), and the ESE associate administrator (AA) approves the AO for release (approve/select). During selection, the PI team advocates its mission through a proposal (perform/manage), reviewers evaluate the proposal (oversee/evaluate), and the ESE AA assesses the integrity of the proposal/review process as part of making selections (approve/select). During execution, the PI team develops the mission (perform/manage), the NASA program/project office oversees and ensures the development process (oversee/evaluate), and the ESE AA confirms that the process has resulted in a mission capable of proceeding to flight and ultimately to launch (approve/select).

All three elements of the checks-and-balances process must work properly to establish an effective solicitation, select viable mission proposals, and carry out the projects to achieve mission success. Furthermore, the three activities must be adequately coupled such that project risk is not introduced at either of the two "handoffs" between activities identified in Figure 5.1. These handoffs are particularly critical as it is at these points that personnel typically leave the activity, introducing possible risks resulting from unrecognized gaps in project knowledge. Failures in any single element of this system are to be expected, but proper implementation of the checks-and-balances approach should produce a robust environment in which single-element failures are caught and rectified.

## Ensuring the Effectiveness of Life-Cycle Processes

PI-led projects are particularly susceptible to both weaknesses in the checks-and-balances system and to risks introduced through inadequate handoffs. Like all programs, a PI-led project must balance performance (in this case, science) against cost and schedule, and this can be addressed during the three life-cycle activities. The committee believes that good science can be accomplished within the limited project budget and schedule of a PI-led mission if the candidate PI develops a project plan that can achieve the AO-defined scientific goals within these constrained resources (including appropriate reserves), and the NASA review process properly evaluates the plan.

The solicitation process must provide science objectives that can be accomplished within programmatic limitations, define a process that is capable of selecting missions that provide both high-priority science and can be implemented, and, once a project is selected, establish a programmatic structure that maximizes the likelihood of mission success. In the preparation of each solicitation, it is incumbent on NASA to consider inputs from the proposers and implementing communities and to build on lessons learned from other PI-led mission solicitations.

The selection process must evaluate all major technical, management, and cost issues; must reflect confidence in the proposers' ability to achieve the outcome; and must be viewed by reviewers as sufficiently thorough that proposal weaknesses cannot be effectively hidden. The approve/select function of the ESE AA is critical for ensuring that the process identified in the solicitation is robust, that it is followed diligently by the reviewers, and that the selections themselves fit credibly the available cost and schedule constraints.

The execution process is not unlike that for similarly constrained non-PI-led projects. To avoid unforeseen project growth, the PI team must follow the proposal plan as closely as possible, and the NASA project office must support this plan with effective but constrained oversight.

Given the many examples of successful PI-led projects (see Appendix C, Tables C.1 through C.5), it is clear that PI-led missions can be accomplished using available processes. PI-led projects that have been canceled or restructured, or that failed on orbit, can generally trace their problems to a breakdown of the checks-and-balances formalism. For example, the ESSP solicitations have encouraged international partnerships, but the selection and decision process has allowed missions to proceed without firm commitments from partners or with partner relationships that could be foreseen as difficult to manage. The solicitations have also encouraged innovative management approaches, but no process has been provided for evaluating the viability of such approaches. As a result, projects have suffered cost and schedule impacts during execution; the flight project status of one project (VCL) had to be suspended (see Appendix C, Table C.4).

In their preparation of new solicitations, ESE officials are applying the lessons learned from projects in which problems developed. However, the committee encourages ESE to continue to review the checks-and-balances process to ensure that it is sufficiently robust to identify problems before they lead to mission cancellation, restructuring, or on-orbit failure.

***Finding:*** Existing NASA guidelines (e.g., *NPG 7120.5B*) establish a management system relevant to PI-led missions, including an essential checks-and-balances formalism for the three PI-led mission project life-cycle processes of solicitation, selection, and execution.

**Recommendation: NASA's Earth Science Enterprise should emphasize formal and regular reviews of the life-cycle system of checks and balances as applied to PI-led missions and should continuously strengthen the processes on which the system is based.**

### PI-Led Project Timeline

The timeline of a PI-led project encompasses the three basic activities of solicitation, selection, and execution. These activities are in turn segmented into elements that correspond to discrete aspects of the project life, as summarized in Figure 5.2, with selection divided into multiple steps[3] and execution divided into project cycle phases.[4] As illustrated in Figure 5.2, both ESE and SSE have historically employed life cycles in which the selection steps have some overlap with the project execution phases.

In general, Step 1 has been used to provide a preliminary competitive selection with a more comprehensive Step 2 proposal used for the final selection. In some programs (e.g., Discovery), Step 2 has corresponded

[3]Competition steps are defined in each AO. Step 1 is generally the period between the release of the AO and a preliminary competitive selection, and Step 2 is the period between the Step 1 competitive selection and a final competitive selection for flight. These generic definitions differ from those used in the ESSP-3 AO, which adds a third competitive down-selection occurring just prior to MCR (defined in this study as Step 2b, because no "step" terminology for this activity is provided in the ESSP-3 AO).

[4]Project cycle phases are defined in each AO and cross-reference guidelines established in *NPG 7120.5B*. Although the information in Figure 5.2 is consistent with the ESSP-3 AO and is representative of the PI-led mission AO process in general, the steps in the development of a particular mission may deviate from those depicted in the figure.

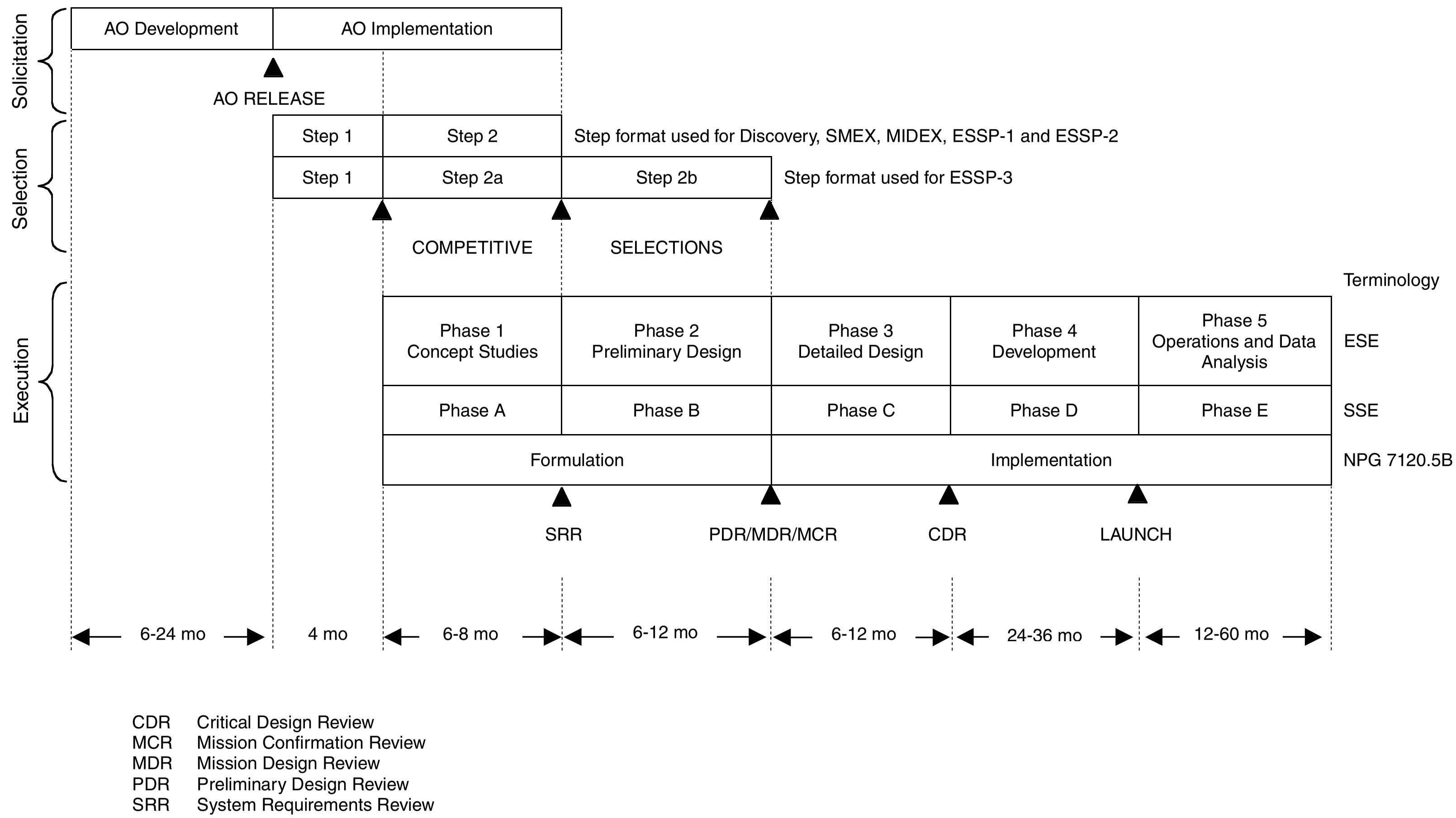

FIGURE 5.2 The project life cycle includes the three activities of solicitation, selection, and execution, with some overlap between the activities.

explicitly to Phase 1 of the project cycle, and the Mission Concept Study Report has functioned as the Step 2 proposal. In other programs (e.g., ESSP), Step 1 has focused primarily on evaluating scientific merit, with Step 2 used primarily to evaluate technical, management, cost, and other (TMCO) merit. The ESSP-3 AO includes a two-part Step 2 selection, with an initial Step 2 selection made by proposal evaluation and a final selection at the end of Phase 2 based on performance during the formulation phase. Typically, of the 20 to 40 proposals that have been received in Step 1, 4 to 10 are selected to proceed to Step 2. At the completion of Step 2, 1 to 3 missions have been selected for flight.

For a project team, the combination of selection and execution activities can be described in terms of two fundamental periods of the project life cycle:

- *Competitive formulation:* Initial solicitation and competitive selection of proposals (Step 1), followed by initial project formulation (Phase 1 or Phases 1-2) and final competitive selection (Step 2), and
- *Noncompetitive formulation/implementation:* Completion of project formulation (Phase 2) and implementation (Phases 3-5).

The competitive formulation period is particularly important to mission success. During this period, a PI faces a wide range of challenges that must be addressed and adequately resolved. Many of the issues arising throughout a mission's lifetime are rooted in decisions made early in the project as the mission concept is developed, team roles and responsibilities are defined, and the management approach is established. Identifying improvements to this portion of the mission process thus provides great leverage for promoting successful implementation of PI-led missions.

Establishing an appropriate balance between competition and formulation during this period is also critical to project success. Both competition and formulation contribute to mission success: competition inspires PI teams to push the limits of missions that can be implemented credibly, and formulation provides teams access to the resources needed to fully demonstrate that the implementation is credible. Effective formulation requires extensive communication with ESE as well as resources tailored to mission needs. The PI team and the ESE project office should be encouraged to jointly identify and resolve all programmatic weaknesses through open dialogue and shared information. Effective competition implies nonpreferential interaction with ESE and resources divided equally among competitors. In contrast to formulation, competition motivates the PI team to emphasize strengths and minimize weaknesses.

Extending the competition period to mission design review (MDR), as was planned for ESSP-3, improves the ability to select the most viable missions among competitors but delays the integration of the selected mission and NASA teams, possibly compromising successful formulation of the selected mission. Projects should include both competition and formulation during the competitive formulation period, with the correct combination tailored to particular program needs. Mission success, however, is enhanced when the competitive formulation period explicitly includes a noncompetitive segment dedicated to formulation, such as when a final Step 2 selection for flight is coincident with the initiation of Phase 2. Furthermore, Phase 2 of the formulation phase must have both adequate funding and an appropriate schedule to achieve proper risk reduction. Resources applied to identifying and resolving problems in the formulation phase are widely recognized as an effective means to avoid significant problems later in the project. Historical guidelines exist for an adequate level of formulation-phase resources, but the particular needs of PI-led missions suggest that such guidelines should be carefully adapted to each AO.

***Finding:*** Many of the issues arising throughout a mission's lifetime are rooted in decisions made by the PI and project team during the formulation phase—early in the project—as the mission concept is developed, team roles and responsibilities (including NASA's) are defined, and the management approach is established. Mission success requires that major technical and programmatic issues be identified and jointly addressed by both the PI team and the NASA program office during the formulation phase. While extending competition between PI teams through the entire formulation phase provides NASA with additional insight into the effectiveness of the PI teams and the maturity of the mission designs, it delays the integration of the PI and NASA teams and motivates the PI teams to emphasize strengths and minimize weaknesses.

*Recommendation:* **NASA's Earth Science Enterprise should avoid extensive overlap between competition and execution activities during the formulation phase of PI-led missions, thus providing an adequate schedule to perform critical formulation tasks after the competitive selection is completed.**

## LIFE CYCLES OF PI-LED EARTH AND SPACE SCIENCE MISSIONS

PI-led missions have been supported by NASA for more than a decade. Within ESE, the Earth Explorers Program has only included ESSP, because UnESS was canceled before the start of any competitively selected missions. PI-led missions in NASA's Office of Space Science have included Discovery, Small Explorers (SMEX), Medium-Class Explorers (MIDEX), and University Explorers (UNEX).[5] This section provides a description of how these programs are structured, including the history of the Earth Explorers programs and how they have evolved.

### ESSP Life Cycle

Throughout its history, ESSP has retained the distinction between a science-focused Step 1 proposal and a TMCO focus in Step 2. Step 1 proposals are prescribed to be relatively short so as to limit time expenditures from a large number of proposers. Step 2 proposals are much more extensive and expensive to prepare. NASA does not fund Step 2 proposal preparation.

Step 1 proposals are prescribed to be about 25 pages, with the greatest emphases on science ideas and proposed investigations (e.g., measurement approach, instrumentation, and technical maturity). Measurements are specifically connected to science questions in a required "Science Traceability Matrix," and technical maturity is quantified in a required "Instrumentation Technical Maturity Matrix." Lesser emphases (in order of importance) are placed on technical aspects of the proposal, management strategies, and cost estimations at Step 1.

A limited number of Step 1 proposal teams are then requested to prepare Step 2 proposals (in the case of ESSP-3, only six proposals were promoted to Step 2). Step 2 proposals are much longer (about 120 pages) and involve a reiteration and refinement of the science ideas and proposed investigation, as well as extensive discussions of technical and management issues, costs and cost estimating procedures, impacts on education and opportunities for underrepresented groups, and any other relevant impacts and factors. Step 2 evaluations can also include site visits.

The records to date for ESSP solicitations, cost caps, and down-selects are summarized in Table 2.1. Step 1 proposal numbers have decreased from the initial response for ESSP-1 at 44 proposals in 1996, to 20 and 18 Step 1 proposals in the responses to ESSP-2 (1998) and ESSP-3 (2001), respectively. The GRACE and VCL missions were selected at the end of Step 2a in the competition for ESSP-1. Three missions—CloudSat, CALIPSO, and VOLCAM—were selected at Step 2a in the competition for ESSP-2. The Volcam mission was identified as an alternate should either of the other two missions fail to adequately address a list of requirements for proceeding with mission formulation over a 3-month period following the conclusion of Step 2a. The 3-month period following Step 2a was funded by NASA for all three missions succeeding at Step 2a in ESSP-2.

The GRACE mission was launched in March 2002; the VCL mission experienced implementation difficulties such that it was necessary for NASA to postpone indefinitely further phases of project execution; and CloudSat and CALIPSO are in prelaunch implementation phases.

The declared cost caps at the times of the solicitations have risen over the history of ESSP: in 1996, the ESSP-1 solicitation called for one mission at $90 million (GRACE) and one at $60 million (VCL); in 1998, the ESSP-2 solicitation called for two missions at $120 million each (CloudSat and CALIPSO). In both of these solicitations launch costs were expected to be included under the proposed cost caps (or provided by a non-NASA partner). The ESSP-3 solicitation cost caps are increased to two missions at $125 million each, and launch costs are not included so long as one of three NASA launch options is proposed.

---

[5]See Appendix C, Tables C.1 through C.5.

For ESSP-3, six candidate missions were asked to prepare Step 2 proposals. The Aquarius and OCO missions were subsequently selected, with the HYDROS mission as an alternate.[6] Based on the provisions contained in the AO, it appears that two missions will be selected at MDR to proceed with mission implementation and launch.

### UnESS Life Cycle

ESE currently supports ESSP as its sole PI-led program. However, as explained in Chapter 2, the UnESS program was announced in 1999 and was supported as a second PI-led program with a stated focus on university-led organization. As such, its AO provided substantially more freedom for the PI team to propose management and development processes consistent with university constraints and tailored to the particular needs of each mission. UnESS was funded in ESE through the FY2001 budget, and then canceled.

The 1999 UnESS AO provided for a two-step competitive process, with Step 1 identified as the concept study selection process and Step 2 as the down-select process. Step 2 was a funded (less than $300,000) competitive segment of approximately 9 months' duration. During Step 2, those missions selected in Step 1 were to refine the mission concept and submit a concept study report to be evaluated as the basis for the final down-selection. Selection criteria for both steps were identical. Selected missions were expected to proceed to Phase 2 (mission definition and preliminary design phase) of the formulation subprocess.

### SSE Life Cycle

NASA's experience with PI-led space science missions provides an instructive comparison to the ESE experience. In fact, many of the concerns with respect to PI-led missions in the Earth sciences have already been debated in reviews of PI-led space science programs, for example, the review of the SSE Explorer Program.[7]

The Discovery (2000),[8] MIDEX (2001),[9] and SMEX (2000)[10] are the SSE's PI-led mission programs. These programs all employ a two-step selection process. As with ESSP, Step 1 is focused primarily on evaluation of science merit and Step 2 on TMCO issues. However, Step 2 consists of a 4-month concept study, funded by NASA at about $450,000. The concept study report serves as the Step 2 proposal. Selected missions proceed to Phase B (equivalent to Phase 2; see Figure 5.2) of the formulation process. Approval for flight is made in the mission confirmation review (MCR) at the completion of Phase B.

## LIFE-CYCLE ACTIVITY 1: SOLICITATION

The quality of the solicitation has an enormous impact on the success or failure of a project. The solicitation establishes both the project expectations and the constraints, and defines the process used to evaluate and select projects. A well-written solicitation provides sufficient time and budget resources to implement missions that satisfy program expectations, and defines a selection process that ensures that this occurs. This section provides a discussion of areas in Earth Explorers solicitations that could be enhanced to increase the likelihood of mission success.

### Cost Caps

Cost caps are an effective NASA management tool for both managing program costs and controlling Enterprise budgets, as has been demonstrated on many PI-led projects. However, the threat of project cancellation for

---

[6]See Appendix C, Table C.4.

[7]National Research Council, Space Studies Board, 1996, *Assessment of Recent Changes in the Explorer Program,* National Academy Press, Washington, D.C.

[8]See Appendix C, Table C.1.

[9]See Appendix C, Table C.2.

[10]See Appendix C, Table C.3.

exceeding cost caps has proven to be ineffective. Both the ESSP-1 and ESSP-2 missions have exceeded the proposed cost cap, though cost increases have occurred in some cases because of events completely outside the control of the project or NASA.

Though maintaining the credibility of cost caps is important, the best interest of NASA and the science community is often served by continuing to fund projects even though they are projected to exceed the cost cap. Cost caps should therefore be redefined from a threshold for an automatic termination review to a threshold for a remedial review that includes an examination of how the division of responsibility and authority between the PI and ESE might be revised to better control costs. ESE (not the PI) would then be responsible for electing whether to increase funding, descope, or cancel the project based on a variety of ESE considerations. In addition, cost caps should be established only when the project has reached a level of maturity that the budgeted cost is realistic. ESSP-3 establishes firm cost caps only when a project has reached MDR, instead of during the Step 2 proposal as in prior solicitations, and this should improve the ability of projects to stay within cost caps.

One technique that has been used successfully by NASA's SSE to help implement cost caps is the application of science floors. Defined by the PI in the mission proposal, the science floor represents the minimum science achievement required to justify the mission. It establishes a lower bound to descoping the mission in order to manage cost within the available cost cap.

Setting science floors for ESSP missions could serve two important purposes. First, assuming that analysis as well as production of the data is funded as part of the mission contract, it helps ensure a minimum science achievement sufficient to justify the mission, consistent with the PI's and NASA's science objectives. Second, it puts both the PI and NASA in a better position up front to know how to assess and make decisions about potential descoping or termination.

***Finding:*** The threat of project cancellation has not proved effective either in motivating the submission of PI-led proposals with adequate reserves or in constraining costs to meet the cost cap.

***Recommendation:*** **NASA's Earth Science Enterprise should redefine cost caps from a threshold that triggers an automatic termination review to a threshold for a remedial review that includes an examination of how the division of responsibility and authority between the PI and ESE might be revised to better control costs. Cost caps should be established only when the project has reached a sufficient level of maturity that the proposed cost is credible, such as at mission design review. ESE should also consider the use of a science floor, a PI-proposed minimum scientific achievement needed to justify the mission, in setting and managing within cost caps.**

## Teaming and Partnerships

Team formation is initiated by the PI and takes place during the earliest stages of the selection process. Recently, ESE has been made aware of the importance of PI team formulation in ESSP PI-led projects.[11] The PI team must include experienced individuals in the roles of project and mission managers. The frequent use of international and/or other agency partnerships in ESSP PI-led missions also necessitates the early identification of responsible science and technical parties outside NASA. However, potential science PIs for ESSP PI-led missions are not uniformly well acquainted with the technical communities that will provide many of these key personnel.

PI-led projects require relationships between the PI institution, NASA centers, NASA-sponsored institutions, and industry partners that are generally different from those of non-PI-led projects, and often these relationships are considerably more complex. As the majority of PI-led projects involve a NASA center or NASA-sponsored

[11]The lead bullet in a slide summarizing lessons learned from the recent NASA Integrated Action Team report on ESSP PI-led missions states that "the quality and experience of team members is an important factor for mission success." NASA/ESSP presentation, "PI Mission Management: NIAT," at the ESSP-3 AO kickoff meeting, Washington, D.C., November 15-16, 2001. Available online at <http://centauri.larc.nasa.gov/essp/ESSP_Kickoff_NIAT_Lessons_Learned_11_5_011.pdf>.

institution, selected missions in many cases can involve both the selected center/institution and the particular NASA center associated with the ESSP project office. These overlapping relationships can introduce conflict between management processes, duplication of reviews, and confusion about authority. While the ESSP project office plays a critical role in mission success, avoiding duplication and conflict between the project office role and that of NASA centers/institutions on the PI team is desirable.

In order to augment science content within the ESSP PI-led mission cost cap, it has become common for PIs to establish partnerships outside NASA with domestic and/or international agencies that contribute funding to the mission. While these partnerships provide the tangible benefits of additional funding and multiagency commitment, often they also introduce complexity and risk to mission formulation. Both the PI team and the ESSP project office need to ensure that partnering agreements are completed early in the formulation period, that interface definition is given highest priority, and that a clear management decision chain is understood and accepted by all parties.

***Finding:*** Domestic and international partners have increasingly been included on PI-led mission teams to enhance the quality of science achievable within the available ESE project budget. Despite the many benefits of such collaborations, more complex and diverse teams increase risk and add costs to pay for team interfaces.

***Recommendation:*** **NASA's Earth Science Enterprise should recognize not only the benefits but also the risks of having domestic and international partners in a PI-led mission program. The mission solicitation should identify the need for processes by which both the PI team and the relevant NASA office ensure that partnering agreements are completed early in the formulation phase, that definition of an interface is given high priority, and that the management decision chain is clear and is understood by all parties.**

## Proposal Preparation Costs

The solicitation process needs to strike a balance between the amount of information required in proposals to enable effective evaluation and the time required to prepare and review proposals.

In each ESSP AO, NASA is challenged to open the mission concept and design process to new and perhaps unexpected ideas from the science community, while defining in precise terms a review system to identify and mitigate risk, and to ensure scientific excellence and engineering, technological, management, and cost feasibility. These challenges imply considerable breadth in the levels of detail necessary in the AO, and the total document is indeed substantial as a result (main text, 42 pages; appendixes, 132 pages). The tendency to micromanage proposal preparation in an effort to ensure adequate information transfer is natural. The AO and materials from a recent preproposal conference illustrate a balance in this regard: Appendix K from the ESSP-3 AO provides a very detailed description of requirements for Step 1 and 2 proposals, while the minimum proposal requirements documentation from the preproposal conference provides a concise practical lower bound for potential investigators.

An AO must not be so burdensome as to discourage PIs from proposing. The two-step AO solicitation is designed to minimize the time and resource commitment required of nonselected PIs, and it has generally achieved that objective. University PIs, however, are particularly affected by funding and time constraints. NASA should therefore continue to refine the two-step process with the objective of obtaining sufficient information for evaluation while minimizing the resources required of proposing PI teams.

Various approaches to funding support for Step 2 have been tried. ESSP currently provides no funding until after the Step 2 selection, while Discovery, SMEX, and MIDEX (and, previously, UnESS) fund Step 2 at amounts under $500,000 per team. Teams that reach Step 2 of the competition have historically spent more on the study report than they received in NASA funding. NASA centers, NASA-sponsored institutions, and industry partners generally have sufficient resources to support Step 2 and are able to make these investments; academic institutions, however, have less access to the needed resources. Step 2 funding thus provides the greatest value to academic institutions and furthers their inclusion in the AO process.

***Finding:*** A properly constructed solicitation balances the need for proposals detailed enough to permit thorough evaluation against the time required both to prepare and to evaluate proposals. The two-step proposal process, in particular the use of short Step 1 proposals within ESSP, has provided a workable balance. However, the lack of NASA-funded support for proposals, particularly during Step 2, is increasingly limiting the ability of smaller organizations and universities to participate.

***Recommendation:*** **NASA's Earth Science Enterprise should maintain the current two-step proposal process for PI-led missions but should provide funding to proposers for Step 2.**

### Science Funding

PI-led mission proposals are evaluated primarily on the basis of their science objectives, and recent AOs have specifically sought projects that introduced innovative methods to address scientific questions outlined in the ESE strategic plan. However, although the ESSP-3 AO specifies that funding will support "implementation, launch, and science data archival and dissemination," it is ambiguous about research funding. The AO states that the PI team may carry out "initial scientific/applications evaluation in support of the proposed research objective(s)," but says that further science funding is anticipated through SDAP proposal solicitations released near the launch date. In contrast, the ESSP-3 AO FAQs specify, "The purpose of a mission is to answer science questions relevant to the ESE science goals. If the [postlaunch science] analysis effort is directed at answering the science questions, then this cost must be included in your mission costs."[12] These statements are likely to be interpreted differently by each of the proposing teams and may lead to difficulties in obtaining objective evaluations of the projects. Since the ESSP-1 and ESSP-2 AO solicitations, NASA has made significant progress in recognizing that support of PI-team postlaunch research is essential both for attracting high-quality PIs and for ensuring achievement of the mission's science objectives. However, the ESSP-3 AO and its associated FAQs remain ambiguous in this area. The committee recommends that future solicitations make clear that postlaunch research by the PI team toward the mission's major science goals should be requested as part of the original ESSP proposal.

Although research toward major science goals should be supported through the original ESSP mission funding, the SDAP science exploitation team also plays a role in ensuring that ESSP missions achieve their scientific objectives. Thus far, GRACE is the only ESSP mission to have been launched.[13] The NASA NRA-01-OES-05 from the Solid Earth and Natural Hazards Research and Applications program was released not long before the launch of GRACE and offered some support for GRACE research, although it was not formally identified as SDAP support. Separate solicitations such as this are valuable for a number of reasons. They can involve investigators with no past history with the mission in order to allow for independent data quality checks. They can also broaden the science team to encourage new data-processing algorithms, improvements in analysis methods, and use of additional sensor data for reasons not anticipated in the original science proposal. Launch-time science solicitations (whether or not they are identified as SDAP solicitations) are important for ensuring that ESSP missions achieve their scientific objectives.

***Finding:*** Scientific results are the primary objective in PI-led missions, but postlaunch science funding commitments are not adequately identified in the mission solicitations.

***Recommendation:*** **NASA's Earth Science Enterprise should clearly specify within the solicitation for a PI-led mission the extent to which scientific investigation and data analysis are expected to be included in the initial mission project budget, as well as the anticipated plans and budget for additional postlaunch science investigations. The science funded for the mission should address a PI-proposed science floor.**

---

[12]"ESSP AO Questions," available at <http://centauri.larc.nasa.gov/essp/ESSP_AO_Questions_Answers.pdf>, question 51.
[13]SORCE is an Earth Explorer mission, but it was not developed as part of the ESSP program.

### Communicating Lessons Learned

Dissemination of lessons learned is an important element of a program to enhance the capacity of potential PIs. Lessons can be communicated through a variety of means, including online libraries, preproposal and postproposal conferences, and mentoring relationships with existing projects. The ESSP office has developed an excellent set of both non-PI-led and PI-led lessons learned[14] and has organized preproposal conference presentations.[15] The preproposal conferences provide a forum for two-way communication so that proposers can learn the nuances of NASA's intentions with respect to solicitations, and NASA can learn more about the technical sophistication of the PI community. These approaches could potentially be extended to include presentations (online and/or at preproposal conferences) demonstrating successful partnering arrangements in past Earth Explorers PI-led projects and similar SSE programs (e.g., UNEX, SMEX, MIDEX). Mentoring relationships could be formed between key personnel from recently successful and newly selected projects, either case by case or as an intended outcome of NASA-sponsored workshops.

***Finding:*** Effective communication and the transfer of lessons learned between the Earth Explorers Program Office, current flight projects, and potential PI proposers can both increase the number of qualified proposers and reduce the risk associated with proposed projects.

*Recommendation:* **NASA's Earth Science Enterprise should continue to emphasize and promote communication and the transfer of lessons learned between the Earth Explorers Program Office, current flight projects, and potential PI proposers.**

## LIFE-CYCLE ACTIVITY 2: SELECTION

The quality of the selection process determines whether viable projects proceed to execution. A robust selection process approves only those projects that can be executed within the proposed resources, and it identifies risk areas and mitigation recommendations upon initiation of the execution activity. This section provides a discussion of areas in the current Earth Explorers selection process that could be enhanced to increase the likelihood of mission success.

### Selection Criteria

As noted in Chapter 3, the Earth Explorers Program faces the challenge of balancing the scientific potential of proposed missions with the likelihood of achieving a successful mission outcome. The need for an accurate evaluation is heightened by the recognition that most mid-course project remedies involve relaxing essential programmatic constraints that had served to define the scope of, and differentiate between, proposals at the early stages of evaluation. Recent examples of this problem include the selection of a UNEX mission with 12 instruments and another (STEDI) mission with 7 major, complex, x-ray and gamma-ray sensors; in both cases the missions were canceled, but only after the investment of several million dollars and several person-years of effort. The funding lost to these missions would have otherwise been available to missions that had the appropriate balance of scientific return with mission risk. NASA, the PIs, the research community, and the U.S. taxpayers are ill served by the selection of missions that cannot be completed within the programmatic constraints by the identified PI team, regardless of the merits of the proposed science. The evaluation leading to selection must therefore determine whether the proposal demonstrates that the PI team has the staff and infrastructure to properly implement the mission.

[14]See links to ESSP "Lessons Learned" at <http://essp.gsfc.nasa.gov/opportunity.html>.
[15]Such as that for ESSP-3 on June 14, 2001.

***Finding:*** The quality of the selection process determines whether viable projects proceed to execution and thus greatly influences the overall success of PI-led missions. Selection criteria for PI-led missions, particularly those employed in Step 2, must adequately consider the ability of the project team to successfully implement a project; the ESE associate administrator must be provided sufficient information to determine the likely success of a project; and the selection decision must reflect an objective evaluation of the likelihood of success.

***Recommendation:*** **NASA's Earth Science Enterprise should carefully review the selection criteria for PI-led missions to ensure that they adequately identify and promote missions that can succeed.**

## Reviewers

The selection of an effective evaluation panel is important to the success of the ESSP mission. Proposers must perceive the evaluation process as fair and accurate in order to justify the efforts and resources required to assemble technical and management teams and to prepare proposals for Steps 1 and 2. In addition, there are significant challenges to the identification and participation of suitably qualified reviewers. However, neither the ESSP-3 AO nor the preproposal conference materials describe how evaluation panel members are to be selected.

Within each Earth science subdiscipline (e.g., atmosphere, land surface processes, geophysics, cryosphere, ocean, biogeochemistry), science and technical experts with satellite data and observing systems experience form relatively small subsets of the larger communities. NASA rules regarding conflict of interest further restrict the number of potential evaluation panel members by excluding NASA center personnel and/or university scientists from reviewing proposals originating in their own institutions.

Participation on the science review panel involves considerable effort on the part of peer reviewers.[16] The AO is both detailed and broad, and the proposals submitted span a wide range of scientific disciplines. In the Step 1 review process, panel reviewers can expect to spend one person-day per proposal for approximately 20 proposals in preparation for the panel meeting, which itself involves another week of effort. For continuity and consistency in reviews, it is desirable that NASA retain all or most of the review panel from Step 1 for review of the Step 2 proposals. This time commitment far exceeds peer review efforts for other Earth science programs, in NASA or in other funding agencies (e.g., NSF, NOAA).

Furthermore, most ESSP proposals include a number of the most knowledgeable people in the field on the PI's science team, and many of the relatively small number of experienced scientists participate formally (as PI or Co-I) on at least one proposal in each solicitation. Otherwise-qualified individuals are therefore often not available to serve as reviewers, given both the level of effort required and conflict-of-interest considerations.

To increase the number of qualified reviewers for ESSP, NASA should consider opening panel review positions to qualified international scientists, and requiring as part of the initial contract that past ESSP (ESE) and Discovery/Explorer series (SSE) PIs serve on subsequent reviews. To the extent that SSE Explorer series and ESE ESSP solicitation and evaluation procedures can be made similar, the reviewers, at least for TMCO considerations, can be shared.

***Finding:*** The number of qualified reviewers for ESE PI-led missions is small, particularly after elimination of scientists with conflicts of interest because of relationships with proposing teams.

***Recommendation:*** **NASA's Earth Science Enterprise should consider enlarging the pool of possible reviewers of PI-led missions by adding qualified international scientists (if feasible, given current International Traffic in Arms Regulations constraints) and scientists from the space science community. ESE should also consider requiring as part of the contract for selected PI-led projects that the PI serve subsequently as a reviewer.**

[16] National Research Council, Space Studies Board, 2000, *The Role of Small Satellites in NASA and NOAA Earth Observation Programs*, National Academy Press, Washington, D.C., highlighted the burden on the peer review community as a "hidden cost" of PI-led small satellite missions.

### Number of Awards

The number of proposals carried forward from Step 1 to Step 2 has always been a controversial issue.[17] On the one hand, NASA would like to have the opportunity for detailed evaluation of the greatest number possible of potentially qualified proposals. On the other hand, carrying forward proposals that have a lower likelihood of winning entails the nonproductive expenditure of resources both among those teams and on the part of NASA and the reviewers. The proposals supported in Step 2 should include only those that have sufficiently high scientific merit and TMCO potential to be fully competitive with all other Step 2 proposals. Informal guidelines for the number of Step 2 awards should be a minimum of two for each flight opportunity to be awarded and a maximum of one-third of the total proposals submitted in Step 1.

***Finding:*** The number of proposals selected for consideration in Step 2 represents a critical compromise between the desire for a large pool of evaluated PI-led mission proposals from which to make the final selection and the need for a pool small enough that available reviewers can perform detailed reviews. Selection for Step 2 of proposals that have a lower probability of final selection results in inefficient use of proposers' resources.

***Recommendation:*** **The proposals supported in Step 2 of the selection process for PI-led missions should include only those that have sufficiently high scientific merit and an acceptable initial evaluation of technical, management, and cost risk so as to be fully competitive with all other Step 2 proposals. As an informal guideline, a minimum of two Step 2 proposals should be selected for evaluation for each flight opportunity to be awarded, and the maximum number considered should be one-third of the total proposals submitted in Step 1.**

### Selection Process Integrity

As discussed previously, competition involves a checks-and-balances process between the proposers, the reviewers, and the selection official. Maintaining and improving this checks-and-balances process and its credibility is the highest priority for enhancing the competition of PI-led mission AOs. As the standard for review quality increases, proposers will increase the quality of their technical concepts, management plans, and cost estimates. The result will be higher-quality proposals recommended to the selection official and a greater likelihood of selecting successful missions.

NASA has commonly included language in its AOs indicating that considerations not related to the merits of the proposals may be included in the selection process.[18] Enterprise objectives clearly go beyond the more focused objectives of review boards convened for a particular AO, and it is widely recognized that AO peer reviews provide only part of the final selection criteria. Nevertheless, every effort should be made to maintain the greatest traceability of the decision to the recommendations of the independent reviews and to established Enterprise priorities.

***Finding:*** Maintaining and improving the credibility of checks and balances is the highest priority for enhancing the selection process for PI-led missions. An effective and credible proposal review process requires a balanced effort among proposers, reviewers, and the selection official. Proposers are motivated to avoid overly optimistic costing if they respect the cost-review process; reviewers are more diligent when their recommendations are likely to be accepted by the selection official; and the selection official relies more readily on reviewer recommendations when the proposal and review process is effective at identifying the best mission candidates.

[17] "Medium-Class Explorers (MIDEX) Lessons-Learned Workshop," Hampton, Va., June 26-27, 1996, available at <http://explorer.larc.nasa.gov/explorer/MIDEX.html>.

[18] The ESSP-3 AO states: "While review panels carry considerable weight, NASA reserves the right to make the final selection of proposals based on the needs of the Earth Science Enterprise, the ESSP and the research priorities stated in the AO."

***Recommendation:*** **NASA's Earth Science Enterprise should strengthen the complementary roles of proposers, reviewers, and the selection official in the selection process for PI-led missions, improving the critical balance between the three roles and focusing on clear traceability of the selection process to independent reviews and established ESE priorities.**

***Finding:*** The availability of accurate cost estimates is a very important element of the mission selection process, but establishing accurate estimates of project cost has historically provided one of the largest challenges to both proposers and reviewers of PI-led missions.

***Recommendation:*** **NASA's Earth Science Enterprise should enhance its cost evaluation capabilities to improve the accuracy of mission selection decisions and to motivate improved fidelity of cost proposals.**

## LIFE-CYCLE ACTIVITY 3: EXECUTION

Project execution encompasses both the formulation and the implementation phases of a mission project. This section discusses several general issues influencing successful project execution and specifically addresses adaptation of the six subelements of mission implementation to a cost- and schedule-constrained PI-led mission.

### Lessons from Non-PI-Led Mission Projects

Many of the problems encountered in recent PI-led missions have root causes in common with non-PI-led missions. In particular, the transition to smaller cost-constrained projects during the 1990s, the aging of the space industry workforce, and other external issues all directly affected project success. These problems should not be attributed to flaws in the PI-led process, but rather applied as general lessons for all small-mission projects.

PI-led projects, however, must be able to address generic issues just as effectively as issues specific to the PI-led process. It is imperative that PI-led missions identify and mitigate mission risks just as rigorously and with as much accountability as non-PI-led missions. Elements of potential failure such as poor team communication, cost and schedule pressure, insufficient reserves, and weak review processes are common to projects both within NASA and in other institutions. Given sufficient time and money, potential failures can often be corrected if they are discovered. The application of cost caps and other program constraints over the last decade, however, has meant that it is more difficult to recover from budget overruns and schedule slips due to unforeseen problems, and mission teams must be adept at adjusting scope to recover. PI-led teams, which tend to be less experienced than NASA-led mission teams, are particularly susceptible to such an experience-driven environment. Within the context of the formulation and implementation phases, it is thus important for ESE to establish processes that emphasize the understanding of generic mission issues and the inclusion of appropriate lessons learned.[19]

***Finding:*** Although some of the difficulties with recent PI-led missions are unique, many of the problems encountered have root causes in common with non-PI-led missions. In particular, the transition to smaller cost-constrained projects during the 1990s and the contraction and aging of the space industry workforce have affected project success. These problems should not be attributed to flaws in the PI-mode process, but rather applied as general lessons for all small-mission projects.

***Recommendation:*** **NASA's Earth Science Enterprise should establish management processes for PI-led missions that emphasize understanding all PI-led and non-PI-led mission issues and the inclusion of appropriate lessons learned from both types of missions.**

[19]It is noteworthy that the ESSP library, as described in the ESSP-3 AO, includes no reference to the 2000 NASA Integrated Action Team report or any other of the many recent lessons-learned documents arising from mission failures.

### Roles of the PI Team, NASA Project Team, and the Associate Administrator

Although the ESSP-3 AO states that "the selected mission team will be totally responsible for the ESSP mission," the AO process has evolved so that many mission elements, including the review process, are now within the control of the NASA program/project office and not subject to PI authority. NASA should explicitly recognize that mission success is a combined responsibility of the PI-NASA team. Split (not shared) authority is appropriate for achieving mission success and is healthy for the PI community. Lines of authority and responsibility, however, become confused when NASA asserts full PI responsibility but practices extensive management control. The result is that issues arise for which nobody claims responsibility or authority, introducing a significant risk to mission success. Each project plan should explicitly designate the split in authority and responsibility between the PI team and NASA, and both parties should concur prior to MDR. This split should accord with the philosophy that the mission should be defined and developed by the science community itself.[20]

***Finding:*** Mission success is appropriately viewed as the combined responsibility of the PI-led team and NASA. Split as opposed to shared authority is appropriate for achieving mission success and is healthy for the PI community; split authority and the resulting allocation of responsibility should be explicitly recognized in the project plan and should also reflect the philosophy inherent in PI-led missions that the mission is to be defined and developed by the science community itself.

***Recommendation:*** **NASA's Earth Science Enterprise should explicitly recognize that mission success is a combined responsibility of the PI team and NASA and should establish project management plans, organizations, and processes that reflect an appropriate split, not a sharing, of authority, with the PI taking the lead in defining and maintaining overall mission integrity.**

### Project Processes

*Project Controls*

Project controls include budgeting, scheduling, procurement (subcontracting), risk management, technical reviews, requirements management, and technical management. If the mission is to succeed, each of these elements of project control has to be executed in an accurate, timely, and comprehensive manner, but without the resources of a large project management team. Customization and scaling are required to map project control functions to small, cost- and schedule-constrained ESSP missions. The committee fully recognizes the difficulty of staffing and implementing a comprehensive project management function with a very small number of people, many of whom have other duties on or off the project. The purpose of this section is to offer ideas and recommendations to NASA concerning how the function of project management might be scaled to a small ESE mission.

***Key Individuals.*** For this discussion it is assumed that the ESE PI has delegated day-to-day project management responsibilities to a project manager (PM). Daily project management on small missions involves a number of activities, including technical decision making, facilitation of communications among team members, acquisition of resources, coordination with NASA, oversight of the project's schedule and budgets, and oversight of the mission's risk management process. Even the smallest of missions requires a full-time PM. An effective PM has been consistently identified as one of the hallmarks of successful missions. The PM in turn has a small number of team leaders who have direct responsibility for the implementation of the various elements of the mission (e.g., camera, spacecraft, integration and test, mission operations).

[20]This is a paraphrase of a portion of the NASA charge to the Space Studies Board calling for the 1996 study "Assessment of Recent Changes in the Explorer Program"; see National Research Council, Space Studies Board, 1996, *Assessment of Recent Changes in the Explorer Program*, National Academy Press, Washington, D.C.

It is also assumed that NASA has delegated coordination and oversight of the ESE mission to the mission manager (MM) and staff. The MM functions as a liaison for the ESE mission, representing the interests of the mission to senior NASA management and likewise conveying the concerns of NASA back to the PI's team. The MM often becomes a part of the PI's management team.

***Schedule and Cost Controls.*** A complete and accurate work breakdown structure (WBS) must be developed and adopted by both the PM and team leaders in order to properly implement a project schedule or cost-reporting system, even on relatively small projects such as ESSP missions. A good WBS should accurately reflect the manner in which work will be performed.

On large projects, cost and schedule controls are implemented with a staff of specialists who may have no other responsibilities. On ESSP missions, there is no such luxury. Project cost and schedule controls are almost certainly the responsibility of the PM with the assistance of perhaps one other person, but NASA must not expect this staff of two people to be able to produce the sorts of comprehensive, detailed cost reports on a monthly basis that are expected from an observatory-class mission.

During the implementation phase of a mission the PM must have a detailed schedule for tracking and reporting progress. Properly used, the schedule can also be resource loaded and used for cost performance evaluation. The PM must have agreement from the team leaders that the schedule accurately portrays the work being done and that they are committed to meeting the milestone dates shown. The team leaders must report their status accurately each month to the PM. In turn, the PM must link the schedules provided by the team leaders in such a way that the mission's critical path can be clearly identified and reviewed with the MM on a monthly basis. Where progress is not being made at the rate needed to meet milestone dates, the PM must take corrective action as soon as a schedule slippage is identified.

The MM must be willing to help in any way to assist the PM in holding to the key milestone dates, because it is essentially impossible for a mission to maintain cost control if the schedule is not controlled. For cost development and tracking a similar process must be adopted, with the PM and team leaders again working together to develop the implementation phase budgets. It is essential that the team leaders as well as the PM be committed to performing the work for the agreed upon budgets. A variety of tools are commercially available for cost tracking and reporting for at least the major systems and sometimes for lower-level systems as well.

Table 5.1 shows a level of cost and schedule control and reporting frequency that the committee suggests as reasonable to serve the interests of NASA ESE and the PI team.

TABLE 5.1 Suggested Level and Frequency of Cost and Schedule Reporting for PI-Led ESE Missions

| Parameter/Item | Reporting Frequency | Level of Detail | Available COTS Tools |
|---|---|---|---|
| Work breakdown structure | At start of the implementation phase and after any major changes | WBS level 3 or greater | Standard word processor or spreadsheet |
| Schedule | Monthly | Equivalent to WBS level 3, or to the level of major subsystems; must be able to see the project's critical path and the total float on the critical path | COTS scheduling software packages are available |
| Cost | Monthly | Total mission costs for labor, travel, purchased parts, subcontracts, and reserves; preferred reporting is costs to WBS level 3<br>Reports usually required to be in NASA 533M format | COTS spreadsheet or can be generated by COTS scheduling software package |
| Cost variance | Monthly | Top-level spending plan for entire mission; preferred reporting is planned vs. actual cost to WBS level 3 | COTS spreadsheet |

***Risk Management.*** The identification and tracking of technical and programmatic risks is a vital element of project management. For ESSP missions it is likely that the PM will serve as the owner and operator of the mission risk management system. A tailored risk management system for ESSP missions includes a list of risk items that categorize the risk by type (technical or programmatic), system, criticality (e.g., how severe are the consequences of this risk?), likelihood, mitigation plans for each risk item that can be controlled or retired, and any dates associated with the risk mitigation plans. While NASA has a right to expect that the risk list will be maintained and reported on a monthly basis, ESE should not expect that an ESSP mission will have a staff of specialists monitoring and reporting risks.

***Technical Reviews.*** Technical reviews have always been an important part of the NASA culture. The ESSP AO requires certain critical or "milestone" reviews, including reviews of the system requirements, preliminary design, critical design, preenvironmental test, preshipment, mission readiness, operations readiness, launch readiness, and flight readiness, and the PI team is expected to schedule and budget for these milestone reviews. Most PI teams also schedule peer reviews on all newly designed or extensively modified systems. ESE should expect that minutes and action items will be recorded for both milestone and peer reviews.

Of concern to the committee is the occurrence of unscheduled reviews initiated by ESE to address a specific concern. At issue are the impacts on the cost and schedule as well as on the workload of the very small number of people who will inevitably be assigned the responsibility to respond to any resulting action items. The following steps are advisable relative to unscheduled reviews:

1. The NASA MM makes the decision to hold such a review after discussing its possible impacts with the PI and PM.
2. The PI team is provided funding, above the cost cap, to support the unscheduled review.
3. The review is led by an individual knowledgeable and current in the field.
4. The review report is produced quickly.

***Requirements Management.*** NASA should expect to see in place on PI-led missions a requirements management process tied to the mission's systems engineering process, which synthesizes science goals and objectives into requirements and specifications for use by the instrument and spacecraft teams in developing their equipment. Missions with a weak or nonexistent systems engineering and requirements management process are not likely to succeed.

A tailored requirements management process will include a single, level 1 science requirements document that provides mission, spacecraft, and instrument requirements. Even a small mission must have a requirements flow-down process that maps these level 1 science requirements down to the individual spacecraft, payload, and ground segment elements of the mission. And for even the smallest of missions some form of verification process must be implemented to ensure that all requirements have been met.

***Technical Management.*** Technical management involves the daily technical oversight and direction of a project. As a rule this is the job of the PM with assistance from a mission systems engineer.

Even ESSP-class missions must have someone functioning in the role of a mission systems engineer, who oversees the operation of the mission's system engineering process and serves as the chief engineer of the project. The mission systems engineer provides daily technical direction, allocates resources, identifies and documents interfaces, manages the requirements-flow-down process, develops the mission's environmental design and test guidelines, and manages the mission verification process. A full-time mission systems engineer is required for ESSP missions and may need the assistance of a part-time electrical engineer and mechanical engineer on small missions to work on specific issues. These two engineers may also be needed full-time in a systems engineering role on small missions, depending on the complexity of the mission.

*Customer Advocacy*

Customer advocacy entails informing the direct customer, the NASA MM, of the status of the mission as well as including the MM in the mission's decision-making process. One of the lessons learned from successful SSE missions is that good communication between the PI, PM, and MM is an essential element of mission success. The advocacy process ensures that the MM is an integral part of the PI's management team. Missions of any size benefit from good communications, but with missions as resource constrained as those of the ESSP, communication is vital.

*Design, Development, and Sustaining Engineering*

The design and development of a small mission such as an ESSP project require a competent, experienced, and dedicated team of engineers with clearly defined requirements, adequate resources to do the job, and enough freedom to develop the mission with minimum management oversight. When supported by a good systems engineering process and a complementary verification program, the design and development team has the best chance of developing its systems within cost and schedule, assuming that the TRL of the systems under development is sufficiently high that the development team can avoid major technical problems that overrun resources. NASA has been forced to cancel missions that suffered from inadequate technology readiness (e.g., FAME, CATSAT) even though the development teams were talented and dedicated. The low TRLs on these missions created huge cost and schedule risks that could not be overcome with available resources, leaving NASA no choice but to cancel the missions. Tailoring for a small mission, the development team must not be saddled with a low TRL as well as cost and schedule constraints if the mission is to be successful. The higher the TRL the more likely the mission success, especially for small missions. A mission should begin its implementation phase with a sufficiently high TRL, adequate resources and margins, a good systems engineering process, and a comprehensive verification program.

*Delivery and Flight Operations*

Completion of the development phase is determined by the successful completion of the mission's verification program. The MSE, working with the team leaders, reviews the acceptance tests of all flight and ground segment elements to ensure that all requirements have been met. The NASA MM must also be an integral part of the acceptance process.

Although overlooked on some small missions, the selection and training of flight controllers are also carried out during the implementation phase. Controllers must be included in mission integration and test activities in order to have enough on-console time to be trusted during initial orbital operations. NASA should work with the PM to ensure proper training of flight controllers. Small missions typically have very small flight operations teams, making it all the more important that the individual controllers be thoroughly trained and experienced through mission simulations.

*Capturing the Knowledge Base*

According to *NPG 7120.5B*, capturing the knowledge base requires the recording of lessons learned throughout the project and calls for the use of performance metrics to measure how well the project has performed and whether corrective action is necessary and possible. The use of performance metrics is an integral part of ISO 9001 quality management systems, compliance with which is a requirement for new NASA AOs.

On small projects this task involves incorporating any outstanding engineering change orders, closing any nonconformance or waiver requests, updating controlled project documents and flight equipment log books, and closing "fabrication travelers."[21] Most small project teams are fighting team exhaustion at this point in the project

[21]Fabrication travelers are manufacturing planning sheets—step by step instructions on how to fabricate, assemble, or test each item.

and frequently overlook the knowledge-capturing process. NASA should work with the PM to ensure that this step is not overlooked so that if a problem occurs on orbit the engineering team will have accurate documentation to troubleshoot the problem. Troubleshooting will be difficult if the required drawings or software listings are out-of-date.

The implementation of PI-led projects for an ESSP-class mission is difficult at best. Resource constraints force small team size with corresponding high workloads for key team members. To promote success under these circumstances, PI-led projects should have:

1. Completely open communications between the PI team and the NASA MM;
2. A proactive NASA MM who becomes an integral part of the PI's management team;
3. A good systems engineering process;
4. Stable requirements;
5. Adequate resources and margins;
6. A proactive schedule and cost management process that includes objective performance metrics;
7. A TRL of 6 or above;
8. A flexible and quick decision-making process;
9. A supportive institutional infrastructure at the PI's home institution;
10. A proactive risk management process; and
11. A comprehensive test program at the observatory level that includes multiple mission simulations for training flight controllers.

***Finding:*** While it may be appropriate for PI-led missions to use management processes that differ from NASA standards, NASA-defined minimum management standards are desirable to reduce programmatic risk to acceptable levels.

***Recommendation:*** **NASA's Earth Science Enterprise should establish and enforce a comprehensive set of minimum standards for program management to be applied to all PI-led missions, while accepting that such missions may employ management processes that differ from those of NASA. These minimum management standards must invoke the rigor that experience has shown is required for success.**

# 6

# Conclusions

PI-led missions should continue to play a role in NASA's ESE observation and science programs because they are the only vehicle available to meet those ESE strategic science goals that are not supported by facility-class missions. So far, however, PI-led missions in NASA's ESSP have experienced serious difficulties with cost overruns and schedule slips. This report focuses on identification of the reasons for these problems and on recommendations to improve PI-led mission performance.

The committee recognizes that strict constraints on mission cost and schedule tend to drive Earth Explorer PI-led missions to small satellites with limited instrument suites and low-risk technology requirements. Yet these "small" missions remain supremely challenging both for NASA and for the PI, especially academic PIs with little or no mission management experience. From the NASA standpoint, mission costs, schedule, and scope are highly constrained; coupled with the mandated PI-led management mode, the agency finds itself with essentially no degrees of freedom following mission selection to control scientific risks. From the perspective of the academic PIs, who are typically inexperienced in project management, the programmatic constraints allow little time and few resources to accommodate management missteps while preserving the proposed scientific scope of the mission.

Moreover, the attention to management issues required for PI-led mission accomplishment is inconsistent with typical academic career advancement criteria (except, perhaps, for those interested in high-level university administration), and the scientific rewards for success are unclear because of NASA's limited funding for post-launch scientific analysis within the selected ESSP mission contract. For example, the PI for a successful ESSP mission must compete for analysis funds through a follow-on Science Data Analysis Program (SDAP) proposal in response to an SDAP NRA issued to the broad scientific community just as the ESSP mission approaches operation. This requirement penalizes the ESSP PI relative to other SDAP competitors because the PI is saddled with time-consuming but essential ESSP management tasks during the SDAP competition.

The committee believes that many PI-led missions would more likely achieve ESE objectives within budget and schedule if the missions were properly structured. As discussed in the previous chapters, the likelihood of mission success increases greatly if:

1. The mission concept is mature at the proposal stage and is not dependent on risky technology development.
2. The mission includes a highly experienced PI who:
   a. Operates within a competent space systems development infrastructure.[1]
   b. Is supported by a strong technical management team.

With a sufficiently strong technical management team and space mission infrastructure, some new PIs will be able to execute successful missions. However, the committee believes that this should not be a general expectation by NASA.

The committee also believes that cost, schedule, and NASA oversight constraints on PI-led missions do not leave much room for innovative management approaches or significant creation or enhancement of space systems development infrastructures, even with the most experienced project teams. The committee thus concludes that it is unrealistic to expect the competitive AO process for PI-led missions to substantially enhance mission management capability at universities that do not already have space mission infrastructure in place.

[1]Space system development of space mission infrastructure includes facilities, trained personnel, processes, and procedures for development of space systems/missions.

# Appendixes

# A

# Statement of Task

## BACKGROUND

The current Earth Science Enterprise (ESE) flight program possesses some special challenges. For example, the Earth science community is largely one of data users rather than system developers; the flight mission design and construction experience base is especially thin in the academic research community. Further, NASA's ESE has adopted a policy in which all flight missions will be selected competitively. An approach based on open competition is fundamental to a strong research program, but it can create uncertainties regarding issues such as the relative responsibilities of selected Principal Investigators (PIs) and NASA centers, particularly if the PI is not located at a NASA center. Cost and schedule problems have recently led NASA/ESE to cancel or consider cancellation of the SPARCLE and the Vegetation Canopy Lidar (VCL) missions. A misunderstanding of the appropriate roles and responsibilities of the various institutions involved in the programs may have contributed to these problems; unexpected costs and technical roadblocks have also played a role.

Developing and implementing a satellite mission is a major task, and many universities and academic scientists may not have the necessary experience and infrastructure. The possibility exists that many of these issues could be addressed as part of the proposal solicitation and evaluation phases. Thus, NASA also wishes to better understand how organizational roles and responsibilities influence the likelihood of success of these PI-missions, as well as how to integrate programmatic guidance with the PI's science objectives. That Earth System Science Pathfinder (ESSP) missions are proposed under a strict cost cap adds to the necessity for realism in cost estimation and the risk of cost growth due to, for example, unanticipated technical problems.

## TASK

The Committee on Earth Studies will focus on successes and failures of both Earth and space science missions that have been led by academic researchers. It will seek out common threads drawn from recent experience and will identify steps that may increase the chances for success for PI-led missions. Issues to be considered will include, but not be limited to, the role of advanced technology development, the proposal solicitation and evaluation process, basic infrastructure needs and capabilities at universities, teaming arrangements and alternative frameworks for partnerships between universities and NASA centers and other organizations, and cost and schedule estimation. In addition, as the use of PI-led missions is only part of the NASA/ESE observational strategy, the committee will examine issues related to the coordination of observations from multiple space missions.

The study will contrast the PI mode with alternative ways of conducting missions, rather than simply comparing it with a NASA center-run operation. Such a comparison would be misleading as NASA centers have capabilities and experience in mission development that would not be expected for university-based PI-led operations. Indeed, one of the objectives of a PI-led mission could be to build up the capabilities of the host institution.

# B

# Committee Meeting Agendas

**DECEMBER 11-13, 2000**

**Monday—December 11, 2000**

*Executive Session*

| | |
|---|---|
| 09:00-10:00 a.m. | Agenda Review and Committee Discussions |

*Open Session*

| | |
|---|---|
| 10:00-11:00 | Overview of NASA Earth Science Enterprise (ESE) Programs<br>Jack Kaye, NASA ESE |
| 12:15-01:00 p.m. | Lunch |
| 01:00-03:30 | The PI Experience and Perspectives on the Study: Part I<br>Peter Harvey, University of California, Berkeley<br>Michael Prather, University of California, Irvine<br>Warren Wiscombe, NASA/Goddard Space Flight Center |
| 03:30-03:45 | Break |
| 03:45-05:00 | Discussion with PIs continues |
| 05:00-05:30 | Recap and prepare for Tuesday |
| 05:30-06:00 | Reception |

| | |
|---|---|
| 06:00 | Committee Dinner<br>Continued discussion of agenda items |
| 08:00 p.m. | Recess for the day |

**Tuesday—December 12, 2000**

*Executive Session*

| | |
|---|---|
| 09:00-10:30 a.m. | Committee Discussions<br>Committee Balance and Composition Discussion<br>Joe Alexander, Space Studies Board |

*Open Sessions*

| | |
|---|---|
| 10:30-12:00 noon | The PI Experience and Perspectives on the Study: Part II<br>Bill Gibson, Southwest Research Institute<br>Prasad Gogineni, University of Kansas |
| 12:00-01:00 p.m. | Lunch |
| 01:00-03:30 | PI Experience, Continued<br>Bill Gibson, Southwest Research Institute<br>Mark Saunders, NASA/Langley Research Center<br>Richard Zurek, NASA/Jet Propulsion Laboratory |
| 03:30-3:45 | Break |
| 03:30-5:30 | PI Experience, continued/Roundtable Discussion |
| 05:30 p.m. | Recess for the day |

**Wednesday—December 13, 2000**

*Executive Session*

| | |
|---|---|
| 09:00-12:00 noon | Committee Discussions<br>Report Outline<br>Writing Assignments and Preparation for Next Meeting |
| 12:00 noon | Adjourn |

## APRIL 25-27, 2001

### Wednesday—April 25, 2001

*Closed Session*

| | |
|---|---|
| 09:00 a.m. | Introductions/Committee Business |

*Open Sessions*

| | |
|---|---|
| 10:00 a.m. | Welcome<br>Dan Baker, Laboratory for Atmospheric and Space Physics (LASP) |
| 10:15 | Lessons Learned from Small Mission Development<br>Bill Gail, Committee on Earth Studies (CES) and Ball Aerospace |
| 11:15 | SuRGE/Thoughts on the CES Study<br>Mike McGrath, LASP |
| 12:00 noon | Lunch |
| 01:00 p.m. | Recent Experiences with ESSP Mission Development<br>Nick Chrissotimos, Goddard Space Flight Center |
| 02:00 | SORCE and Lessons for PI-led Missions<br>Gary Rottman, LASP |
| 03:00 | Committee Discussions with Guests |
| 04:00 | LASP Tour |
| 05:30 p.m. | Adjourn |

### Thursday—April 26, 2001

*Open Sessions*

| | |
|---|---|
| 09:00 a.m. | Welcome and Introductions<br>Mike Freilich, CES |
| 09:15 | SNOE and Lessons for PI-led Missions<br>Charles Barth, LASP |
| 10:00 | Lessons Learned from Sampex and Other Small Missions<br>Dan Baker, LASP |
| 10:50 | Break |
| 11:00 | GRACE and Lessons for PI-led Missions<br>Byron Tapley, University of Texas |

| | |
|---|---|
| 12:00 noon | Lunch |
| 01:00 p.m. | Picasso/CENA and other Experiences with PI-led Missions<br>Pat McCormick, Hampton University |
| 02:00 | CloudSat and Lessons for PI-led Missions<br>Graeme Stephens, Colorado State University |
| 03:00 | Development of Small Planetary Missions<br>Ben Clark, Lockheed-Martin |
| 04:00 | Roundtable Discussion<br>Committee, Guests, and LASP Personnel |
| 05:30 p.m. | Adjourn |

**Friday—April 27, 2001**

*Closed Session*

| | |
|---|---|
| 08:30 a.m. | Committee Discussions<br>—CES Contribution to SSB "Data Mining" Study<br>—Outline and Writing Assignments for PI-mode Study<br>—Plans for Next Meeting |
| 12:00 noon | Adjourn |

# C

# PI-Led Missions and Their Characteristics

This appendix provides a tabular "database" of PI-led missions and programs addressed in the report. Although they do not provide a complete list of all PI-led missions, Tables C.1 through C5 include a sufficient set of examples to illustrate the issues discussed in the report. Included are a range of missions in various disciplines, not only Earth science, and a range of scope from instrument-focused PI projects to multisensor payload missions where the PI was responsible for the entire mission from conception to spacecraft and sensor integration and launch, operations, and data analysis through orbit decommissioning. Mission examples are provided in all stages of a mission life cycle, including the study phase (formulation), the design, development, operations, and data analysis phases (implementation), and some that are completed. The tables also include missions that were canceled or descoped, usually due to cost and schedule difficulties associated with technology development, and several that failed on orbit.

Tables C.1 to C.5 list and describe the missions grouped by program: Discovery (Table C.1), MIDEX (Table C.2), SMEX (Table C.3), Earth System Science Pathfinder (Table C.4), and others (Table C.5). Each row of each table contains a brief summary of mission characteristics as follows:

*Column Heading—Content*

Mission—Name
Objectives—Mission science goals
Launch, S/C—Launch date and vehicle, spacecraft
Instruments—Instruments included in the mission manifest
Principal Team Institutions—Industrial or government agencies or laboratories, and universities participating in the mission
Management—Principal investigator and institution
Selection—Program solicitation under which the mission was selected
Status—Whether the mission has been successfully completed, was launched and is in successful operation, is in development, was canceled, or has failed on orbit.

TABLE C.1 Discovery Missions and Characteristics

| Mission | Objectives | Launch, S/C | Instruments |
|---|---|---|---|
| Kepler | Detecting extrasolar terrestrial planets | Oct 2007 Launch – D2925-10 Delta II | Single instrument: Photometer |
| Dawn | Asteroid flyby | May 2006 Launch – Delta 7529H Orbital Spacecraft with xenon ion propulsion | Framing Camera, Mapping Spectrometer, Gamma Ray and Neutron Spectrometer, Laser Altimeter, Magnetometer |
| Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) | Mercury orbiter | 2004 Launch – Delta II 7925H | Mercury Dual Imaging System, Gamma Ray and Neutron Spectrometer, Magnetometer, Mercury Laser Altimeter, Atmospheric and Surface Composition Spectrometer, Energetic Particle and Plasma Spectrometer, X-Ray Spectrometer, Radio Science |
| Deep Impact | Comet impactor/flyby | Dec 2004 Launch – Delta II | High-Resolution Instrument, Medium-Resolution Instrument, Impactor Targeting Sensor |
| Genesis | Solar wind sample return to obtain precise measures of solar isotopic abundances | Aug 2001 Launch | Sample Collection Arrays |
| Comet Nucleus Tour (CONTOUR) | Multiple comet flyby (2) | Jul 2002 Launch – Boeing Delta | Neutral Gas and Ion Mass Spectrometer, Remote Imaging Spectrograph, Dust Analyzer, Forward Imager |
| Stardust | Comet flyby sample return | Feb 1999 Launch – Delta II, 7425 | Dust Flux Monitor, Cometary and Interstellar Dust Analyzer |
| Lunar Prospector | Moon orbiter/impactor | Jan 1998 Launch – Athena II (Lockheed Martin) | Gamma Ray Spectrometer, Neutron Spectrometer, Alpha Particle Spectrometer, Magnetometer, Electron Reflectrometer |
| Near Earth Asteroid Rendezvous (NEAR) | Asteroid orbiter | 1996 Launch – Delta 2 | Multi-Spectral Imager, NEAR Infrared Spectrometer, NEAR Laser Rangefinder, X-ray/Gamma Ray Spectrometer, Magnetometer |

| Principal Team Institutions | Management | Selection | Status |
|---|---|---|---|
| Ball Aerospace | PI – Bill Borucki (NASA Ames) | Discovery-4 (2002) | Formulation phase |
| JPL, Orbital | PI – Chris Russell (UCLA) | Discovery-4 (2002) | Formulation phase |
| JHU Applied Physics Laboratory, GenCorp Aerojet, Composite Optics, NASA GSFC, U. Colo., U. Mich. | PI – Sean Solomon (Carnegie Institution of Washington) | Discovery-3 | Formulation phase |
| U. Md., JPL, Ball Aerospace | PI – Mike A'Hearn (U. Md.) | Discovery-3 | Critical design review, Jan 2002; now in 34-month implementation phase |
| JPL, NASA JSC, Lockheed Martin, LANL | PI – Don Burnett (Caltech) | Discovery-2 | Operating |
| Rockwell Science, Cincinnati Elec. APL: incorporation of spacecraft maindeck and frame | PI – Joe Veverka (Cornell U.) | Discovery-2 | Lost contact with spacecraft following orbital maneuver on August 15, 2002 |
| JPL, Lockheed Martin, Max-Planck-Institut, NASA Ames, NASA JSC, U. Chicago | PI – Donald Brownlee (U. Wash.); Deputy PI – P. Tsou (JPL) | Discovery-1 | Operating |
| NASA Ames, Lockheed Martin, Lunar Research Institute | PI – Alan Binder (Lunar Research Institute) | Discovery-1 | Mission completed |
| JHU/APL, JPL, Cornell U., MIT, U. Md., U. Ariz., SW Research Inst., Malin Space Science Systems, Inc. | Program Executive – Anthony Carro (NASA HQ) | Discovery-0 (noncompetitive) | Mission completed Feb 2001 |

TABLE C.2 MIDEX Missions and Characteristics

| Mission | Objectives | Launch, S/C | Instruments |
|---|---|---|---|
| Swift Gamma Ray Burst Explorer | Observe gamma-ray bursts | 2003 Launch – Delta 7320 | Burst Alert Telescope, X-Ray Telescope, Ultraviolet and Optical Telescope |
| Full-sky Astrometric Mapping Explorer (FAME) | Astrometry | 2004 Launch – Delta 7425 | Astrometric Telescope |
| Microwave Anisotropy Probe (MAP) | Map the temperature fluctuations of the CMB radiation | 2001 Launch – Delta II-7425-10 | High Electron Mobility Transistor |
| Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) | Image Earth's magnetosphere | Mar 2000 Launch – Boeing Delta II 7326-9.5 | Neutral Atom Imagers, Far-Ultraviolet Imaging System, Extreme Ultraviolet Imager, Radio Plasma Imager, Central Instrument Data Processor |
| Far Ultraviolet Spectroscopic Explorer (FUSE) | Make far-ultraviolet observations of hydrogen and deuterium | Jun 1999 Launch – Delta 7320-10 | Far-Ultraviolet Spectrograph |

TABLE C.3 SMEX Missions and Characteristics

| Mission | Objectives | Launch, S/C | Instruments |
|---|---|---|---|
| Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) | Explore basic physics of particle acceleration and explosive energy release in solar flares | Feb 2002 Launch – Orbital Sciences Corp. Pegasus XL, L1011 aircraft | Imaging Telescope Assembly, Grid Tray and Grids, Spectrometer, Attenuators |
| Galaxy Evolution Explorer (GALEX) | Study star formation history of the universe | Mar 2003 Launch – Pegasus XL | Single Instrument with 2 UV Microchannel Plate Detectors |
| Wide Field Infrared Explorer (WIRE) | Obtain infrared astronomy | Mar 1998 Launch – Pegasus XL | Cryogenically Cooled 30-cm Ritchey-Chretien Telescope |
| Transition Region and Coronal Explorer (TRACE) | Obtain high-resolution solar imagers | Apr 1998 Launch – Pegasus XL | TRACE Imaging Telescope |
| Submillimeter Wave Astronomy Satellite (SWAS) | Detect chemical composition of interstellar gas clouds | Dec 1998 Launch – Pegasus XL | Submillimeter Telescope |
| Fast Auroral Snapshot Explorer (FAST) | Investigate plasma physics of auroral phenomena | Aug 1996 Launch – Pegasus XL | 16 Electrostatic Analyzers, 4 Langmuir Probes on 30-m Booms, 2 Langmuir Probes on 3-m Booms, Searchcoil and Fluxgate Magnetometers, Time-of-Flight Mass Spectrometer |
| Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX) | Measure elemental and isotopic composition of solar energy particles and cosmic rays | Jul 1992 Launch – Scout | High-Energy Particle Detectors |

| Principal Team Institutions | Management | Selection | Status |
|---|---|---|---|
| NASA GSFC, Penn. State U., Leicester U., Brera Observatory, Mullard Space Science Lab., Spectrum Astro, Inc. | PI – Neal Gehrels (NASA GSFC) | MIDEX 98 | Implementation phase |
| U.S. Naval Observatory, Lockheed Martin, Naval Research Laboratory, Smithsonian Astrophysical Observatory | PI – Ken Johnston (U.S. Naval Observatory) | MIDEX 98 | Rescoped in Phase B; canceled in 2002 |
| NRAO, Lockheed Martin, Litton, UCLA | PI – Charles Bennett (NASA GSFC) | MIDEX 95 | Operating |
| SW Research Inst., Lockheed Martin | PI – Jim Burch (SW Research Inst.) | MIDEX 95 | Operating |
| JHU, NASA GSFC, Canadian Space Agency, Centre National d'Etudes Spatiale, U. Colo., UC Berkeley | PI – Warren Moos (JHU) | Pre-MIDEX | Operating |

| Principal Team Institutions | Management | Selection | Status |
|---|---|---|---|
| UC Berkeley, Paul Scherrer Institute, NASA GSFC, Spectrum Astro, Inc. | PI – Robert Lin (UC Berkeley) | SMEX 97 | Operating |
| Caltech, JPL, Orbital Sciences | PI – Chris Martin (Caltech) | SMEX 97 | Implementation phase |
| Caltech Infrared Processing and Analysis Center, Vanguard Research, Inc., JPL, NASA GSFC, Cornell U., Ball Aerospace | PI – Perry Hacking (JPL) | SMEX 94 | Failed during on-orbit commission |
| NASA GSFC, Lockheed Martin | PI – Alan Title (Lockheed Martin) | SMEX 94 | Operating |
| Harvard-Smithsonian Center for Astrophysics, NASA GSFC, Ball Aerospace | PI – Gary Melnick (Harvard-Smithsonian Center for Astrophysics) | SMEX 89 | Operating |
| Lockheed Martin., UC Berkeley, U. N.H., LANL, NASA GSFC | PI – Charles Carlson (UC Berkeley) | SMEX 89 | Operating |
| U. Md., Caltech, NASA GSFC, Aerospace Corp., NASA LaRC, Max-Planck-Inst. for Extraterrestrial Research | PI – Glenn Mason (U. Md.) | SMEX 89 | Operating |

TABLE C.4 Earth System Science Pathfinder (ESSP) Missions and Characteristics

| Mission | Objectives | Launch, S/C | Instruments |
|---|---|---|---|
| Gravity Recovery and Climate Experiment (GRACE) | Measure time variations of Earth gravity | Mar 2002 Launch | Microwave Ranging Sensors |
| Vegetation Canopy Lidar (VCL) | Provide first global inventory of vertical structure of forests | Originally Spring 2000 | Multi-Beam Laser Altimeter from NASA GSFC |
| Chemistry and Circulation Occultation Spectroscopy Mission (CCOSM) | Understand how atmospheric circulation controls the evolution of trace gases, aerosols, and pollutants | N.A. | Fourier Transform Spectrometer |
| Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), formerly Pathfinder Instrument for Cloud and Aerosol Spaceborne Observation – Climatologie Etendue des Nuages et des Aerosols (PICASSO–CENA) | Measure aerosol and cloud properties to improve climate predictions | Mar 2005 Launch – Delta 7420-10C (co-manifested with CloudSat), PROTEUS spacecraft (Alcatel) | Lidar (nadir-viewing, 2-wavelength, polarization sensitive), Visible Wide-Field Camera, Imaging Infrared Radiometer |
| CloudSat | Measure cloud profiles | 2004 Launch – Delta 7420-10 launch vehicle, Ball RS2000 spacecraft bus | 94-GHz Cloud Profiling Radar |
| Volcanic Ash Mapper (VOLCAM) | Monitor volcanic clouds and aerosols from geostationary orbit | Piggyback on spacecraft and flight of opportunity | Ultraviolet and Infrared Detectors |
| Aquarius | Globally map salt concentration on ocean surface | Launch date TBD | 3 Polarimetric Radiometers, 1 Polarimetric Scatterometer |
| Orbiting Carbon Observatory (OCO) | Make global measurements of atmospheric carbon dioxide | Launch date TBD – Taurus 2110 launch vehicle, Orbital LEOStar 2 spacecraft | 3 Grating Spectrometers |
| Hydrosphere State Mission (HYDROS) | Monitor soil moisture, land surface freeze/thaw conditions | 2006 Launch – Taurus 2110 launch vehicle, Spectrum Astro SA-200HP Spacecraft | L Band Radar/Radiometer |

| Principal Team Institutions | Management | Selection | Status |
|---|---|---|---|
| JPL, Space Systems/Loral, U. Tex., Eurockot | PI – Byron Tapley (U. Tex.) | ESSP-1 | Operating |
| Lab. Terrestrial Physics, U. Md., Omicron, Orbital, Raytheon, Swales, NASA GSFC | PI – Ralph Dubayah (U. Md.) | ESSP-1 | Descoped to technology development program; canceled in 2003 |
| Lockheed Martin, Spectrum Astro, Inc., JPL | PI – Michael Prather (UC Irvine) | ESSP-1 Alternate | Not continued as alternate |
| NASA LaRC, Ball Aerospace, Hampton U., Centre National d’Etudes Spatiales, Institut Pierre Simon LaPlace | PI – Dave Winker (NASA LaRC) | ESSP-2 | Implementation phase |
| USAF, Colo. State U., JPL, Ball Aerospace | PI – Graeme Stephens (Colo. State U.) | ESSP-2 | Implementation phase |
| Ball Aerospace, Raytheon STX Corp., FAA, NOAA, USGS, Smithsonian Institution | PI – Arlin Krueger (NASA GSFC) | ESSP-2 Alternate | Not continued as alternate |
| NASA GSFC, Argentine space program; >17 university, corporate, and international partners | PI – Chester Koblinsky (NASA GSFC) | ESSP-3 | Formulation phase |
| JPL, Hamilton Sunstrand, Orbital Sciences; >19 university, corporate, and international partners | PI – David Crisp (JPL) | ESSP-3 | Formulation phase |
| MIT, JPL, NASA GSFC, Spectrum Astro, Inc. | PI – Dara Entekhabi (MIT) | ESSP-3 Alternate | Formulation phase |

TABLE C.5 Other Missions and Characteristics

| Mission | Objectives | Launch, S/C | Instruments |
|---|---|---|---|
| Solar Radiation and Climate Experiment (SORCE) | Measure solar irradiance | 2002 Launch – Pegasus XL | Total Irradiance Monitor, Solar Stellar Irradiance Comparison Experiment, Spectral Irradiance Monitor, and Extreme Ultraviolet Photometer System |
| Cosmic Hot Interstellar Plasma Spectrometer (CHIPS) | Perform all-sky spectroscopy of diffuse UV background | Jan 2003 Launch – Delta II secondary (with ICESat) | Spectrograph |
| Tomographic Experiment using Radiative Recombinative Ionospheric EUV and Radio Sources (TERRIERS) | Model electron density and photo emissive components | May 1996 Launch – Pegasus XL | 5 Tomographic Extreme Ultraviolet Spectrographs, Gas Ionization Solar Spectral Monitor, 2 Photometers |
| Student Nitric Oxide Explorer (SNOE ) | Measure effects of energy from the Sun and from the magnetosphere on the density of nitric oxide | Feb 1998 Launch – Pegasus XL | UV Spectrometer, Auroral Photometer, Solar X-Ray Photometer |
| High Energy Transient Explorer (HETE)-2 | Analyze gamma-ray bursts | Oct 2000 Launch – Standard Pegasus | Gamma Ray Telescope, Wide-field X-ray Monitor, Soft X-ray Camera |
| Triana | Monitor Earth's energy balance, diurnal changes, solar wind, space weather | Launch date TBD – Space Shuttle, S/C Type – SMEX-Lite | Scripps Earth Polychromatic Imaging Camera, Advanced Radiometer Package, Plasma Magnetometer |

| Principal Team Institutions | Management | Selection | Status |
|---|---|---|---|
| U. Colo., Orbital, NASA GSFC | PI – Gary Rottman (U. Colo. LASP) | 1999 consolidation of two EOS PI missions: SOLSTICE and TSIM (SOLSTICE: AO-88-OSSA-1 selected 2/1989; TSIM: AO-97-MTPE-01 selected 2/1999) | Implementation phase |
| UC Berkeley, SpaceDev, Inc. | PI – Mark Hurwitz (UC Berkeley) | UNEX | Operating |
| Boston U., NRL, MIT, U. Ill., Aero Astro, Inc. | PI – Daniel Cotton (Boston U.) | STEDI 1995 | Failed during on-orbit commission |
| U. Colo. LASP, USRA, NASA, Ball Aerospace, Orbital, NCAR, NASA GSFC | PI – Charles Barth (U. Colo.) | STEDI 1995 | Operating |
| MIT, LANL, France's CNES and CESR, Japan's RIKEN | PI – George Ricker (MIT) | 1997 | Operating |
| Scripps Inst., NASA GSFC, Lockheed Martin, Ball Aerospace/NIST | PI – Francisco P.J. Valero (Scripps Inst. of Oceanography) | 1998 | In storage awaiting opportunity for launch |

## REFERENCES

### Briefings to Committee on Earth Studies

Jack Kaye, State of the Earth Science Enterprise, December 11, 2000
Peter Harvey, HESSI: The PI-Mode Experience, December 11, 2000
Michael Prather, Experiences as PI on ESSP AO-1 and AO-2, December 11, 2000
Richard Zurek, Some Thoughts on PI-Led Missions, December 11, 2000
Warren Wiscombe, Triana: Experiences and Lessons Learned, December 11, 2000
Bill Gibson, The IMAGE Mission PI Team Experience, December 12, 2000
Prasad Gogineni, ESSP Missions, December 12, 2000
Mark Saunders, A Perspective on PI-Mode Missions, December 12, 2000
William Gail, Perspectives on PI-Led AO Missions, April 25, 2001
Michael McGrath, Comments on PI Missions, April 25, 2001
Gary Rottman, The Solar Radiation and Climate Experiment (SORCE), April 25, 2001
Nicholas Chrissotimos, Earth Explorers Program PI-Mode Mission Management, April 26, 2001
Charles A. Barth, SNOE and Lessons for PI-Led Missions, April 26, 2001
Dan N. Baker, Managing and Developing Small Scientific Spacecraft, April 26, 2001
Byron Tapley, GRACE and Lessons for PI-led Missions, April 26, 2001
Graeme Stephens, CloudSat and Lessons for PI-led Missions, April 26, 2001
Ben Clark, Discovery Missions, April 26, 2001

### NASA Missions

#### Discovery, Explorer, and Solar-Terrestrial Probes

CONTOUR: http://www.contour2002.org/
Deep Impact: http://deepimpact.umd.edu/
GALEX: http://www.srl.caltech.edu/galex/
Genesis: http://genesismission.jpl.nasa.gov/
Kepler: http://www.kepler.arc.nasa.gov/
RHESSI: http://hesperia.gsfc.nasa.gov/hessi/
Mars Express: http://mars.jpl.nasa.gov/missions/future/express.html
MESSENGER: http://sd-www.jhuapl.edu/messenger/
IMAGE: http://pluto.space.swri.edu/image/
MAP: http://map.gsfc.nasa.gov/
SNOE: http://lasp.colorado.edu/snoe/
Stardust: http://stardust.jpl.nasa.gov/
TRACE: http://vestige.lmsal.com/trace/
Lunar Prospector: http://lunar.arc.nasa.gov/
Mars Climate Orbiter: http://mars.jpl.nasa.gov/msp98/orbiter/
Mars Pathfinder: http://mpfwww.jpl.nasa.gov/default.html
NEAR: http://near.jhuapl.edu/

#### Earth System Science Pathfinders

Orbiting Carbon Observatory: http://essp.gsfc.nasa.gov/oco/index.html
Aquarius: http://essp.gsfc.nasa.gov/aquarius/index.html
HYDROS: http://essp.gsfc.nasa.gov/hydros/index.html
CloudSat: http://essp.gsfc.nasa.gov/cloudsat/index.html

GRACE: http://essp.gsfc.nasa.gov/grace/index.html
Vegetation Canopy Lidar: http://essp.gsfc.nasa.gov/vcl/index.html

## Reports

National Research Council, Space Studies Board, Assessment of Recent Changes in the Explorer Program, 1996, National Academy Press, Washington, D.C.

Kenneth Lang, MIDEX Lessons-Learned Workshop Final Report, Proceedings from the Medium-Class Explorer (MIDEX) Lessons-Learned Workshop, June 26-27, 1996, Hampton, Virginia, August 1996, available online at <http://explorer.larc.nasa.gov/explorer/MIDEX.html>

Mars Program Independent Assessment Team, Summary Report, March 14, 2000, available online at <http://www.jpl.nasa.gov/marsreports/mpiat_summary.pdf>

Mars Climate Orbiter Mishap Investigation Board, Report on Project Management at NASA, March 13, 2000

## Announcement of Opportunity/Earth System Science Pathfinder

NASA, ESSP-3 AO, AO-01-OES-01, May 2001, available online at <http://centauri.larc.nasa.gov/essp/selection.html>

NASA, ESSP-2 AO, AO-98-OES-01, April 13, 1998

NASA, ESSP-1 AO, AO-96-OES-01, 1996

# D

# NASA Technology Development Programs Relevant to PI-Led Earth Explorers Missions

## ADVANCED COMPONENT TECHNOLOGIES

The Advanced Component Technologies (ACT) program (formerly Advanced Technology Initiative, ATI)

> is designed to bring instruments, platforms, and information system components to a maturity level that allows their integration into other NASA technology development programs such as the Instrument Incubator Program and the New Millennium Program. Some components are directly infused into mission designs by ES [Earth science] flight projects. The program also develops new ways to perform measurements and to process ES data products to expand ES research and application capabilities.[1]

The first ATI NASA Research Announcement (NRA) in 1999 focused on instrument technology with an emphasis on the needs documented in the 1998 Earth Science Technology Office's Capabilities and Needs Assessment. This competition resulted in 23 awards at $150,000 to $300,000 per year for 1- to 3-year programs: 8 to NASA field centers, 8 to federally funded research and development centers (FFRDCs) (mostly the Jet Propulsion Laboratory (JPL)), 5 to industry, and 2 to universities. Awards were made in five categories: active optical, active microwave, passive optical, passive microwave, and other. A second NRA was issued in February 2002 with proposals due in April 2002. A list of awards is available online at <http://esto.nasa.gov/obs_technologies_invest.html>.

## ADVANCED INFORMATION SYSTEMS TECHNOLOGY

Per the Advanced Information Systems Technology (AIST) program's Web site,[2]

> The objectives of the AIST Program are to identify, develop and (where appropriate) demonstrate advanced information system technologies which:
>
> - Enable new Earth observation measurements and information products;
> - Increase the accessibility and utility of Earth science data; and
> - Reduce the risk, cost, size, and development time of ESE space-based and ground-based information systems.

[1]See the ACT program Web site at <http://www.esto.nasa.gov/programs/act/>.
[2]See the AIST Web site at <http://esto.nasa.gov/programs/aist/>.

The first AIST NRA, issued in 1999, resulted in 30 awards: 5 to NASA field centers, 9 to FFRDCs, 7 to industry, and 9 to universities. A second AIST NRA was issued in September 2002 with proposals due in November 2002. A list of awards is available at <http://esto.nasa.gov/info_technologies_aist2.html>.

## INSTRUMENT INCUBATOR PROGRAM

The Instrument Incubator Program (IIP) attempts to bridge the gap between low-TRL (technology readiness level) development efforts like the ACT program and the instrument technical maturity needs of future missions. Instrument development under the IIP typically starts around TRL 3 to 5 and increases maturity to TRL 6 or 7. The latest IIP NRA states that "the results at the exit point should provide convincing evidence that the instrumentation can make the proposed measurements and that an operational instrument can be built within the context of the new shorter acquisition cycles."[3] This typically requires an exit point of TRL 6 or higher.

The first IIP NRA (NRA-98-OES-05) resulted in 123 proposals and 27 awards (8 to universities) totaling about $20 million, with 12- to 36-month periods of performance. The second IIP NRA (NRA-01-OES-01) solicitation resulted in 64 proposals and 11 awards (2 to universities) totaling $29.5 million. A third IIP NRA (NRA-02-OES-03) resulted in 28 proposals and 9 awards (2 to universities) totaling $22 million.

If adequately funded, the Instrument Incubator Program has the potential to provide the continuous stream of new instruments needed to support future Earth Science Enterprise (ESE) missions. Planned project funding levels seem consistent with instrument designs that can be adequately validated with ground testing. For those instruments that require flight validation to sufficiently settle questions of development risk, NASA offers the New Millennium Program.

## THE NEW MILLENNIUM PROGRAM

The New Millennium Program (NMP) is managed by NASA's Office of Space Science but addresses technologies that may be needed by both the space and Earth sciences. NMP missions have been fielded every few years to flight-test new suites of technologies. Early NMP missions had a science component and were designated as DS (Deep Space) or EO (Earth Observation) missions. More recently the program has been restructured and refocused on technology, and missions are now designated Space Technology (ST).

The recent NMP Technology Announcements (TAs) and NASA NRAs demonstrate a more structured and open competitive process for formulating New Millennium missions than had prevailed for the early missions. The process now includes three phases: Technology Concept Definition Study, Formulation Refinement, and Implementation. The TA/NRA is an open competition within a defined set of technology study areas (e.g., autonomy and on-board processing) drawn from NASA's strategic planning process. Multiple Technology Concept Definition Study awards are made, followed by a down-select (up to 5) for the formulation refinement phase. At the conclusion of formulation refinement, the NMP office determines the readiness of the project to proceed into the implementation phase, which is approved following a successful NASA HQ confirmation review (mission confirmation review for the ESE). The TAs for ST-6 and ST-7 also included a provision apparently designed to protect intellectual property and promote greater participation by universities and industry: "NASA will reject any proposals received from government, national laboratories or FFRDCs that are substantially the same as an industry or university proposal."

With the proviso that the process for selecting the specific study areas in a given TA/NRA should be open for input, review, and comment by the science and technology communities, the NMP mission formulation process as defined in the ST-6 and ST-7 TAs and the ST-8 NRA appears to be a substantial improvement over prior practice.

As a technology demonstration program, NMP can accept somewhat more development risk than can science missions such as the Earth System Science Pathfinder (ESSP) or Earth Observing System, particularly if the risk

[3]NASA Research Announcement, Instrument Incubator Program, NRA 01-OES-01, issued March 9, 2001, is available online at <http://research.hq.nasa.gov/code_y/nra/current/NRA-01-OES-01/NRA01OES01.pdf>.

is to specific technology demonstrations and not to the entire mission. Investigators must propose technology that, at the start of the study phase, is at least at the end of TRL 3 and is capable of reaching TRL 4 at down-select to the formulation refinement phase and TRL 5 or higher at project approval.

## MISSION AND SCIENCE MEASUREMENT TECHNOLOGY

The Office of Aerospace Technology seeks to "define new system concepts and demonstrate new technologies which enable new science measurements" under its Mission and Science Measurement Technology theme. Programs under this theme include Engineering for Complex Systems; Computing, Information and Communications Technology; and Enabling Concepts and Technologies.

This activity has incorporated the former Cross-Enterprise Technology Development Program, which was a primary vehicle for undertaking basic research to enable planned missions and stimulate new mission concepts. The program addressed low-TRL development of technologies with application across multiple NASA enterprises to support the long-range strategic goals of the offices of space science, earth science, human exploration and development of space, and the office of the NASA chief technologist. It moved technology readiness from articulation of initial concept through laboratory field demonstration in 10 thrust areas: power and propulsion, aerial and space operations, sensors, distributed spacecraft, communications, micro-nano spacecraft, computational tools, surface systems, automation, and structures.

A 1999 NRA led to more than 1,200 meritorious proposals from a wide range of investigators, indicating a large body of talent and ideas available to support the program. Funding limitations permitted only 111 awards, of which 56 went to universities, 10 to NASA field centers, 15 to FFRDCs, and 30 to industry. The committee is pleased to note the high percentage of awards to universities in this procurement, an open competition that had excellence and relevance to the NASA enterprises as key evaluation criteria. This bodes well for the university technology development infrastructure, an important prerequisite for successful PI-led missions.

## COMPUTATIONAL TECHNOLOGIES

The Computational Technologies (CT) project addresses applications of massive parallel computing, at the teraflop level, to further understanding of and the ability to predict the dynamically interacting physical, chemical, and biological processes characteristic of Earth, the Sun, the solar system, and the broader universe. Applications of relevance to ESE include massive data management, data processing algorithms, and weather and climate modeling.

The CT project is led by NASA Goddard Space Flight Center and supported by JPL. Science teams are chosen to address problems related to the Grand Challenges, science and engineering problems that can be addressed with computational technology. Science Team III has 11 Grand Challenge Investigator Teams participating. Science Team I (1992-1996) had 8 teams (plus 21 guest teams) and Science Team II (1996-2000) had 9 teams.

## THE SMALL BUSINESS INNOVATION RESEARCH AND SMALL BUSINESS TECHNOLOGY TRANSFER PROGRAMS

The Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs provide opportunities for small high-technology companies and nonprofit research institutions (e.g., universities) to participate cooperatively in government-sponsored R&D efforts. Through annual solicitations NASA's SBIR/STTR program supports a wide range of technology development efforts with fixed-price awards up to $670,000.

SBIR/STTR programs have had numerous successes. However, they must be approached with care by principal investigators when formulating cost- and schedule-constrained PI-led missions under programs like ESSP. The mission PI has limited influence over SBIR/STTR projects, which must be under the management control of the small business that holds the contract.

# E

# Biographies of Committee Members

MICHAEL H. FREILICH, *Chair*, is a professor in the College of Oceanic and Atmospheric Sciences at Oregon State University. Dr. Freilich's research interests include microwave ocean remote sensing, especially surface wind measurement and analysis techniques; surface wave modeling; and nearshore processes. His current work focuses on development of empirical models relating radar backscatter to near-surface winds; characterization of centimetric ocean surface roughness and atmospheric mesoscale phenomena using satellite measurements; and development and application of advanced statistical validation techniques. Dr. Freilich heads the Ocean Vector Wind Science Team on NASA's QuikScat mission. Dr. Freilich served on the National Research Council's (NRC's) Oceans Studies Board from 1992 to 1995. He was also a member of the Panel on the NOAA Coastal Ocean Program from 1993 to 1994.

ANTONIO J. BUSALACCHI, JR., is director of the Earth System Science Interdisciplinary Center (ESSIC) and professor of meteorology at the University of Maryland, College Park. ESSIC is a joint center among the Departments of Meteorology, Geology, and Geography at the University of Maryland in collaboration with the Earth Sciences Directorate at NASA's Goodard Space Flight Center. Dr. Busalacchi is a research scientist with past government laboratory experience. He brings expertise in applying research instruments and data to operational oceanography with particular emphasis on study of the tropical ocean response to surface fluxes of momentum and heat and tropical ocean circulation and its role in the coupled climate system. Dr. Busalacchi began his professional career as an oceanographer at the NASA/Goodard Space Flight Center. In 1991, he was appointed as the chief of the NASA/Goddard Laboratory for Hydrospheric Processes. In that capacity he furnished scientific direction to a broad, many-faceted program in Earth system science. Dr. Busalacchi has extensive NRC experience, having served as a member of the Panel on the Tropical Ocean Global Atmosphere Program, the Panel on Ocean Atmosphere Observations Supporting Short-Term Climate Predictions, and the Climate Research Committee. Currently, he serves as co-chair of the Scientific Steering Group for the World Climate Research Programme.

JOHN R. CHRISTY is a professor of atmospheric science and director of the Earth System Science Center at the University of Alabama in Huntsville. In November 2000, he was appointed as the Alabama state climatologist. Dr. Christy has served as a contributor to and lead author of the United Nations' reports by the Intergovernmental Panel on Climate Change in which satellite temperatures were included as a high-quality data set for studying global climate change. Dr. Christy has also been a member of several NRC committees, including the Committee to Review NASA's Earth Science Enterprise Science Plan and the Panel on Reconciling Temperature Observations. Dr. Christy is a fellow of the American Meteorological Society.

CAROL ANNE CLAYSON is an associate professor in the Department of Meteorology at Florida State University (FSU) and is director designate of the FSU Geophysical Fluid Dynamics Institute. From 1995 to 2001, she was an assistant and associate professor in the Department of Earth and Atmospheric Sciences at Purdue University. Dr. Clayson's research interests are in air-sea interaction, ocean and atmosphere boundary layers, numerical ocean and coupled ocean-atmosphere modeling, and remote sensing of air-sea surface fluxes. She was the recipient in 2000 of a Presidential Early Career Award for Scientists and Engineers and an Office of Naval Research Young Investigator Award. She was also the recipient in 1996 of an NSF career award. Her professional service activities include program chair for the 12th AMS Conference on Air-Sea Interactions, held in 2003, and membership on a number of committees and working groups, including the AMS Committee on Interaction of the Sea and Atmosphere; AMS Board of Meteorological and Oceanographic Education in Universities; NASA TRMM Science Team; TOGA COARE Air-Sea Flux Working Group and TOGA COARE Radiation Working Group; and the AMS, the AGU, and the Oceanography Society.

WILLIAM B. GAIL is director, Advanced Programs for Earth Science, Ball Aerospace and Technologies Corp. Dr. Gail is responsible for business development and proposal activities for NASA, NOAA, and international customers covering instruments, spacecraft, and space systems in the areas of space and Earth sciences. He has also directed program development activities leading to contracts on numerous space science programs. Dr. Gail was instrumental in establishing international science mission partnerships in Europe and Asia and for developing innovative program implementation approaches, including government/commercial partnerships and commercial geo-platform leasing for government payloads.

CATHERINE GAUTIER is a professor of meteorology and Earth system science at the University of California, Santa Barbara. Dr. Gautier heads the Earth Space Research Group of the Institute for Computational Earth Systems Science, a research unit at UCSB, where research is focused on Earth system science modeling and observations. Her research utilizes satellite-derived data relating to El Niño, Indian Ocean monsoons, air-sea interactions, development of a system for processing geostationary satellite data, and other topics related to weather and climate. Dr. Gautier's other research interests include Earth radiation budget and cloud processes, radiative transfer and remote sensing, and global climate processes.

WILLIAM C. GIBSON is assistant vice president, Space Science and Engineering Division, Southwest Research Institute. He has extensive experience in the management of projects involving the development of scientific instruments and support systems for use on the space shuttle, free-flying satellites, sounding rockets, and high-altitude research balloons. Mr. Gibson has served as the project manager for the Imager for Magnetopause-to-Aurora Global Exploration Medium-Sized Explorer (MIDEX). His areas of technical specialization include the design of spacecraft data systems, spacecraft telemetry and control systems, and spacecraft heat transfer systems.

SARAH T. GILLE holds a joint appointment as an assistant professor at Scripps Institution of Oceanography and in the Department of Mechanical and Aerospace Engineering, University of California, San Diego. Prior to her current position, she was on the faculty of the Earth System Science Department at the University of California, Irvine. Dr. Gille's research interests are in climate and ocean dynamics. She interprets satellite observations from altimetry and scatterometry, with the goal of understanding physical processes controlling ocean climate. She is a member of the NASA Jet Propulsion Laboratory (JPL) Ocean Vector Wind Science Team and the NASA JPL Jason Science Working Team.

ROSS N. HOFFMAN is vice president, Prediction and Radiation Studies, and manager, Numerical Weather Prediction Group, at Atmospheric and Environmental Research (AER), Inc. Dr. Hoffman is an industry scientist with emphasis on data assimilation and uses, not satellite mission development or operations. His principal areas of interest cover objective analysis and assimilation methods, atmospheric dynamics, climate theory, and atmospheric radiation. He has been the principal investigator for several projects at AER and has made significant contributions in the field of data assimilation, including the development of some variational techniques. Dr. Hoffman is a member of the NASA NSCAT Science Team and the EOS SeaWinds Science Team. He is also a member of the NRC Committee on Status and Future Directions in U.S. Weather Modification Research and Operations.

BRUCE D. MARCUS is retired from TRW, Inc., where he was the chief scientist of the Space and Laser Programs Division. His technical background includes research in heat and mass transfer, heat pipes, thermosiphons, spacecraft thermal control, and thermo-mechanical design of telescopes. Dr. Marcus is a former member of the NRC Task Group on Technology Development in NASA's Office of Space Science and is currently a member of the Space Studies Board.

RALPH F. MILLIFF is a research scientist at the Colorado Research Associates Division of NorthWest Research Associates. His expertise is in numerical modeling of the ocean and atmosphere, and the relation of air-sea dynamics to climate. Prior to his current position, Dr. Milliff was a staff scientist at the National Center for Atmospheric Research. Dr. Milliff has served as a member of the NASA Ocean Vector Winds Science Team for the NSCAT and QSCAT missions (1991 to the present). His current research involves the application of global surface vector wind data sets to studies of upper ocean mixing and the ocean general circulation; the Madden-Julian Oscillation; and the quasi-stationary waves of the Southern Hemisphere. In addition, he is adapting methods of Bayesian hierarchical models from probability and statistics to problems of air-sea interaction.

MICHAEL J. PRATHER is a professor in the Department of Earth System Science, University of California, Irvine. His areas of expertise are atmospheric chemistry and physics, with a special emphasis on modeling atmospheric composition. His publications also extend to planetary atmospheres and his doctoral work in astrophysics. Prior to his position at UC Irvine, Dr. Prather was employed by NASA at the Goddard Institute for Space Studies. He currently serves as editor-in-chief of *Geophysical Research Letters*. His extensive NRC service includes membership on the Board on Atmospheric Sciences and Climate.

R. KEITH RANEY is principal professional staff scientist with the Johns Hopkins University Applied Physics Laboratory. He is on special assignment in the APL Space Department, where his responsibilities include new initiatives in microwave remote sensing and satellite system configurations. Prior to his employment at Johns Hopkins, Dr. Raney was at the Canada Centre for Remote Sensing (CCRS), where he was its chief radar scientist and co-founder of RADARSAT, Canada's first remote sensing satellite program. He participated in the conceptual design phase of several satellite programs.

STEVEN W. RUNNING is a professor of ecology and director, Numerical Terradynamic Simulation Group, School of Forestry, at the University of Montana. His research interests include remote sensing of vegetation, bioclimatology, terrestrial ecosystem modeling theory, and regional hydrologic and carbon balance responses of forests resulting from global climate change. He is a member of the science team for NASA's Moderate Resolution Imaging Spectroradiometer, and he chaired NASA's Land Panel for the Earth Observing System (1999). Dr. Running has served on numerous committees, including for the International Geosphere-Biosphere Program's Biospheric Aspects of the Hydrologic Cycle (vice chair, 1991-1996), the NASA Earth Observing System, the World Climate Research Program's Terrestrial Observation Panel for Climate, and the WMO (1995-1998). He also served on the NRC BASC Climate Research Committee (1996-1999), the Panel on Climate Observing Systems Status (1998-1999), and the Committee to Review NASA's ESE Science Plan (2000). He is a fellow of the American Geophysical Union.

LAWRENCE C. SCHOLZ retired from Lockheed Martin as engineering fellow/manager, Systems Engineering and Flight Software Development, after 44 years as an engineer and physicist with 34 years of spacecraft design and systems engineering experience. He managed engineering groups and technical programs and has expertise in flight software, spacecraft operations, and instrument accommodations, and generally in spacecraft systems design. Dr. Sholz's commercial program experience includes communication satellites such as RCA Satcom, GE-1 (A2100 series), Telstar, and Intelsat. As the architect and manager of the Astro Satellite Operations Center, he was the mission director for communications spacecraft transfer-orbit operations. Working directly with NASA personnel at GSFC and Headquarters, he participated in the earliest studies of instrument accommodation on EOS.

CARL F. SCHUELER is chief scientist, Raytheon Santa Barbara Remote Sensing (SBRS). Dr. Schueler's experience and expertise are principally in satellite remote sensing. He has led numerous advanced sensor development studies and proposals for polar and geosynchronous Earth observation, as well as planetary exploration. He also managed the mid-1990s Defense Meteorological Satellite Program Block 6 studies and Polar-orbiting Operational Environmental Satellite 2000 studies leading to Raytheon's participation in the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program. He is currently technical director for the NPOESS Visible/Infrared Imager/Radiometer Suite (VIIRS) Program at SBRS and serves on the Advisory Committee for the Institute for Computational Earth System Science at the University of California, Santa Barbara.

ROBERT A. SHUCHMAN is senior vice president and chief technical officer of the Altarum Institute. Prior to his appointment at Altarum, Dr. Shuchman was vice president for Government Products and Services as well as director of the Earth Sciences Group at the Environmental Research Institute of Michigan. At Altarum, he is responsible for providing collaboration and overall technical direction and facilitating technical exchanges between business lines to create new business opportunities and collaboration of teams across those business lines. Dr. Shuchman manages corporate IR&D, utilizing inputs from the Altarum Science Advisory Council and business line presidents. Altarum's Emerging Technologies Group also reports to Dr. Shuchman. Dr. Shuchman is an expert in the use of remote sensing for terrestrial and oceanographic applications, including hydrology, land cover mapping, sea ice mapping, and coastal and marine management. He is also a recognized expert in intergrating remote sensing data into geographic information systems. His NRC service includes membership on the Panel on the Implications of Future Space Systems for the U.S. Navy (1985-1993), the Advanced Radar Technology Panel, and the Task Group 5 – Space Inputs (1994-1996).

ROY W. SPENCER serves as principal investigator on the global precipitation studies with Nimbus-7 and DMSP SSM/I at the Earth System Science Center of the University of Alabama in Huntsville. Dr. Spencer has been a member of several science teams: the Tropical Rainfall Measuring Mission (TRMM) Space Station Accommodations Analysis Study Team, Science Steering Group for TRMM, TOVS Pathfinder Working Group, and NASA HQ Earth Science and Applications Advisory Subcommittee. Since 1992 Dr. Spencer has been the U.S. team leader for the Multichannel Imaging Microwave Radiometer team and the follow-on AMSR-E team. In 1994 he became the AMSR-E science team leader. He received the NASA Exceptional Scientific Achievement Medal in 1991, the Marshall Space Flight Center's Director's Commendation in 1989, and the American Meteorological Society's Special Award in 1996. He served on the NRC Panel on Reconciling Temperature Observations (1999-2000).

WILLIAM STONEY is principal engineer at Mitretek Corporation. Following a varied history in NASA, including service as director of engineering for the Apollo Program, Mr. Stoney began his career in satellite remote sensing as director of NASA's Earth Observation Program in 1972, the year that Landsat 1 was launched. His tenure at NASA included the launch of Landsats 2 and 3 and the development of the Thematic Mapper and NOAA's TIROS and GEOS satellites and sensors. Since leaving NASA, he has worked for RCA and GE supporting the development of the EOS program, and for MITRE, and now Mitretek, supporting the current and future Landsat systems. Recently, he has been closely involved with the Stennis Science Commercial Data Buy Program.

JAN SVEJKOVSKY is the founder and president of Ocean Imaging, Inc., where he is responsible for managing and directing all scientific and corporate developments. His company focuses on added-value uses of space.

Dr. Svejkovsky is principal investigator on research grants from NOAA, NASA, NSF, the Navy, the State of California, and corporations. Dr. Svejkovsky's prime interest is in identifying new potential markets for remote sensing technology and developing customized products/services for those markets. In recent years, he has directed advanced development and commercialization of satellite and nonsatellite oceanographic techniques for diverse research and coastal applications, including sewage, storm runoff, and other pollution effluent monitoring (using optical, infrared, and synthetic aperture radar sensors); high-resolution surface current detection (using infrared, synthetic aperture radar, and optical imagery); and multispectral algorithms for bathymetry surveys and bottom substrate mapping. Since mid-1998, Ocean Imaging has operated its own multispectral aerial sensor for coastal research and environmental monitoring and, since 1999, for rapid-response agricultural remote sensing.

KURT THOME is an associate professor in the Optical Sciences Center at the University of Arizona. Dr. Thome's current research activities focus on NASA's Earth Observing System (EOS). This work includes developing algorithms for the absolute radiometric calibration after launch of the Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER), Landsat-7 Enhanced Thematic Mapper+ (ETM+), and MODIS. He is also involved in developing atmospheric correction algorithms for ASTER and ETM+ and is a member of the ASTER and Landsat-7 Science Teams.

JOHN R.G. TOWNSHEND holds a joint appointment as a professor in the Institute for Advanced Computing Studies and the Department of Geography at the University of Maryland. He is also a member of the Department of Geography's Laboratory for Global Remote Sensing Studies. Dr. Townshend's research centers on the use of remote sensing and advanced computing methods for improvements in the characterization of regional and global land cover. He has been a member of NASA's MODIS Science Team (since 1996) and he is a principal investigator on the Landsat Pathfinder Project for monitoring Earth's tropical moist forests. Dr. Townshend has also been chair of the Joint Scientific and Technical Committee of the Global Climate Observing System. His previous NRC service includes membership on the Committee on Geophysical and Environmental Data (1992-1998) and on the Board on Earth Sciences and Resources (1999). He also served as a member of the NRC Committee for Review of the Science Implementation Plan of the NASA Office of Earth Science.

## Staff

ARTHUR CHARO, *Study Director*, 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. Dr. Charo then pursued his interests in national security and arms control at Harvard University's Center for Science and International Affairs, where he was a fellow from 1985 to 1988. From 1988 to 1995, he worked in the International Security and Space Program in the U.S. Congress's Office of Technology Assessment (OTA). He has been a senior program officer at the Space Studies Board (SSB) of the National Research Council since OTA's closure in 1995. Dr. Charo is a recipient of a MacArthur Foundation Fellowship in International Security (1985-1987) and was the American Institute of Physics Congressional Science Fellow for 1988 to 1989. He is the author of research papers in the field of 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).

THERESA FISHER is a senior program assistant with the Space Studies Board. During her 25 years with the National Research Council (NRC) she has held positions in the Executive, Editorial, and Contract Offices of the National Academy of Engineering, as well as positions with several NRC boards, including the Energy Engineering Board, the Aeronautics and Space Engineering Board, the Board on Atmospheric Sciences and Climate, and the Marine Board.

# F

# Acronyms

| | |
|---|---|
| AA | associate administrator |
| ACT | Advanced Component Technologies |
| AIST | Advanced Information Systems Technology |
| AO | Announcement of Opportunity |
| CALIPSO | Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations |
| CATSAT | Cooperative Astrophysics and Technology Satellite |
| CCOSM | Chemistry and Circulation Occultation Spectroscopy Mission |
| CDR | critical design review |
| CETDP | Cross-Enterprise Technology Development Program |
| Co-I | co-investigator |
| COTS | commercial off-the-shelf |
| CT | Computational Technologies |
| EC&TP | Enabling Concepts and Technologies Program |
| EOS | Earth Observing System |
| ESE | Earth Science Enterprise |
| ESSP | Earth System Science Pathfinder |
| ESTO | Earth Science Technology Office |
| ESTP | Earth Science Technology Program |
| EUV | extreme ultraviolet |
| FAA | Federal Aviation Administration |
| FAME | Full-sky Astrometric Mapping Explorer |
| FFRDC | federally funded research and development center |
| GRACE | Gravity Recovery and Climate Experiment |
| GSFC | Goddard Spaceflight Center |

| | |
|---|---|
| HYDROS | Hydrosphere State Mission |
| IIP | Instrument Incubator Program |
| JPL | Jet Propulsion Laboratory |
| LANL | Los Alamos National Laboratory |
| LASP | Laboratory for Atmospheric and Space Physics |
| MAP | Microwave Anisotropy Probe mission |
| MCR | mission confirmation review |
| MDR | mission design review |
| MIDEX | Medium-Class Explorers |
| MM | mission manager |
| MSMT | Mission and Science Measurement Technology |
| NASA | National Aeronautics and Space Administration |
| NCAR | National Center for Atmospheric Research |
| NEAR | Near Earth Asteroid Rendezvous mission |
| NMP | New Millennium Program |
| NOAA | National Oceanic and Atmospheric Administration |
| NPG | NASA Procedures and Guidelines |
| NRA | NASA Research Announcement |
| NRL | Naval Research Laboratory |
| NSF | National Science Foundation |
| OCO | Orbiting Carbon Observatory |
| PDR | preliminary design review |
| PI | principal investigator |
| PM | project manager |
| QuikSCAT | Quick Scatterometer mission |
| SAGE | Stratospheric Aerosol and Gas Experiment |
| SBIR | Small Business Innovation Research |
| SDAP | Science Data Analysis Program |
| SeaWiFS | Sea-viewing Wide Field-of-view Sensor |
| SMEX | Small Explorers |
| SORCE | Solar Radiation and Climate Experiment |
| SRR | system requirements review |
| SSE | Space Science Enterprise |
| STEDI | Student Explorer Demonstration Initiative |
| STTR | Small Business Technology Transfer |
| TMCO | technical, management, cost, and other |
| TOMS | Total Ozone Mapping Spectrometer |
| TOPEX/Poseidon | Ocean Topography Experiment |
| TRL | technology readiness level |
| TRMM | Tropical Rainfall Measuring Mission |

| | |
|---|---|
| UARS | Upper Atmosphere Research Satellite |
| UnESS | University Earth System Science |
| UNEX | University Explorers |
| UNOLS | University-National Oceanographic Laboratory System |
| USGS | U.S. Geological Survey |
| USRA | Universities Space Research Association |
| | |
| VCL | Vegetation Canopy Lidar |
| VOLCAM | Volcanic Ash Mapper |
| | |
| WBS | work breakdown structure |