Review of the Science Mission Directorate's (SMD's) Draft Science Plan: Letter Report

Committee on Review of NASA Science Mission Directorate Science Plan, National Research Council

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September 15, 2006

Dr. Mary Cleave
Associate Administrator
Science Mission Directorate
NASA Headquarters
300 E Street SW
Washington, DC 20546

Dear Dr. Cleave:

In your letter of April 12, 2006, to Space Studies Board (SSB) Chair Lennard Fisk, you requested that the Space Studies Board conduct a review of the Science Mission Directorate's (SMD's) draft Science Plan[1] and provide its assessment and recommendations for how the draft might be improved. You asked for comments in the following areas:

- Responsiveness to National Research Council (NRC) recommendations in recent reports;
- Attention to interdisciplinary aspects and overall scientific balance;
- Utility to stakeholders in the scientific community; and
- General readability and clarity of presentation.

In response to your request, the ad hoc Committee on Review of NASA Science Mission Directorate Science Plan was established and met July 11-13, 2006, in Washington, D.C., to review the draft Science Plan. This report discusses the committee's findings and offers related recommendations.

The committee found the draft Science Plan to be an informative document demonstrating that a major NASA objective is to conduct scientific research to advance the fundamental understanding of Earth, the solar system, and the universe beyond. Some portions of the plan, such as that concerning astrophysics, do a truly excellent job of outlining why NASA carries out its science missions.

The committee also found that the draft plan outlines a defensible set of rules for prioritizing missions within each of SMD's discipline divisions, and it believes that SMD has made a serious effort to base its plans on the mission priorities established by the scientific communities that undertake and benefit from the missions that NASA conducts. Many of these priorities were established in NRC reports such as the decadal surveys, NASA's responsiveness to which the committee evaluates in the attached report. Historically, NASA has benefited from the advice provided by its several scientific advisory structures, and their health is vital to the agency's success in implementing its mission.

Although NASA was asked by Congress to develop a single prioritized list for missions across all four science disciplines (astrophysics, Earth science, heliophysics, and planetary science), for various reasons outlined in the report the committee does not believe that NASA should or could produce a prioritized list across disciplines at this time.

However, the committee does have some concerns about the draft plan. The committee found that the lack of a comparison of the current plan to plans produced in 2003 obscured the fact that NASA's space science plans have been significantly scaled back due to budget changes, and it recommends that

[1] NASA Science Plan, Draft 3.0, June 23, 2006.

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NASA include a comparison between the current plan and those produced in 2003 for the Earth and space sciences.

The committee further notes that the NRC's recent report *An Assessment of Balance in NASA's Science Program*[2] is largely neglected in the draft Science Plan. Although the NRC report was released shortly before the completion of the draft Science Plan, NASA representatives informed the committee that they had sufficient time to consider it. The committee acknowledges that the draft plan is based on the assumptions contained in the FY 2007 budget request and that the *Balance* report was critical of the adequacy of the budget to accomplish the total NASA plan. Nevertheless, the committee believes that the *Balance* report's recommendations are worthy of consideration and, where appropriate, incorporation in the NASA Science Plan.

The committee found that the current plan overemphasizes mission-specific work at the expense of strategies and steps for achieving goals in mission-enabling areas such as research and analysis, maintaining the Deep Space Network, and technology development. In addition, the committee noted that the draft plan often declares an intention to implement a program or identifies a goal or mission as a top priority, but then does not indicate what steps NASA will take to achieve the goals or what strategies it will pursue to accomplish its priorities.

The committee is concerned about the problem of mission cost growth and believes that if it is not successfully addressed, NASA will face the possibility of having to abandon either flagship missions or the ability to execute a balanced program. Mission cost growth and other factors identified in the attached report threaten the execution of the NASA Science Plan. The committee believes that addressing the issue of executability is a prerequisite for confidently defining a robust Science Plan, and it offers several recommendations on this subject.

The committee recognizes that NASA is awaiting the forthcoming NRC decadal survey on Earth sciences. However, the committee wishes to express its concerns about recent developments in Earth science, particularly recent decisions concerning the National Polar Orbiting Environmental Satellite System (NPOESS) program, whereby climate science instruments were deleted from the satellites. Many of these instruments are crucial to understanding the changing Earth system, and a strategy is needed to deal with their deletion from NPOESS.

By design, the draft plan addresses only those science programs that are conducted by SMD. The committee notes that an appreciation of the full extent of NASA's science activity requires a look at a number of programs outside SMD, in particular, the lunar precursor and robotic program, and the life and microgravity science activities within the Exploration Systems Mission Directorate (ESMD). The committee understands that Congress directed NASA to produce a Science Plan only for SMD. The committee concludes that the document would be improved if the introduction made clear the boundaries of the Science Plan's scope and also acknowledged that science is performed elsewhere within NASA as well, and the extent to which these other science programs are sensibly complementary to those within SMD.

Some of the committee's recommendations are broad and apply to all four of SMD's science disciplines, but the difficulties underlying the committee's concerns are more acute in some disciplines than in others. For example, the problems associated with controlling mission cost growth and preserving proper balance between large and small missions are now particularly pressing in astrophysics and, prospectively, in planetary science. The need to develop strategies for meeting future computing and modeling capabilities is particularly noticeable for Earth science and heliophysics. In addition, although the committee makes discipline-specific recommendations for the planetary and Earth sciences, it stresses that the astrophysics and heliophysics sections of the draft plan are also addressed in the more general recommendations and require equal attention.

The committee's recommendations on the implementation and viability of the draft NASA Science Plan follow:

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[2] National Research Council, *An Assessment of Balance in NASA's Science Programs*, The National Academies Press, Washington, D.C., 2006.

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1. The NASA Science Plan should compare the key aspects of its 2003 Earth and space science plans with the 2006 plan in a list or table that shows how the current plan differs from the previous ones. This comparison would also provide some indication of the starting point for the new Science Plan, and the changes that have occurred since 2003.

2. NASA/SMD should provide some indication of the strategy it will use to determine how critically needed technologies will be developed for future missions and their proposed timescales. The committee recommends that NASA outline a strategic technology plan, providing an indication of the resources needed and the schedule that must be met to enable the ambitious goals of the plan. But NASA should also seek to protect general R&A funding from encroachment by technology R&A.

3. The NASA Science Plan should explicitly address realistic strategies for achieving the objectives of the mission-enabling elements of the overall program. The committee recommends that NASA:

a. Undertake appropriate studies through its advisory structure in order to develop a strategic approach to all of its R&A programs (this strategy should include metrics for evaluating the proper level of R&A funding relative to the total program, the value of stability of funding levels in the various areas, and metrics for evaluating the success of these programs); and

b. Develop a strategic plan to address computing and modeling needs, including data stewardship and information systems, which anticipates emergent developments in computational sciences and technology, and displays inherent agility.

4. NASA should improve mechanisms for managing and controlling mission cost growth so that if and when it occurs it does not threaten the remainder of the program, and should consider cost-capping flagship missions. Although NASA already does seek to manage and control mission cost growth, these efforts have been inadequate and the agency needs to evaluate them, determine their failings, and improve their performance. NASA should undertake independent, systematic, and comprehensive evaluations of the cost-to-complete of each of its space and Earth science missions that are under development, for the purpose of determining the adequacy of budget and schedule.

5. NASA/SMD should move immediately to correct the problems caused by reductions in the base of research and analysis programs, small missions, and initial technology work on future missions before the essential pipeline of human capital and technology is irrevocably disrupted.

6. For planetary science, the committee recommends as follows:

a. NASA/SMD should incorporate into its Science Plan relevant recommendations from the NRC interim report on lunar science,[3] when they are available, in such a way as to maintain the overall science priorities advocated by previous NRC studies, while recognizing that science advice will change as scientific understanding and technology improve.

b. Although Mars should remain the prime target for sustained science exploration, the NASA Science Plan should acknowledge that missions to other targets in the solar system should not be neglected.

c. Where the question of habitability (i.e., the ability of a planet to support life) is determined to be the main focus for exploration, a proper hierarchy of scientific goals and objectives should be developed, stronger pathways between the concept of habitability and proposed missions should be articulated and maintained, and basic discovery science should not be ignored.

d. Life detection techniques should be clearly identified as an astrobiology strategic technology development area.

7. For Earth science, the committee recommends as follows:

[3] National Research Council, *The Scientific Context for the Exploration of the Moon—Interim Report*, The National Academies Press, Washington, D.C., 2006.

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a. NASA/SMD should incorporate into its Science Plan the recommendations of the NRC Earth science decadal survey interim report,[4] and should incorporate the recommendations of the Earth science decadal survey final report when it is completed.

b. NASA/SMD should develop a science strategy for obtaining long-term, continuous, stable observations of the Earth system that are distinct from observations to meet requirements by NOAA in support of numerical weather prediction.

c. NASA/SMD should present an explicit strategy, based on objective science criteria for Earth science observations, for balancing the complementary objectives of (i) new sensors for technological innovation, (ii) new observations for emerging science needs, and (iii) long-term sustainable science-grade environmental observations.

The committee elaborates on its findings and recommendations in the attached report.

Sincerely,

A. Thomas Young, *Chair*
Committee on Review of NASA Science Mission Directorate Science Plan

Attachment: A Review of NASA's 2006 Draft Science Plan

cc: Bryant Cramer, Acting Director, Earth Science Division, NASA
Richard Fisher, Director, Heliophysics Division, NASA
James Green, Acting Director, Planetary Science Division, NASA
Richard Howard, Acting Director, Astrophysics Division, NASA

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

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A Review of NASA'S 2006 Draft Science Plan

In a letter dated April 12, 2006 (Appendix A), the NASA Associate Administrator for Science requested that the National Research Council's (NRC's) Space Studies Board review the agency's Science Mission Directorate (SMD) draft Science Plan.[1] NASA provided the draft plan on June 23 to the NRC's ad hoc Committee on Assessment of NASA's Science Mission Directorate Draft 2006 Science Plan (Appendix B). NASA requested that the committee assess the draft according to the following criteria:

- Responsiveness to NRC recommendations in recent reports;
- Attention to interdisciplinary aspects and overall scientific balance;
- Utility to stakeholders in the scientific community; and
- General readability and clarity of presentation.

The Science Plan responds both to a congressional reporting requirement that was specified in the 2005 NASA Authorization Act and to SMD's need for a strategy document that implements the 2006 NASA Strategic Plan in the areas of Earth and space sciences. The NRC has reviewed previous NASA science plans that have been produced at 3-year intervals (coincident with the preparation of NASA's strategic plans).[2]

INPUT USED IN PREPARING THE ASSESSMENT

Detailed recommendations from the NRC decadal surveys and other recent NRC reports provided important input to the committee.[3] In addition, five of the discipline-oriented standing committees[4] of the Space Studies Board were asked to provide comments to the committee. Finally, NASA representatives, congressional staff members, and NRC staff briefed the committee during its meeting on July 11-13, 2006.[5]

This report is divided into six sections in keeping with the committee's charge: (1) general observations, (2) responsiveness to recent NRC recommendations, (3) attention to interdisciplinary aspects and overall scientific balance, (4) utility to stakeholders in the scientific community, (5) general readability and clarity of presentation, and (6) summary findings and recommendations.

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[1] NASA Science Plan, Draft 3.0, June 23, 2006.

[2] For the most recent NRC reviews see "Assessment of NASA's Draft 2003 Space Science Enterprise Strategy," letter report, 2003, and "Assessment of NASA's Draft 2003 Earth Science Enterprise Strategy," letter report, 2003.

[3] The NRC decadal surveys have been widely used by the scientific community and by program decision makers because they (a) present explicit, consensus priorities for the most important, potentially revolutionary science that should be undertaken within the span of a decade; (b) develop priorities for future investments in research facilities, space missions, and/or supporting programs; (c) rank competing opportunities and ideas and clearly indicate which ones are of higher or lower priority in terms of the timing, risk, and cost of their implementation; and (d) make the difficult decisions about which meritorious ideas cannot be accommodated within realistically available resources. The most recent relevant decadal surveys are *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001; *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003; and *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., 2003.

[4] The standing committees are the Committee on Astronomy and Astrophysics, the Committee on Planetary and Lunar Exploration, the Committee on Solar and Space Physics, the Committee on the Origins and Evolution of Life, and the Committee on Earth Studies.

[5] The meeting agenda is in Appendix C.

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GENERAL OBSERVATIONS

The committee finds that the draft NASA Science Plan provides an informative overview of SMD's objectives, goals, and associated missions. One of the plan's overarching strengths is its demonstration that a major NASA objective is to conduct scientific research to advance the fundamental understanding of Earth, the solar system, and the universe beyond. Portions of the plan do an excellent job of outlining why NASA carries out its science missions. The draft also outlines a defensible set of rules for prioritizing missions within each of SMD's discipline divisions.

The committee notes that as NASA continues to pursue a broad-based and impressive science program, SMD has made a serious effort to base its plans on the mission priorities established by the scientific communities that undertake and benefit from the missions that NASA conducts. The committee commends NASA for this effort.

The committee does note, however, that the draft Science Plan makes no reference to the constrained budget situation that NASA is currently facing. Any analysis of the fate of past NASA science plans would demonstrate that these can undergo significant transformation during actual implementation, usually as a result of financial exigencies. Thus, the committee found it difficult to assess how realistic the current draft plan is. The draft Science Plan is almost surely optimistic. **The committee recommends that the NASA Science Plan compare the key aspects of its 2003 Earth and space science plans with the 2006 plan in a list or table that shows how the current plan differs from the previous ones.** This comparison would also provide some indication of the starting point for the new Science Plan, and the changes that have occurred since 2003.

By design, the draft plan addresses only those science programs that are conducted by SMD. The committee notes that an appreciation of the full extent of NASA's science activity requires a look at a number of programs outside SMD, in particular, the lunar precursor and robotic program, and the life and microgravity science activities within the Exploration Systems Mission Directorate (ESMD). The committee understands that Congress directed NASA to produce a Science Plan only for SMD. The committee concludes that the document would be improved if the introduction made clear the boundaries of the Science Plan's scope and also acknowledged that science is performed elsewhere within NASA as well, and the extent to which these other science programs are sensibly complementary to those within SMD.

Establishing Priorities

NASA's science planning is typically guided by priority lists established in the NRC decadal surveys. Although the NRC has produced decadal surveys in astronomy and astrophysics for four decades, equivalent surveys in the other disciplines have been instituted more recently. The first Earth science decadal survey is currently underway, with the final report due in December 2006, and will not be complete in time for consideration in the final version of the current NASA Science Plan. NASA officials informed the committee that they plan to incorporate the recommendations of the forthcoming Earth science decadal survey into a revised version of the Science Plan scheduled for release in spring 2007. While the committee supports the concept of this planned revision it notes with concern that, other than reinstating the Glory mission, there is little evidence in the SMD Science Plan of a response to the interim report of the Earth science decadal survey, which was released in April 2005.[6]

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[6] National Research Council, *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation*, The National Academies Press, Washington, D.C., 2005. The interim report put forward six recommendations under the overarching title "Critical Needs for Today": (1) Proceed with the Global Precipitation Measurement (GPM) and Atmospheric Soundings from Geostationary Orbit (GIFTS) missions; (2) evaluate plans for transferring needed capabilities to NPOESS (Ocean Vector Winds, Landsat Data Continuity (LDCM), aerosols and total irradiance (GLORY); (3) develop a technology base for future Earth observation; (4) reinvigorate the

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The decadal surveys involve a lengthy and complex process whereby the community of scientists within a particular discipline establishes research goals and identifies and prioritizes important investments in research capability, including, but not limited exclusively to, future NASA missions. The value of this process is that the community itself selects and ranks the priorities in a relatively open way, thereby bestowing community ownership and legitimacy on these choices.

The committee emphasizes that decadal surveys are not merely lists of missions but describe an overall research agenda. It is relatively easy to think and plan only in terms of missions. But an overall Science Plan must include consideration of *all* of the elements needed to ensure success, including the supporting research and data analysis (R&A), advanced technology development, theory and modeling, and data archiving. *In the committee's opinion, the current draft plan overemphasizes mission-specific work at the expense of strategies and steps for achieving goals in such mission-enabling areas as research and analysis and technology development.*

The committee is aware that Congress specifically asked NASA to develop a single prioritized list of missions across the scientific disciplines, and it notes that NASA has not produced such a list in the current draft Science Plan. Congressional staff members who appeared before the committee reiterated this point and explained their interest in having an integrated prioritized list as guidance for budgetary situations that may be even more difficult in the future than the present.

The committee believes that, although not impossible, prioritization on a purely scientific basis across disciplines, with the intention of cutting programs, is a daunting challenge for several reasons:

- *Fundamental difficulty.* To be credible, those establishing the scientific priorities must have mastered the intellectual foundations of the proposed programs across the disciplines, the implications for success or failure, and the implications for allied fields. This requires that the purely scientific priorities of such diverse and necessary fields as astronomy, heliophysics, planetary science, and all the subdisciplines of Earth science (e.g., meteorology versus earthquake prediction) must be weighed against one another in a convincing manner.
- *Current state of NASA's advisory structure.* In practice, such integrated prioritization is based on community input provided primarily by the NRC decadal surveys and is accomplished with the ongoing, collective judgment of managers—with the support of advisory committees—who ideally weigh the scientific merits, the financial and human resources, technical issues, balance, and the political implications of these decisions. NASA has recently put in place a new advisory structure that may in the longer term address cross-disciplinary prioritization in a meaningful way. It is the opinion of the committee that the current advisory structure has not existed for sufficient time to constructively address SMD-wide prioritization.
- *Incompatible strategies.* The committee noted that the requested integrated prioritized list, even if attainable, would not have the desired operational utility in guiding cuts in a possibly difficult future budget climate. The strategy for developing a prioritized list of ongoing programs is quite different from the strategy for developing a prioritized list of programs to be cut. In the former case, the purpose is to indicate the order in which problems with ongoing programs get fixed, and mission-enabling activities unfortunately usually end up at the bottom. It is likely that an integrated prioritized list would take this form and therefore provide little guidance in a program-cutting scenario driven by budget reductions. The net result could be a significant loss of scientific balance.

NASA Earth Explorer Missions Program; (5) strengthen research and analysis programs; and (6) strengthen baseline climate observations and climate data records. Of these six, the draft Science Plan addresses recommendation 2, and LDCM and GLORY were brought back from canceled status to launch dates of 2011 and 2008, respectively.

Recommendation 1 regarding GPM and GIFTS has not been followed. GPM remains delayed by 4 years after the end of TRMM, thus threatening continuity of precipitation and latent heating data, and both the GIFTS and Ocean Vector Winds missions remain canceled. Recommendations 3, 4, and 6 are mentioned in the Science Plan but without providing objectives, as well as strategic or tactical vision. Recommendation 5 is not addressed at all.

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For all of these reasons, the committee does not believe that NASA should or could produce a prioritized list across disciplines at this time.

NASA has, however, clearly addressed the subject of establishing priorities within the SMD divisions. Chapter 2 of the draft Science Plan presents an overall strategy for setting priorities in specific discipline areas. The strategy includes the following actions:

- Base the program in each discipline on key scientific questions and research objectives that have been defined by the scientific community and/or national policy directives.
- Prioritize spaceflight missions in a single list for each major discipline area. (Currently operating missions are treated separately via the senior review process.)
- Constrain launch schedules to fit within the FY 2007 budget request.
- Begin prioritization by using recommended priorities from decadal surveys as an input to preparing community-led implementation roadmaps.
- Seek a balanced portfolio of mission sizes.
- Give missions closest to being ready for launch priority over less mature missions.
- Consider technology readiness, mission science interrelationships, opportunities for partnerships, government mandates, and programmatic factors.
- Acknowledge that cost can override decadal survey recommendations for cadence.

The committee's review of this strategy and of the discussions of priorities in each of the four major SMD discipline areas led it to reach the following conclusions:

1. Recent NRC reviews of earlier NASA science strategic plans noted failures to explicitly identify priorities and the resources that would be required to implement the plans. The 2006 draft NASA Science Plan does make an effort to address priorities and is consistent with available resources as defined by the budget submittal for FY 2007, and the committee finds that this is a clear improvement that will make the plan more useful and informative. The committee commends NASA for adopting this approach.
2. The overall strategy, as summarized in Chapter 2 of the draft plan, is reasonable, and it entails an appropriate approach to setting priorities for spaceflight missions.
3. The sets of priorities for the three science discipline areas for which there are completed NRC decadal surveys—i.e., astrophysics, heliophysics, and planetary science—are all largely responsive to the flight mission priorities presented in the decadal surveys. Notable exceptions or gaps are as follows:

- *Astrophysics.* It is becoming progressively more problematic in astronomy and astrophysics to respond effectively to decadal surveys as mission costs increase across the board. This is already evident in the draft Science Plan, which includes recent major cuts or delays to the extrasolar planet initiative, despite its high ranking in the decadal survey, weakening of the R&A and MO&DA resources for fundamental scientific research, severely reduced opportunities for Explorer-class missions, and the loss of short-wavelength capabilities after 2011.
- *Heliophysics.* The heliophysics section is largely responsive to the NRC decadal survey. However, the committee believes that there may be a problem with implementation of two closely spaced Living With a Star missions starting in the next decade. This is discussed in the section below titled "Threats to Science Plan Execution."
- *Planetary science.* The planetary decadal survey called for significant technology development and "an increase over the decade in the funding for fundamental research and analysis programs at a rate above inflation that parallels the increase in the number of missions, amount of data, and diversity of objects studied."[7] The draft Science Plan does not respond to these recommendations.

[7] National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, p. 9.

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- *Earth science.* The decadal survey on Earth science is expected to be complete by the end of 2006. An interim report, however, was published in 2005. The present draft of the SMD plan does not address critical needs raised by the interim report such as providing a rationale for why missions have been delayed or how NASA will meet long-term needs for science observations of the Earth system.

4. Although the overall approach described in the draft Science Plan for setting priorities is sound, the committee notes that this approach does not appear to have been used in practice in every discipline area. The actual approach appears to vary from discipline to discipline. For example, priorities in astrophysics (for missions after the infrared James Webb Space Telescope [JWST]) depend largely on planned launch date, whereas priorities in heliophysics are influenced by mission costs, scientific value, and strategic value.
5. The draft Science Plan's discussion and presentation of priorities address only spaceflight missions. There is no discussion of how critical non-flight elements of the program—e.g., R&A, suborbital flights (including balloon missions), and data analysis—are to be folded into an integrated set of strategic priorities for SMD or its four discipline programs. (See below the discussion titled "Balance" in this report.)
6. The draft Science Plan does not address the need to protect core activities, research capacity retention, and the importance of sponsoring creativity and innovation within the disciplines. Cuts to the budget threaten specific technical expertise inside and outside the agency that can make it difficult to reinstate certain types of missions in the future.

Threats to Science Plan Execution

An important characteristic of a plan that aims to direct a successful national program is clear evidence of sufficient resources to ensure that the plan is robust and appropriately resilient. Finding 2 of the NRC report *An Assessment of Balance in NASA's Science Program*[8] (published in May 2006 and hereafter referred to as the *Balance* report) cites significant budget deficiencies in R&A, astrobiology research, the Explorer program and other small missions, and initial technology work on future missions. Finding 1 of that report states that NASA is being asked to accomplish too much with too little.

Based on recent NASA experience, numerous science missions have experienced significant cost growth that will destabilize a science plan as tightly integrated as the current draft plan. If this trend continues the plan will not be executable. The committee believes that this issue must be addressed before a credible science plan can be established. The committee notes that some disciplines are in better shape than others, but that in each division aspects of this plan cannot be executed in the manner that NASA intends.

- *Astrophysics.* The committee notes that cost growth with the JWST has forced delays or modifications to many other programs, significantly unbalancing the program. The committee also finds that although the Space Interferometry Mission (SIM) is currently in the plan, it cannot be conducted on the timescales specified if, as expected, NASA reinstates the Stratospheric Observatory for Infrared Astronomy (SOFIA) by taking money from SIM. These examples illustrate the way in which cost, risk, and schedule delays can make it impossible to implement plans described.
- *Heliophysics.* The committee believes that the heliophysics plans are generally satisfactory, with the exception of the plan to launch two missions only a year apart in the next decade. The Ionosphere/Thermosphere Storm Probes and the Inner Heliospheric Sentinels are planned to launch only 1 year apart, and the committee believes that this approach is unrealistic from both a budgetary and an operational standpoint.

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[8] National Research Council, *An Assessment of Balance in NASA's Science Programs*, The National Academies Press, Washington, D.C., 2006.

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- *Planetary science.* The committee believes that the planetary science plans are generally satisfactory, but shares the broader concern expressed in the *Balance* report about the importance of managing and controlling cost growth for missions. The committee is also concerned about the delay of the next flagship mission to the outer planets.
- *Earth science.* The draft Science Plan does not address the problems of the post-Earth-Observing-System era or the implications of problems with NPOESS, nor does it provide a strategy for sustaining the discipline until the recommendations of the decadal survey can be implemented. While the committee recognizes that strategies for Earth science will be developed in the upcoming decadal survey, their absence in the current draft Science Plan means that including them in NASA's plans will require significant programmatic changes.

The committee notes that implementation of full-cost accounting at NASA has had a deleterious and unanticipated effect on science execution and balance. In effect, in many cases the applicable cost of in-house NASA personnel is now being charged to research and analysis budgets that have not been increased to compensate for this charge.

NASA's Science Mission Directorate is currently operating in a particularly dynamic budgetary climate, posing a significant challenge in balancing flagship missions, moderate-scale missions, and other critical program elements. As the *Balance* report indicates, the underlying foundation of research, technology, and small missions has been disproportionately cut. Furthermore, as the discipline-specific examples above illustrate, problems with key missions that are assumed to be integral to the scientific program outlined in the draft plan in fact threaten its scientific feasibility.

The committee notes that NASA's policy has been to expect funding problems to be solved within the individual divisions. Thus, if an astrophysics program experiences a cost overrun, that division cannot take money from the heliophysics division, and vice versa. The committee approves of this approach, because it encourages the divisions to solve their own problems. However, none of the divisions will be immune to overall budget pressures, in the form of both cuts to the top-line budget and cost growth within the programs, and this combination may make it difficult to execute current plans.

The committee believes that the issue of executability must be addressed before a robust Science Plan can be defined. Again, the findings and recommendations in the NRC *Balance* report provide an approach to establishing a robust Science Plan.

2
RESPONSIVENESS TO NRC RECOMMENDATIONS IN RECENT REPORTS

Part of the committee charge is to assess the draft Science Plan's responsiveness to recent NRC reports. A list of some of the most recent reports is included in Appendix D.

The committee finds that the Science Plan *is* responsive to the NRC decadal surveys, with the notable exception that the mission-enabling elements, which are critical to an integrated science plan, are much less integrated and emphasized than the missions themselves. The NASA FY 2007 budget request, upon which the draft Science Plan is based, illustrates the pitfalls of addressing budgetary shortfalls without also considering the relative benefits of mission-specific and mission-enabling programs. Although NASA is primarily a mission-based agency, supporting activities that involve building and maintaining the technology, workforce, and scientific infrastructure necessary to ensure the success of these missions are essential, as pointed out in the NRC *Balance* report. The committee recommends that the mission-enabling elements important to the integrated plan receive greater emphasis in the NASA Science Plan. The agency should review the decadal surveys, and particularly the *Balance* report, for further guidance on the importance of mission-enabling elements. The committee acknowledges the difficulty that the agency faces in determining the proper levels of R&A funding and addresses them in

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the section titled “Balance” in this report, including offering a recommendation about the need to determine proper levels of R&A.[9]

The committee does note, however, that although Mars Sample Return was rated as a top priority in the planetary decadal survey, it is mentioned only once in the draft Science Plan, and only in reference to planetary protection, not as an actual planned mission.

Although the Science Plan is generally responsive to the decadal surveys, there is one notable exception. The NRC released an interim report for its Earth sciences decadal survey over a year ago. As already noted, with the exception of the reinstatement of the Glory mission, the draft Science Plan does not reflect the recommendations made in this interim report.

The draft plan responds well to other recent NRC reports, and the committee commends NASA for this. Examples include the instigation of the decadal survey for Earth sciences and applications from space, recommended by the NRC in 2003.[10] The agency also adopted 2005 NRC advice to conduct senior reviews of extended Earth observing missions to determine if such missions were worth continuing or had outlived their usefulness.[11]

The committee commends NASA for responses by the agency to issues raised in previous recent NRC reviews of NASA science plans. Two prior reviews of Space Science Enterprise plans[12] and the 2003 review of the Earth Science Enterprise plan all cited the lack of explicit discussion of priorities and resources in those plans as weakening their utility for decision making.[13] The 2006 NASA Science Plan does address explicit priorities for spaceflight missions, and it does indicate that the plan is based on budget projections outlined in NASA’s FY 2007 budget request. While the committee remains concerned about aspects of these elements of the Science Plan, it nonetheless applauds the fact that NASA has included priorities and relationship to the budget as key features of the plan.

In 2003, the NRC assessment of NASA’s Space Science Enterprise strategy’s balance of astrobiology across the enterprise’s scientific themes expressed concern that the search for life had been referred to in many places in the strategy but lacked any real scientific substance. The current draft Science Plan does a better job of integrating the subject into the two most relevant discipline areas—astrophysics and planetary exploration. Notably, the draft does not overstate the role of astrobiology as a scientific driver in these two discipline areas. However, the committee believes that further refinements are possible. These are discussed in greater detail in the next section of this report.

The 2005 NRC report *Science in NASA’s Vision for Space Exploration* emphasized the need for better integration of NASA’s science program and the objectives of the Vision for Space Exploration. The committee notes that this is a challenging objective and that the agency has made good progress by evaluating science programs in terms of how they support the agency’s broad science mission. The committee applauds this approach. However, the committee finds that in some areas the integration of science objectives into the exploration program remains ambiguous and could be improved.

The committee further notes that the NRC’s *Balance* report is largely neglected in the draft Science Plan. The committee acknowledges that the plan is based on the assumptions contained in the FY 2007 budget request and that the *Balance* report was critical of the adequacy of the budget to accomplish

[9] The decadal surveys refer to the importance of mission-enabling programs. For example, see: “The committee emphasizes that telescopes alone do not lead to a greater understanding of the universe. . . . The committee recommends a vigorous and balanced program of astrophysical theory, data archiving and mining, and laboratory astrophysics.” *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001, p. 96.

[10] National Research Council, “Assessment of NASA’s Draft 2003 Earth Science Enterprise Strategy,” letter report, 2003.

[11] National Research Council, *Extending the Effective Lifetimes of Earth Observing Research Missions*, The National Academies Press, Washington, D.C., 2005.

[12] National Research Council, “On the Space Science Enterprise Draft Strategy Plan,” letter report, 2000; National Research Council, “Assessment of NASA’s Draft 2003 Space Science Enterprise Strategy,” letter report, 2003.

[13] National Research Council, “Assessment of NASA’s Draft 2003 Earth Science Enterprise Strategy,” letter report, 2003.

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the total NASA plan. The committee believes that the *Balance* report's recommendations are worthy of consideration and, where appropriate, incorporation in the Science Plan. This aspect is discussed in greater detail in the next section of this report.

The committee found no rationale for the agency's allocation of R&A funding, or the fraction devoted to technology development, computational capabilities, modeling, and data analysis. Both in the summary chapters and in the various discipline chapters, the Science Plan emphasizes the need for R&A, suborbital, and facilities programs. There is a clear description of the intrinsic role of these programs as mission enablers and as cost-effective methods for achieving science and technology advances. This aspect of the draft Science Plan is completely consistent with the recommendations of numerous NRC documents such as the recent *Balance* report, and with the recommendations of every NASA-commissioned community roadmap. What the draft plan does not do is outline how NASA will prioritize the programs in terms of budgets, or how it will achieve its goals in these areas. **The committee recommends that the NASA Science Plan explicitly address realistic strategies for achieving the objectives of the mission-enabling elements of the program.**

3
ATTENTION TO INTERDISCIPLINARY ASPECTS AND OVERALL SCIENTIFIC BALANCE

Some of NASA's scientific projects are, such as Mars exploration, are significantly more interdisciplinary than others, or cross administrative boundaries. Often it is difficult to conceptualize, prioritize, communicate, and budget for these projects because of the problems of crossing divisions within NASA, government organizations, and scientific disciplines. Although many of NASA's scientific undertakings are interdisciplinary, the committee identified three areas of NASA's science planning that are particularly challenging because of their interdisciplinary nature and/or the fact that they also cross administrative (i.e., bureaucratic) boundaries: lunar exploration, astrobiology, and Earth sciences. The committee believes that all three need additional attention within the draft Science Plan.

Lunar Science

Chapter 8 of the draft Science Plan, "Science Enabling & Enabled by Human Exploration," states that SMD and ESMD are "working closely." However, based on statements made by NASA officials at the committee's July meeting, it appears to the committee that enhanced consultation and communication between the two directorates are needed to optimize the broader science benefits that could be derived from these ESMD exploration-related, and potentially science-related, activities. The committee notes that Chapter 8 of the Science Plan is especially general and lacks specifics on how NASA intends to incorporate science into the agency's lunar exploration plans.

Robotic lunar missions currently planned by NASA are the responsibility of ESMD because such investigation has as its primary purpose the characterization of the lunar environment in preparation for eventual human activity on the surface of the Moon. However, given that one of the goals of the Vision for Space Exploration is "to advance U.S. scientific . . . interests," the science community should have the same opportunity to influence the planning and prioritization of ESMD's exploration science activity as it has to influence other space science activity conducted by NASA. The committee is pleased to see that NASA has requested that the NRC identify science opportunities and establish priorities for exploration-enabled science activities on the Moon.[14] That committee will produce an interim report by fall 2006 and a final report in 2007. The committee supports this planning activity as a means to improve the science benefits of NASA's exploration activity. **The committee recommends that NASA incorporate**

[14] National Research Council, *The Scientific Context for the Exploration of the Moon—Interim Report*, The National Academies Press, Washington, D.C., 2006.

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relevant recommendations from the NRC interim report on lunar science into its Science Plan in such a way as to maintain the overall science priorities advocated by previous NRC studies, while recognizing that science advice will change as scientific understanding and technology improve.

Astrobiology

Astrobiology crosses multiple disciplines, creating unique challenges for science management, especially in terms of mission prioritization. Thus, the planetary section of the draft Science Plan emphasizes assessing "habitability" in the solar system. Habitability is loosely defined by the astrobiology community as the ability of a planet to support life, based on the presence of the key requirements: water, nutrients, and energy. NASA's exploration of Mars is focused on the search for evidence of life, and this issue is important for future missions to Europa and eventually to Titan and Enceladus. In the astrophysics chapter of the plan, astrobiology is presented in a narrower context—exploring the habitable zones around other stars, primarily through missions like the Terrestrial Planet Finder (TPF) and the Space Interferometry Mission (SIM).

The draft plan discusses the astrobiology field largely in the context of solar system exploration, although it acknowledges the importance of astrobiology as a driver in other disciplines. In the draft Science Plan, astrobiology is highlighted in a text box at the end of the planetary science chapter. The committee believes this presentation underemphasizes the interdisciplinary nature of astrobiology and sets limiting boundaries that are inconsistent with the actual subject matter. The committee notes, for instance, that even subjects that appear to have no direct connection to astrobiology can be relevant to the field. For instance, lunar studies can provide information on the impact flux of asteroids in the early solar system and therefore the hazards they present to the formation of life. The committee suggests that the draft plan would be improved by the addition of an overarching section that includes a balanced discussion of the connections between astrobiology, planetary science, and astrophysics. In the present draft, this discussion would benefit from a deeper treatment of astrobiology as a science, its value as a unifying theme, and a few of the many scientific advances in this field since its inception over a decade ago.

The draft plan does not mention or take account of NASA's Astrobiology Roadmap, which is the primary source of information on the field and its scientific objectives, as defined by the community. The committee suggests that this roadmap be included in the Science Plan as a list or table.[15]

The text box in Chapter 6 of the draft plan asserts that while the Planetary Science Division provides the institutional home for the core astrobiology R&A program, integrating its efforts, answers are pursued in the research programs and flight missions of "all four SMD Divisions." The committee could find no explicit mention of astrobiology programs or missions in the Earth science or heliophysics sections. In this context, it is worth noting that the NRC's 2003 assessment of NASA's science plan found no indication of how the Sun-Earth Connection program could advance the agency's strategic goal to "understand the origin and evolution of life and search for evidence of life elsewhere."[16] Potentially strong links could be made through studies of the origin and evolution of terrestrial life, both of which are active research areas in astrobiology. For example, access to the historical record of climate change (a major focus of the Earth science enterprise), through studies of the fossil record and the impact of long- and short-term environmental changes on biosphere diversity and evolution, are logical connections. Such research is certainly consistent with current R&A efforts in evolutionary biology under the astrobiology program.

Also worrisome is the omission of any discussion of the needs of astrobiology in the context of overall technology development goals, despite the implicit requirement to develop reliable approaches for

[15] Office of Space Science, National Aeronautics and Space Administration, "Astrobiology Roadmap," Ames Research Center, Moffett Field, Calif., 1999.

[16] National Research Council, "Assessment of NASA's Draft 2003 Space Science Enterprise Strategy," letter report, 2003.

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life detection within the next 6 to 8 years in order to support proposed investigations of the Astrobiology Field Laboratory (launch of which is anticipated in 2016). Efforts to develop life detection technologies and protocols are in fact being funded under two key astrobiology technology development programs—Astrobiology Science and Technology for Exploring Planets (ASTEP) and Astrobiology Science and Technology Instrument Development (ASTID). Neither program is mentioned in the draft. Indeed, there seems to be a general unawareness of the immaturity of the field of life detection and of the time required to develop and adequately test the technologies needed to actually explore for life elsewhere.[17] **The committee recommends that life detection techniques be clearly identified as an astrobiology strategic technology development area.**

Finally, although the draft plan raises the important topic of planetary protection, the area of backward contamination is insufficiently discussed, even though it could prove to be a serious consideration for future sample returns from Mars. The committee notes that the NRC recently published a report on planetary protection and Mars and encourages NASA to incorporate the recommendations of that report into the Science Plan.[18]

Earth Science

Another example of interdisciplinary science within SMD is the field of Earth system science, which was initiated by NASA. Conceived in the 1980s and implemented in the 1990s with the Earth Observing System Interdisciplinary Science Program, Earth system science is uniquely suited to the global perspective of the interconnected nature of the atmosphere, oceans, land, cryosphere, and biosphere of our planet that Earth observing satellites provide. NASA is unique in this field. No other U.S. government agency has the discipline breadth, or requisite technological, observational, and modeling capabilities, to nurture and develop such an important field of science.

Although still in its infancy, over the past 15 to 20 years Earth system science has produced new and significant insights of atmosphere-ocean, land-atmosphere, and physical-biogeochemical coupling and cycles. The committee believes that the draft Science Plan does not adequately explain or illustrate the impressive developments in this field. For instance, global altimeter, scatterometer, ocean color, and rain radar observations of phenomena such as El Niño were not possible until relatively recently. The Science Plan could incorporate this and other examples to illustrate the evolution from inconsistent and spot observations to the development of highly integrated, global views of the Earth system (e.g., 30 years of observations of sea ice concentration and extent or space-based observations of the ozone hole). NASA has been at the forefront of these developments, and the draft Science Plan should adequately reflect the agency's impressive achievements. In short, the Earth science section does not provide the historical context for Earth remote sensing and does not appropriately capture the significance of NASA's accomplishments to date in Earth remote sensing. The committee notes that the Earth science section of the draft plan appears to reflect less community input than other sections, and trusts that this will be rectified following publication of the Earth science decadal survey.

The extraordinary progress in Earth system science has altered dramatically the capabilities and requirements to conduct leading-edge science and has unlocked a wealth of applications of immediate social relevance. Today scientists and Earth science stakeholders expect and depend on data for climate science and broader climate R&D applications. This has created a frequently unrecognized change in the types of data about Earth that satellites collect. In addition to requirements for data such as weather observations and "science" data, there is now a requirement for long time series of scientific observations. Traditionally NOAA has performed weather-related data collection and NASA has conducted scientific data collection. Today, however, the scientific community expects NASA to conduct long-term

[17] National Research Council, *Assessment of NASA's Mars Architecture 2007-2016*, The National Academies Press, Washington, D.C., 2006.
[18] National Research Council, *Preventing the Forward Contamination of Mars*, The National Academies Press, Washington, D.C., 2006.

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collection of scientific data that has no immediate use for decision making but is needed to study and understand natural climate fluctuations on interannual to decadal time scales, and is necessary for the development of integrated climate models, and thus requires long-term programmatic and funding commitments.[19]

Recent developments in the NPOESS program reflect the wide gap between community expectations for data collection and current plans. When NPOESS experienced severe development problems and cost overruns, the climate research and monitoring instruments were deleted from the NPOESS satellites whereas the weather instruments were preserved. Many of the instruments removed from NPOESS are crucial to understanding the changing Earth system, and some strategy is badly needed to deal with their elimination from NPOESS. Unless this is done, when the current fleet of Earth Observing System (EOS) satellites expires, there will be nothing to replace them.

The Earth science portion of the draft Science Plan is relatively vague with respect to the strategy for pursuing Earth system science beyond the EOS era. It states that the program will "exploit the vast wealth of new data from EOS," "promote interdisciplinary research . . . identified as emerging sciences areas in the Strategic Plan of the U.S. CCSP [Climate Change Science Plan]," and "pursue innovative interdisciplinary research in new topical areas." These statements begin to convey what the agency will do and why. But they do not indicate how these goals will be achieved, or when they will be achieved.

The draft NASA Science Plan lacks a strategy for an integrated synthesis of the variety and volume of Earth observations generated by NASA. The plan mentions but does not describe the unique modeling, prediction, and computational capabilities and requirements for Earth science. In addition, the plan lacks a science strategy for the development of Earth system models and a discussion of a strategy for developing understanding to enable a predictive capability for the Earth system. Finally, the committee found no indication of NASA's strategy for linking and crosscutting the six interdisciplinary science focus areas: atmospheric composition, carbon cycle and ecosystems, climate variability and change, Earth surface and interior, water and energy cycle, and weather. **The committee recommends that NASA begin immediately to develop a science strategy for obtaining long-term, continuous, stable observations of the Earth system that are distinct from observations to meet requirements by NOAA in support of numerical weather prediction.**

The committee recognizes that the Earth science decadal survey to guide NASA's research priorities in this area will not be completed until the end of 2006 and that, at that time, the agency expects to incorporate decadal survey report recommendations into a revised Science Plan. However, other than the reinstatement of the Glory mission, the committee is troubled to see no reference in the current plan to the findings and recommendations in the Earth sciences decadal survey interim report that was issued more than one year ago. By addressing in the current Science Plan the recommendations from the interim report, NASA could establish the framework for accommodating the recommendations to come from the decadal survey.

The committee is concerned that the draft Science Plan suggests that NASA is waiting for the expected decadal survey, when the agency needs a more coordinated effort to develop its Earth systems science strategy now. The Earth science fiscal situation has deteriorated since the interim report was released, specifically due to cuts to R&A programs, degradation of existing missions, and the current turmoil in the NPOESS program. NASA needs to have an observing strategy in Earth sciences that balances technological innovation (new sensors), emerging science needs (new observations), and the foundational requirements of long-term sustainable science-grade environmental observations.

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[19] National Research Council, *Climate Data Records from Environmental Satellites: Interim Report*, The National Academies Press, Washington, D.C., 2004, p. 95; National Research Council, *Issues in the Integration of Research and Operational Satellite Systems for Climate Research: Part I. Science and Design*, National Academy Press, Washington, D.C., 2000, pp. 8-9.

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Balance

The NRC report *An Assessment of Balance in NASA's Science Programs* defined several different dimensions of "balance." One key aspect is scientific balance, meaning that at least the minimum health of major scientific disciplines is maintained so that each discipline can make progress toward its major scientific goals. A second dimension involves balance between the support of ongoing programs and missions, on the one hand, and opportunities for new initiatives, capacity building, and longer-term scientific development, on the other. A third, particularly important, aspect of balance is the ability to sustain a mix of large, medium, and small programs and missions and a core program of research, data analysis, technology development, theoretical studies, and modeling.

Scientific Balance

With respect to scientific balance, the committee has not found any serious imbalance across the four major discipline areas. There are specific concerns within each discipline, which are addressed here, but no particular discipline area appears to be placed at a disadvantage with respect to the others; for instance, the disciplines receive generally similar levels of funding. Furthermore, the draft Science Plan correctly notes that each discipline area can look forward to making notable scientific progress over the period covered by the plan.

Nevertheless, the committee has several concerns about scientific balance within the disciplines. Because fiscal realities do not allow NASA to maintain continuity in flagship missions, the small missions are increasingly important. However, the mix of small missions in astrophysics and planetary science has been drastically curtailed, as has the opportunity to participate in foreign missions. Under the current plan the astrophysical community faces an extended period with no access to short wavelengths on NASA's major instruments. Such gaps are probably unavoidable, but when they have occurred in the past a strong program of international participation, supporting research, and technology development sustained a healthy community, ready to support the next major NASA mission when it finally took place. This makes the current loss of such balance particularly troubling at this time.

In the past decade, planetary exploration has increasingly been divided into two parts, Mars exploration and exploration of the rest of the solar system. This has presented unique challenges for balancing efforts between these two areas. The committee notes that the NRC recently produced a report on the future of robotic Mars exploration and suggests that the Science Plan incorporate the recommendations of this report.[20] **The committee recommends that Mars should remain the prime target for sustained science exploration; the NASA Science Plan should acknowledge that missions to other targets in the solar system should not be neglected.**

Furthermore, the committee wishes to repeat the recommendations of the 2006 NRC report *Review of Goals for NASA's Space and Earth Sciences*, which reviewed NASA's science roadmaps, concerning the role that habitability should serve as an objective for exploration. **The committee recommends that where habitability is determined to be the main focus for exploration, a proper hierarchy of scientific goals and objectives should be developed and stronger pathways between the concept of habitability and proposed missions be articulated and maintained. The committee notes that basic discovery science should not be ignored in the Science Plan.**

As noted above in the discussion of interdisciplinary aspects of the plan, the Earth science section of the plan does not provide a strategy for ensuring that there will be continuity of measurements that will provide the long-term data sets needed for scientific studies of the Earth system, including climate. No strategy is provided for how such observations will enable prediction of the Earth system. Lastly, the funding situation and programmatic priorities permit only the next new start for an Earth System Science Pathfinder (ESSP), which is the small-mission component of the Earth science program, to be launched in

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[20] National Research Council, *Assessment of NASA's Mars Architecture 2007-2016*, The National Academies Press, Washington, D.C., 2006.

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2014. Although two ESSP missions are currently in development, the nearly decade-long gap between the selection of new ESSP missions undercuts the entire purpose of the program, which was to produce missions rapidly, taking advantage of new scientific discovery.

Balance Between Mission and Mission-Enabling Elements

A second aspect of balance about which the committee has serious concerns relates to the balance between spaceflight missions and non-flight elements of the program, especially R&A. This problem was discussed at length in the *Balance* report, which found that under NASA's FY 2007 budget request the proposed "cuts to the R&A grants program cause disproportionately large damage to the viability of the space sciences disciplines as well as to future programs." Because the Science Plan is based on funding levels proposed in the administration's budget for FY 2007-2011, including the proposed reductions in R&A and other small programs, the draft plan also suffers from the problems that are cited in the *Balance* report. These small programs are vital for the training and development of the scientific and engineering workforce. Furthermore, new technology development both enables future missions and makes them more cost-effective. Consequently, **the committee fully concurs with the findings in the *Balance* report and reiterates that report's recommendation that "NASA should move immediately to correct the problems caused by reductions in the base of research and analysis programs, small missions, and initial technology work on future missions before the essential pipeline of human capital and technology is irrevocably disrupted"** (p. 3). While the draft Science Plan presents good arguments for the importance of these programs, it does not present a strategy for how they will be integrated into the overall program or how NASA will respond to concerns raised in the *Balance* report.

Balance of Mission Sizes

A third important balance issue in the plan relates to the mix of mission sizes and to problems that confront NASA over the feasibility of sustaining a properly mixed portfolio of mission sizes. In the plan, the Heliophysics and Planetary Sciences divisions have managed to maintain a degree of balance with respect to mission sizes—i.e., there are small and medium missions in the plan. However, the number of Explorer missions, which constitute the small mission component in astrophysics and heliophysics, and which are vital for training the scientists and engineers of the future, have been reduced substantially, creating problems that call into question the long-term health of the disciplines. As noted above, there is a similar problem with respect to opportunities for new ESSP missions in Earth science. The committee notes that the draft Science Plan makes almost no mention of suborbital and balloon programs.

Perhaps the greatest current threat to the feasibility of a mixed portfolio of flight mission sizes is the cost of execution of currently approved missions. Cost growth for NASA's large flagship missions has drawn considerable attention, but the problem has occurred across all mission sizes. SMD now faces a situation in which the overall balance of the program has been distorted by escalating costs for flight missions. The *Balance* report concluded that "the major missions in space and Earth science are being executed at costs well in excess of those estimated at the time when the missions were recommended in the National Research Council's decadal surveys for their disciplines. Consequently, the orderly planning process that has served the space and Earth science communities well has been disrupted, and balance among large, medium, and small missions has been difficult to maintain" (p. 3). This problem is especially acute in astrophysics, where the costs for the division's two highest-priority missions—HST and JWST—and funding requirements for near-term missions such as SOFIA, GLAST, and Kepler are threatening the overall program balance.

The longer-term implications of the mission cost growth problem are particularly alarming. *If the problem is not successfully addressed, the committee believes there are very real prospects that SMD will be faced with having to abandon either flagship missions or the ability to execute a balanced program.*

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Therefore ***the committee fully concurs with and reiterates the recommendation of the*** **Balance** ***report that "NASA should undertake independent, systematic, and comprehensive evaluations of the cost-to-complete of each of its space and Earth science missions that are under development, for the purpose of determining the adequacy of budget and schedule"*** (p. 3). This assessment should be the first step in a strategy for resolving the current mission cost growth problem and ensuring that future missions can be executed within manageable costs, schedules, and content.[21] **The committee further recommends that NASA improve mechanisms for managing and controlling mission cost growth so that if and when it occurs it does not threaten the remainder of the program, and also that NASA consider cost-capping flagship missions.** Although NASA already does seek to manage and control mission cost growth, these efforts have been inadequate and the agency needs to evaluate them, determine their failings, and improve their performance. The committee notes that a number of past missions have been successfully descoped. Examples include the Grand Tour (Voyager), the original Voyager (Viking), the Venus Orbiter Imaging Radar (Magellan), AXAF (Chandra) and SIRTF (Spitzer), where descoping and scientific reassessment were successfully used to control mission cost while preserving the most important science capabilities.

As eloquently stated in the draft plan, SMD cannot achieve its stated objectives with missions alone. Additional programs are needed in order to provide necessary infrastructure for performing the missions and in order to realize the science advances that lead to and are derived from the missions. These mission-enabling components of the strategy include R&A programs, including supporting research and technology and suborbital investigations, that consist of regularly competed principal-investigator-led projects covering the whole range of SMD disciplines and science techniques (theory, data analysis, and instrumentation). The mission-enabling components include essential facilities, such as the Deep Space Network and other space communications systems. Essential facilities include information technology infrastructure, such as the virtual observatories for accessing and storing data, and computational resources for analyzing the vast amounts of data gathered by the missions and for developing and running the models that are the expected products from the flight missions.

Although the draft Science Plan contains impressive language about the importance of mission-enabling programs, the committee found that a number of crucial elements are missing from the draft Science Plan in the following areas:

1. The plan does not present a strategy for determining the size and adjustments to the R&A programs. The lack of such a strategy can lead to arbitrary and potentially damaging decisions such as the 15 percent cut to R&A in NASA's FY 2007 budget submission. The committee notes that even small increases in data analysis budgets are frequently difficult to obtain, whereas the actual missions themselves are expensive and prone to cost increases that dwarf data analysis budgets. The committee recognizes that developing a strategy will require more time than is available for this particular Science Plan. The committee further recognizes that while past reports have called explicitly for such a strategy, this will be a difficult task for which there has been no specific guidance from previous NRC or community reports concerning the optimum size for the mission-enabling programs.[22] **The committee recommends that NASA immediately undertake appropriate studies through its advisory structure in order to develop a strategic approach to all of its R&A programs. This strategy should include metrics for determining the success of the programs.**

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[21] A number of previous NRC reports have commented on the need for descoping and/or reprioritization of major missions (see National Research Council, "Review of Progress in Astronomy and Astrophysics Toward the Decadal Vision," letter report, 2005; "Review of the Redesigned Space Interferometry Mission," letter report, 2002; and "Scientific Assessment of the Descoped Mission Concept for the Next Generation Space Telescope," letter report, 2001).

[22] "The more the R&DA activities are integrated into the strategy and managed the implementation and evolution of the strategy, the stronger is the overall program." National Research Council, *Supporting Research and Data Analysis in NASA's Science Programs: Engines for Innovation and Synthesis*, National Academy Press, Washington, D.C., 1998, p. 42.

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2. The plan identifies a number of critically needed technologies for future missions (e.g., in the planetary, Earth sciences, and heliophysics sections), but it does not present a mechanism or schedule for achieving these technologies. It is not clear, for example, if the technologies are to be developed in the R&A program or via some other dedicated technology program. The committee notes that placing technology development under R&A may lead to an erosion of the scientific R&A programs. The plan is unclear if technologies are being sought in an integrated SMD-wide manner, or are only being developed in each separate division. **The committee recommends that NASA provide some indication of the strategy it will use to determine how critically needed technologies will be developed for future missions and their proposed timescales. The committee recommends that NASA outline a strategic technology plan, providing an indication of the resources needed and the schedule that must be met to enable the ambitious goals of the plan.** NASA should also seek to protect general R&A funding from encroachment by technology R&A. In addition, the committee notes that NASA support of technology development within the science program needs to be tightly coupled to evolving science needs.

3. The plan clearly identifies the need for extensive computational technologies and facilities in order to achieve the science and application goals. This is especially true for Earth science and heliophysics, which are working toward developing operational models, but the draft plan does not present a plan and a schedule for achieving them. **The committee recommends that NASA develop a strategic plan to address computing and modeling needs, including data stewardship and information systems.**

4. The plan identifies needed enhancements to communications infrastructure such as the Deep Space Network, but again no strategy is presented as to how these enhancements will be obtained.

Finally, the committee notes that the launch rate for new missions continues to decrease, an indication of unhealthy trends for the overall program and a situation that the agency experienced before, in the 1980s. NASA faces the problem of rising launch costs, which is a situation that is largely beyond the agency's control. These increases pose a serious threat to the overall science program. The committee endorses NASA's efforts to address this problem.

4
UTILITY TO STAKEHOLDERS IN THE SCIENTIFIC COMMUNITY

The committee believes that the NASA Science Plan will be useful to scientists and graduate students as a broad overview of the agency's space science portfolio. However, scientists and graduate students are primary recipients of R&A funds, and it is therefore important that they understand the agency's strategy for allocating R&A funds, something that is lacking in the current draft. Furthermore, the committee notes that if the Science Plan clearly indicates how cost overruns will be addressed in the future, this will provide clarity that will be useful to industry when developing spacecraft and developing cost estimates for projects.

The committee believes that the draft Science Plan does not explain how NASA's Science Mission Directorate can partner with other government agencies to achieve its goals. For instance, the Department of Energy has some interests that overlap with NASA's Beyond Einstein program. The Department of Defense and the National Reconnaissance Office have technology that has been adapted to scientific uses. The plan should acknowledge these resources in other government agencies and explain how SMD can make use of them.

The committee commends the draft plan's positive assessment of the benefits of international cooperation and the plan's endorsement of playing both senior partner and junior partner NASA roles in international Earth and space science programs. International cooperation is not to be undertaken for its own sake, but rather where value is added to the NASA program and the benefits to be gained warrant the risks in taking on an external partner.

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The draft plan's recognition of the importance of carefully selecting, structuring, and managing cooperative programs represents a balanced statement about the legal and policy issues that NASA faces. Joint planning can ideally lead to the coordination of national programs via the identification of synergies and the development of interdependencies among programs. The goal would be to minimize gaps and overlaps in discipline areas, while maximizing the leveraging among one another's programs. All partners should be seeking to complement one another's scientific work rather than duplicating it or competing with it.

Historically, the launching of Explorer and Discovery missions has been frequent enough to accommodate missions of opportunity, which have often included international participation. If the interval between such opportunities becomes too long, their utility as a mechanism for international involvement degrades, and an alternative strategy needs to be identified in the plan. The committee encourages NASA to seek an alternative strategy to accomplish such cooperation.[23]

5
GENERAL READABILITY AND CLARITY OF PRESENTATION

The draft NASA Science Plan is a lengthy document, and it could benefit from an executive summary that concisely outlines the contents of the report. The committee suggests that the Science Plan include graphics such as roadmap timelines and checklists, in each of its four disciplines—astrophysics, Earth science, heliophysics, and planetary exploration. The committee suggests that the report include the NASA astrobiology roadmap as well.

When discussing such a broad subject as NASA's science goals and plans, it is necessary to provide the reader with information to make comparisons. The committee suggests that NASA include a chart comparing and defining the different size missions across disciplines. This chart could compare the cost ranges of missions such as Explorers (MIDEX and SMEX), ESSPs, Discovery, Scout, New Frontiers, and flagship missions. Furthermore, it would be useful to provide the reader with an indication of the average development times for these missions.

The committee finds that the overall length of the Science Plan is appropriate, considering the amount of information that must be discussed. However, the committee recommends that the report strive to achieve a more uniform tone and quality of presentation. The astrophysics section does an especially good job at explaining the wonder of scientific discovery and the breadth of the program, and serves as an excellent model for the other chapters to emulate.

During its July 2006 meeting, the SMD Heliophysics division representative presented a table indicating the decadal survey priorities for heliophysics. The committee recommends that each of the section chapters include such a table to give the reader easy access to the decadal priorities within the document. It would be helpful for the table to indicate the status of each decadal priority in the current Science Plan.

6
FINDINGS AND RECOMMENDATIONS

Findings

1. The committee finds that the draft NASA Science Plan successfully demonstrates that a major NASA objective is conducting scientific research to advance the fundamental understanding of the Earth, the solar system, and the universe beyond. Portions of the plan do an excellent job of outlining the

[23] See also, National Research Council, *Review of Goals and Plans for NASA's Space and Earth Sciences*, The National Academies Press, Washington, D.C., 2006.

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reasons that NASA carries out science missions. The draft outlines a defensible set of rules for prioritizing missions within each of SMD's discipline divisions.

2. The committee supports the plan's treatment of priorities on a discipline-by-discipline basis and concludes that NASA should not or could not produce a prioritized mission list across disciplines.

3. In the committee's view, the current draft plan overemphasizes mission-specific work at the expense of strategies and steps for achieving goals in mission-enabling areas. The value of space missions to the nation is not determined merely by successful launches, but by the scientific return from those missions. The research and analysis portion of the program is where the public receives its return on investment in the missions.

The committee reiterates the findings in the *Balance* report and that report's recommendation that "NASA/SMD should move immediately to correct the problems caused by reductions in the base of research and analysis programs, small missions, and initial technology work on future missions before the essential pipeline of human capital and technology is irrevocably disrupted" (p. 3).

4. The draft Science Plan often declares an intention to implement a program or identifies a goal or mission as a top priority, but it does not indicate what steps it would take to achieve the goals or strategies it would pursue to accomplish its priorities. Based on recent NASA experience, the committee believes that unless the agency takes a stronger approach to managing program cost, risk, and schedule, the current Science Plan is not executable. Clear strategies are required to ensure that the plan can be executed, and in some cases these are missing. While some disciplines are in better shape in the plan than others, each division has some parts of its plan that cannot be executed in the manner that the draft Science Plan presents.

If the problem of mission cost growth is not successfully addressed, the committee believes there are very real prospects that SMD will be faced with having to abandon either flagship missions or the ability to execute a balanced program. Therefore the committee fully concurs with and reiterates the recommendation of the *Balance* report that "NASA should undertake independent, systematic, and comprehensive evaluations of the cost-to-complete of each of its space and Earth science missions that are under development, for the purpose of determining the adequacy of budget and schedule" (p. 3).

5. The Science Plan lacks a strategy for an integrated synthesis of the variety and volume of Earth observations generated by NASA. The plan mentions but does not describe the unique modeling, prediction, and computational capabilities and requirements for Earth science. In addition, the plan lacks a science strategy for the development of Earth system models and a discussion of a strategy to develop understanding for enabling a predictive capability for the Earth system. Finally, the committee found no indication of NASA's strategy for linking and crosscutting the six interdisciplinary science focus areas: atmospheric composition, carbon cycle and ecosystems, climate variability and change, Earth surface and interior, water and energy cycle, and weather.

Recommendations

Some of the committee's recommendations are broad and apply to all four of SMD's science disciplines, but the difficulties underlying the concerns reflected in the recommendations are more acute in some disciplines than others. For example, the problems associated with controlling mission cost growth and preserving proper balance between large and small missions are now particularly pressing in astrophysics. The need to develop strategies for meeting future computing and modeling capabilities is particularly noticeable for Earth science and heliophysics. In addition, although the committee makes discipline-specific recommendations for the planetary and Earth sciences, it stresses that the astrophysics and heliophysics sections of the draft plan are also addressed in the more general recommendations and require equal attention.

The committee's recommendations on the implementation and viability of the draft NASA Science Plan are as follows:

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1. The NASA Science Plan should compare the key aspects of its 2003 Earth and space science plans with the 2006 plan in a list or table that shows how the current plan differs from the previous ones. This comparison would also provide some indication of the starting point for the new Science Plan, and the changes that have occurred since 2003.

2. NASA/SMD should provide some indication of the strategy it will use to determine how critically needed technologies will be developed for future missions and their proposed timescales. The committee recommends that NASA outline a strategic technology plan, providing an indication of the resources needed and the schedule that must be met to enable the ambitious goals of the plan. But NASA should also seek to protect general R&A funding from encroachment by technology R&A.

3. The NASA Science Plan should explicitly address realistic strategies for achieving the objectives of the mission-enabling elements of the overall program. The committee recommends that NASA:

a. Undertake appropriate studies through its advisory structure in order to develop a strategic approach to all of its R&A programs (this strategy should include metrics for evaluating the proper level of R&A funding relative to the total program, the value of stability of funding levels in the various areas, and metrics for evaluating the success of these programs); and

b. Develop a strategic plan to address computing and modeling needs, including data stewardship and information systems, which anticipates emergent developments in computational sciences and technology, and displays inherent agility.

4. NASA should improve mechanisms for managing and controlling mission cost growth so that if and when it occurs it does not threaten the remainder of the program, and should consider cost-capping flagship missions. Although NASA already does seek to manage and control mission cost growth, these efforts have been inadequate and the agency needs to evaluate them, determine their failings, and improve their performance. NASA should undertake independent, systematic, and comprehensive evaluations of the cost-to-complete of each of its space and Earth science missions that are under development, for the purpose of determining the adequacy of budget and schedule.

5. NASA/SMD should move immediately to correct the problems caused by reductions in the base of research and analysis programs, small missions, and initial technology work on future missions before the essential pipeline of human capital and technology is irrevocably disrupted.

6. For planetary science, the committee recommends as follows:

a. NASA/SMD should incorporate into its Science Plan relevant recommendations from the NRC interim report on lunar science,[24] when they are available, in such a way as to maintain the overall science priorities advocated by previous NRC studies, while recognizing that science advice will change as scientific understanding and technology improve.

b. Although Mars should remain the prime target for sustained science exploration, the NASA Science Plan should acknowledge that missions to other targets in the solar system should not be neglected.

c. Where the question of habitability (i.e., the ability of a planet to support life) is determined to be the main focus for exploration, a proper hierarchy of scientific goals and objectives should be developed, stronger pathways between the concept of habitability and proposed missions should be articulated and maintained, and basic discovery science should not be ignored.

d. Life detection techniques should be clearly identified as an astrobiology strategic technology development area.

[24] National Research Council, *The Scientific Context for the Exploration of the Moon—Interim Report*, The National Academies Press, Washington, D.C., 2006.

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7. For Earth science, the committee recommends as follows:

a. NASA/SMD should incorporate into its Science Plan the recommendations of the NRC Earth science decadal survey interim report,[25] and should incorporate the recommendations of the Earth science decadal survey final report when it is completed.

b. NASA/SMD should develop a science strategy for obtaining long-term, continuous, stable observations of the Earth system that are distinct from observations to meet requirements by NOAA in support of numerical weather prediction.

c. NASA/SMD should present an explicit strategy, based on objective science criteria for Earth science observations, for balancing the complementary objectives of (i) new sensors for technological innovation, (ii) new observations for emerging science needs, and (iii) long-term sustainable science-grade environmental observations.

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

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Appendix A
Letter of Request for Study

National Aeronautics and
Space Administration
Headquarters
Washington, D.C. 20854-0001

Reply to Attn of:
SMD/Management and Policy Division APR 12 2006

Dr. Lennard A. Fisk
Chair
Space Studies Board
National Research Council
500 5th Street, N.W.
Washington, DC 20001

Dear Dr. Fisk:

NASA's Science Missions Directorate (SMD) has begun development of a Science Plan to guide the Directorate's implementation of the 2006 NASA Strategic Plan. We also intend that this document fulfill the requirement of the Congress in the 2005 NASA Authorization Act for a plan that identifies science and mission priorities as well as addresses a number of related topics specified in the legislation.

This Science Plan will serve much the same function for SMD as the Enterprise Strategy documents did for its predecessor organizations. We will also employ an analogous process in its development using community roadmaps based on decadal surveys as a starting point, and engaging science advisory groups and the Space Studies Board in review of the draft document.

We plan to have a draft Science Plan available for review by June 15. I request that the Space Studies Board conduct a review of this draft and provide its assessment and recommendations for how the draft might be improved. Comments in the following areas will be particularly helpful:

- Responsiveness to National Research Council's (NRC's) recommendations in recent reports;
- Attention to interdisciplinary aspects and overall scientific balance;
- Utility to stakeholders in the scientific community; and
- General readability and clarity of presentation.

Given the target date of mid-December for delivery of the Science Plan to Congress, it would be most useful if the Board's comments were available by September 15. I would like to request that the NRC submit a proposal for execution of the proposed performance review by the Space Studies Board. Once agreement on the scope, cost and schedule of the proposed study has been achieved, the Contracting Officer will issue a task order for implementation. The technical point of contact for this study within SMD will be Mr. Greg Williams, who can be reached at (202) 358-0241, and gregory.j.williams@nasa.gov.

We greatly value the Board's advice, and look forward to its help in crafting our Science Plan.

Sincerely,
{signed}
Mary L. Cleave
Associate Administrator for
Science Mission Directorate

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Appendix B
Committee Membership

COMMITTEE ON REVIEW OF NASA SCIENCE MISSION DIRECTORATE SCIENCE PLAN

A. THOMAS YOUNG, Lockheed Martin (retired), *Chair*
SPIRO K. ANTIOCHOS, Naval Research Laboratory
ANA P. BARROS, Duke University
JAMES BURCH, Southwest Research Institute
ANTONIO J. BUSALACCHI, JR., University of Maryland, College Park
JACK FARMER, Arizona State University
MARGARET FINARELLI, George Mason University
JOHN HUCHRA, Harvard-Smithsonian Center for Astrophysics
RALPH LORENZ, Lunar and Planetary Laboratory, University of Arizona
DAN McCAMMON, University of Wisconsin
ANNEILA SARGENT, California Institute of Technology
JESSICA SUNSHINE, University of Maryland
CARL WUNSCH, Massachusetts Institute of Technology

Staff

DWAYNE A. DAY, Study Director
JOSEPH ALEXANDER, Senior Staff Officer
CARMELA CHAMBERLAIN, Senior Program Assistant

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Appendix C
Committee Meeting Agenda

TUESDAY, JULY 11, 2006

Closed Session

8:30-10:30 am

Open Session

10:45 am	General Overview Presentation of the Science Plan	Gregory Williams, NASA
12:00 pm	Lunch	
1:00	Heliophysics	Barbara Giles, NASA SMD
2:00	Earth Science	Lucia Tsaoussi, NASA SMD
3:00	Break	
3:15	Planetary Exploration	Doug McCuistion, NASA SMD
4:15	Astronomy and Astrophysics	Michael Salamon, NASA SMD
5:15	General Discussion	Committee
5:45 pm	Adjourn	

WEDNESDAY, JULY 12, 2006

Closed Session

8:00-10:00 am

Open Session

10:00 am	Congressional Perspective	Jeff Bingham David Goldston Richard Obermann

Closed Session

11:00 am-5:00 pm

THURSDAY, JULY 13, 2006

Closed Session

8:00 am-12:00 pm

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Appendix D
Relevant Recent NRC Reports

CROSS-PROGRAM REPORTS

Assessment of Mission Size Trade-offs for NASA's Earth and Space Science Missions, 2000
"On Continuing Assessment of Technology Development in NASA's Office of Space Science," letter report, 2000
"On the Space Science Enterprise Draft Strategic Plan," letter report, 2000
Assessment of the Usefulness and Availability of NASA's Earth and Space Mission Data, 2002
"Assessment of NASA's Draft 2003 Space Science Enterprise Strategy," letter report, 2003
Principal-Investigator-Led Missions in the Space Sciences, 2005
Science in NASA's Vision for Space Exploration, 2005
Review of Goals and Plans for NASA's Space and Earth Sciences, 2006
An Assessment of Balance in NASA's Science Programs, 2006

ASTROPHYSICS

Astronomy and Astrophysics in the New Millennium, 2000
Connecting Quarks with the Cosmos, 2003
"Review of Progress in Astronomy and Astrophysics Toward the Decadal Vision," letter report, 2005
Assessment of Options for Extending the Life of the Hubble Space Telescope: Final Report, 2005
The Astrophysical Context of Life, 2005

EARTH SCIENCE[1]

Ensuring the Climate Record from the NPP and NPOESS Meteorological Satellites, 2000
Issues in the Integration of Research and Operational Satellite Systems for Climate Research: Part I. Science and Design, 2000
Review of NASA's Earth Science Enterprise Research Strategy for 2000-2010, 2000
The Role of Small Satellites in NASA and NOAA Earth Observation Programs, 2000
Issues in the Integration of Research and Operational Satellite Systems for Climate Research: Part II. Implementation, 2001
Review of NASA's Earth Science Enterprise Applications Program Plan, 2002
Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations, 2003
"Assessment of NASA's Draft 2003 Earth Science Enterprise Strategy," letter report, 2003
Utilization of Operational Environmental Satellite Data: Ensuring Readiness for 2010 and Beyond, 2004
Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation, 2005

HELIOPHYSICS

The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics, 2002
Solar and Space Physics and Its Role in Space Exploration, 2004
Plasma Physics of the Local Cosmos, 2004

PLANETARY SCIENCE

New Frontiers in the Solar System: An Integrated Exploration Strategy, 2002
Review of the Next Decade of Mars Architecture, 2006

[1]Reflects only SSB reports, but not all NRC reports, on Earth science.

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