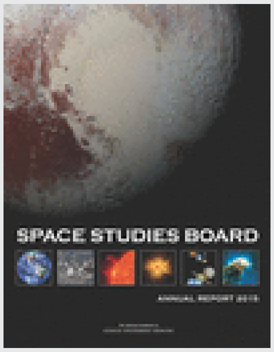

Space Studies Board Annual Report 2015

DETAILS

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Space Studies Board

Annual Report

2015

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Cover: NASA's New Horizons spacecraft captured this high-resolution enhanced color view of Pluto on July 14, 2015. The image combines blue, red and infrared images taken by the Ralph/Multispectral Visual Imaging Camera (MVIC). Pluto's surface sports a remarkable range of subtle colors, enhanced in this view to a rainbow of pale blues, yellows, oranges, and deep reds. Many landforms have their own distinct colors, telling a complex geological and climatological story that scientists have only just begun to decode. The image resolves details and colors on scales as small as 0.8 miles (1.3 km). *Credit: NASA/Johns Hopkins University Applied Physics Laboratory/ Southwest Research Institute*.

From the Chair

The Space Studies Board (SSB) has had a busy and productive year.

The most important task of the SSB is to advise the government about space policy through the decadal survey process. The recently released report *The Space Science Decadal Surveys: Lessons Learned and Best Practices* synthesizes the experience of multiple surveys in our different subfields and identifies a set of best practices for future surveys. The SSB has also launched its most complex survey, the Decadal Survey for Earth Science and Applications from Space. No other survey covers such a wide breadth of science and involves such a diverse community of scientists and users. NASA, the National Oceanic and Atmospheric Administration, and the U.S. Geological Survey are co-sponsoring the survey with its panels covering global hydrological cycles and water resources, weather and air quality, marine and terrestrial ecosystems, climate variability and change, and the Earth surface and interior-dynamics and hazards. The survey aims to issue its report by October 2017.

As part of the decadal process, Congress has charged NASA with requesting mid-decadal reviews in each of the subfields. Over the past year, the SSB launched the mid-decadal review of the astronomy and astrophysics programs, examining progress toward the goals of the *New Worlds, New Horizons in Astronomy and Astrophysics* report. In addition, the SSB hosted a symposium in Irvine, California, dedicated to understanding scientific progress in astronomy and astrophysics since the release of the decadal survey and the changing intellectual landscape as we look forward to the next astronomy and astrophysics survey that is anticipated to start in 2018.

The Space Studies Board has also been involved in several other exciting studies this past year. We issued the report from our education workshop, *Sharing the Adventure with the Student—Exploring the Intersections of NASA Space Science and Education: A Workshop Summary*, one of our biannual workshops on topics in space sciences. Victoria Hamilton, Southwest Research Institute, and Harvey Tannenbaum, Smithsonian Astrophysical Observatory, are leading an ad hoc committee charged with evaluating the scientific return from missions in extended operations, examining the balance between starting new missions and continuing older missions, as well as evaluating the senior review process. That report is expected to be issued in the summer of 2016. Perhaps our most novel study this year has been “Achieving Science Goals with Cubesats.” The committee was charged with identifying the potential of CubeSats to do high-priority science and to identify ways of increasing the scientific value of this potentially exciting new platform. Thomas Zurbuchen, University of Michigan, and Bhavya Lal, IDA Science and Technology Policy Institute, are leading this committee which will issue its report in May 2016.

The Space Studies Board continues to work with its international partners on both policy planning and enhancing scientific interaction. For the first time in many years, the SSB developed a joint study with our European Science Foundation colleagues on planetary protection issues for so-called “Special Regions” on Mars. In addition, the SSB and the National Space Science Center of the Chinese Academy of Sciences co-sponsored a forum for young space scientists in Shanghai that focused on studies of planetary bodies in the solar system and Earth science from space. This forum built on previous meetings focused on astrophysics and heliophysics. In summary, this has been a productive year for the Board, and it has been a pleasure to work with all the committees in pursuing the SSB’s mandate to provide NASA and the broader federal government with the highest quality advice. Many thanks to all in the government and the research community who make that possible.

David N. Spergel
Chair
Space Studies Board

Space Studies Board Chairs and Vice Chairs

SPACE STUDIES BOARD CHAIRS

Lloyd V. Berkner (deceased), 1958–1962

Harry H. Hess (deceased), 1962–1969

Charles H. Townes (deceased), 1970–1973

Richard M. Goody, 1974–1976

A.G.W. Cameron (deceased), 1977–1981

Thomas M. Donahue (deceased), 1982–1988

Louis J. Lanzerotti, 1989–1994

Claude R. Canizares, 1994–2000

John H. McElroy (deceased), 2000–2003

Lennard A. Fisk, 2003–2008

Charles F. Kennel, 2008–2014

David N. Spergel, 2014–

SPACE STUDIES BOARD VICE CHAIRS

George A. Paulikas, 2003–2006

A. Thomas Young, 2006–2010

John M. Klineberg, 2011–2014

Robert D. Braun, 2014–

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THE ORIGINS OF THE SPACE SCIENCE BOARD

To meet the government's urgent need for an independent adviser on scientific matters, President Lincoln signed a congressional charter forming the National Academy of Sciences in 1863 to "investigate, examine, experiment, and report upon any subject of science." As science began to play an ever-increasing role in national priorities and public life, the National Academy of Sciences (NAS) eventually expanded to include the National Research Council in 1916, the National Academy of Engineering (NAE) in 1964, and the National Academy of Medicine (NAM), which was established in 1970 as the Institute of Medicine. Collectively they are referred to as The National Academies of Sciences, Engineering, and Medicine (the Academies). More information is available at http://nationalacademies.org.

The original charter of the Space Science Board was established in June 1958, 3 months before the National Aeronautics and Space Administration (NASA) opened its doors. The Space Science Board and its successor, the Space Studies Board (SSB), have provided expert external and independent scientific and programmatic advice to NASA on a continuous basis from NASA's inception until the present. The SSB has also provided such advice to other executive branch agencies, including the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), the U.S. Geological Survey (USGS), and the Department of Defense, as well as to Congress.

The fundamental charter of the Board today remains that defined by NAS President Detlev W. Bronk in a letter to Lloyd V. Berkner, first chair of the Board, on June 26, 1958, which established the Space Science Board:

> We have talked of the main task of the Board in three parts—the immediate program, the long-range program, and the international aspects of both. In all three we shall look to the Board to be the focus of the interests and responsibilities of the Academy-Research Council in space science; to establish necessary relationships with civilian science and with governmental science activities, particularly the proposed new space agency, the National Science Foundation, and the Advanced Research Projects Agency; to represent the Academy-Research Council complex in our international relations in this field on behalf of American science and scientists; to seek ways to stimulate needed research; to promote necessary coordination of scientific effort; and to provide such advice and recommendations to appropriate individuals and agencies with regard to space science as may in the Board's judgment be desirable.
>
> As we have already agreed, the Board is intended to be an advisory, consultative, correlating, evaluating body and not an operating agency in the field of space science. It should avoid responsibility as a Board for the conduct of any programs of space research and for the formulation of budgets relative thereto. Advice to agencies properly responsible for these matters, on the other hand, would be within its purview to provide.

The Space Science Board changed its name to the Space Studies Board in 1989 to reflect its expanded scope, which now includes space applications and other topics. Today, the SSB exists to provide an independent, authoritative forum for information and advice on all aspects of space science and applications, and it serves as the focal point within the Academies for activities on space research. It oversees advisory studies and program assessments, facilitates international research coordination, and promotes communications on space science and science policy among the research community, the federal government, and the interested public. The SSB also serves as the U.S. National Committee for the Committee on Space Research (COSPAR) of the International Council for Science.

THE SPACE STUDIES BOARD TODAY

The SSB is a unit of the Division on Engineering and Physical Sciences (DEPS). DEPS is one of the major program units of the the Academies through which the institution conducts its operations on behalf of NAS, NAE, and NAM. Within DEPS, there are a total of 13 boards that cover a broad range of physical science and engineering disciplines and mission areas.

Members of the DEPS Committee (DEPSCOM) provide advice on Board membership and on proposed new projects to be undertaken by ad hoc study committees formed under the SSB's auspices. About every 3 years, DEPSCOM reviews the overall operations of each of the DEPS boards. The next review of the SSB should take place in 2016.

The "Space Studies Board" encompasses the Board itself, its standing committees (see Chapter 2) and ad hoc study committees (see Chapter 3), and its staff. The Board is composed of prominent scientists, engineers, industrialists, scholars, and policy experts in space research appointed for 2-year staggered terms. They represent seven space research disciplines: space-based astrophysics, heliophysics (also referred to as solar and space physics), Earth science and applications from space, solar system exploration, microgravity life and physical sciences, space systems and technology, and science and technology policy. In 2015, there were 19-21 Board members. The Executive Committee (XCOM) assists the chairs of the Board in oversight of activities. A liaison member of the Academies' Aeronautics and Space Engineering Board (ASEB) and the U.S. representative to COSPAR are ex officio participants. A standing liaison arrangement also has been established with the European Space Science Committee (ESSC), part of the European Science Foundation.

Organization

The organization of the SSB in 2015 is illustrated in Figure 1.1. Taken together, the Board and its standing and ad hoc study committees generally hold as many as 30 meetings during the year.

Major Functions of the Space Studies Board

The Board provides an independent, authoritative forum for information and advice on all aspects of space science and applications and serves as the focal point within the Academies for activities on space research. The Board itself does not conduct studies, but it oversees advisory studies and program assessments conducted by ad hoc study committees (see Chapter 3) generally formed in response to a request from a sponsor. All projects proposed to be conducted by ad hoc study committees under the auspices of the SSB must be reviewed and endorsed by the chair and vice chair of the Board (as well as other Academies officials).

Decadal surveys are a signature product of the SSB, providing strategic direction to NASA, NSF, the Department of Energy (DOE), NOAA, USGS, and other agencies on the top priorities over the next 10 years in astronomy and astrophysics (joint effort with the Board on Physics and Astronomy), solar system exploration, solar and space physics, Earth science and applications from space, and biological and physical sciences in space (joint effort with the ASEB). The Board serves as a communications bridge on space research and science policy among the scientific research community, the federal government, and the interested public.

The Board ordinarily meets at least two times per year (spring and fall) to review the activities of its committees and to be briefed on and discuss major space policy issues. Every second year, the Board hosts a workshop on a topic of current interest, resulting in a workshop report. The latest of these workshops was held in 2014 (see Chapter 4).

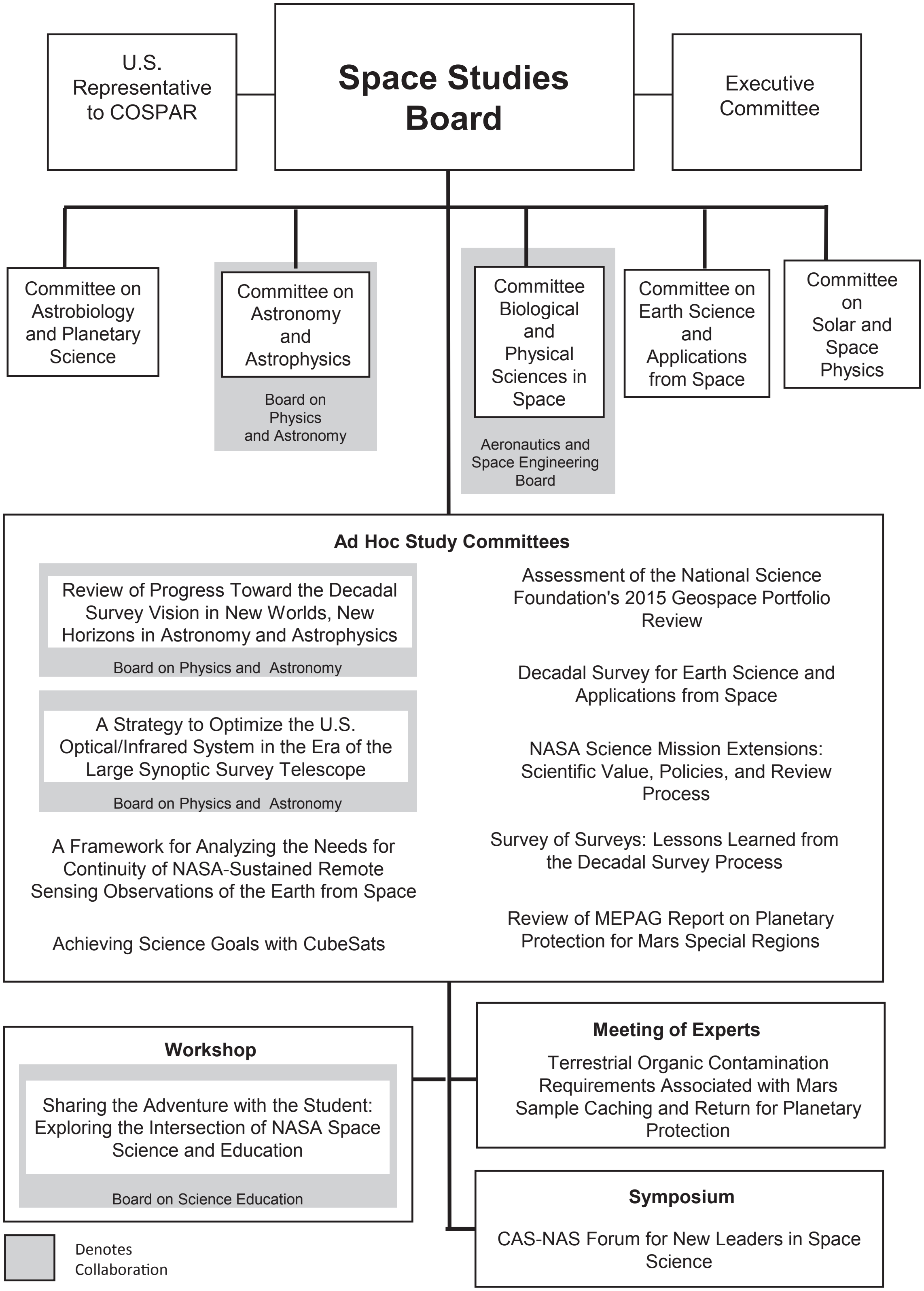

FIGURE 1.1 Organization of the Space Studies Board, its standing committees, ad hoc study committees, and special projects in 2015. Shaded boxes denote activities performed in cooperation with other units of the National Academies of Sciences, Engineering, and Medicine.

International Representation and Cooperation

The Board serves as the U.S. National Committee for COSPAR, an international, multidisciplinary forum for exchanging space science research. Board members may individually participate in COSPAR scientific sessions to present their research or present the results of an SSB report to the international community, or conduct informal information exchange sessions with national entities within COSPAR scientific assemblies. See Chapter 2 for a summary of COSPAR's 2015 activities.

The Board also has a regular practice of exchanging observers with the ESSC, which is part of the European Science Foundation (see http://www.esf.org/).

Space Studies Board Committees

Executive Committee

The Executive Committee, composed entirely of Board members, facilitates the conduct of the Board's business, permits the Board to move rapidly to lay the groundwork for new study activities, and provides strategic planning advice. XCOM meets annually for a session on the assessment of SSB operations and future planning. Its membership normally includes the chair and vice chair of the Board and at least one Board member for each discipline.

Standing Committees

Discipline-based standing committees are the means by which the Board conducts its oversight of specific space research disciplines. Each standing committee is composed of about a dozen specialists, appointed to represent the broad sweep of research areas within the discipline. Like the Board itself, each standing committee serves as a communications bridge with its associated research community and participates in identifying new projects and prospective members of ad hoc study committees. Standing committees do not, themselves, write reports, but oversee reports written by ad hoc study committees created under their auspices.

In 2015, SSB had five standing committees:

- Committee on Astrobiology and Planetary Science (CAPS),
- Committee on Astronomy and Astrophysics (CAA),[1]
- Committee on Biological and Physical Sciences in Space (CBPSS),[2]
- Committee on Earth Science and Applications from Space (CESAS), and
- Committee on Solar and Space Physics (CSSP).

Ad Hoc Study Committees

Ad hoc study committees are created by Academies action to conduct specific studies at the request of sponsors. These committees typically produce reports that provide advice to the government and therefore are governed by Section 15 of the Federal Advisory Committee Act (FACA). Ad hoc study committees usually write their reports after holding two or three information-gathering meetings, although in some cases they may hold a workshop or symposium in addition to or instead of information-gathering meetings.

In other cases, workshops are organized by ad hoc planning committees that serve as organizers only, where a workshop report is written by a rapporteur and does not contain findings or recommendations. In those cases, the study committee is not governed by FACA Section 15, since no advice results from the workshop.

The ad hoc study committees that were in place during 2015 are summarized in Chapter 3.

[1] In collaboration with the Board on Physics and Astronomy.
[2] In collaboration with the Aeronautics and Space Engineering Board.

COLLABORATION WITH OTHER UNITS OF THE ACADEMIES

Much of the work of the SSB involves topics that fall entirely within its principal areas of responsibility and can be addressed readily by its members and committees. However, there are other situations in which the need for breadth of expertise, alternative points of view, or synergy with other projects leads to collaboration with other units of the Academies.

The SSB has engaged in many such multi-unit collaborations. Other boards with which the SSB has worked most often are the ASEB, the BPA, and the Board on Atmospheric Sciences and Climate. The SSB has also collaborated with the Board on Science Education, the Committee on Science, Technology, and Law, the Committee on National Statistics, the Board on Earth Sciences and Resources, and the Ocean Studies Board, among others. This approach to projects has the potential to bring more of the full capability of the Academies to bear in preparing advice for the federal government and the public. Multi-unit collaborative projects also present new challenges—namely, to manage the projects in a way that achieves economies of scale and true synergy rather than just adding cost or complexity. Collaborative relationships between the SSB and other units during 2015 are illustrated in Figure 1.1.

ASSURING THE QUALITY OF SPACE STUDIES BOARD REPORTS

A major contributor to the quality of the SSB reports (Table 1.1 lists the 2015 releases) is the requirement that Academies reports be peer-reviewed. Except for the *Space Studies Board Annual Report—2014,* all of the reports were subjected to extensive peer review, which is overseen by the Report Review Committee (RRC). Typically 7 to 10 reviewers (occasionally as many as 15 or more) are selected on the basis of recommendations by NAS and

TABLE 1.1 Space Studies Board Reports Released in 2015

Report Title	Sponsor(s)	Oversight Committee or Board[a]	Principal Audiences[b]				
			NASA/ SMD	NASA/ HEOMD	NOAA	NSF	Other
Continuity of NASA Earth Observations from Space: A Value Framework	NASA	SSB	X				
Sharing the Adventure with the Student: Exploring the Intersections of NASA Space Science and Education: A Workshop Summary	NASA	SSB BOSE	X			X	
Review of MEPAG Report on Mars Special Regions	NASA	SSB	X				ESF
Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System	NSF	BPA SSB				X	
The Space Science Decadal Surveys: Lessons Learned and Best Practices	NASA	SSB BPA					OMB, OSTP, Congress
Space Studies Board Annual Report—2014	NASA	SSB	X	X	X	X	DOE, USGS

[a] Oversight committee or board within the Academies:

BPA	Board on Physics and Astronomy
SSB	Space Studies Board
BOSE	Board on Science Education

[b] Principal audiences: Federal agencies and others that have funded or shown interest in SSB reports.

DOE	Department of Energy
ESF	European Science Foundation
NASA	National Aeronautics and Space Administration
NASA/HEOMD	NASA Human Exploration and Operations Mission Directorate
NASA/SMD	NASA Science Mission Directorate
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
USGS	United States Geological Survey

NAE section liaisons, SSB members, other Academies volunteers, and staff. The reviewers are subject to approval by the Academies. The identities of external reviewers are not known to a report's authors until after the review has been completed and the report has been approved by the RRC. The report's authors, with the assistance of SSB staff, must provide some response to every specific comment from every external reviewer. To ensure that appropriate technical revisions are made to the report and that the revised report complies with policies and standards of the Academies, the response-to-review process is overseen and refereed by an independent arbiter (called a monitor) that is knowledgeable about the report's issues. In some cases, there is a second independent arbiter (called a coordinator) that has a broader perspective on policy issues affecting the Academies or a more narrow focus on the subject matter of the report, depending on the expertise of the monitor. All of the reviews emphasize the need for scientific and technical clarity and accuracy and for proper substantiation of any findings, conclusions, and recommendations presented in the report. Names of the external reviewers, including the monitor (and coordinator if one was appointed), are published in the final report, but their individual comments are not released.

Another important method to ensure high-quality work derives from the size, breadth, and depth of the cadre of experts who serve on the SSB and its committees or participate in other ways in the activities of the SSB. Some highlights of the demographics of the SSB in 2015 are presented in Tables 1.2 and 1.3. During 2015, a total of 253 individuals from 66 colleges and universities and 56 other public or private organizations served as formally appointed members of the Board and its committees. Approximately 175 individuals participated in SSB activities either as presenters or as invited participants. The report review process is as important as the writing of reports, and during 2015, 42 different external reviewers contributed to critiques of draft reports. During 2015, the Board and committees included 56 members of NAS, NAE, or NAM. Being able to draw on such a broad base of expertise is a unique strength of the advisory process of the Academies.

AUDIENCE AND SPONSORS

The SSB's efforts have been relevant to a full range of government audiences in civilian space research—including NASA's Science Mission Directorate (SMD), NASA's Human Exploration and Operations Mission Directorate (HEOMD), NASA's Program Analysis and Evaluation Office, NSF, NOAA, USGS, and DOE. Reports on NASA-wide issues were addressed to multiple NASA offices or the whole agency; reports on science issues, to SMD; and reports on exploration systems issues, to HEOMD. Within NASA, SMD has been the leading spon-

TABLE 1.2 Experts Involved in the Space Studies Board and Its Committees, January 1, 2015, to December 31, 2015

	Number of Board and Committee Members	Number of Institutions or Agencies Represented
Academia	180	66
Government and national facilities	10	7
Private industry	18	17
Nonprofit and other[a]	45	32
Total[b]	253[c]	122

[a] Other includes foreign institutions and entities not classified elsewhere.
[b] Includes 56 National Academy of Sciences, National Academy of Engineering, and National Academy of Medicine members.
[c] Includes 22 Board members and 231 committee members.

TABLE 1.3 Summary of Participation in Space Studies Board Activities, January 1, 2015, to December 31, 2015

	Academia	Government and National Facilities	Private Industry	Nonprofit and Other	Total Individuals
Board/committee members	180	10	18	45	253
Guest experts	61	66	1	17	175
Reviewers	29	4	2	7	42

NOTE: Counts of individuals are subject to an uncertainty of ±3 due to possible miscategorization.

sor of SSB reports. Reports have also been sponsored by or of interest to agencies besides NASA—for example, NOAA, NSF, DOE, and the USGS.

OUTREACH AND DISSEMINATION

Enhancing outreach to a variety of interested communities and improving dissemination of SSB reports is a high priority. In 2015, the SSB continued to distribute its quarterly newsletter by electronic means to subscribers.

The Board teamed with other units of the Academies (including boards within the Division on Earth and Life Studies, the BPA, the National Academies Press, the Office of News and Public Information, and the Proceedings of the National Academy of Sciences) to exhibit at the national meetings of the American Geophysical Union, the American Astronomical Society, the American Meteorological Society, and the American Association for the Advancement of Science. More than 2,000 reports were disseminated in addition to the copies distributed to study committee members, the Board, and sponsors. A DVD compilation of SSB reports since 1958 is also included with the annual report and disseminated by mail and at exhibits and meetings.

Formal reports delivered to government sponsors constitute one of the primary products of the work of the SSB, but the dissemination process has a number of other important elements. The Board is always seeking ways to ensure that its work reaches the broadest possible appropriate audience and that it has the largest beneficial impact. Copies of reports are routinely provided to key executive branch officials, members and staffs of relevant congressional committees, members of other interested units of the Academies, and federal advisory bodies. Members of the press are notified about the release of each new report, and the SSB maintains a substantial mailing list for distribution of reports to members of the space research community. The SSB publishes summaries of all new reports in its quarterly newsletter. The SSB also offers briefings by committee chairs and members or SSB staff to officials in Congress, the executive branch, and scientific societies. Reports are posted on the SSB home page at http://nas.edu/ssb and linked to the National Academies Press website for reports at http://www.nap.edu.

LLOYD V. BERKNER SPACE POLICY INTERNSHIP

The Space Studies Board has operated a very successful competitive internship program since 1992. The Lloyd V. Berkner Space Policy Internship is named after Dr. Berkner, the Board's first chair, who played an instrumental role in creating and promoting the International Geophysical Year, a global effort that made it possible for scientists from around the world to coordinate observations of various geophysical phenomena.

The general goal of each internship is to provide a promising undergraduate student an opportunity to work in civil space research policy in the nation's capital, under the aegis of the Academies. Internships are offered twice a year; in the summer for undergraduates and in autumn for undergraduate and graduate students. Interns typically work with the Board, its committees, and staff on one or more of the advisory projects currently underway. Other interns, paid or unpaid, also join the SSB staff on an ad hoc basis. In 2015, the SSB had the pleasure of hosting five interns through the summer and fall programs.

For current intern opportunities at the SSB, and a list of past SSB interns, visit the SSB website at http://sites.nationalacademies.org/SSB/ssb_052239.

2
Board and Standing Committees: Activities and Membership

The Space Studies Board (SSB) of the National Academies of Sciences, Engineering, and Medicine[1] and its standing committees provide strategic direction for and oversee activities of its ad hoc study committees (see Chapter 3), interact with sponsors, and serve as a communications conduit between the government and the scientific community. They do not provide formal advice and recommendations and, therefore, are not subject to the Federal Advisory Committee Act, Section 15.

During 2015, the SSB had five standing committees representing various disciplines: the Committee on Astrobiology and Planetary Science (CAPS), the Committee on Astronomy and Astrophysics (CAA; jointly with the Board on Physics and Astronomy, BPA), the Committee on Earth Science and Applications from Space (CESAS), the Committee on Solar and Space Physics (CSSP), and the Committee on Biological and Physical Sciences in Space (CBPSS; jointly with the Aeronautics and Space Engineering Board, ASEB).

SPACE STUDIES BOARD

HIGHLIGHTS OF SPACE STUDIES BOARD ACTIVITIES

The Space Studies Board held its spring meeting on April 22-23, 2015, at the National Academy of Sciences Building in Washington, D.C. The joint session with the ASEB on April 22 began with David Miller (NASA Chief Technologist), Ralph Roe (NASA Chief Engineer), and Ellen Stofan (NASA Chief Scientist), followed by an update on the International Space Station (ISS) by Sam Scimemi and Julie Robinson from NASA. The Boards then held discussions with staff representatives from Capitol Hill (Pam Whitney, Nick Cummings, and Allen Cutler) and from the White House (Paul Shawcross, Grace Hu, and Ben Roberts). Chris Hart from the National Transportation Safety Board then gave a presentation on space launch accident investigations. The Boards then received an update on CBPSS from its co-chairs, Betsy Cantwell and Rob Ferl. The end of the day was devoted to a session with Mary Lynn Dittmar (former member of the Committee on Human Spaceflight) and Bill Gerstenmaier (NASA), where Dr. Dittmar recapped the main messages of the 2014 report *Pathways to Exploration—Rationales and Approaches for a U.S. Program of Human Space Exploration*, and Mr. Gerstenmaier provided reactions and commentary from NASA during the presentation. That was followed by a roundtable discussion between the Boards, Dr. Dittmar, and Mr. Gerstenmaier. On April 23, the SSB met and heard updates from its standing committees (Todd Hoeksema, CSSP; Mark Abbott and Joyce Penner, CESAS; Greg Ferry, CAPS; and Marcia Rieke,

[1] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council are used in an historical context identifying programs prior to July 1.

CAA). The Board received an update on the key issues at NASA's Science Mission Directorate (SMD) from John Grunsfeld (Associate Administrator, NASA SMD) and had a roundtable discussion with Dr. Grunsfeld and the SMD Division Directors (Mike Freilich, Earth Science; Jeff Newmark, Heliophysics; Jim Green, Planetary; and Paul Hertz, Astrophysics). That discussion was followed by a session on international issues with an update from the European Space Sciences Committee (ESSC) from Jean Claude Worms, European Science Foundation (ESF), and an update on COSPAR (Committee on Space Research) activities from David Smith (SSB staff). The final session was a planning session for the second Earth science and applications from space decadal survey, which included Tony Busalacchi (CESAS member), Mike Freilich (NASA), Steve Volz (NOAA), and Sarah Ryker (U.S. Geological Survey [USGS]) and was moderated by SSB member Tony Janetos.

The Executive Committee (XCOM) of the SSB met July 28-29, 2015, in Washington, D.C. The XCOM was joined by John Culberson, Chairman of the House Appropriations Commerce, Justice, Science Subcommittee (CJS), and Congressman Chaka Fattah, Ranking Member of the House CJS Appropriations Subcommittee, for a discussion on congressional perspectives. The XCOM was also joined by John Grunsfeld (NASA SMD) to discuss potential topics that SMD might ask the SSB to address. Discussions on the views from Capitol Hill and the White House on space science issues were held with congressional, Office of Science and Technology Policy (OSTP), and Office of Management and Budget (OMB) staff. The XCOM was given briefings and had discussions with the chairs of two completed studies, Phil Christensen (*Sharing the Adventure with the Student: Exploring the Intersections of NASA Space Science and Education: A Workshop Summary*) and Alan Dressler (*The Space Science Decadal Surveys: Lessons Learned and Best Practices*); and one ongoing study chair, Thomas Zurbuchen (for the Committee on Achieving Science Goals with CubeSats). The XCOM also had discussions with standing committee chairs and amongst themselves about various potential topics for new studies, the biennial SSB workshop, and planning for the fall 2015 and spring 2016 meetings.

The SSB held its fall meeting in Irvine, California, at the Arnold and Mabel Beckman Center of the National Academies of Sciences, Engineering and Medicine on November 3-5, 2015. During the first day of the meeting, the Board heard reports from the standing committee co-chairs and held a discussion on committee issues and future actions. Standing committee co-chairs in attendance included Marcia Rieke (CAA), Phil Christensen and J. Greg Ferry (CAPS), Joyce Penner (CESAS), Todd Hoeksema (CSSP), and Rob Ferl (CBPSS). The day continued with an update on COSPAR 2018 and other COSPAR activities from Gregg Vane (a member of the 2018 Organizing Committee) and SSB staff member David Smith. The Board then received a status report and had a discussion with John Grunsfeld (NASA SMD). The day ended with a variety of briefings on topics of interest to the Board, including an update on ESSC activities (Athena Coustenis, ESSC Chair), the COSPAR Roadmap on Space Weather (Sarah Gibson, Board member), and the status of the 2016 SSB workshop (Michael Moloney, SSB Director). The briefings also included a discussion of the issues that the ad hoc Committee on NASA Science Mission Extensions will be focusing on, with Committee Co-Chair Vicky Hamilton, and the outcome of the *Continuity of NASA Earth Observations from Space: A Value Framework* report from committee member Randy Friedl.

The second day of the fall meeting included several focus sessions and a science talk on the Stratocruiser by Board member Jim Anderson. The first focus session on NASA SMD and Education included impressions from the SSB 2014 workshop on education by workshop planning committee members Phil Christensen and Jim Manning; a summary of the restructuring of SMD Education by Kristen Erickson (NASA SMD); and a discussion about next steps. The second focus session was on the space science decadal surveys and included an overview of the *The Space Science Decadal Surveys* report from Alan Dressler, committee chair; a summary of how NASA Astrophysics is preparing for the next astronomy and astrophysics decadal survey, given by Paul Hertz (NASA); a personal perspective given by Board member Tony Janetos on how the Earth science decadal survey might incorporate some of the lessons learned from the report; and a general discussion amongst the Board and guests. The final focus session was on science and human exploration beyond low Earth orbit, including presentations on the work of the International Space Exploration Coordination Group (ISECG) Science Advisory Group by Greg Schmidt (NASA); science and human exploration of Mars by Richard Zurek (Jet Propulsion Laboratory [JPL]); science and human exploration of the Moon by Clive Neal (NASA's Lunar Exploration Analysis Group Chair); and the science and human exploration of asteroids by Erik Asphaug (Arizona State University); followed by a discussion.

The spring meeting will be held in Washington, D.C., on April 26-28, 2016. Visit http://www.nas.edu/ssb to stay up to date on Board, workshop, and study committee meetings and developments.

SPACE STUDIES BOARD MEMBERSHIP

July 1, 2014–June 30, 2015

David N. Spergel, Princeton University (chair)
Robert D. Braun, Georgia Institute of Technology (vice chair)
Mark R. Abbott, Oregon State University
James Anderson, Harvard University
James Bagian, University of Michigan
Jeff M. Bingham, Consultant
Penelope J. Boston, New Mexico Institute of Mining and Technology
Joseph Fuller, Jr., Futron Corporation
Thomas R. Gavin, California Institute of Technology
Neil Gehrels, NASA Goddard Space Flight Center
Sarah Gibson, National Center for Atmospheric Research
Roderick Heelis, University of Texas, Dallas
Wesley T. Huntress, Carnegie Institution of Washington
Anthony C. Janetos, Boston University
Dava J. Newman,[2] Massachusetts Institute of Technology
Saul Perlmutter, Lawrence Berkeley National Laboratory
Louise M. Prockter, Johns Hopkins University, Applied Physics Laboratory
Marcia J. Rieke, University of Arizona
Mark Thiemens, University of California, San Diego
Meenakshi Wadhwa, Arizona State University
Clifford M. Will, University of Florida
Thomas H. Zurbuchen, University of Michigan

July 1, 2015–June 30, 2016

David N. Spergel, Princeton University (chair)
Robert D. Braun, Georgia Institute of Technology (vice chair)
James Anderson, Harvard University
James Bagian, University of Michigan
Jeff M. Bingham, Consultant
Penelope J. Boston, New Mexico Institute of Mining and Technology
Mary Lynne Dittmar, Dittmar Associates
Joseph Fuller, Jr., Futron Corporation
Thomas R. Gavin, California Institute of Technology
Neil Gehrels, NASA Goddard Space Flight Center
Sarah Gibson, National Center for Atmospheric Research
Wesley T. Huntress, Carnegie Institution of Washington
Anthony C. Janetos, Boston University
Chryssa Kouveliotou, The George Washington University
Saul Perlmutter, Lawrence Berkeley National Laboratory
Louise M. Prockter, Johns Hopkins University, Applied Physics Laboratory
Mark Thiemens, University of California, San Diego
Meenakshi Wadhwa, Arizona State University
Thomas H. Zurbuchen, University of Michigan

Ex Officio and Liaison Participants

Lennard Fisk, University of Michigan (liaison, U.S. Representative to COSPAR through March)
Charlie Kennel, University of California, San Diego (liaison; U.S. Representative to COSPAR)
Lester Lyles, The Lyles Group (ex-officio; chair, Aeronautics and Space Engineering Board)
Athena Coustenis, National Centre for Scientific Research of France (liaison; chair, European Space Science Committee)

Membership of the SSB Executive Committee

July 1, 2014–June 30, 2015

David N. Spergel, Princeton University (chair)
Robert D. Braun, Georgia Institute of Technology (vice chair)
Mark R. Abbott, Oregon State University
Wesley T. Huntress, Carnegie Institution of Washington
Dava J. Newman,[3] Massachusetts Institute of Technology
Marcia J. Rieke, University of Arizona
Thomas H. Zurbuchen, University of Michigan

July 1, 2015–June 30, 2016

David N. Spergel, Princeton University (chair)
Robert D. Braun, Georgia Institute of Technology (vice chair)
Mary Lynne Dittmar, Dittmar Associates
Neil Gehrels, NASA Goddard Space Flight Center
Wesley T. Huntress, Carnegie Institution of Washington
Anthony Janetos, Boston University
Chryssa Kouveliotou, The George Washington University
Thomas H. Zurbuchen, University of Michigan

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[2] Resigned from Board in April 2015 to be confirmed as Deputy Administrator of NASA.
[3] Resigned from Board in April 2015 to be confirmed as Deputy Administrator of NASA.

Staff in 2015

Michael H. Moloney, Director for Space and Aeronautics
Arthur A. Charo, Senior Program Officer
Sandra J. Graham, Senior Program Officer
David H. Smith, Senior Program Officer
Dwayne A. Day,* Senior Program Officer, ASEB
David Lang,* Program Officer, BPA
Abigail A. Sheffer, Program Officer
Katie Daud, Research Associate
Charlie Harris, Research Associate (from September 28)
Celeste A. Naylor, Information Management Associate
Tanja E. Pilzak, Manager, Program Operations
Meg A. Knemeyer, Financial Officer
Sandra Wilson, Senior Financial Assistant (through October)
Carmela J. Chamberlain, Administrative Coordinator
Andrea Rebholz,* Program Coordinator, ASEB
Dionna Williams, Program Coordinator
Anesia Wilks, Senior Program Assistant

Space Policy Interns

Angela Dapremont, 2015 Spring Lloyd V. Berkner Space Policy Intern
Danielle Youngsmith, 2015 Summer Lloyd V. Berkner Space Policy Intern
James Alver, 2015 Summer Lloyd V. Berkner Space Policy Intern
Thomas Katucki, 2015 Fall Lloyd V. Berkner Space Policy Intern

U.S. NATIONAL COMMITTEE FOR COSPAR

The SSB, acting in its role as the U.S. National Committee for COSPAR held its annual series of business meetings at its Paris headquarters on March 23-26, 2015. These meetings were notable for two reasons: they were the first meeting presided over by Lennard A. Fisk, following his election as president of COSPAR at the August 2014 Scientific Assembly in Moscow, and they were the first where Charles Kennel participated in his new, dual role as U.S. representative to COSPAR and vice chair of the COSPAR Scientific Advisory Committee. Also present to report to the COSPAR Bureau were Gregg Vane and Rosaly Lopes, the chair of the Local Organizing Committee and vice chair of the Science Program Committee, respectively, for the 2018 COSPAR Scientific Assembly in Pasadena, California.

COSPAR held the second of its new series of "off-year" symposia at Foz do Iguacu, Brazil, on November 9-13, 2015. The SSB continues to follow closely the arrangements for COSPAR's 41st and 42nd Scientific Assemblies, to be held in Istanbul, Turkey, on July 30-August 7, 2016, and Pasadena, California, on July 14-22, 2018, respectively. The next milestone in the planning for the latter is the site visit to Pasadena by COSPAR's leadership scheduled for January 25-26, 2016. The next round of COSPAR business meetings will be held at the organization's Paris headquarters on March 22-24, 2016.

U.S. Representative to COSPAR

Charlie Kennel, Scripps Institute of Oceanography, University of California, San Diego

Staff

David H. Smith, Senior Program Officer, SSB (Executive Secretary of U.S. National Committee for COSPAR)
Carmela J. Chamberlain, Administrative Coordinator, SSB

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* Staff from other Boards who are shared with the SSB.

STANDING COMMITTEES

The National Research Council (NRC) Space Science Week (http://sites.nationalacademies.org/SSB/SSB_153141) was held March 31-April 2, 2015, in Washington, D.C. All five of the SSB's active standing committees met in parallel (see descriptions of the individual standing committee sections meetings below). On the afternoon of March 31, the standing committees conducted a plenary session at which there was a presentation on the NASA SMD budget and its current program and priorities by Marc Allen, NASA SMD Deputy Associate Administrator for Research. The committees also participated in two roundtable discussions, the first on SMD inter-divisional cooperation with Jack Kaye, Earth Science Division (ESD), Jim Green, Planetary Science Division (PSD), Paul Hertz, Astrophysics Division (ASD) and Jeff Newmark, Heliophysics Division (HSD); and the second on NASA inter-directorate cooperation with Greg Williams, Human Exploration and Operations Mission Directorate (HEOMD), Jeff Sheehy, Space Technology Mission Directorate (STMD), and Jim Green (SMD). The committees were also briefed on an upcoming SSB study on achieving science with CubeSats, to be chaired by Thomas Zurbuchen, University of Michigan, and on the current science on the ISS by NASA's Julie Robinson. The afternoon concluded with briefings from the White House by Tammy Dickinson, OSTP, and Grace Hu, OMB, and from Capitol Hill by Tom Hammond (House Science, Space and Technology Committee) and Nick Cummings (Senate Space, Science and Competitiveness Subcommittee).

On the evening of April 1, the NRC Space Science Week Public Lecture by Jason Kalirai (Space Telescope Science Institute) marked the 25th Anniversary of the Hubble Space Telescope. To view a video replay of *Our Place in the Universe: As Seen Through Past, Present, and Future Telescopes*, please visit http://sites.nationalacademies.org/ssb/ssb_153311. The next Space Science Week will be held on March 29-31, 2016, in Washington, D.C.

COMMITTEE ON ASTROBIOLOGY AND PLANETARY SCIENCE

The Committee on Astrobiology and Planetary Science met on March 31-April 2, 2015, in Washington, D.C., as part of the third annual NRC Space Science Week. In addition to joint plenary sessions with the other SSB standing committees, CAPS received briefings on the status of NASA's planetary science, astrobiology, and planetary protection programs. In addition, the committee heard updates on NASA's Mars and exoplanet exploration activities, the NASA Astrobiology Institute, and the status of Europa mission development work. The committee also heard presentations on the recent Europa Plumes workshop, a joint NASA-National Science Foundation (NSF) Alternative Chemistries of Life Workshop, a series of perspectives on Mars exploration after Mars 2020, and synergies between human exploration and planetary science. CAPS also held a joint session with CSSP, during which both committees received briefings on China's future planetary and space physics missions and a presentation on the results from MAVEN.

CAPS held its fall meeting on September 16-17, 2015, in Irvine, California. At this meeting, CAPS was presented with a Europa mission update from Robert Pappalardo and Barry Goldstein of JPL. Gregg Vane (JPL) discussed preparing for COSPAR 2018. Neil Murphy (JPL) presented on ice giant mission status and planning. CAPS received a briefing on the *Space Science Decadal Surveys* report by committee chair Alan Dressler (Carnegie Observatories) and committee member Steve Mackwell (Lunar and Planetary Institute). Michael New (NASA) gave a presentation regarding NASA's Astrobiology strategy, and Carl Pilcher (NASA) gave an update on the status of the NASA Astrobiology Institute. Michael Mumma (NASA) presented about martian methane and Chris Webster (JPL) discussed MSL observations of martian methane. CAPS also heard a presentation from Ken Farley (California Institute of Technology) on the Mars 2020 and sample caching study. Jim Green presented a NASA PSD update. A major membership rotation is scheduled to take place in the first quarter of 2016.

A historical summary of a selection of SSB advisory reports on astrobiology and planetary protection is presented in Figure 2.1. A historical summary of a selection of SSB advisory reports on solar system exploration is presented in Figure 2.2.

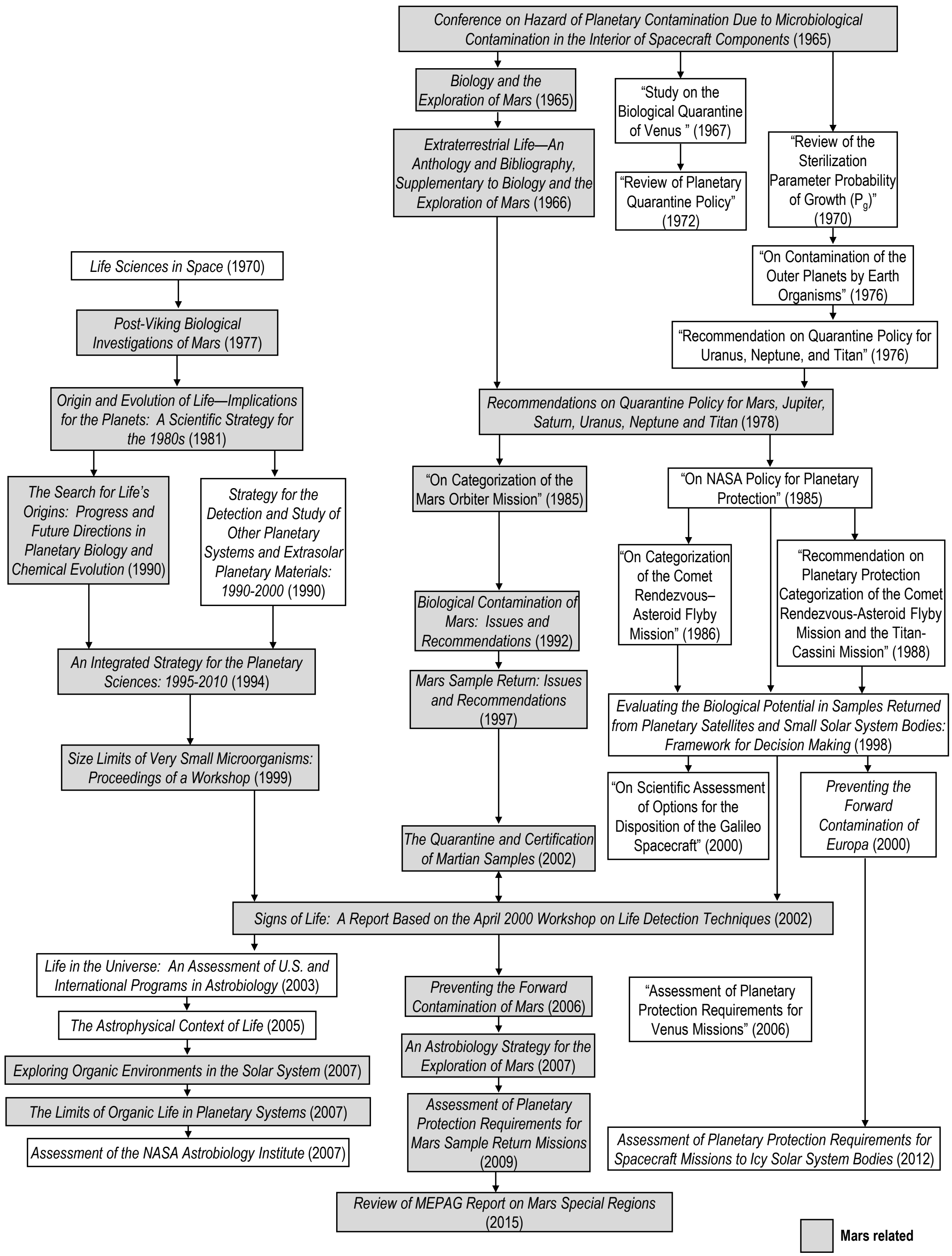

FIGURE 2.1 SSB advice associated with CAPS—astrobiology and planetary protection (1965-2015).

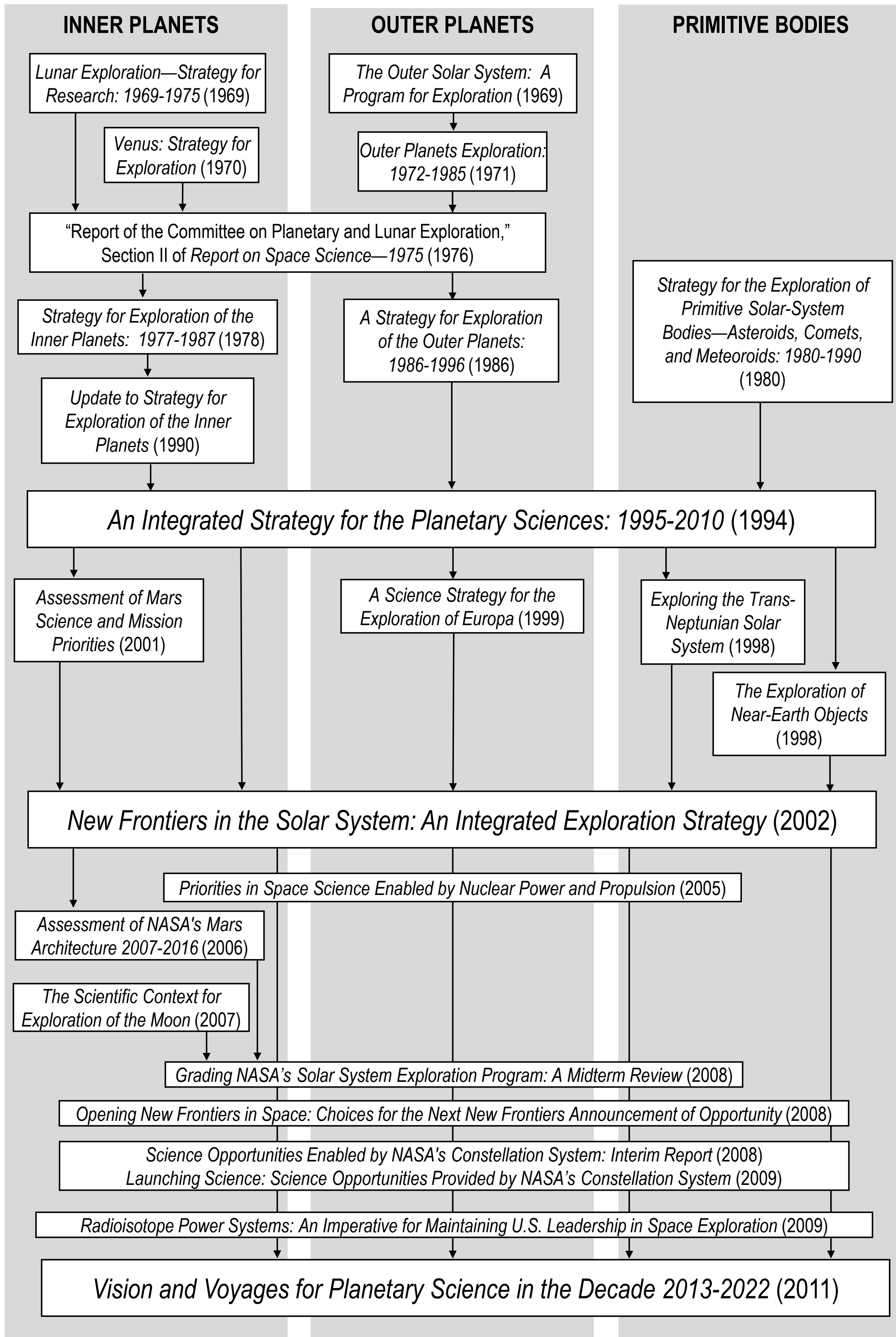

FIGURE 2.2 SSB advice associated with CAPS—solar system exploration (1969-2015). Origins of life topics are covered in Figure 2.1.

Membership

Philip R. Christensen, Arizona State University (co-chair)
J. Gregory Ferry, Pennsylvania State University (co-chair)
Sushil K. Atreya, University of Michigan
Amy C. Barr, Independent Consultant
Richard P. Binzel, Massachusetts Institute of Technology
Ronald Breaker, Yale University
John Clarke, Boston University
Geoffrey Collins, Wheaton College
Pascale Ehrenfreund, George Washington University
Linda T. Elkins-Tanton,[4] Arizona State University
James F. Kasting, Pennsylvania State University
Stephen Mackwell, Lunar and Planetary Institute
Norman R. Pace, University of Colorado, Boulder
Gary Ruvkun, Massachusetts General Hospital
Mark P. Saunders, Independent Consultant
Gerald Schubert,[5] University of California, Los Angeles
Norman H. Sleep, Stanford University
Cristina Takacs-Vesbach, University of New Mexico
Roger V. Yelle, University of Arizona

Staff

David H. Smith, Senior Program Officer, SSB
Katie Daud, Research Associate, SSB
Andrea Rebholz,[6] Program Coordinator, ASEB

COMMITTEE ON ASTRONOMY AND ASTROPHYSICS

The Committee on Astronomy and Astrophysics met on March 31-April 2, 2015, in Washington, D.C., as part of the third annual NRC Space Science Week. In addition to joint plenary sessions with the other SSB standing committees, CAA received briefings from and held discussions with Jim Ulvestad (NSF) on NSF's Division of Astronomical Sciences program; Kathy Turner (DOE) on DOE's High Energy Physics program; Paul Hertz (NASA) on the NASA Astrophysics Division program; Eric Smith (NASA) on progress on the James Webb Space Telescope; Steve Kahn (LSST) on the progress of the LSST; Lyman Page (Princeton University) on ways to observe the tensor-scalar ratio from the ground and space; Bruce Macintosh (Stanford University) on ground- and space-based coronagraph science; Ji Wu (Chinese Academy of Sciences) on the Chinese Academy of Sciences program; Angela Olinto (University of Chicago) on the 2014-2015 Astronomy and Astrophysics Advisory Committee Annual Report; and Pierre Binétruy (APC Université Paris Diderot) as the ESSC liaison on the ESSC's activities.

In July, the committee held a teleconference with Debra Elmegreen to discuss the recent report authored by the committee she chaired, *Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System*. Six new members were added in 2015: Bruce Macintosh, Lee Hartmann, Vassiliki Kalogera, Steven Ritz (co-chair), Lisa Kaltenegger, and Mark Phillips. The committee did not hold a fall meeting; it was placed on hiatus during the execution of the ad hoc Committee on the Review of Progress Toward the Decadal Survey Vision in New Worlds, New Horizons in Astronomy and Astrophysics. The committee's next in-person meeting will take place during the fourth annual Space Science Week on March 29-31, 2016, in Washington, D.C.

A historical summary of a selection of SSB advisory reports on astronomy and astrophysics is presented in Figure 2.3.

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[4] Resigned from the committee on October 14, 2015.
[5] Resigned from the committee on July 4, 2015.
[6] Staff from other Boards who are shared with the SSB.

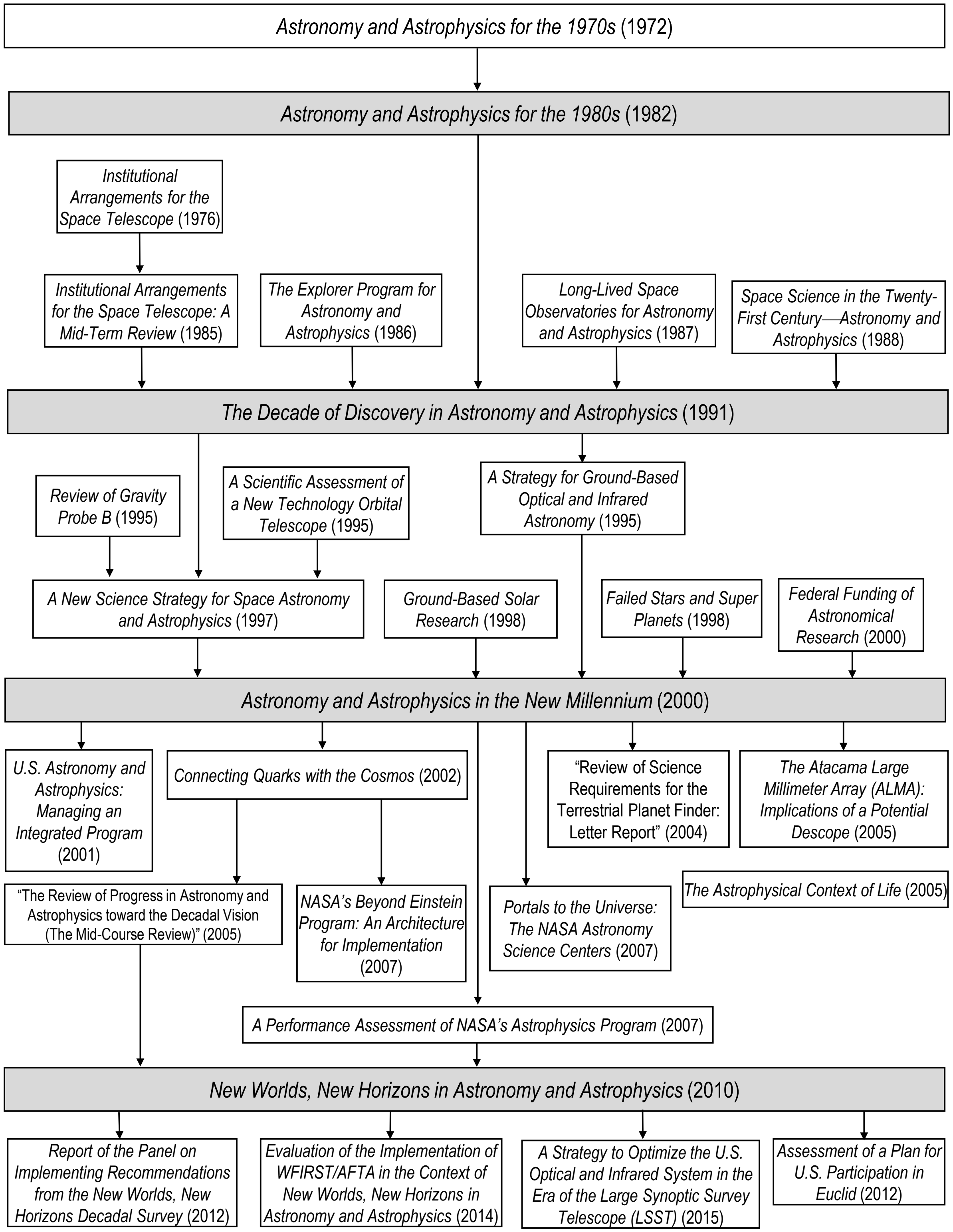

FIGURE 2.3 SSB advice associated with CAA—astronomy and astrophysics (1979-2015).

Membership

Paul L. Schechter,[7] Massachusetts Institute of Technology (co-chair)
Marcia Reike, University of Arizona (co-chair)
Steven M. Ritz,[8] University of California, Santa Cruz (co-chair)
Jeremiah K. Darling, University of Colorado, Boulder
Megan Donahue, Michigan State University
Joshua A. Frieman,[9] Fermi National Accelerator Laboratory and University of Chicago
Thomas Greene, NASA Ames Research Center
Lee W. Hartmann,[10] University of Michigan
Timothy M. Heckman,[11] Johns Hopkins University
Lynne Hillenbrand,[12] California Institute of Technology
Vassiliki Kalogera,[13] Northwestern University
Lisa Kaltenegger,[14] Cornell University
Bruce Macintosh,[15] Stanford University
Christopher F. McKee, University of California, Berkeley
Rene A. Ong, University of California, Los Angeles
Mark M. Phillips,[16] Carnegie Observatories
James M. Stone,[17] Princeton University
Alexey Vikhlinin,[18] Harvard-Smithsonian Center for Astrophysics
J. Craig Wheeler,[19] University of Texas, Austin
Eric M. Wilcots, University of Wisconsin, Madison
A. Thomas Young, Lockheed Martin Corporation (retired)

Staff

David B. Lang, Senior Program Officer, BPA
Katie Daud, Research Associate, SSB
Dionna Williams, Program Coordinator, SSB

COMMITTEE ON BIOLOGICAL AND PHYSICAL SCIENCES IN SPACE

The Committee on Biological and Physical Sciences in Space worked with NASA to select the related topics of Open Science and GeneLab Platform development as the focus of a 1-day symposium held on April 1, 2015, as part of the committee's scheduled March 31-April 2, 2015, meeting, held during the third annual NRC Space Science Week. The symposium brought together experts from a range of government, academic, and private database groups to discuss common development challenges. The discussion focused on challenges relevant to NASA Open Science approaches in general, and potential design input for NASA GeneLab in particular. Included in the symposium were two panels with 10 experts representing diverse database efforts and platforms in the very rapidly growing field of "omics" research. During the non-symposium portion of the meeting, the committee also heard a presentation on the role of the Center for the Advancement of Science in Space (CASIS) in supporting micrograv-

[7] Term ended in 2015.
[8] Became co-chair on September 22, 2015.
[9] Term ended in 2015.
[10] Became a member in September 2015.
[11] Term ended in 2015.
[12] Term ended in 2015.
[13] Became a member in September 2015.
[14] Became a member in September 2015.
[15] Became a member in February 2015.
[16] Became a member in September 2015.
[17] Became a member in October 2014.
[18] Became a member in October 2014.
[19] Term ended in 2015.

ity research on the ISS, and a status update on NASA's Space Life and Physical Sciences Research and Applications program. The committee also met in plenary with the other standing committees of the SSB on March 31.

CBPSS Co-Chair Robert Ferl and staffer Sandra Graham both attended the International Space Station R&D Conference on July 7-9 in Boston, Massachusetts, where Dr. Ferl participated as a panelist discussing the role of the ISS as a catalyst. In addition, committee member Jim Pawelczyk was invited to testify at a July 10 congressional hearing in front of the House Subcommittee on Space (Committee on Science, Space and Technology). The hearing focused on the challenges and rationales, including science, pertaining to an extension of the operational lifetime of the ISS. His testimony is reprinted in Chapter 6.

CBPSS held its fall meeting on October 27-29, 2015, in Irvine, California. The meeting was organized to explore both near-term challenges and opportunities in the microgravity research endeavor and long-term planning for the post-ISS period. At the meeting, CBPSS received a presentation on NASA's Space Life and Physical Sciences Research and Applications (SLPSRA) program status and issues from Marshall Porterfield, who also updated the committee on the status of GeneLab and Open Science. David Tomko (NASA) presented on space biology planning, and Steve Davison (NASA) discussed human research planning. Francis Chiaramonte (NASA) briefed CBPSS on physical sciences, and Nan Yu (JPL) presented on fundamental physics planning. The committee also heard briefings from Robyn Gatens (NASA) regarding commercial low Earth orbit (LEO) for research; Warren Bates (CASIS) on promoting LEO ecosystem development, and Ben Roberts (OSTP) for a discussion on commercial LEO and ISS follow-on issues. The committee also held a focused panel session on the potential of CubeSats for microgravity research, which included a presentation from Tony Ricco (NASA) and Wayne Nicholson (University of Florida). The panel session included discussions with A.C. Matin (Stanford University), John Hines (JH Technology Associates), Sharmila Bhattacharya (NASA Ames Research Center), and Andrew Pohorille (NASA). CBPSS also heard from Jeff Smith (NASA) on the potential for biological experiments on the Orion EM-1 mission. The open sessions concluded with parallel breakout discussion groups focused on needs, challenges, and long-term directions.

Throughout the year, co-chairs and/or staff remained abreast of discipline and policy developments by participating in meetings and conferences such as the American Society for Gravitational and Space Research on November 11-14, 2015, and SpaceCom on November 17-19. After consideration of the most rapidly developing programs and research areas, the committee added membership expertise in statistics and translational bioinformatics, the science of decision making, and fluid dynamics in low gravity by appointing Mohammed Kassemi, Marylyn D. Ritchie, and Pol D. Spanos. Also during this period, the committee was planning its meeting during NRC Space Science Week, which included a 1-day symposium on research in commercial LEO. CBPSS also discussed a midterm review of the decadal survey with NASA.

A historical summary of a selection of SSB advisory reports on space biology and medicine is presented in Figure 2.4, and a historical summary of a selection of SSB advisory reports on microgravity research is presented in Figure 2.5.

Membership

Elizabeth Cantwell, Arizona State University (co-chair)
Robert J. Ferl, University of Florida (co-chair)
Kenneth M. Baldwin, University of California, Irvine
Robert L. Byer, Stanford University
Ofodike A. Ezekoye, University of Texas, Austin
Mohammad Kassemi,[20] NASA Glenn Research Center
Ronald G. Larson, University of Michigan
Richard E. Lenski, Michigan State University
James A. Pawelczyk, Pennsylvania State University
Marylyn D. Ritchie,[21] Pennsylvania State University
Pol D. Spanos,[22] Rice University

[20] Became a member in October 2015.
[21] Became a member in October 2015.
[22] Became a member in October 2015.

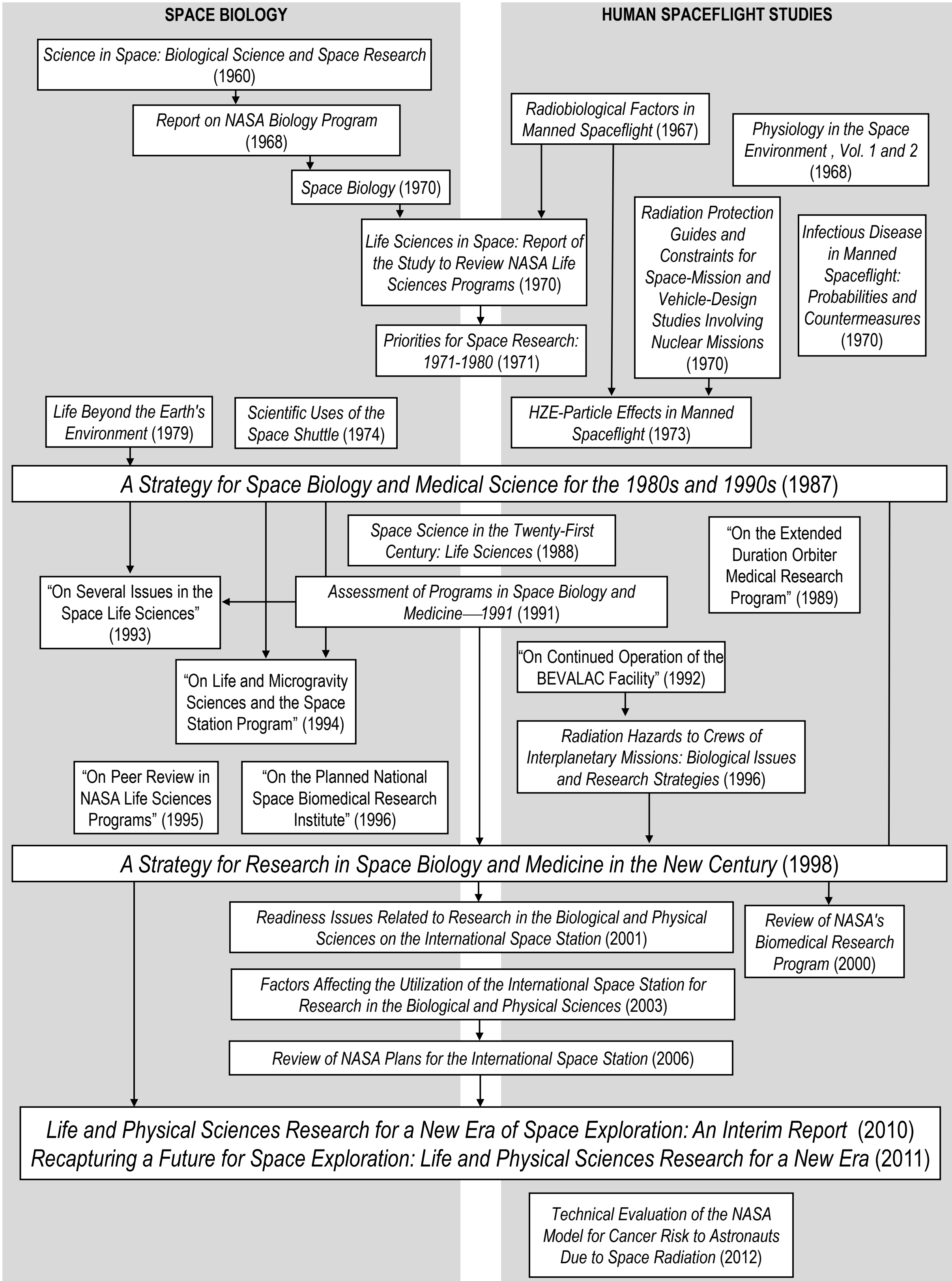

FIGURE 2.4 SSB advice associated with CBPSS—space biology and medicine (1960-2015).

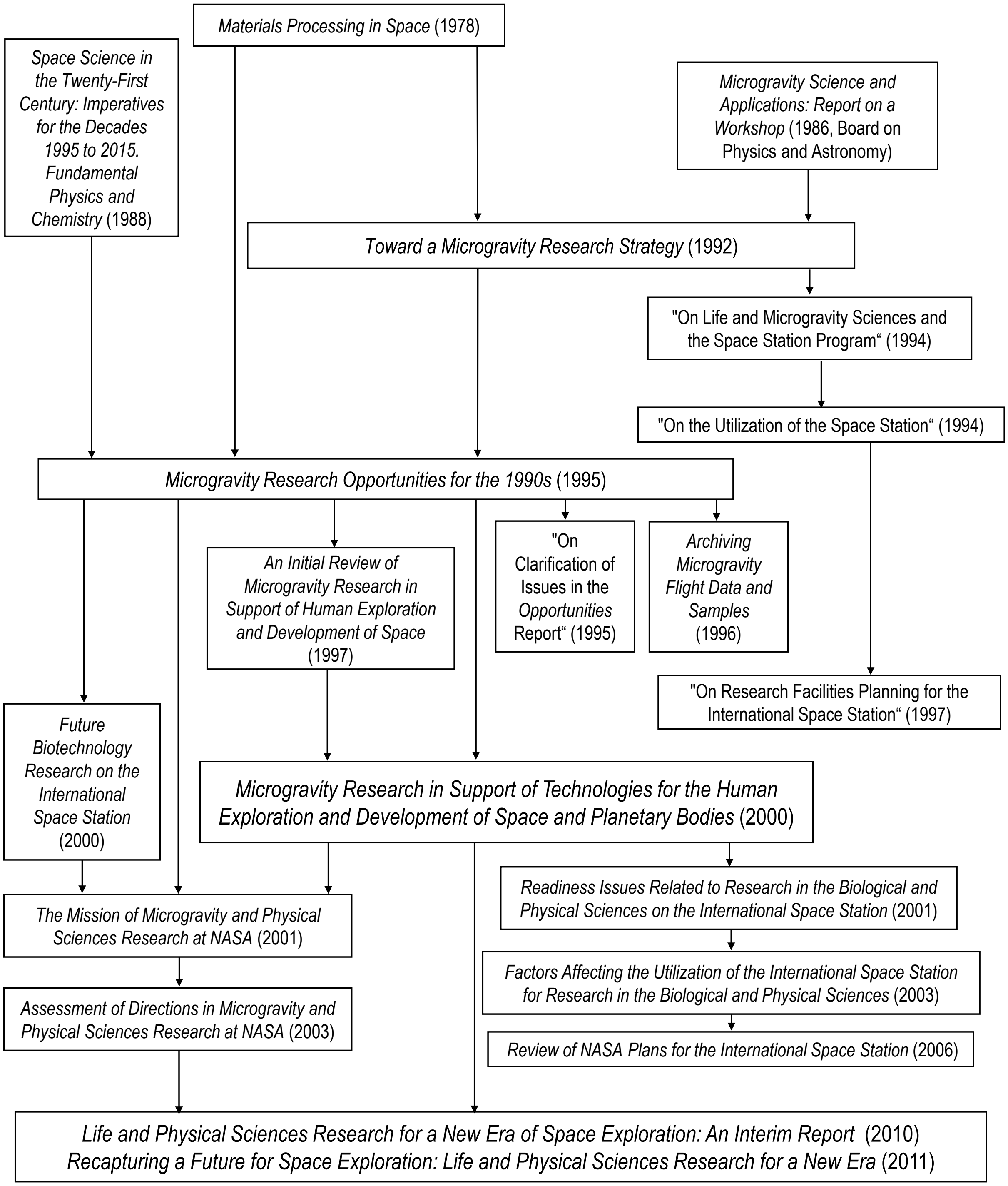

FIGURE 2.5 SSB advice associated with CBPSS—microgravity research (1978-2015).

Krystyn J. Van Vliet, Massachusetts Institute of Technology
Peter W. Voorhees, Northwestern University
Erika Wagner, Blue Origin, LLC
Eugenia Y.-H. Wang, University of Louisville

Staff

Sandra J. Graham, Senior Program Officer, SSB
Katie Daud, Research Associate, SSB
Dionna Williams, Program Coordinator, SSB

COMMITTEE ON EARTH SCIENCE AND APPLICATIONS FROM SPACE

The Committee on Earth Science and Applications from Space (http://sites.nationalacademies.org/SSB/SSB_066587) met on March 31-April 2, 2015, in Washington, D.C., as part of the third annual NRC Space Science Week. In addition to joint plenary sessions with the other SSB standing committees, CESAS received briefings from and held discussions with Jack Kaye (NASA) on current and planned activities within NASA's Earth Science Division (ESD); Paula Bontempi (NASA) on the Pre-Aerosol, Clouds, and ocean Ecosystem mission (PACE); Tom Burns (NOAA) on current and planned activities within NOAA NESDIS (National Environmental Satellite, Data, and Information Service); Sarah Ryker (U.S. Geological Survey [USGS]), on the Landsat program and plans for Landsat-9; Tim Stryker (OSTP) on the National Plan for Civil Earth Observations and thoughts on its use in the upcoming Earth science decadal survey; and Stacey Boland (JPL) on RapidScat, a low-cost instrument recently deployed on the ISS that is providing measurements of ocean vector winds.

The March meeting also had two roundtable discussions with a particular focus on planning for the second decadal survey in Earth science and applications from space ("ESAS 2017"). ESAS 2017 will generate consensus recommendations from the environmental monitoring and Earth science and applications community on an integrated and sustainable approach to the conduct of the U.S. government's civilian space-based Earth-system science programs. Planning for the survey was a major activity for CESAS throughout 2015; in particular, the committee and staff from the SSB had extensive discussions with other Earth Science-related units of the Academies (including the Board on Atmospheric Science and Climate, the Board on Earth Science and Resources, the Ocean Studies Board, the Polar Research Board, and the Water Science and Technology Board) and potential study sponsors on the survey's terms of reference. NASA, NOAA, and USGS reached consensus on the statement of task in April 2015; on May 6, 2015, the study was approved by the Governing Board of the Executive Committee of the Academies.

CESAS met virtually via WebEx on September 24-25 and received briefings from Michael Freilich (Director, NASA ESD); Ajay Mehta (Deputy Director, NOAA's Joint Polar Satellite System); and Tim Newman (Land Remote Sensing Program Coordinator, USGS), who briefed the committee on the OSTP-led, Second Earth Observation Assessment. The committee also continued its planning work for the decadal survey. Prior to initiation of the survey, CESAS requested community input on the questions that should drive space-based Earth observations in the decade defined roughly from 2017 to 2027. This request for information (RFI) did not seek input on candidate satellite missions or sensors; instead, it asked the community for their thoughts on the science questions and key challenges that should inform efforts to understand the Earth as a system (versus discipline-focused questions and challenges). It also asked if these questions and challenges differ from those that guided the inaugural decadal survey. The RFI generated more than 200 responses, which are posted on the survey's website (www.nas.edu/esas2017).

CESAS met on December 2-3 in Washington, D.C., where the committee heard from Dan St. Jean (NOAA) regarding NOAA NESDIS programs and activities and from Greg Snyder (USGS) who reviewed progress in the 2nd National Assessment for Civil Earth Observations. The committee also held sessions on the recently completed report *Continuity of NASA Earth Observations from Space: A Value Framework* (2015). Committee Chair Byron Tapley (University of Texas) and committee members Randy Friedl (JPL) and Bruce Wielicki (NASA LaRC) briefed the committee on the report, which was followed by a roundtable discussion on "Incorporating the Decision Framework in Decadal Survey and Agency." The committee also held a session on guidance for the upcoming decadal survey, based on the 2015 report *Space Science Decadal Surveys*, led by Stacey Boland (JPL), a member of the study committee as well as a member of CESAS. Finally, Thomas Zurbuchen (University of Michigan) provided the committee with an update on the ad hoc SSB study he is chairing, the Committee on Achieving Science Goals with CubeSats. In closed session, the committee reviewed progress in organizing ESAS 2017.

A historical summary of a selection of SSB advisory reports on Earth science and applications from space is presented in Figure 2.6.

Membership

Mark R. Abbott,[23] Oregon State University (co-chair)
Joyce E. Penner,[24] University of Michigan (co-chair)
Steven A. Ackerman, University of Wisconsin, Madison
Stacey W. Boland, Jet Propulsion Laboratory
Antonio J. Busalacchi, Jr., University of Maryland
Lennard A. Fisk, University of Michigan
Efi Foufoula-Georgiou, University of Minnesota, Twin Cities
Lee-Lueng Fu, Jet Propulsion Laboratory
Chelle L. Gentemann, Earth and Space Research, Seattle
Michael D. King, University of Colorado, Boulder
Molly K. Macauley, Resources for the Future
David L. Skole, Michigan State University
Steven C. Wofsy, Harvard University

Staff

Arthur A. Charo, Senior Program Officer, SSB
Charlie Harris, Research Associate, SSB (from September 28)
Andrea Rebholz,[25] Program Coordinator, ASEB

COMMITTEE ON SOLAR AND SPACE PHYSICS

The Committee on Solar and Space Physics met on March 31-April 2, 2015, at the National Academy of Sciences Building in Washington, D.C., during the third annual NRC Space Science Week. During the meeting, the committee received updates on programs at NASA HPD, NSF's Division of Atmospheric and Geospace Sciences (GEO/AGS), and NOAA's Space Weather Prediction Center (SWPC) from Jeffrey Newmark (Interim Director, HPD), Vladimir Papitashvili (Geospace Section Head, Acting, GEO/AGS), and Thomas Berger (Director, SWPC), respectively. The committee also heard about the ESSC and European activities in solar and space physics from Athena Coustenis (ESSC and Paris Observatory) and Nicholas Walter (ESF). In joint session with CAPS, the committee heard from Bruce Jakosky (University of Colorado) about results from the MAVEN mission at Mars and from Ji Wu (Chinese Academy of Sciences National Space Science Center) regarding China's activities in solar and space physics. The committee also received an update on the construction of the Daniel K. Inouye Solar Telescope from David Boboltz (NSF). The committee conducted a roundtable discussion about space weather that included the above mentioned representatives from NASA, NOAA, and NSF as well as a presentation on the national Space Weather Operations Research and Mitigation (SWORM) task force from William Murtagh (OSTP). Sarah Gibson (High Altitude Observatory [HAO]) led a discussion on the initiation of the DRIVE initiative that was recommended in the 2013 solar and space physics decadal survey. Len Fisk (University of Michigan) gave an update on the American Geophysical Union's Solar Physics and Aeronomy Section advocacy group, which was followed by a discussion of possible outreach activities for committee members and the community. Finally, the committee and representatives from the NASA HPD discussed accelerating the Solar Terrestrial Probes science program.

CSSP held its fall meeting October 14-15, 2015, in Washington, D.C. During the meeting, the committee

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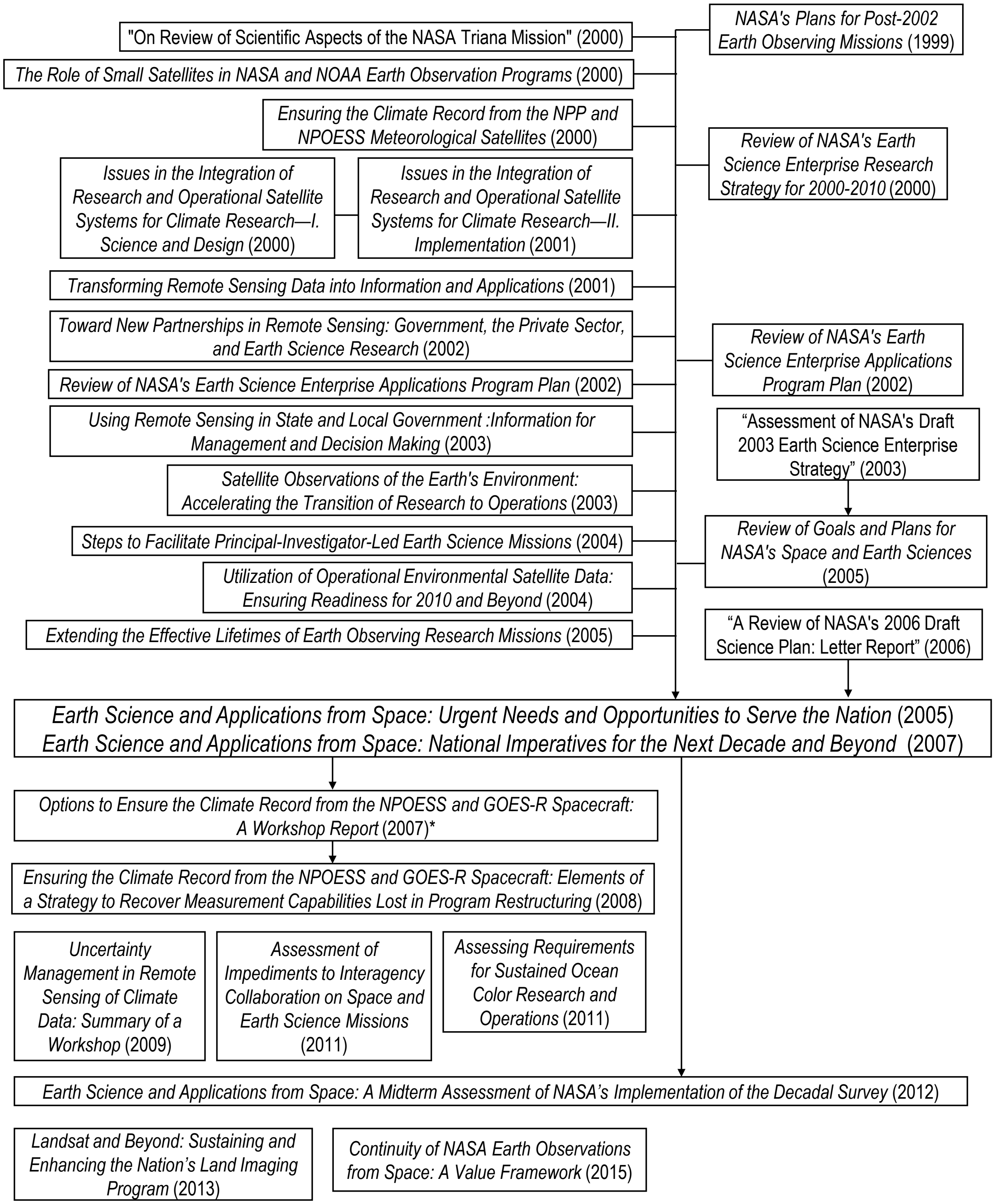
[23] Became a member as of September 2015.
[24] Became chair as of September 2015.
[25] Staff from other Boards who are shared with the SSB.



*The edited and final version of this Workshop Summary is also included as Appendix B in *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft (2008)*

FIGURE 2.6 SSB advice associated with CESAS—Earth science and applications from space (1979-2015).

received updates on programs at HPD, GEO/AGS, NSF Astronomical Sciences (AST), and SWPC from Steven Clarke (Director, HPD), Janet Kozyra (NSF), James Ulvestad (Director, AST), and Thomas Berger (Director, SWPC), respectively. The committee also heard briefings from Ralph Stoffler on Air Force Perspectives on Space Weather; William Lotko on the NSF Geospace Portfolio Review; and Todd Hoeksema on the Grants Success Rate study.

CSSP held discussions on the DRIVE initiative at NASA and NSF and on the pacing of new NASA Explorer missions. They also held discussions on the status of the space weather action plan implementation, heliophysics mission management and possibilities for the start of an IMAP-like mission, possible future study ideas for the SSB, and strategies for including solar and space physics in transition information for the incoming presidential administration. Robyn Millan (Dartmouth College) gave an overview of the BARREL (Balloon Array for RBSP Relativistic Electron Losses) mission and coordination with the Radiation Belt Storm Probes mission. CSSP also heard an update on the Achieving Science Goals with CubeSats study from its chair, Thomas Zurbuchen. The committee also met via teleconference on November 24, 2015, to discuss current events.

A historical summary of a selection of SSB advisory reports on space and solar physics is presented in Figure 2.7.

Membership

J. Todd Hoeksema, Stanford University (co-chair)
Mary K. Hudson, Dartmouth College (co-chair)
Timothy S. Bastian, National Radio Astronomy Observatory
Amitava Bhattacharjee, Princeton University
Stephen A. Fuselier, Southwest Research Institute
George M. Gloeckler, University of Maryland (emeritus)
Thomas J. Immel, University of California, Berkeley
Justin Kasper, University of Michigan
Louis J. Lanzerotti, New Jersey Institute of Technology
Judith L. Lean, Naval Research Laboratory
Elizabeth MacDonald, NASA Goddard Space Flight Center
Robyn Millan, Dartmouth College
Terrance G. Onsager, NOAA Space Weather Prediction Center
Aaron Ridley, University of Michigan
Nathan A. Schwadron, University of New Hampshire
Joshua Semeter, Boston University

Staff

Abigail Sheffer, Program Officer, SSB
Charlie Harris, Research Associate, SSB (from September 28)
Anesia Wilks, Senior Program Assistant, SSB

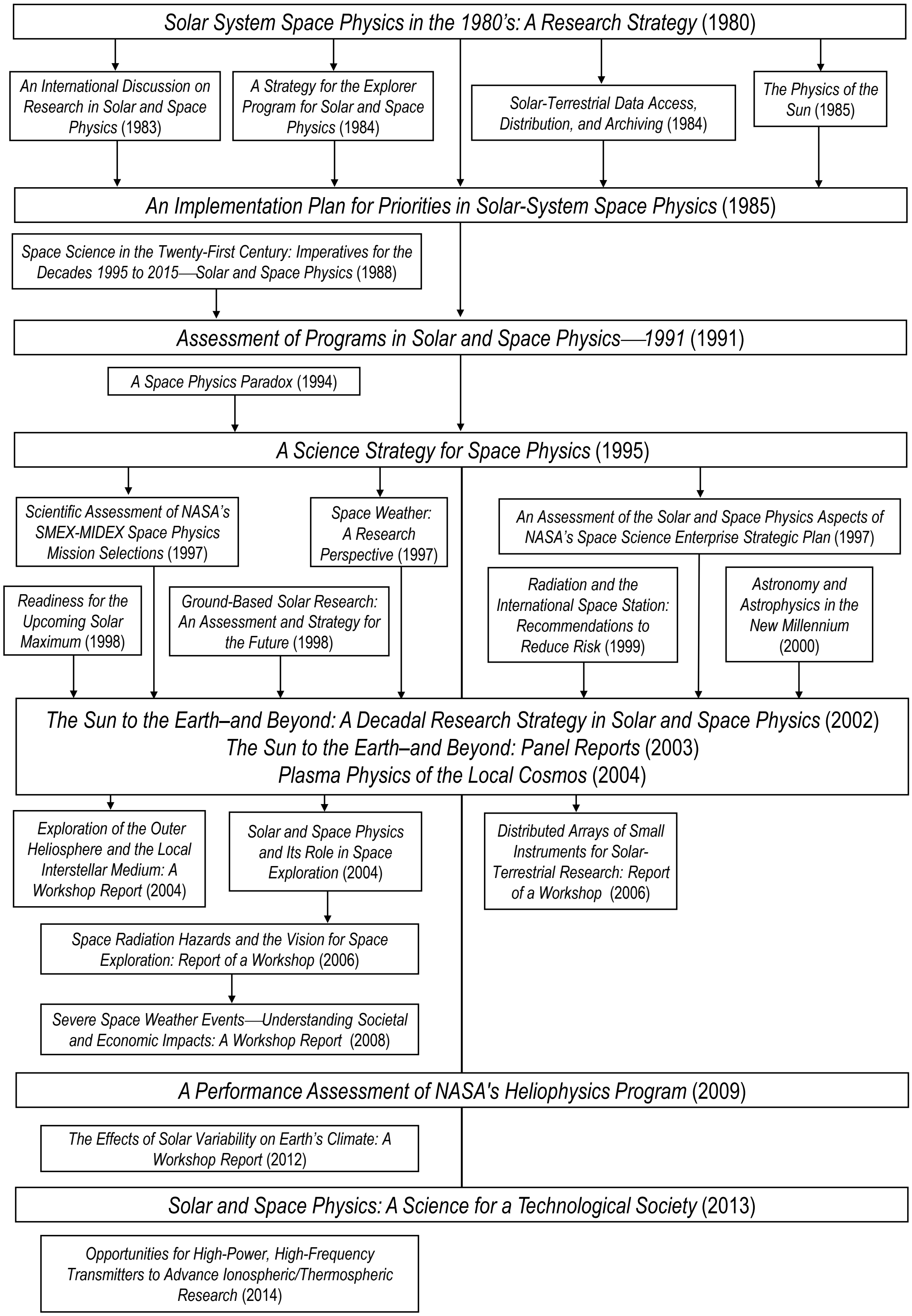


FIGURE 2.7 SSB advice associated with CSSP—solar and space physics (1980-2015).

3
Ad Hoc Study Committees: Activities and Membership

When a sponsor requests that the National Academies of Sciences, Engineering, and Medicine[1] conduct a study, an ad hoc committee is established for that purpose. The committee terminates when the study is completed. These study committees are subject to the Federal Advisory Committee Act, Section 15, because they provide advice and recommendations to the federal government. The Space Studies Board (SSB) and/or one of its standing committees provide oversight for ad hoc study committee activities. Eight ad hoc study committees were active during 2015; their activities and membership are summarized below. The SSB collaborated on two studies with the Board on Physics and Astronomy (BPA) and on one study with the following boards of the Division on Earth and Life Studies: the Board on Atmospheric Science and Climate, the Board on Earth Science and Resources, the Water Science and Technology Board, and the Ocean Studies Board.

The Review of NASA's Planetary Science Division's Restructured Research and Analysis Programs study was formally initiated toward the end of 2015. Recruitment of committee members will commence in 2016 and a report is scheduled to be delivered to NASA by December 2016.

ACHIEVING SCIENCE GOALS WITH CUBESATS

The ad hoc Committee on Achieving Science Goals with CubeSats had their first meeting on June 22-23, 2015, at the Keck Center in Washington, D.C. During the meeting, the committee received agency perspectives on CubeSats from NASA, the National Science Foundation (NSF), the Department of Defense (DOD), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey (USGS). The committee also received an update on space debris from the Secure World Foundation. The committee had their second meeting, which included a community symposium, on September 2-3, followed by a committee-only session on September 4 at the Arnold and Mabel Beckman Center of the National Academies of Sciences and Engineering in Irvine, California. The symposium began with keynote presentations on CubeSats and science return from David Korsmeyer (NASA Ames Research Center) and on technology trends from Richard Welle (Aerospace Corporation). The symposium continued with a series of keynote speakers and panel discussions. The first four sessions involved science areas: CubeSats in heliophysics, with a keynote by Harlan Spence (University of New Hampshire); CubeSats in planetary science, with a keynote by Julie Castillo-Rogez (Jet Propulsion Laboratory); CubeSats in astronomy and astrophysics, with a keynote by Kerri Cahoy (Massachusetts Institute of Technology); and CubeSats in Earth science, with a keynote by Antonio Busalacchi (University of Maryland). Additional panel discussions were held on technology for CubeSats, CubeSats for technology development, industry capabilities, and CubeSats in

[1] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council are used in an historical context identifying programs prior to July 1.

education. The symposium also included a poster session with more than 60 participants. The committee had its third committee meeting in closed session on October 22-23, in Washington, D.C., followed by a policy-focused meeting on October 30 in Washington, D.C. The meeting opened with perspectives on CubeSat policy issues from Thomas Kalil (Office of Science and Technology Policy). The committee then held a panel discussion regarding orbital debris and space situational awareness, with participation from Josef Koller (DOD); J.-C. Liou (NASA); Lt. Col. Scott Putnam (Joint Space Operations Center); Michael Romanowski (Federal Aviation Administration); Dan Oltrogge (Analytical Graphics, Inc.); and Brian Weeden (Secure World Foundation). In the afternoon, the committee held a panel discussion on spectrum, with participation from Kathryn Medley (Federal Communications Commission); Jonathan Williams (National Telecommunications and Information Administration); Brennan Price (American Radio Relay League); William Horne (NASA); and Therese Moretto Jorgensen (NSF). The final discussion of the day regarded ITAR (International Traffic in Arms Regulations) current issues presented by Kevin Schmadel and Martin Ruzek (Universities Space Research Association). The committee is currently writing its draft report, and the anticipated prepublication release date is May 2016.

Membership[2]

Thomas H. Zurbuchen,[3] University of Michigan (chair)
Bhavya Lal, IDA Science and Technology Policy Institute (vice chair)
Julie Castillo-Rogez,[4] California Institute of Technology
Andrew Clegg, Google, Inc.
Paulo Lozano, Massachusetts Institute of Technology
Malcolm Macdonald, University of Strathclyde
Robyn Millan, Dartmouth College
Charles D. Norton, California Institute of Technology
William H. Swartz, Johns Hopkins University
Alan Title, Lockheed Martin
Thomas Woods, University of Colorado
Edward L. Wright, University of California, Los Angeles
A. Thomas Young, Lockheed Martin (retired)

Staff

Abigail Sheffer, Program Officer, SSB
Katie Daud, Research Associate, SSB
Dionna Williams, Program Coordinator, SSB

CONTINUITY OF NASA-SUSTAINED REMOTE SENSING OBSERVATIONS OF THE EARTH FROM SPACE

NASA's Earth Science Division (ESD) conducts a wide range of satellite and suborbital missions to observe Earth's land surface and interior, biosphere, atmosphere, cryosphere, and oceans as part of a program to improve understanding of Earth as an integrated system. Earth observations provide the foundation for critical scientific advances, and environmental data products derived from these observations are used in resource management and for an extraordinary range of societal applications, including weather forecasts, climate projections, sea-level change, water management, disease early warning, agricultural production, and response to natural disasters.

As the complexity of societal infrastructure and its vulnerability to environmental disruption increases, the demands for deeper scientific insights and more actionable information continue to rise. To serve these demands, ESD is challenged with optimizing the partitioning of its finite resources among measurements intended for exploring new science frontiers, carefully characterizing long-term changes in the Earth system, and supporting ongoing societal applications. This challenge is most acute in the decisions the division makes between support-

[2] All terms began on May 14, 2015, unless otherwise noted.
[3] Term began March 10, 2015.
[4] Term began October 13, 2015.

ing measurement continuity of data streams that are critical components of Earth science research programs and in developing new measurement capabilities.

The current ESD decision-making process is primarily qualitative. Completing a study requested by NASA, the Committee on a Framework for Analyzing the Needs for Continuity of NASA-Sustained Remote Sensing Observations of the Earth from Space published the report *Continuity of NASA Earth Observations from Space: A Value Framework* in November 2015. The decision framework presented in this report provides a transparent and partially quantitative alternative that prioritizes the relative importance of different measurements based on their scientific value. The report identifies key evaluation factors and puts forward a decision-making framework that quantifies the need for measurement continuity and the consequences of measurement gaps for achieving long-term science goals. Following publication, Committee Chair Byron Tapley (University of Texas) briefed the report to NASA, NOAA, the Committee on Earth Science and Applications from Space, and the SSB. The report is available at http://www.nap.edu. The Summary of the report is reprinted in Chapter 5.

Membership[5]

Byron D. Tapley, University of Texas, Austin (chair)
Michael D. King, University of Colorado, Boulder (vice chair)
Mark R. Abbott, Oregon State University
Steven A. Ackerman, University of Wisconsin, Madison
John J. Bates, National Oceanic and Atmospheric Administration
Rafael L. Bras, Georgia Institute of Technology
Robert E. Dickinson, University of Texas, Austin
Randall R. Friedl, Jet Propulsion Laboratory
Lee-Lueng Fu, Jet Propulsion Laboratory
Chelle L. Gentemann, Remote Sensing Systems
Kathryn A. Kelly, University of Washington
Judith L. Lean, Naval Research Laboratory
Joyce E. Penner, University of Michigan
Michael J. Prather, University of California, Irvine
Eric J. Rignot, University of California, Irvine
William L. Smith, Hampton University
Compton J. Tucker, NASA Goddard Space Flight Center
Bruce A. Wielicki, NASA Langley Research Center

Staff

Arthur A. Charo, Senior Program Officer, SSB
Anesia Wilks, Senior Program Assistant, SSB
Katie Daud, Research Associate, SSB

DECADAL SURVEY FOR EARTH SCIENCE AND APPLICATIONS FROM SPACE

The 2017-2027 decadal survey for Earth science and applications from space (ESAS 2017) began in late 2015. Sponsored by NASA, NOAA, and USGS, the survey will produce a report by July 31, 2017, that will

1. Assess progress in addressing the major scientific and application challenges outlined in the 2007 survey;
2. Develop a prioritized list of top-level science and application objectives to guide space-based Earth observations over the survey interval;
3. Identify gaps and opportunities in the programs of record at NASA, NOAA, and USGS in pursuit of the top-level science and application challenges—including space-based opportunities that provide both sustained and experimental observations; and

[5] All terms ended on March 31, 2015.

4. Recommend—considering science priorities, implementation costs, new technologies and platforms, interagency partnerships, international partners, and in situ and other complementary programs—approaches to facilitate the development of a robust, resilient, and appropriately balanced U.S. program of Earth observations from space.

Like the 2007 inaugural decadal survey, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, ESAS 2017 will help shape science priorities and guide agency investments into the next decade. Detailed information about the survey and a calendar of upcoming events is available at http://www.nas.edu/esas2017. Notable events that occurred in 2015 included appointment of the Survey Steering Committee (http://sites.nationalacademies.org/DEPS/esas2017/DEPS_169444), receipt of more than 200 responses to the survey's request for information (RFI), the organization of a town hall on December 14, 2015, at the fall meeting of the American Geophysical Union (AGU), and planning for the first meeting of the steering committee on January 18-20, 2016, in Washington, D.C. Additional town halls were also planned at 96th annual meeting of the American Meteorological Society and the AGU Ocean Sciences meeting in January and February 2016, respectively. Presentations from these events will be posted on the survey's website. The survey steering committee is supported by several study panels (http://sites.nationalacademies.org/DEPS/esas2017/DEPS_170909) and cross-disciplinary working groups; in total, some 100 members of the community are expected to participate on one or more of the survey's committees.

Membership[6]

Waleed Abdalati, University of Colorado, Boulder (co-chair)
Antonio J. Busalacchi Jr., University of Maryland, College Park (co-chair)
Steven J. Battel, Battel Engineering, Inc.
Stacey Boland, Jet Propulsion Laboratory
Robert D. Braun, Georgia Institute of Technology
Shuyi S. Chen, University of Miami, Rosenstiel School of Marine and Atmospheric Sciences
William E. Dietrich, University of California, Berkeley
Scott C. Doney, Woods Hole Oceanographic Institution
Christopher B. Field, Carnegie Institution for Science
Helen A. Fricker, Scripps Institution of Oceanography
William B. Gail, Global Weather Corporation
Sarah T. Gille, Scripps Institution of Oceanography
Dennis L. Hartmann, University of Washington
Daniel J. Jacob, Harvard University
Anthony C. Janetos, Boston University
Everette Joseph, University of Albany, State University of New York
Molly K. Macauley, Resources for the Future
Joyce E. Penner, University of Michigan
Soroosh Sorooshian, University of California, Irvine
Graeme L. Stephens, Jet Propulsion Laboratory/California Institute of Technology
Byron D. Tapley, University of Texas, Austin
W. Stanley Wilson, National Oceanic and Atmospheric Administration

Staff

Arthur A. Charo, Senior Program Officer, SSB
Charlie Harris, Research Associate, SSB (from September 28)
Andrea Rebholz,[7] Program Coordinator, ASEB

[6] All terms began on December 1, 2015.
[7] Staff from other Boards who are shared with the SSB.

NASA SCIENCE MISSION EXTENSIONS: SCIENTIFIC VALUE, POLICIES, AND REVIEW PROCESS

The Committee on NASA Science Mission Extensions was formed in October 2015 and held a committee-only teleconference in December. The committee, co-chaired by Vicky Hamilton and Harvey Tananbaum, is to hold its first in-person meeting February 1-2, 2016, at the Keck Center in Washington, D.C., and a second meeting is scheduled for March 2-4, 2016, at the Beckman Center in Irvine, California. The committee will be looking at the process by which NASA conducts science mission extensions. Its report is tentatively scheduled for delivery to NASA in late summer 2016.

Membership[8]

Victoria E. Hamilton, Southwest Research Institute (co-chair)
Harvey D. Tananbaum, Smithsonian Astrophysical Observatory (co-chair)
Alice Bowman, John Hopkins University Applied Physics Laboratory
John R. Casani, Jet Propulsion Laboratory (retired)
James H. Clemmons, The Aerospace Corporation
Neil Gehrels, NASA Goddard Space Flight Center
Fiona A. Harrison, California Institute of Technology
Michael D. King, University of Colorado, Boulder
Margaret G. Kivelson, University of California, Los Angeles
Ramon E. Lopez, University of Texas, Arlington
Amy Mainzer, Jet Propulsion Laboratory
Alfred S. McEwen, University of Arizona
Deborah G. Vane, Jet Propulsion Laboratory

Staff

Dwayne Day, Senior Program Officer, ASEB
Katie Daud, Research Associate, SSB
Anesia Wilks, Senior Program Assistant, SSB

REVIEW OF MEPAG REPORT ON PLANETARY PROTECTION FOR MARS SPECIAL REGIONS

The Committee for the Review of the Mars Exploration Program Analysis Group (MEPAG) Report on Planetary Protection for Mars Special Regions, an ad hoc activity of the Academies and the European Science Foundation, held its second and final full meeting in Irvine, California, on February 12-13, 2015. The committee completed delivery of its report to NASA and the European Space Agency (ESA) in mid-September and presented its conclusions and recommendations at the COSPAR (Committee on Space Research) Planetary Protection Workshop held at the International Space Science Institute in Bern, Switzerland, on September 22-24. The committee completed its work and was dissolved at the end of December 2015. The final, printed version of the committee's report, *Review of the MEPAG Report on Mars Special Regions*, was released in late December 2015. The Executive Summary of the report is reprinted in Chapter 5. A paper derived from the committee's final report has been accepted for publication and is scheduled to appear in the February 2016 issue of *Astrobiology*.

Membership[9]

Petra Rettberg, German Aerospace Center, Cologne (chair)
Alexandre Anesio, University of Bristol, United Kingdom
Victor R. Baker, University of Arizona

[8] All terms began on October 28, 2015.
[9] All terms ended on November 30, 2015.

John A. Baross, University of Washington
Sherry L. Cady, Pacific Northwest National Laboratory
Christine M. Foreman, Montana State University
Ernst Hauber, German Aerospace Center, Berlin
Gian Gabriele Ori, Universita d'Annunzio, Pescara, Italy
David Pearce, Northumbria University, United Kingdom
Nilton O. Renno, University of Michigan
Gary Ruvkun, Massachusetts General Hospital
Birgit Sattler, University of Innsbruck, Austria
Mark P. Saunders, Independent Consultant
Dirk Wagner, German Research Center for Geosciences, Potsdam
Frances Westall, Centre National de la Recherche Scientifique, Orléans, France

Staff

David H. Smith, Senior Program Officer, SSB
Emmanouil Detsis, Science Officer, ESF
Andrea Rebholz,[10] Program Coordinator, ASEB

REVIEW OF PROGRESS TOWARD THE DECADAL SURVEY VISION IN NEW WORLDS, NEW HORIZONS IN ASTRONOMY AND ASTROPHYSICS

The ad hoc Committee for the Review of Progress Toward the Decadal Survey Vision in New Worlds, New Horizons in Astronomy and Astrophysics, chaired by Jacqueline Hewitt, Massachusetts Institute of Technology, held its first meeting on October 8-10, 2015, in Washington, D.C. The committee heard from the NASA Astrophysics Division (APD), the NSF Division of Astronomical Sciences (AST), the Department of Energy High Energy Physics (HEP) program, the Office of Science and Technology Policy, the Japan Aerospace Exploration Agency, ESA, and project teams from or representatives of the Wide-Field Infrared Survey Telescope, NSF Mid-Scale Innovations Program, U.S. Laser Interferometer Space Antenna project, and U.S. Athena project.

The committee held a science symposium during its second meeting on December 12-14 at the Beckman Center in Irvine, California. The committee heard an opening keynote address from Roger Blandford, who chaired the 2010 astronomy and astrophysics decadal survey (Astro2010). The symposium continued with a series of speakers and panel discussions, many of whom participated in the Astro2010 process. The sessions assessed what progress had been made on the high-priority science questions and discovery areas identified in the 2010 *New Worlds, New Horizons in Astronomy and Astrophysics* report. During the second day of the meeting, the committee heard talks from representatives of the Large Synoptic Survey Telescope (LSST), the Thirty Meter Telescope, the Giant Magellan Telescope, and the Cherenkov Telescope Array, as well as presentations from the European Consortium's eLISA mission and a community leader in exoplanet technology for direct imaging space-based missions. The symposium was webcast and has been made available for later viewing at https://vimeo.com/album/3742483.

The committee also held bi-weekly teleconferences, hearing from Daniel Eisenstein, Harvard University, on the Dark Energy Spectroscopic Instrument; Debra Elmegreen, Vassar College, on the 2015 National Research Council (NRC) report *Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System*; Randall Smith, Smithsonian Astrophysical Observatory, on IXO-Athena-preparations; Amber Miller, Columbia University, on cosmic microwave background polarization; Eric Smith, NASA, on the James Webb Space Telescope; and Terry Herter and Riccardo Giovanelli, Cornell University, on the CCAT telescope.

[10] Staff from other Boards who are shared with the SSB.

Membership[11]

Jacqueline N. Hewitt,[12] Massachusetts Institute of Technology (chair)
Adam S. Burrows, Princeton University
Neil J. Cornish, Montana State University
Andrew W. Howard, University Hawaii, Manoa
Bruce Macintosh, Stanford University
Richard F. Mushotzky, University of Maryland
Angela V. Olinto, University of Chicago
Steven M. Ritz, University of California, Santa Cruz
Alexey Vikhlinin, Harvard-Smithsonian Center for Astrophysics
David H. Weinberg, Ohio State University
Rainer Weiss, Massachusetts Institute of Technology
Eric M. Wilcots, University of Wisconsin
Edward L. Wright, University of California, Los Angeles
A. Thomas Young, Lockheed Martin Corporation (retired)

Staff

David Lang, Program Officer, BPA
Katie Daud, Research Associate, SSB
Dionna Williams, Program Coordinator, SSB

A STRATEGY TO OPTIMIZE THE U.S. OPTICAL/INFRARED SYSTEM IN THE ERA OF THE LARGE SYNOPTIC SURVEY TELESCOPE

With funding from NSF, the NRC conducted a study that recommends a strategy to optimize the U.S. ground-based optical and infrared astronomy observatory system in preparation for the full operation of the LSST. The BPA-SSB ad hoc Committee on a Strategy to Optimize the U.S. Optical and Infrared System in the Era of LSST, appointed in July 2014, held three meetings in 2014. The committee's report, *Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System*, entered the review process in early February 2015, and the report was released on April 17, 2015. The committee chair briefed interested government parties in conjunction with the release of the report. The Executive Summary of the report is reprinted in Chapter 5.

Membership[13]

Debra M. Elmegreen, Vassar College (chair)
Todd A. Boroson, Las Cumbres Observatory Global Telescope Network
Debra Fischer, Yale University
Joshua A. Frieman, Fermi National Accelerator Laboratory
Lynne Hillenbrand, California Institute of Technology
Buell T. Jannuzi, University of Arizona
Robert P. Kirshner, Harvard-Smithsonian Center for Astrophysics
Lori M. Lubin, University of California, Davis
Robert Lupton, Princeton University
Paul L. Schechter, Massachusetts Institute of Technology
Paul Adrian Vanden Bout, National Radio Astronomy Observatory
J. Craig Wheeler, University of Texas, Austin

[11] All terms began on August 12, 2015, unless otherwise noted.
[12] Term began on June 10, 2015.
[13] All terms ended on May 1, 2015.

Consultant to the Committee

Joel Parriott, American Astronomical Society

Staff

David B. Lang, Senior Program Officer, BPA
Katie Daud, Research Associate, SSB
Linda Walker, Program Coordinator, BPA
Beth Dolan, Financial Manager, BPA

SURVEY OF SURVEYS: LESSONS LEARNED FROM THE DECADAL SURVEY PROCESS

The ad hoc Committee on Survey of Surveys: Lessons Learned from the Decadal Survey Process completed a draft of its report in February 2015, and it was sent to 12 reviewers for comment in early March. The committee completed its responses to reviewer comments in late May, and the report was approved for release on June 15. The committee released its final report, *The Space Science Decadal Surveys: Lessons Learned and Best Practices,* as a prepublication on July 29, and the final printed version was delivered in late October. The Summary of the report is reprinted in Chapter 5.

Membership[14]

Alan Dressler, Observatories of the Carnegie Institution for Science (chair)
Daniel N. Baker, University of Colorado, Boulder
David A. Bearden, Aerospace Corporation
Roger D. Blandford, Stanford University
Stacey Boland, Jet Propulsion Laboratory
Wendy M. Calvin, University of Nevada, Reno
Athena Coustenis, Centre National de la Recherche Scientifique, France
J. Todd Hoeksema, Stanford University
Anthony C. Janetos, Boston University
Stephen Mackwell, Lunar and Planetary Institute
J. Douglas McCuistion, X-energy, LLC
Norman H. Sleep, Stanford University
Charles E. Woodward, University of Minnesota, Minneapolis
A. Thomas Young, Lockheed Martin Corporation (retired)

Staff

David H. Smith, Senior Program Officer, SSB
Katie Daud, Research Associate, SSB
Dionna Williams, Program Coordinator, SSB

[14] All terms ended on June 30, 2015.

4
Workshops, Symposia, Meetings of Experts, and Other Special Projects

In 2015, the Space Studies Board (SSB) held one forum and one meeting of experts. These activities do not result in the provision of advice and, therefore, are not governed by the Federal Advisory Committee Act, Section 15.

CHINESE ACADEMY OF SCIENCES-NATIONAL ACADEMY OF SCIENCES FORUM FOR NEW LEADERS IN SPACE SCIENCE

The SSB continued its engagement with space scientists affiliated with the National Space Science Center (NSSC) of the Chinese Academy of Sciences (CAS) and other Chinese institutions by holding a “Forum for New Leaders in Space Science.” The forum series is designed to provide opportunities for a highly select group of young space scientists from China and the United States to discuss their research activities in an intimate and collegial environment at meetings held in China and the United States.

The goals of the forum are threefold:

1. To identify and highlight the research achievements of the best and brightest young scientists currently working at the frontiers of their respective disciplines;
2. To build informal bridges between the space-science communities in China and the United States; and
3. To enhance the diffusion of insights gained from participation in the forums to the larger space-science communities in China and the United States.

Following the successful completion of the first forum in Beijing and Irvine, California, in May and November of 2014, respectively, planning for the second forum began. The first session of the second forum took place in Shanghai, China, on October 9-10, 2015, and the second session will be held in Irvine, California, on May 16-17, 2016. Funding has been sought from the Academies Presidents’ Committee to continue the forums in 2016-2017.

New Leaders in Space Science—2015

Michael Busch, SETI Institute
Abigail Fraeman, California Institute of Technology
Rebecca Greenberger, Jet Propulsion Laboratory
Wenbiao Han, Shanghai Astronomical Observatory, Chinese Academy of Sciences
Jun Huang, China University of Geosciences, China
Edwin Kite, University of Chicago

Han Li, National Astronomical Observatories, Chinese Academy of Sciences
Hao Liu, National Space Science Center, Chinese Academy of Sciences
Orenthal J. Tucker, University of Michigan
Meng Su, Massachusetts Institute of Technology
Ying Sun, University of Texas
Xiaobin Yin, National Space Science Center, Chinese Academy of Sciences
Qingjiang Bai, National Space Science Center, Chinese Academy of Sciences
Yurong Cui, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences
Tingting Song, National Space Science Center, Chinese Academy of Sciences
Tailai Zhu, Shanghai Branch, Chinese Academy of Sciences

Senior Participants and Members of Selection Committee

Philip Christensen, Arizona State University
Byron Tapley, University of Texas
Feng Tian, Tsingua University, China
Jiancheng Shi, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences
Ji Wu, National Space Science Center, Chinese Academy of Sciences

Staff

David Smith, Senior Program Officer, SSB
Anesia Wilks, Senior Program Assistant, SSB

SHARING THE ADVENTURE WITH THE STUDENT: EXPLORING THE INTERSECTIONS OF NASA SPACE SCIENCE AND EDUCATION: A WORKSHOP

The SSB and the Board on Science Education released a workshop summary in June 2015 entitled *Sharing the Adventure with the Student: Exploring the Intersections of NASA Space Science and Education: A Workshop Summary*. The workshop itself took place on December 2-3, 2014, at the National Academy of Sciences Building in Washington, D.C., and focused on the contribution of NASA's Science Mission Directorate to K-12 science education. The workshop served as a venue for dialog between space and Earth scientists, engineers, education specialists ranging from high school principals to education researchers and state STEM (science, technology, engineering, and mathematics) education leaders, professional development providers, and informal science education institutions, among others. The Introduction and Background of the summary is reprinted in Chapter 5.

Planning Committee Membership[1]

Philip R. Christensen, Arizona State University (co-chair)
Brett D. Moulding, Utah Partnership for Effective Science Teaching and Learning (co-chair)
Albert Byers, National Science Teachers Association
Heidi B. Hammel, Association of Universities for Research in Astronomy
Wesley L. Harris, Massachusetts Institute of Technology
Charles F. Kennel, Scripps Institution of Oceanography
James Manning, Independent Consultant
Richard A. McCray, University of California, Berkeley
Mitchell Nathan, University of Wisconsin, Madison
Patricia H. Reiff, Rice University
Theresa Schwerin, Institute for Global Environmental Strategies

[1] All terms expired on June 30, 2015.

Staff

Abigail Sheffer, Program Officer, SSB
Katie Daud, Research Associate, SSB
Anesia Wilks, Senior Program Assistant, SSB

Heidi A. Schweingruber, Director, Board on Science Education
Michael A. Feder, Senior Program Officer, Board on Science Education

TERRESTRIAL ORGANIC CONTAMINATION REQUIREMENTS ASSOCIATED WITH MARS SAMPLE CACHING AND RETURN FOR PLANETARY PROTECTION: A MEETING OF EXPERTS

As a result of a request from NASA's planetary protection officer in 2014, SSB's staff organized a series of meetings of selected experts and government officials to provide the former with a candid critique of the findings relating to the contamination of martian samples by terrestrial organic materials contained in an interim report prepared by the Mars 2020 Organic Contamination Panel (OCP). The OCP was established by NASA's Mars Program Office to assess the potential contamination of samples collected on Mars with organic material inadvertently introduced into the martian environment by the Mars 2020 rover mission. The first such meeting was held at the Beckman Center in Irvine, California, on May 28-29, 2014, and the second was held at the J. Erik Jonsson Conference Center of the National Academy of Sciences in Woods Hole, Massachusetts, on May 11-13, 2015. In both meetings, the members of the SSB-convened group were acting in their own capacities as experts in relevant scientific and technical disciplines, and no NRC-endorsed product resulted from either meeting. A continuation of the meetings in 2016 is not anticipated at this time.

Staff

David Smith, Senior Program Officer, SSB
Carmela J. Chamberlain, Administrative Coordinator, SSB

5
Summaries of Major Reports

This chapter reprints the summaries of Space Studies Board (SSB) reports that were released in 2015. Reports are often written in conjunction with other boards and divisions, as noted, including the Aeronautics and Space Engineering Board (ASEB) and the Board on Physics and Astronomy (BPA).

5.1 Continuity of NASA Earth Observations from Space: A Value Framework

SSB ad hoc Committee on a Framework for Analyzing the Needs for Continuity of NASA-Sustained Remote Sensing Observations of the Earth from Space

Summary

NASA's Earth Science Division (ESD) conducts a wide range of satellite and suborbital missions to observe Earth's land surface and interior, biosphere, atmosphere, cryosphere, and oceans as part of a program to improve understanding of Earth as an integrated system. Earth observations provide the foundation for critical scientific advances, and environmental data products derived from these observations are used in resource management and for an extraordinary range of societal applications, including weather forecasts, climate projections, sea level change, water management, disease early warning, agricultural production, and the response to natural disasters.

As the complexity of societal infrastructure and its vulnerability to environmental disruption increases, the demands for deeper scientific insights and more actionable information continue to rise. To serve these demands, NASA's ESD is challenged with optimizing the partitioning of its finite resources among measurements intended for exploring new science frontiers, carefully characterizing long-term changes in the Earth system, and supporting ongoing societal applications. This challenge is most acute in the decisions the division makes between supporting measurement continuity of data streams that are critical components of Earth science research programs (including, but not limited, to climate-related measurements) and the development of new measurement capabilities.

While the distinction between measurements oriented toward "research" and "applications" is somewhat artificial (both types of measurements are typically needed in support of a particular societal application, and both research and application objectives may require continuous or sustained measurements), their requirements are not consistent. In particular, while many applications are associated with a requirement for near real-time data availability, climate change science objectives typically require accurate measurements and long, stable, uninterrupted time-series. Further, within the class of measurements with a science/research focus, the need for new measurements to enable Earth System process studies contrasts with the need to continue well-understood measurements related to key climate change indicators.

Community guidance to NASA ESD from the first National Research Council (NRC)[1] Earth science and applications from space decadal survey (NRC, 2007) largely focused on new measurements, owing to assumptions made about the role of other agencies in supporting high-priority climate, weather, and land surface continuity measurements. However, for a variety of reasons, including technical and budgetary challenges, some of these assumptions were not met (NRC, 2012). In response to these changes, as well as to guidance from the Administration and Congress, NASA's Earth science portfolio has expanded to include new responsibilities for the continuation of several previously initiated measurements that were formerly assigned to other agencies.

As decadal survey recommendations are executed and new capabilities and applications are demonstrated, NASA anticipates an increasing number of measurements and associated instruments and missions will be candidates for follow-ons. The agency's request for the present study (the statement of task is reprinted in Appendix A) recognizes this trend and the importance of establishing a more quantitative understanding of the need for measurement continuity and the consequences of measurement gaps. In addition to requesting a working definition of "continuity," the task statement asks that a decision framework be provided to help optimize the allocation of resources.

This report, from the Committee on a Framework for Analyzing the Needs for Continuity of NASA-Sustained Remote Sensing Observations of the Earth from Space, is the response to these requests. As detailed in the report, the committee recommends to NASA a decision-making framework, based on key continuity characteristics, that

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NOTE: "Summary" reprinted from *Continuity of NASA Earth Observations from Space: A Value Framework,* The National Academies Press, Washington, D.C., 2015, pp. 1-5.

[1] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council are used in an historic context identifying programs prior to July 1.

effectively discriminates between competing continuity measurements. The recommended framework carries a strong emphasis on quantitative evaluation methods in order to achieve process objectivity and transparency.

In developing a readily implementable framework, the committee focused on climate change science goals where space-based continuity measurements are expected to make substantial contributions. With this specific focus, the recommended framework is intended as a new method for evaluating science-driven continuity missions and represents a complement to the existing NASA proposal evaluation processes for NASA Research Announcements and Earth Venture Announcements of Opportunity.

This framework should be viewed as an initial step toward a more comprehensive methodology. As discussed in the report, modifications to the framework would allow it to be used to establish priorities among new, first-of-a-kind measurements, as well as to examine operational- or applications-based measurements. Developed appropriately, the committee envisions a single comprehensive evaluation approach for both new and continuity measurements, driven by science and/or application objectives.

ELEMENTS OF THE COMMITTEE'S DECISION FRAMEWORK

The committee's approach in developing the desired decision-framework begins with a clear definition of measurement continuity in time and space. Ensuring continuity of a geophysical variable[2] from a sequence of "improved" instruments, or from copies of the same instrument, requires a careful program of calibration, instrument characterization and comparison, and validation. While the vantage point of space facilitates global and repeatable observations of Earth, the development of long-term measurement time-series having small, combined standard uncertainties on multiple spatial scales is particularly challenging. In operational programs, copies of instruments have been flown multiple times with the goal of simplifying this process. Although copies do not eliminate the need for calibration and characterization studies, such an approach—including carefully chosen group procurements of instruments or spacecraft—will reduce costs and typically reduces the risk in providing a long-term continuous record.

The *quality* of a measurement is particularly relevant in the context of continuity and is characterized primarily by its combined standard uncertainty, which is the consequence of instrument calibration uncertainty, repeatability; time and space sampling; and data systems and delivery for climate variables (algorithms, reprocessing, and availability)—each of which depends on the scientific objective. Changes in platform observing characteristics (for example, altitude and local observing time) introduce perturbations into the entire system. Development of calibration methods through mission overlaps, in situ validation, and ground-based calibration traceable to National Institute of Standards and Technology standards are necessary to provide repeatable long-term measurements of geophysical variables.

With this in mind, the committee finds that the following is a sufficient, high-level definition of continuity across the Earth science subdisciplines for use in an analysis framework focused on scientific objectives:

Finding: Continuity of an Earth measurement exists when the quality of the measurement for a specific quantified Earth science objective is maintained over the required temporal and spatial domain set by the objective.

The notion of a quantified objective is the starting point for the committee's recommended decision framework. The characteristics of a well-formulated quantified objective are the following:

- It is directly relevant to achieving an overarching science goal of NASA ESD;
- It is presented in such a way that the required measurement(s) and their resolution (spatial, temporal, and radiometric), calibration uncertainty and repeatability, and other requirements have traceability to the overarching science goal; and
- It is expressed in a way that allows an analytical assessment of the importance of the objective to an Earth science goal and the utility of the targeted geophysical variable(s) for meeting the science objective.

Chapter 3 presents several examples of quantified objectives.

[2] See Box 2.1 for the committee's definition of geophysical variable and several other terms used in this report.

Recommendation: Proposed space-based continuity measurements should be evaluated in the context of the quantified Earth science objectives they address.

The committee envisions NASA ESD establishing a small set of quantified objectives from the same sources that inform the development of its program plan, notably the scientific community's consensus priorities expressed in NRC decadal surveys and guidance from the executive and congressional branches. Congressionally mandated midterm assessments of the decadal survey afford an additional opportunity for community evaluation of the objectives. Continuity of an established data set will compete with proposed new measurements as well as multi-measurement "intensives," campaigns that may be mounted to, for example, gain a detailed understanding of a particular climate process. The latter proposals should be defined through a quantified objective that could then be evaluated via the committee's proposed framework or whatever similar quantitative, open, and objective evaluation ESD establishes for continuity measurements.

Recommendation: NASA, which is anticipated to be a principal sponsor of the next decadal survey in Earth science and applications from space, might task the decadal survey with the identification, and possible prioritization, of the quantified Earth science objectives associated with the recommended science goals.

In addition to their research-oriented objectives, Earth observations and their derived information products support numerous user communities within and outside of the government. Extension of the committee's decision framework to measurements focused on societal-benefit applications is desirable but will require expertise outside of the Earth science community to formulate analogous quantified objectives in Earth applications. Toward this end, the committee makes the following recommendation:

Recommendation: NASA should initiate studies to identify and assess quantified Earth applications objectives related to high-priority, societal-benefit areas.

Based on lessons from cost-benefit analysis and decision theory, the committee found that a value-centered framework is capable of effectively distinguishing among the relevant Earth measurements; implemented appropriately, it will achieve an improved degree of openness and transparency. The value-centered approach recommended in this report includes both measurement benefit and affordability considerations. The study identified a relatively small set of characteristics that enable a tractable evaluation of benefit, which along with affordability allow discrimination in value among competing measurement/quantified objective pairs.[3] They are:

1. The scientific *importance* (*I*) of the quantified objective;
2. The *utility* (*U*) of a geophysical variable record for achieving a quantified objective;
3. The *quality* (*Q*) of a measurement for providing the desired geophysical variable record; and
4. The *success probability* (*S*) of achieving the measurement and its associated geophysical variable record.
5. The *affordability* (*A*) of providing the measurement and its geophysical variable record.

Additional cross-cutting factors are recognized to impact both benefit and affordability, and methods to treat them appropriately within the framework are discussed in the report. Examples of cross-cutting factors include the ability to leverage other measurement opportunities in pursuit of the science objective and the resilience of a geophysical variable record to unexpected degradation (or gaps) in the measurement quality.

[3] The committee debated at length regarding the choice of framework characteristics; the object was to derive a minimal set of largely independent characteristics (metrics) that would provide meaningful evaluations of proposed continuity measurements. That the factors are not completely independent in a statistical sense is recognized. For example, success probability (*S*) and affordability (*A*) are not completely independent; however, the relationship between them is sufficiently complex that it was necessary to retain both in the framework. As an example: NASA's ability to "buy down" risk (i.e., increase *S* by decreasing *A*) is not easily quantified for complex technologies; similarly, accounting for the strategic plans of other national and international partners—a difficult problem—is easier to handle in a framework with separate success and affordability factors. Accordingly, the committee elected to retain both the success probability and affordability characteristics. By retaining success probability, the treatment of uncertainty in the decision process is more readily achieved.

As discussed in the report, the committee finds that the quality metric plays a decisive role in determining when a measurement should be collected for durations longer than the typical lifetimes of single satellite missions. The most critical factor is whether (or not) the combined standard uncertainty of the measurement is sufficient for addressing the quantified objective. A related factor is the impact of a data gap (see Section 3.4.2 in Chapter 3), which itself depends on the measurements calibration uncertainty (i.e., traceability to an absolute scale) as well as on the natural variability of the measurand over the gap's duration. While there are numerous ways to evaluate quality in the context of continuity measurements, a useful quality metric is expected to vary between continuity required for short-term operational use (e.g., weather prediction, hazard warnings, agricultural crop monitoring) versus longer-term science objectives, such as those related to global climate change.[4] Examples for assessing quality are given in Chapter 4.

Finding: Assessing the quality of a particular continuity measurement requires knowledge of a measurement's combined standard uncertainty, which is derived from the instrument calibration uncertainty, repeatability, time and space sampling, and data systems and delivery of climate variables (algorithms, reprocessing, and availability), and the consequences of data gaps on the relevant quantified science objective(s).

Recommendation: The committee recommends that NASA be responsible for refining the assessment approach for the quality characteristic.

Evaluation of a measurement's affordability and benefit for decision-making purposes can likely be accomplished through a number of equally valid methods, some of which are examined in this report. Regardless of the evaluation methods that NASA and the community adopt, the application of those methods should make consistent use of well-documented and understood tools and studies, as highlighted in the following recommendations.

Recommendation: NASA should foster a consistent methodology to evaluate the utility of geophysical variables for achieving quantified Earth science objectives. The committee notes that such a methodology could also be utilized by the Earth science decadal survey in its priority recommendations.

Recommendation: NASA should extend their current mission cost tools to address continuity measurement-related costs needed for the decision framework.

The ability of ESD officials to make informed decisions requires unbiased and consistent information on benefits and affordability that is re-evaluated regularly and presented on a time frame appropriate for NASA planning. The committee advises that inputs to these evaluations be derived from sources such as submitted proposals and face-to-face interactions with measurement advocates.

Recommendation: NASA's Earth Science Division should establish a regular process for critical evaluation and modification of quantified objectives in Earth science and applications and their associated measurements. The committee suggests creating an analog to the senior review of current satellite operations, which uses senior researchers from a range of communities and results in consistent recommendations to the ESD director.

In summary, the committee offers the following recommendation:

Recommendation: NASA should establish a value-based decision approach that includes clear evalu-

[4] The committee notes that the quality requirements for measurements related to climate change objectives will often be most stringent at a global scale and less stringent at zonal or regional scales. (Antarctic ozone, regional aerosol change, and polar ice sheets are exceptions where regional anthropogenic signals can be detected before global average signals.) Instrument accuracy and repeatability will, therefore, often be driven by global average analysis as in many of the examples in this report. However, the committee's analysis framework can be used at any spatial scale required by the quantified objective.

ation methods for the recommended framework characteristics and well-defined summary methods leading to a value assessment.

REFERENCES

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

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5.2 Sharing the Adventure with the Student: Exploring the Intersections of NASA Space Science and Education: A Workshop Summary

Dwayne Day, Rapporteur

Introduction and Background

On December 2-3, 2014, the Space Studies Board and the Board on Science Education of the National Research Council (NRC) held a workshop on the NASA Science Mission Directorate (SMD) education program—"Sharing the Adventure with the Student." The discussion of NASA SMD's education efforts is particularly timely because of recent changes in K-12 science education policy and practices and a proposed reorganization of all of NASA SMD's science, technology, engineering, and mathematics (STEM) education efforts.

"Sharing the Adventure with the Student: Exploring the Intersections of NASA Space Science and Education—A Workshop" was organized by an ad hoc committee under the auspices of members from the Space Studies Board, serving as representatives of the space science community; the Board on Science Education, serving as representatives of experts in the creation and evaluation of STEM education efforts; as well as other experts. The workshop brought together these respective communities to promote a new dialog with the aim of increasing mutual understanding of how best to translate space science into useful educational materials and experiences.

This workshop summary has been prepared by the workshop rapporteur as a factual summary of what occurred at the workshop. The planning committee's role was limited to planning and convening the workshop. The views contained in the report are those of individual workshop participants and do not necessarily represent the views of the workshop participants as a whole, the planning committee, or the NRC.

This is the second in a series of workshops on NASA science communication and education. Previously, on November 8-10, 2010, the Space Studies Board held a public workshop, "Sharing the Adventure with the Public,"[1] that brought together scientists and professional communicators to discuss how NASA and its associated science and exploration communities can be more effective in communicating with the public.[2] The 2010 workshop participants discussed examples of where communication with the public has been challenging—such as for climate change—and where communication can be used more effectively to increase public support for space science. Science journalists offered tips for improving scientists' communication—such as becoming more active on social media sites. The gathering together of these communities in itself helped to improve communication in science, with all groups leaving the workshop with a better understanding of each other.

THE BACKGROUND OF NASA EDUCATION EFFORTS

The National Aeronautics and Space Act of 1958, which created NASA, directed that the agency should pursue several goals. Among these are the following:

- The expansion of human knowledge of Earth and of phenomena in the atmosphere and space; and
- The preservation of the role of the United States as a leader in aeronautical and space science and technology and in the application thereof to the conduct of peaceful activities within and outside the atmosphere.

NOTE: "Introduction and Background" reprinted from *Sharing the Adventure with the Student: Exploring the Intersections of NASA Space Science and Education: A Workshop Summary,* The National Academies Press, Washington, D.C., 2015, pp. 1-4.

[1] National Research Council, *Sharing the Adventure with the Public: The Value and Excitement of "Grand Questions" of Space Science and Exploration: Summary of a Workshop*, The National Academies Press, Washington, D.C., 2011.

[2] More information and video recordings of Sharing the Adventure with the Public: The Value and Excitement of "Grand Questions" of Space Science and Exploration are available at http://sites.nationalacademies.org/SSB/CompletedProjects/SSB_065881.

NASA has interpreted these goals to include support for the goals of American educational institutions at all levels. A 2008 NRC report, *NASA's Elementary and Secondary Education Program: Review and Critique,*[3] recommended the following:

> NASA should continue to engage in education activities at the K-12 level, designing its K-12 education activities so that they capitalize on NASA's primary strengths and resources, which are found in the mission directorates. These strengths and resources are the agency's scientific discoveries; its technology and aeronautical developments; its space exploration activities; the scientists, engineers, and other technical staff (both internal and external) who carry out NASA's work; and the unique excitement generated by space flight and space exploration (p. 6).

The report also noted that among the large number of agency staff who focus on science, engineering, and technology, only limited numbers have primary expertise in education that allows them to develop effective education products on their own.

The workshop summarized here was prompted by a number of changes both in NASA policy and in how the United States as a whole is changing the teaching of science in kindergarten through grade 12. The larger context of the workshop involves several significant events. These are the 2012 NRC report *A Framework for K-12 Science Education*[4] (generally referred to as "the Framework"), a set of K-12 science standards based upon the Framework known as the Next Generation Science Standards (NGSS), and the November 2014 release by NASA SMD of a Cooperative Agreement Notice (CAN) soliciting proposals that address NASA SMD's science education requirements.[5]

A Framework for K-12 Science Education

A Framework for K-12 Science Education (i.e., "the Framework"), released by the NRC in 2011, consists of the most up-to-date information on how students in grades K-12 should learn science (see Figure I.1). The development process of the Framework study consisted of a committee that included science education policy experts and researchers. Design teams in the following disciplines were utilized in the development process as well: engineering, Earth and space science, life science, and physical science. The Framework includes research on how students acquire knowledge of science in an effective manner, and it served as the basis for the NGSS, which were developed to provide an international benchmark for science education.[6]

NEXT GENERATION SCIENCE STANDARDS

The NGSS are a set of K-12 science standards developed through a state-led process to provide students with a benchmark for science education.[7] These standards are based on the NRC's Framework.[8]

The NGSS were produced due to the time gap in the development of guiding documents for state science education standards and the need to build interest among K-12 students in STEM disciplines. The standards are meant to better prepare high school students for college and the workforce with the objective of providing employers with the ability to hire individuals with strong science, critical thinking, and problem-solving skills.

Each NGSS consists of the following three dimensions: core ideas, science and engineering practices, and crosscutting concepts. Core ideas are meant to focus science curriculum and instruction on the most significant aspects of the discipline. Practices are applicable to both scientists and engineers; they describe the behavior of

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[3] National Research Council, *NASA's Elementary and Secondary Education Program: Review and Critique,* The National Academies Press, Washington, D.C., 2008.

[4] National Research Council, *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*, The National Academies Press, Washington, D.C., 2012.

[5] NASA, "A—Draft SMD Science Education Cooperative Agreement Notice," Solicitation Number NNH15ZDA002J, FedBizOpps.gov, posted November 6, 2014, http://www.fbo.gov.

[6] Next Generation Science Standards (NGSS), "Framework for K-12 Science Education," http://www.nextgenscience.org/framework-k-12-science-education, accessed January 15, 2015.

[7] NGSS, "Science Education in the 21st Century—Why K-12 Science Standards Matter—and Why the Time Is Right to Develop Next Generation Science Standards," May 2012 Draft, http://www.nextgenscience.org/sites/ngss/files/Why%20K12%20Standards%20Matter%20-%20FINAL.pdf.

[8] NGSS, "Development Overview," http://www.nextgenscience.org/development-overview, accessed January 15, 2015.

THE THREE DIMENSIONS OF THE FRAMEWORK

1 Scientific and Engineering Practices

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information

2 Crosscutting Concepts

1. Patterns
2. Cause and effect: Mechanism and explanation
3. Scale, proportion, and quantity
4. Systems and system models
5. Energy and matter: Flows, cycles, and conservation
6. Structure and function
7. Stability and change

3 Disciplinary Core Ideas

Physical Sciences
PS1: Matter and its interactions
PS2: Motion and stability: Forces and interactions
PS3: Energy
PS4: Waves and their applications in technologies for information transfer

Life Sciences
LS1: From molecules to organisms: Structures and processes
LS2: Ecosystems: Interactions, energy, and dynamics
LS3: Heredity: Inheritance and variation of traits
LS4: Biological evolution: Unity and diversity

Earth and Space Sciences
ESS1: Earth's place in the universe
ESS2: Earth's systems
ESS3: Earth and human activity

Engineering, Technology, and Applications of Science
ETS1: Engineering design
ETS2: Links among engineering, technology, science, and society

FIGURE I.1 Framework for K-12 Science Education produced by the National Research Council. SOURCE: National Research Council, *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*, The National Academies Press, Washington, D.C., 2012, p. 3.

scientists as they build theories pertaining to the natural world and the practices of engineers as they build systems. Crosscutting concepts link different science domains, and examples include cause and effect, as well as energy and matter.[9] The focus of the standards is a progression of knowledge from grade to grade starting in kindergarten all the way through 12th grade. The standards emphasize engineering and technology, and they coordinate with the Common Core State Standards in mathematics as well as English language arts. The NGSS were released in April 2013 for adoption by states and continue to be implemented today.[10]

NASA's Cooperative Agreement Notice

NASA SMD's draft Science Education CAN issued in November 2014 sought comments from members of formal and informal education, and science research communities.[11] According to SMD, the directorate's vision for education is as follows:

> To share the story, the science, and the adventure of NASA's scientific explorations of our home planet, the solar system, and the universe beyond, through stimulating and informative activities and experiences created by experts, delivered effectively and efficiently to learners of many backgrounds via proven conduits, thus providing a return on the public's investment in NASA's scientific research.

The draft CAN was issued for a 30-day discussion period with a request for responses by mid-December 2014. NASA chose to use a cooperative agreement in lieu of a contract or grant, with the expectation that the agency would engage in substantial interaction with the parties that are selected.

A cooperative agreement occurs when there is a transfer of something of value to an entity, such as a municipality, state government, or private company, to be used for a public purpose. This legal agreement involves two parties: the federal government and another entity.[12] The goal of the CAN is to meet the following education objectives of NASA SMD: enable STEM education, improve science literacy in the United States, advance national education goals, and utilize partnerships to leverage science education. CAN awards are anticipated by September 2015, and NASA has the intention to select one or multiple science discipline teams(s).

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[9] NGSS, "Three Dimensions," http://www.nextgenscience.org/three-dimensions, accessed January 15, 2015.

[10] NGSS, "Implementation," http://www.nextgenscience.org/implementation, accessed January 15, 2015.

[11] NASA, "A—Draft SMD Science Education Cooperative Agreement Notice," Solicitation Number NNH15ZDA002J, FedBizOpps.gov, posted November 6, 2014, http://www.fbo.gov.

[12] Kristen Erickson, NASA SMD, "NASA Science Mission Directorate Education Discussion with The National Academies Space Studies Board," presentation to the workshop, 2014.

5.3 Review of MEPAG Report on Mars Special Regions

A Report of the SSB and European Science Foundation ad hoc Committee on the Review of MEPAG Report on Planetary Protection for Mars Special Regions

Executive Summary

Planetary protection is a guiding principle in the design of an interplanetary mission, aiming to prevent biological contamination of both the target celestial body and Earth. Planetary protection reflects both the frequently unknown nature of the space environment and the desire of the scientific community to preserve the pristine nature of planetary bodies until they can be studied in detail. The planetary protection policy maintained by the Committee on Space Research (COSPAR 2015) defines guidelines and specific requirements depending on the mission target and mission type based on the actual state of knowledge. New findings and new technology developments require the COSPAR planetary protection policy to be updated on a regular basis.

High-priority science goals, such as the search for life and the understanding of the martian organic environment, may be compromised if Earth microbes—that is, prokaryotic or eukaryotic single-cell organisms—carried by spacecraft grow and spread on Mars. This has led to the definition of "Special Regions" on Mars where strict planetary protection measures have to be applied before a spacecraft can enter these areas. The concept of a Special Region was developed as a way to refer to those places where the conditions might be conducive to microbial growth as we understand this process. In particular, this refers to places that might be warm and wet enough to support microbes that might be carried by spacecraft from Earth. COSPAR's planetary protection policy defines a Mars Special Region as a "region within which terrestrial organisms may be able to replicate, OR a region which is interpreted to have a high potential for the existence of extant martian life. Given current understanding, Special Regions are defined as areas or volumes within which sufficient water activity AND sufficiently warm temperatures to permit replication of terrestrial organisms may exist. In the absence of specific information, no Special Regions are currently defined on the basis of martian life."

The physical parameter space defined in COSPAR planetary protection policy (COSPAR 2015) for Special Regions is constrained by the following:

- Water activity: lower limit, 0.5; upper limit, 1.0;
- Temperature: lower limit, –25°C; no upper limit defined; and
- Timescale within which limits can be identified: 500 years.

In 2014, NASA requested the Mars Exploration Program Analysis Group (MEPAG) to review the definition of Special Regions. In particular, the MEPAG group SR-SAG2 (Special Regions Science Analysis Group 2) was asked to address a number of topics including the following:[1]

- "Reconsider information on the known physical limits of life on Earth . . ."
- "Evaluate new (i.e., since 2006) observational data sets and models from Mars that could be relevant to our understanding of the natural variations on Mars of water activity and temperature;" and
- "Reconsider the parameters used to define the term 'special region;' propose updates to the threshold values for temperature and water activity, as needed . . . "

The result of this analysis was published as a journal article (Rummel et al. 2014). In response to parallel requests from the European Space Agency (ESA) and NASA, the European Science Foundation and the U.S. National Academies of Sciences, Engineering, and Medicine initiated a joint review of the SR-SAG2 report by an

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NOTE: "Executive Summary" reprinted from *Review of MEPAG Report on Mars Special Regions,* The National Academies Press, Washington, D.C., 2015, pp. 1-4.

[1] See Rummel et al. (2014, Appendix A, pp. 945-946). Note that the identifiers "SR-SAG2 report" and "Rummel et al. 2014" are used interchangeably in this document.

international group of experts, the Committee to Review the MEPAG Report on Mars Special Regions (hereafter the "review committee").

The SR-SAG2 report provides findings about the Mars-relevant physical and chemical limits of life (as we know it), the various phenomena observed on Mars that might be indicative of a Special Region and possible mechanisms for their formation, and the considerations related to spacecraft-induced Special Regions. The findings are followed by a discussion of human spaceflight and, in particular, the resources needed to support humans on Mars. The report also discusses the findings and makes recommendations to COSPAR for consideration in updating the Special Regions definition in the COSPAR planetary protection policy.

The review committee discussed the SR-SAG2 report during two face-to-face meetings, via conference calls, and by email exchange. The committee notes that its statement of task (see the Preface) could be interpreted as requiring a review and update of the requirements levied on a spacecraft venturing into a Special Region. However, discussions with the planetary protection officers from NASA and ESA confirmed that the committee's task was limited to a review of the definition of a Mars Special Region and related revisions to COSPAR's planetary protection policy as proposed in the SR-SAG2 report. The review committee understands that its report, like the SR-SAG2 report, will inform the process by which COSPAR will revise and update its planetary protection policies.

The findings from the SR-SAG2 report were discussed by the committee in view of additional information from scientific publications not addressed by the SR-SAG2 report and from new knowledge obtained by ongoing space missions, field studies, and laboratory experiments. This included discussions about the breadth and depth of SR-SAG2 analysis with respect to survivability of life forms singularly versus in communities and SR-SAG2 approach to defining geographical areas as Special Regions. The review committee agreed with many of SR-SAG2's individual findings, including retaining the current limits for life specified by COSPAR, but arrived at different conclusions in some cases and is of the opinion that a more detailed consideration is necessary (see Chapters 2 to 5). The review committee summarizes its comments concerning the findings and presents a new definition of Special Regions that changes the way geographical features are designated as Special Regions in Chapter 6. In Chapter 7, the review committee revisits the scientific basis of the bioburden assays used to assess the microbiological contamination of spacecraft and comments on the necessity of updating planetary protection requirements so that they are based on the latest scientific facts concerning the probability of life surviving in the martian environment.

This report concludes with a series of appendices containing the following information: Suggestions for future research that could reduce uncertainties in the identification of Special Regions on Mars (Appendix A); a complete listing of the findings from the SR-SAG2 report and, where appropriate, the review committee's comments thereon (Appendix B); the letter from NASA requesting the Academies' participation in this study (Appendix D); and brief biographies of committee members and staff (Appendix E).

In summary, the review committee reached the following conclusions:

1. The authors of the SR-SAG2 report are to be commended for their comprehensive review of the issues associated with Special Regions and the factors used to define them. The SR-SAG2 report contained 45 specific findings. Of these, the review committee does not support one (3-14), supports 13 in revised form (2-1, 2-4, 3-1, 4-1, 4-2, 4-8, 4-9, 4-14, 4-16, 5-3, 5-4, 5-7, and 5-9), suggests that two (4-6 and 4-7) be combined, proposes no changes for the remaining 29, and adds one new finding (6-1). The specific list can be found in Appendix B.
2. The environmental parameters used to define Special Regions (currently in the COSPAR policy and agreed upon in the SR-SAG2 report) of temperature and water activity are still appropriate. However, the review committee believes that if the detection of methane in the martian atmosphere—which may indicate biogenic activity—is confirmed, that may demand that the source region—that is, the location where methane is being produced—be designated as a Special Region.
3. The identification of Mars Special Regions is problematic for several reasons. First, detailed knowledge of the physical and chemical conditions of the surface and sub-surface of Mars at various scales is lacking, particularly the microscale. Second, current understanding of the ability of life to propagate is limited. It is not known if one, ten, or a million cells from a single species are required for propagation in an extraterrestrial environment. Alternatively, propagation may only be possible for microbial communities (i.e., collections of many different species). In view of the rapid development of powerful new techniques in biology and the increase in knowledge of the martian environment by ongoing and future space missions,

the current practice of reassessing the concept of a Special Region and its definition every 2 years is both appropriate and essential.

4. The specific terrains identified as Special Regions in both the COSPAR policy and in the SR-SAG2 report (i.e., "gullies, and bright streaks associated with gullies, pasted-on terrains, subsurface below 5 meters, others, to be determined, including dark streaks, possible geothermal sites, fresh craters with hydrothermal activity, modern outflow channels, or sites of recent seismic activity" and "spacecraft-induced Special Regions") are best regarded as "Uncertain Regions." The final determination of a Special Region would depend on the review of the latest scientific knowledge about a specific site in order to verify if it is within the environmental parameters defining Special Regions, taking into consideration the potential existence of microscale habitats.

In addition, the review committee makes one recommendation.

Recommendation: Maps should only be used to illustrate the general concept of Special Regions and should not be used to delineate their exact location. Uncertain Regions in planned landing ellipses should be evaluated on a case-by-case basis as part of the site selection process. The goal of such an evaluation is to determine whether or not the landing ellipse contains water, ice, or subsurface discontinuities with a potential to contain hydrated minerals that could be accessed via a landing malfunction or by the operation of subsurface-penetrating devices (e.g., drills). As an example, landing site analysis will likely include a geological analysis, drawing on the Mars geologic literature (covering a broad range of relevant topics, including ground truth at previous lander locations) as well as orbital imaging, infrared spectroscopy, gamma-ray spectroscopy, and ground-penetrating radar sounding of the specific region.

Finally, the review committee proposes the following update to the definition of a Special Region (COSPAR 2015): A Special Region is defined as a region within which terrestrial organisms are likely to replicate. Any region which is interpreted to have a high potential for the existence of extant martian life forms is also defined as a Special Region.

Given current understanding of terrestrial organisms, Special Regions are defined as areas or volumes within which sufficient water activity AND sufficiently warm temperatures to permit replication of Earth organisms may exist. The physical parameters delineating applicable water activity and temperature thresholds are given below:

- Water activity: lower limit, 0.5; upper limit, 1.0;
- Temperature: lower limit, –25°C; no upper limit defined; and
- Timescale within which limits can be identified: 500 years.

Observed features for which there is a significant (but still unknown) probability of association with liquid water, and which should be considered as Uncertain Regions and treated as Special Regions until proven otherwise:

- Sources of methane (if identified);
- Recurring slope lineae;
- Gullies and bright streaks associated with gullies;
- Pasted-on terrains;
- Caves, subsurface cavities and subsurface below 5 meters; and
- Others, to be determined, including dark slope streaks, possible geothermal sites, fresh craters with hydrothermal activity, modern outflow channels, or sites of recent seismic activity.

Spacecraft-induced special regions are to be evaluated, consistent with these limits and features, on a case-by-case basis.

Organizations proposing to investigate any region that may meet the criteria above, have the responsibility to demonstrate, based on the latest scientific evidence and mission approach, whether or not their proposed landing sites are or are not Special Regions.

In the absence of specific information, no Special Regions are currently identified on the basis of possible martian life forms. If and when information becomes available on this subject, Special Regions will be further defined on that basis.

5.4 Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System

A Report of the BPA and SSB ad hoc Committee on a Strategy to Optimize the U.S. Optical and Infrared System in the Era of the Large Synoptic Survey Telescope (LSST)

Executive Summary

Revolutionary discoveries undoubtedly will follow from the realization of the Large Synoptic Survey Telescope (LSST) under construction, the planned 30-meter-class telescopes, and new instrumentation on existing optical and infrared (OIR) telescopes. The challenge is to extract the best science from these and other astronomical facilities in an era of potentially flat federal budgets for both the facilities and the research grants necessary to exploit them. In the 2010s, there is increasing scientific opportunity combined with decreasing purchasing power. This report describes a vision for a nighttime U.S. OIR System that includes a telescope time exchange designed to enhance science return by broadening access to capabilities for a diverse community; an ongoing planning process to identify and construct next-generation capabilities to realize decadal science priorities; and near-term critical coordination, planning, training, and instrumentation needed to usher in the era of LSST and giant telescopes.

The guiding principles used by the National Research Council's (NRC's) Committee on a Strategy to Optimize the U.S. Optical and Infrared System in the Era of the Large Synoptic Survey Telescope (LSST) in its deliberations were as follows:

- An integrated OIR System can achieve the best science when it engages a broad population of astronomers to pursue a diversity of science and scientific approaches.
- Federal investment in LSST follow-up capabilities and in community-prioritized instrumentation across the OIR System will help to maximize scientific output.
- Federal support to sustain technology, instrumentation, and software development, and expertise in these fields, is necessary to optimize future science returns.

This report highlights some of the progress on science questions raised by the NRC decadal surveys *New Worlds, New Horizons in Astronomy and Astrophysics*[1] (NWNH) and *Vision and Voyages for Planetary Science in the Decade 2013-2022*[2] (VVPS), the existing facilities and capabilities, and the human resources that make up the U.S. OIR astronomical enterprise. The report then considers the science that will be enabled by new instruments and facilities. It highlights the critical OIR instruments that are necessary in the near term to achieve decadal objectives, enable innovative research, and augment LSST with follow-up observations. It then addresses how to optimize scientific return from available resources through cooperation among public and private observatories.

The committee's top-level recommendations are presented here in priority order, driven by the statement of task (see Preface) and motivated by the guiding principles above. The committee did not have a budget or guidelines for funding; these recommendations are based on science considerations and provided as advice for the National Science Foundation (NSF), the sponsor requesting the report. The accompanying descriptions and justifications for the recommendations are in subsequent chapters.[3]

The committee's highest priority is a U.S. OIR System that is well coordinated and facilitates broad access to achieve the best science. Broad access at non-federal telescopes can be accomplished in a number of creative ways,

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NOTE: "Executive Summary" reprinted from *Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System,* The National Academies Press, Washington, D.C., 2015, pp. 1-5.

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

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

[3] For convenience, all of the conclusions and recommendations that appear in individual sections are listed in the Epilogue in order of appearance.

including, but not limited to, engaging in limited term partnerships for partnering on telescopes, instruments, and data; bartering time on one facility for another; and swapping instruments.

> **RECOMMENDATION 1. The National Science Foundation (NSF) should direct the National Optical Astronomical Observatory to administer a new telescope time exchange with participating observatories of the U.S. Optical and Infrared System. Observatory representatives would barter facilities, swap instruments, or engage in limited term partnerships for telescope time or data access on behalf of their respective constituencies, as appropriate, and NSF would barter telescope time or data access or engage in limited term partnerships to carry out proposals competed through a system-wide time allocation committee. (Chapter 6)**

Maximum returns from federal investment will be achieved when the community has the capabilities necessary to address the decadal science priorities. Those capabilities include not only existing ones but also new ones that are developed as the science evolves. The decadal surveys identify long-term goals for community facilities, but capabilities needed in the short term, particularly in rapidly evolving areas of research, would benefit from shorter planning timescales. Achieving these capabilities through coordination or partnerships can be accomplished by establishing at the national level an ongoing planning process that will engage the entire OIR user community in identifying and realizing small- and medium-scale projects and programs between decadal and mid-decadal reviews.

> **RECOMMENDATION 2. The National Science Foundation should direct the National Optical Astronomical Observatory (NOAO) to administer an ongoing community-wide planning process to identify the critical Optical and Infrared System capabilities needed in the near term to realize the decadal science priorities. NOAO could facilitate the meeting of a system organizing committee, chosen to represent all segments of the community, which would produce the prioritized plan. NSF would then solicit, review, and select proposals to meet those capabilities, within available funding. (Chapter 6)**

As a start in the OIR System planning, and as charged, the committee has in this report identified a number of instrumentation and coordination requirements that would enhance the science output from medium (3.5- to 5-meter) and large (6- to 12-meter) telescopes, including augmenting LSST data once they come online.

> **RECOMMENDATION 3. The National Science Foundation should support the development of a wide-field, highly multiplexed spectroscopic capability on a medium- or large-aperture telescope in the Southern Hemisphere to enable a wide variety of science, including follow-up spectroscopy of Large Synoptic Survey Telescope targets. Examples of enabled science are studies of cosmology, galaxy evolution, quasars, and the Milky Way. (Chapter 5)**

LSST, the top-ranked, large, ground-based facility recommended in NWNH and highly ranked in VVPS, will enable a broad range of science across the community. The science returns will be even greater through complementary and supplementary work at other facilities. Recommendations 4a-4d target the optimization of science from data obtained with LSST. The large number of transient events that will be detected nightly by LSST will require a software event broker system to identify significant objects that need spectroscopic and higher-cadence photometric follow-up. Coordination of federally supported facilities and capabilities in the Southern Hemisphere will enable a rapid response to these events and therefore promote maximum scientific productivity.

> **RECOMMENDATION 4a. The National Science Foundation should help to support the development of event brokers, which should use standard formats and protocols, to maximize Large Synoptic Survey Telescope transient survey follow-up work. (Chapter 5)**

> **RECOMMENDATION 4b. The National Science Foundation should work with its partners in Gemini to ensure that Gemini South is well positioned for faint-object spectroscopy early in the era of Large Synoptic Survey Telescope operations, for example, by supporting the construction of a rapidly configurable, high-throughput, moderate-resolution spectrograph with broad wavelength coverage. (Chapter 5)**

RECOMMENDATION 4c. The National Science Foundation should ensure via a robustly organized U.S. Optical and Infrared (OIR) System that a fraction of the U.S. OIR System observing time be allocated for rapid, faint transient observations prioritized by a Large Synoptic Survey Telescope event broker system so that high-priority events can be efficiently and rapidly targeted. (Chapter 5)

RECOMMENDATION 4d. The National Science Foundation should direct its managing organizations to enhance coordination among the federal components of medium- to large-aperture telescopes in the Southern Hemisphere, including Gemini South, Blanco, the Southern Astrophysical Research (SOAR) telescope, and the Large Synoptic Survey Telescope (LSST), to optimize LSST follow-up for a range of studies. (Chapter 5)

Looking to the future, it is beneficial for NSF and the community to consider facilities and technologies that will bring the greatest scientific return for the investment. The largest telescopes, the Giant Segmented Mirror Telescopes (GSMTs), are being constructed by private and international partners. It is important for a broad U.S. community to have direct access to the GSMTs through federal investment so that the best science can be achieved.

RECOMMENDATION 5. The National Science Foundation should plan for an investment in one or both Giant Segmented Mirror Telescopes in order to capitalize on these observatories' exceptional scientific capabilities for the broader astronomical community in the Large Synoptic Survey Telescope era, for example, through shared operations costs, instrument development, or limited term partnerships in telescope or data access or science projects. (Chapter 4)

Many types of technologies are in various stages of development. Adaptive optics (AO), for example, has become a mainstay of telescopes but needs more investment in order for AO-assisted telescopes to achieve the most stable images with the best possible resolution; detector technology continues to improve. Sustaining technological developments and maintaining U.S. expertise in instrumentation and software are important for remaining competitive in the rapidly advancing world stage of OIR astronomy.

RECOMMENDATION 6. The National Science Foundation (NSF) should continue to invest in the development of critical instrument technologies, including detectors, adaptive/active optics, and precision radial velocity measurements. NSF should also use existing instrument and research programs to support small-scale exploratory programs that have the potential to develop transformative technologies. (Chapter 4)

RECOMMENDATION 7. The National Science Foundation (NSF) should support a coordinated suite of schools, workshops, and training networks run by experts to train the future generation of astronomers and maintain instrumentation, software, and data analysis expertise. Some of this training might best be planned as a sequence, with later topics building on earlier ones. NSF should use existing instrument and research programs to support training to build instruments. (Chapter 3)

There are a number of important topics for which the committee has reached conclusions but not recommendations. Among these are conclusions regarding data archives and their public availability and means of access (Section 3.3), the Dark Energy Camera (DECam) and Dark Energy Spectroscopic Instrument (DESI) (Section 5.1), the Mid-Scale Innovations Program (MSIP) structure (Section 6.3), and international discussions (Section 6.5).

5.5 The Space Science Decadal Surveys: Lessons Learned and Best Practices

A Report of the SSB ad hoc Committee on Survey of Surveys: Lessons Learned
from the Decadal Survey Process

Summary

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

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

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

Eleven decadal surveys have now been completed; the last four have been for Earth science and applications from space (Earth2007), astronomy and astrophysics (Astro2010), planetary science (Planetary2011), and solar and space physics (Helio2013).[3] The 2012 Academies' workshop "Lessons Learned in Decadal Planning in Space Science," invited participants from recent surveys and "stakeholders," such as NASA and NSF division directors, congressional staffers, and representatives of the executive branch. Presentations and moderated panel discussions, with inputs from the gathered attendees, covered all aspects of these recent decadal surveys. The resulting report, *Lessons Learned in Decadal Planning in Space Science: Summary of a Workshop,*[4] captures the breadth and depth of this exceptional, challenging process.

The Committee on Survey of Surveys: Lessons Learned from the Decadal Survey Process (hereinafter "the committee") was appointed by the Academies with the task of distilling the content of the 2012 workshop, adding the input from presentations to the committee, and providing its own evaluations of the issues. The committee's goal has been twofold: (1) to provide a handbook to guide the organizers of future surveys, with a moderately detailed discussion of both "tried and true" and novel methods and (2) to identify *lessons learned* from prior surveys and *best practices* that have been gleaned from them. Along the way, the committee has identified valuable

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NOTE: "Summary" reprinted from *The Space Science Decadal Surveys: Lessons Learned and Best Practices,* The National Academies Press, Washington, D.C., 2015, pp. 1-6.

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

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

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

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

aspects of decadal surveys that could be taken further, as well as some challenges future surveys are likely to face in searching for the richest areas of scientific endeavor, seeking community consensus of where to go next, and planning how to get there. What decadal surveys are asked to do is no simple task.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

One rather obvious *lesson learned* is that a reliable CATE process is crucial for the largest, most ambitious missions—high-profile missions—where cost growth can threaten the health of a wide set of activities over a discipline, and beyond. A *best practice* for future surveys is to give greater attention and added care in assessing and recommending potentially "discipline-disrupting" programs. A thorough and rigorous CATE process can help, but too often the true cost of such a mission cannot be well established until the program is well under way.

Surveys can provide clear decision rules and decision points that will effectively establish cost caps, with the intent of triggering reconsideration of the mission and the possibility, or necessity, of rescoping its science capability.

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

6
Congressional Testimony

Members of Space Studies Board (SSB) committees of the National Academies of Sciences, Engineering, and Medicine may be invited to testify before committees of the U.S. House of Representatives or the U.S. Senate about the findings and recommendations of their reports. During 2015, two hearings were held where members of the SSB family testified to Congress—James Pawelczyk on July 10, 2015, and Anthony Busalacchi on November 17, 2015.

THE INTERNATIONAL SPACE STATION: ADDRESSING OPERATIONAL CHALLENGES

On July 10, 2015, the U.S. House of Representatives Subcommittee on Space (Committee on Science, Space and Technology) held a hearing titled "The International Space Station: Addressing Operational Challenges." Dr. James Pawelczyk, associate professor of physiology and kinesiology at Pennsylvania State University, and a member of the Academies' Committee on Biological and Physical Sciences in Space, provided testimony on behalf of the Academies' Division on Engineering and Physical Sciences, the Aeronautics and Space Engineering Board, and the SSB. More information and the full testimony is available at https://www.legistorm.com/hearings/view/HHRG103709/house.html and reprinted, unedited, below.

> Mr. Chairman and Members of the Sub-Committee:
>
> Good morning. I thank you for the opportunity to discuss the status of research using the International Space Station. I have been a space life sciences researcher for more than 25 years, regularly funded by grants from NASA. From 1996-1998 I took leave from my academic position at The Pennsylvania State University to serve as a payload specialist astronaut, or guest researcher, on the STS-90 Neurolab Spacelab mission, which flew on the space shuttle Columbia in 1998. I have more than 15 years of experience advising Page 2 NASA on its life sciences strategy and portfolio, either as a direct consultant or through committees of the National Academies of Science, Engineering and Medicine. I help evaluate NASA's Bioastronautics Research Program for the Institute of Medicine. I am also inaugural member of the National Research Council's (NRC) newly constituted Committee on Biological and Physical Sciences in Space (CBPSS). Part of our charge is to monitor NASA's progress in implementing the recommendations contained in, "Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era," published by the NRC in 2011.[1]
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> The ISS provides a unique platform for research. Past NRC studies have noted the critical importance of the ISS's capabilities to support the goal of long-term human exploration in space. These capabilities include the ability to

[1] http://www.nap.edu/catalog/13048/recapturing-a-future-for-space-exploration-life-and-physical-sciences.

perform experiments of extended duration, the ability to continually revise experiment parameters on the basis of previous results, the flexibility in experimental design provided by human operators, and the availability of sophisticated experimental facilities with significant power and data resources. The ISS is the only platform of its kind, and it is essential that its presence and dedication to research for the life and physical sciences be fully employed for as long as it is practicable to do so.

To prepare for this hearing, you asked four specific questions:

1. What are the opportunities and challenges in conducting space life and physical science research on the ISS and what should be done to address them?
2. What are some of the most critical areas of ISS research in space life and physical sciences to enabling the long-term goal of sending humans to the surface of Mars, and what is the status of progress on that research?
3. How are priorities for research on the ISS established and is there a clear and well understood process for aligning ISS resources with those priorities?
4. What are the implications of the proposed extension of ISS operations to 2024 on research and what criteria should Congress use to consider the proposed extension?

In the time allotted, I'd like to share my generally positive view of NASA's progress, and provide some specific suggestions to maximize the use of this extraordinary national resource that has been orbiting our planet every 90 minutes for the past 17 years. My comments will not stray far from my areas of expertise in the life sciences, but many of them should be applicable to the physical sciences as well.

1. What are the opportunities and challenges in conducting space life and physical science research on the ISS and what should be done to address them?

The 2009 report from the Review of U.S. Human Spaceflight Plans Committee (the "Augustine Commission") emphasized that future astronauts will face three unique stressors[2]:

- prolonged exposure to solar and galactic radiation;
- prolonged periods of exposure to microgravity; and,
- confinement in close, relatively austere quarters along with a small number of other crew members who must live and work as a cohesive team for many months while having limited contact with their family, friends and culture.

All of these stressors are present in the ISS environment. Martian operations add more stressors: a dusty, dim, energetic environment and a gravitational field that is a little more than a third of our own. Research to address the biological response to fractional gravity is perhaps the area most impacted by changes to the ISS program over the decades. Unless we improve our research centrifuge capabilities on the ISS, we accept a risk of sending humans to Mars with little or no knowledge of how mammalian biology responds in a gravitational field other than Earth's.

My colleagues in the science community report that two of the major challenges to the biology research portfolio are limited access to the ISS and limited crew time. Some types of research, particularly that employing small mammals, is very time consuming to execute. Animal husbandry for a single rodent experiment can easily outstrip available ISS crew time for research during an increment. We can reasonably anticipate that competition for crew time will become worse as the facility ages, and demands on crew time to perform necessary maintenance become more acute.

Access to the ISS for research is not just a matter of access to space, it is a matter of competing programs. ISS research time is allocated in roughly equal proportions between NASA sponsored, peer-reviewed science and projects sponsored by the Center for the Advancement of Science in Space (CASIS), regardless of what that research might be. The outcome is that National Laboratory research and peer-reviewed, NASA-sponsored research vie for scarce resources such as crew time and positions on the flight manifest; in some cases forcing NASA research to lower-fidelity Earth-based analogs such as bed rest research for muscle atrophy and bone demineralization.

The extension criteria report requested by Congress in the NASA Authorization Act of 2015 creates opportunities

[2] http://www.nasa.gov/pdf/396093main_HSF_Cmte_FinalReport.pdf.

to better coordinate NASA and CASIS sponsored research. For example, the ISS Program Office could require an experimental definition phase to maximize science return by combining compatible experiments and expanding biospecimen-sharing experiments to answer the most pressing research questions.

2. ***What are some of the most critical areas of ISS research in space life and physical sciences to enabling the long-term goal of sending humans to the surface of Mars, and what is the status of progress on that research?***

The biological risks associated with exploration-class spaceflight are far from being mitigated. This conclusion is based on analysis of 40 years of NASA-sponsored research.

Since the days of Skylab, NASA-funded investigators conducted an aggressive and successful biological research program that was robust, comprehensive, and internationally recognized. Beginning with those early efforts, and continuing with our international partners on the Mir and the ISS, we have built a knowledge base that defines Page 4 the rate at which humans adapt during spaceflight up to six-months duration, with four data points exceeding one-year duration. Right now, we are expanding the one-year database! To prepare for Mars, we need to extend the duration further—up to three years—using a combination of astronaut volunteers and small mammals such as rats and mice.

In *Life of Reason*,[3] George Santayana warned that, "those who cannot remember the past are condemned to repeat it." We should not forget the precipitous drop in NASAsponsored research in the first decade of the millennium. The 2001 peak of 1014 separate research tasks was slashed to just 364 in 2010. Space biology and the physical sciences were particularly hard hit, losing about 80% of their research portfolio.

Congress heard the research community's concerns, and we are most thankful for your response. The NRC's Life and Physical Sciences (LPS) Decadal Survey—completed in 2011 as a response to a request from Congress introduced in 2008 authorization language—prompted a sea change in NASA's approach to biological and physical sciences research.

The LPS Decadal summarized and sequenced 65 high priority research tasks. Furthermore, the Decadal study created two notional research plans aligned with specific priorities; one being a goal of rebuilding a research enterprise and the other a goal of a human mission to Mars. More about these goals later.

3. ***How are priorities for research on the ISS established and is there a clear and well understood process for aligning ISS resources with those priorities?***

My response to this question considers general aspects of peer-reviewed research projects that are solicited through open competition. All NASA-sponsored space life and physical sciences research is conducted in this way.

Developing strategic priorities for ISS research is not a new concept. Notable examples from this millennium include:

- The NASA-sponsored Research Maximization and Prioritization Task Force, commonly known as ReMAP, which reported its findings in 2002, representing the breadth of translational research in the biological and physical sciences.
- The ISS utilization studies organized by the National Research Council in 2005.
- Most recently, the Life and Physical Sciences (LPS) Decadal Research Plan; the first decadal survey of NASA's life and physical sciences programs. The guiding principle of the study was, "to set an agenda for research in the next decade that would use the unique characteristics of the space environment to address complex problems in the life and physical sciences, so as to deliver both new knowledge and practical benefits for humankind as it embarks on a new era of space exploration." Furthermore, the LPS Decadal organizers were tasked with establishing priorities for an integrated portfolio of biological and physical sciences research in the decade of 2010-2020.

Why have we asked the prioritization question so many times, and why must we do so again? Because space research

[3] http://www.gutenberg.org/ebooks/15000.

informs two broad, often competing, goals: One centers on intrinsic scientific importance or impact; research that illuminates our place in the universe, but cannot be accomplished in a terrestrial environment. The other goal values research that enables long-term human exploration of space beyond low-earth orbit, and develops effective countermeasures to mitigate the potentially damaging effects of longterm exposure to the space environment. Over the past 25 years, other review panels, both internal and external to NASA, have defined similar goals. In the case of the LPS, research was categorized as either (1) required to enable exploration missions or (2) enabled or facilitated because of exploration missions. I prefer the more contemporary synonyms of "discovery" and "translational" research.

Throughout the history of the United States space program both goals have been important, but their relative importance has changed over time. In the early part of the Apollo era, the limited amount of biological and physical research that occurred was focused on the health and safety of astronaut crews in a microgravity environment. Until late in the Apollo program, significant research questions that did not contribute directly to a successful Moon landing received lower priority. In contrast, more regular access to space provided by the space shuttle afforded an opportunity for discovery research to take higher priority; an emphasis that fared poorly in the austere NASA budgetary environment of the mid-2000's.

Thus, the relative priority of these two goals of research—enabling long-term human exploration of space (translation) and answering questions of intrinsic scientific merit (discovery enabled by space research)—shifts according to NASA's programmatic goals.

I make note of the fact that section 201 NASA Authorization Act of 2015 articulates a translational goal of sending humans to Mars, while section 718 emphasizes discovery research. The key question is this: Shall discovery or translational research takes precedence in the mature years of the ISS research program? If it is translational research to prepare for a human trip to Mars, then the ISS research portfolio should be tailored accordingly.

The LPS Decadal Survey provides a very detailed scheme to evaluate the importance of proposed research on the International Space Station. It includes eight unique criteria to prioritize research,[4] as follows:

- *Positive Impact on Exploration Efforts, Improved Access to Data or to Samples, Risk Reduction*. The extent to which the results of the research will reduce uncertainty about both the benefits and the risks of space exploration.
- *Potential to Enhance Mission Options or to Reduce Mission Costs*. The extent to which the results of the research will reduce the costs of space exploration.
- *Positive Impact on Exploration Efforts, Improved Access to Data or to Samples*. The extent to which the results of the research may lead to entirely new options for exploration missions.
- *Relative Impact Within a Research Field*. The extent to which the results of the research will provide full or partial answers to grand science challenges that the space environment provides a unique means to address.
- *Needs that are Unique to NASA Exploration Programs*. The extent to which the results of the research are uniquely needed by NASA, as opposed to any other agencies.
- *Research Programs That Could Be Dual-Use*. The extent to which the results of the research can be synergistic with other agencies' needs.
- *Research Value of Using Reduced-Gravity Environment*. The extent to which the research must use the space environment to achieve useful knowledge.
- *Ability to Translate Results to Terrestrial Needs*. The extent to which the results of the research could lead to either faster or better solutions to terrestrial problems or to terrestrial economic benefit.

Some of these criteria emphasize discovery; others translation. The LPS Decadal Survey prioritizes specific research tasks for each criterion. Again, the Survey appropriately stopped short of weighting or prioritizing criteria against each other because of the programmatic implications. That responsibility—to prioritize either discovery research or Mars—falls largely to the executive and legislative branches. When this question is decided, then the LPS decadal should be a useful tool to program research for the remaining life of the ISS.

Operationally, the ISS Program Office prioritizes all the research to be conducted on each ISS increment. It is a well understood process: CASIS receives a 50% allocation, followed by human research, then technology demonstrations. What resources remain are allocated to the Biological and Physical Sciences Program and the Science Mission

[4] http://www.nap.edu/catalog/13048/recapturing-a-future-for-space-exploration-life-and-physical-sciences.

Directorate payloads. Both the Human Research and Biological and Physical Science utilize the LPS Decadal criteria for prioritization within their respective programs, but it is not apparent the extent, if any, that LPS Decadal criteria are used to prioritize research across the four programs.

Lastly, it is worth noting that ISS research expenditures, which in FY 2012 constituted about 8%, or $225M, of ISS program costs, are not anticipated to keep pace with overall cost growth of the ISS program.

4. ***What are the implications of the proposed extension of ISS operations to 2024 on research and what criteria should Congress use to consider the proposed extension?***

To evaluate the proposed extension, one of the first tests that Congress should apply can be answered with a yes or no. "Is NASA prepared to operate a robust research program through 2024?" In my opinion, the answer is an unqualified, "yes!" The scope of change in NASA life and physical sciences in the past four years has been remarkable. Allow me to highlight some notable examples:

- In 2011 NASA reorganized the remnants of a once robust life and physical sciences program to form the Space Life and Physical Sciences Research and Applications Division (SLPSRA). The program is formulated to execute high quality, high value research and application activities in the areas of space life sciences, physical sciences and human research. This reorganization acknowledges—in point of fact, celebrates—both the discovery and translational outcomes of research in the biological and physical sciences.
- Consistent with recommendations in the LPS Decadal, the Biological and Physical Sciences Program has restarted regular research announcements for ground-based and flight experiments. As a rule, these proposals are externally peer reviewed. In FY2014, 30 proposals were funded; 9 of them flight experiments.
- NASA is making greater use of advisors in the National Academies of Science, Engineering and Medicine. In October of 2014 the NRC instituted a new Committee on Biology and Physical Sciences in Space (CBPSS) chaired by Betsy Cantwell (University of Arizona) and Rob Ferl (University of Florida). Part of the Committee's charge is to monitor the progress in implementation of the recommendations contained in, the LPS Decadal.
- The Human Research Program has been aligned with a global exploration strategy. Annual solicitations for research have resumed. The past four quarters for which summaries are available included 212 research publications and more than 277 research proposals.
- We now have an American astronaut on a one-year mission to the ISS, with a unique opportunity to examine his genomic response to this environment.
- The technical content of the Human Bioastronautics Roadmap is in the middle of a five-year review of its 33 risks and 299 research gaps relevant to health and operations in space. The project is being conducted by the Institute of Medicine.
- NASA's Human System Risk Board tracks a subset of 23 risks that require additional research. While all but one have some level of risk mitigation for a one-year stay on the Moon, about half (N=11) do not have any substantive level of risk mitigation for three-year planetary operations.

I think it's reasonable to conclude that NASA has planned its life and physical sciences enterprise to take advantage of ISS research capabilities. The greatest remaining knowledge gaps are for Design Reference Missions on Mars for more than one year.

A recent NASA Office of the Inspector General (OIG) report[5] identified several concerns for continued ISS operations through 2024. There are four aspects of the report that I'd like to address:

First, the OIG found that ISS extension to 2024 could permit NASA enough time to mitigate an additional seven risks of long duration spaceflight. Nevertheless, extended utilization was not expected to fully mitigate another 11 human health risks prior to 2024, and two additional risks could not be mitigated using the ISS. The OIG concluded that NASA, "needs to prioritize its research aboard Station to address the most important risks in the time available." I think this conclusion misses an important point. The likelihood and consequences of at least 11 of the 13 unmitigated risks are dependent on the tasks required of a crew during a Mars Design Reference Mission. Today, there are simply too many degrees of freedom in the task set to establish useful risk criteria. Therefore, before the

[5] http://oig.nasa.gov/audits/reports/FY14/IG-14-031.pdf.

capabilities of the ISS to mitigate these risks can be evaluated, the risk must be better understood by performing a thorough task analysis of Martian operations.

Second, the report did not address powered down mass to any great extent. This is a critical need when biological samples, including live organisms, are to be returned to the ground for additional study.

Third, the OIG emphasized average crew time as a metric to quantify research utility. Although there are other metrics, including number of investigations, use of allocated space, up-mass, down-mass, and power, thermal, and data usage; in general, NASA does not consider these measures primary indicators of research utilization.[6] What is missing is a method to evaluate the efficiency of on-orbit research. Specifically, what percentage of crew time allocated to research is used to conduct it, compared to ancillary functions for such as setting up and stowing equipment? A similar focus has improved extravehicular operations on the ISS. I suspect that we will find that some of the highest priority research, such as studies using small mammals, is also the least efficient; requiring substantial amounts of crew time to set up experiments. If this is true, then increasing efficiency, for example, by improving coordination between NASA and CASIS, could be another way to capture more crew time for research in high priority areas.

Fourth, the OIG notes that research time is constrained with a six person crew. To maximize research utilization, we need to think about a seventh scientist crew member when commercial crew systems can support him or her. Summary We desperately need to increase research capabilities in space by translating findings from cell culture to reference organisms and mammalian models such as mice and rats to future flight crews. Translational research is the "gold standard" of the NIH, and it is what the research community, and the American people, should expect from the International Space Station. We need the capability to house and test model organisms on the ISS for extended periods of time, and whenever possible, to expose them to loading forces that approximate Mars. But equally important, we need adequate time for crew to prepare and conduct these experiments. The potential return is immense; the application of this research to our aging public could become one of the most important justifications for an extended human presence in space. My LPS Decadal Survey colleagues and I contend that NASA can and should continue to restore a high level of programmatic vision and dedication to life and physical sciences research, to ensure that the considerable obstacles to human exploration missions to Mars can be resolved. This will depend on NASA embracing life and physical sciences research as part of its core exploration mission and re-energizing a community of life and physical scientists and engineers focused on both discovery and translational research.

To maximize ISS research, it is of paramount importance . . .

- That the life and physical sciences research portfolio supported by NASA, both extramurally and intramurally, receive high attention.
- That NASA's research management structure be optimized to meet its discovery research, translational research, and commercialization goals. The utility of a coherent research plan that is appropriately resourced and consistently applied to enable exploration cannot be overemphasized. This will require improved coordination with CASIS.
- That the research portfolio be based on both discovery and translational programmatic priorities, and with specific destination(s) and mission tasks in mind.
- That there is sufficient external oversight to help NASA reach its research goals.

My top recommendations are the following:

- Articulate a timeframe for delivering and completing an operational risk mitigation plan for a multi-year human mission to Mars, and vet both the plan and the timeframe with the external scientific community.
- Review the essential resources for extended mammalian research on the ISS, including a seventh crew member; a scientist-astronaut whose nominal responsibilities are science programming.
- Extend biological science experiments to cover a substantial portion of a mammalian life cycle, and incorporate fractional (Martian) gravity exposure where possible.

Mr. Chairman, given sufficient resources, I am optimistic that NASA can deliver another decade of rigorous translational research. It's what the scientific community expects, and the American people deserve. I sincerely thank you for your vigilant support of the nation's space program, and the opportunity to appear before you today.

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[6] https://oig.nasa.gov/audits/reports/FY13/IG-13-019.pdf.

EXPLORING COMMERCIAL OPPORTUNITIES TO MAXIMIZE EARTH SCIENCE INVESTMENTS

On November 17, 2015, the U.S. House of Representatives Subcommittee on Space and Subcommittee on Environment (Committee on Science, Space and Technology) held a hearing titled "Exploring Commercial Opportunities to Maximize Earth Science Investments." Dr. Anthony Busalacchi, Professor and Director of the Earth System Science Interdisciplinary Center at the University of Maryland, and one of the co-chairs of the Academies' Decadal Survey for Earth Science and Applications from Space, provided testimony on behalf of the Academies' Division on Engineering and Physical Sciences, the Aeronautics and Space Engineering Board, and the SSB. More information and the full testimony is available at https://www.legistorm.com/hearings/view/HHRG104181/house.html and reprinted, unedited, below.

Good Morning Chairman Babin, Chairman Bridenstine, Ranking Members Edwards and Bonamici, and members of the subcommittees. I am Dr. Tony Busalacchi and I am Director of the Earth System Science Interdisciplinary Center and Professor of Atmospheric and Oceanic Science at the University of Maryland. Prior to coming to the University of Maryland 15 years ago, I was a civil servant for 18 years at the NASA Goddard Space Flight Center (GSFC), the last 10 years of which I was a laboratory chief and member of the Senior Executive Service. While at Goddard I also served as the source selection official for the SeaWiFS Ocean Color Data Buy from Orbital Sciences Corporation that is directly relevant to this hearing.

Presently, I also serve as the Co-Chair of Decadal Survey for Earth Sciences and Applications from Space being carried out by the National Academies of Sciences, Engineering, and Medicine. The report from this study will provide the sponsors—NASA, NOAA and the USGS—with consensus recommendations from the environmental monitoring and Earth science and applications communities for an integrated and sustainable approach to the conduct of the U.S. government's civilian space-based Earth-system science programs.

The decadal survey's prioritization of research activities will be based on our committee's consideration of identified science priorities; broad national operational observation priorities as identified in U.S. government policy, law, and international agreements (for example, the 2014 National Plan for Civil Earth Observation) and the relevant appropriation and authorization acts governing NASA, NOAA, and USGS; cost and technical readiness; the likely emergence of new technologies; the role of supporting activities such as in situ measurements; computational infrastructure for modeling, data assimilation, and data management; and opportunities to leverage related activities including consideration of interagency cooperation and international collaboration. With the expectation that the capabilities of non-traditional providers of Earth observations will continue to increase in scope and quality, the decadal survey has also been asked to suggest approaches for evaluating these new capabilities and integrating them, where appropriate, into NASA, NOAA and USGS strategic plans. The committee will also consider how such capabilities might alter NOAA's and USGS's flight mission and sensor priorities in the next decade and beyond.

Before continuing with my testimony I should note that I am speaking on my own behalf today, not on behalf of the other co-chair of the decadal survey—Dr. Waleed Abdalati of the University of Colorado—or the survey's steering committee that is being assembled as we meet today. Nothing in my testimony today should be construed as indicating anything about what the decadal survey committee may recommend when our report is published in the summer of 2017.

Following the suggestion in the committee's letter inviting me to testify, I will organize my testimony around the following questions:

1. *What are the opportunities and challenges associated with potential public private partnerships for NASA's Earth science program?*
2. *What were the key lessons learned from prior public private partnerships, such as Sea-viewing Wide Field-of-view Sensor (SeaWiFS), and what were the most challenging aspects?*
3. *Provide a summary of prior National Academies work relevant to NASA Earth observations and partnerships with commercial entities.*
4. *What processes and policies are needed to identify if public private partnerships should be used and when, and how they should be evaluated? What, if any, are the next steps for Congress?*

1. What are the opportunities and challenges associated with potential public private partnerships for NASA's Earth science program?

Public-private partnerships have the potential for cost savings to the government and the possibility for accelerating innovation. While this potential may exist it is far from being realized and proven possible.

NASA's Earth Science Division (ESD) conducts a wide range of satellite and sub-orbital missions in order to better understand Earth as an integrated system. Earth observations provide the foundation for critical scientific advances and data products derived from these observations that are used for an extraordinary range of societal applications including resource management, weather forecasts, climate projections, agricultural production, and natural disaster response. ESD develops its observing strategy in response to Congressional and Executive Branch direction and through consultation with the scientific community. In particular, the consensus views of the scientific community as expressed in Academies' decadal survey reports are used to guide future investments.

In addition to the ambitious plans recommended to NASA in the inaugural decadal survey, Earth Science and Applications from Space (2007),[1] starting in Fiscal Year 2014 NASA was directed to assume additional responsibilities for sustaining a number of measurements previously assigned to other agencies.[2] With these constraints and against the backdrop of an austere budgetary environment that is likely to persist for the foreseeable future, and facing increased demands for Earth information products critical to the nation's welfare, the Earth Science Division is actively examining evolving opportunities to use smaller and less costly spacecraft, spacecraft constellations, hosted payloads, and "missions of opportunity"—all with the objective of "doing more with less." For example, following a recommendation in the 2007 decadal survey, ESD developed a new "Venture" class series of science-driven, competitively selected, comparatively low-cost missions that are providing more frequent opportunities for investment in innovative Earth science using smaller satellites, the International Space Station, hosted payloads, and sub-orbital platforms.

The private sector is rightfully known as an engine of innovation. This is seen, for example, in the myriad of companies that are now developing novel Earth imaging capabilities. Public-private partnerships *may* offer a way for NASA ESD to acquire—at lower cost—the data it and the nation require. While this approach may prove practical in the case of Earth imaging where there is over 60 years of heritage, in my view there is no *a priori* reason to believe it will prove practical for new remote-sensing methodologies and technologies. As I discuss later in my testimony, issues of data access and data quality pose particular challenges in a government partnership with a profit-generating private entity.

2. What were the key lessons learned from prior public private partnerships, such as Sea-viewing Wide Field-of-view Sensor (SeaWiFS), and what were the most challenging aspects?

SeaWiFS[3] was a science data buy in which NASA served as the anchor tenant to a private entity that was responsible for building and launching a spacecraft and instrument with particular capabilities. While my testimony today focuses on SeaWiFS, it should be recognized that other types of public-private partnerships have been successfully demonstrated; for example, the hosted payload model whereby NASA utilizes available capacity on commercial satellites to accommodate an additional instrument(s).

From a scientific perspective, SeaWIFS was a grand success in terms of the quality of the global ocean color data that

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

[2] These include Precision Altimetry following the launch of Jason-3; Solar Irradiance (TSIS-2 and follow-on missions transferred to NASA in FY14); Earth Radiation Balance (RBI instrument--RBI being developed by NASA for flight on JPSS-2 (~April 2019 instrument delivery date); and the OMPS-L instrument for ozone profiles. In addition, the FY14 and FY15 President's budget for NASA called for design and initiation of an affordable, sustained, Land Imaging Satellite System (with USGS) to extend the Landsat data record for decades.

[3] Subtle changes in ocean color signify various types and quantities of marine phytoplankton (microscopic marine plants), the knowledge of which has both scientific and practical applications. It became apparent to the oceanographic community that because of the dynamic nature of the world's oceans and climate, and the importance of the ocean's role in global change, a follow-on sensor to the Coastal Zone Color Scanner (CZCS) should be flown…The SeaWiFS Project was designated to develop and operate a research data system to gather, process, archive, and distribute data received from an ocean color sensor…The data was procured as a "data buy" from a private contractor, Orbital Sciences Corporation (OSC), which subcontracted with the Hughes Santa Barbara Research Center (SBRC) to build the SeaWiFS ocean color sensor. OSC built and launched the SeaStar satellite carrying the sensor on August 1, 1997. Following launch, the satellite's name was changed to OrbView-2(OV-2), and operations were turned over to ORBIMAGE, a spinoff of OCS. From the NASA SeaWiFS brochure: http://oceancolor.gsfc.nasa.gov/SeaWiFS/BACKGROUND/SEAWIFS_970_BROCHURE.html.

was acquired and the subsequent research on marine ecosystems. The structure of the data buy was such that NASA had insight-without-oversight. Overall, this strategy worked well primarily because our SeaWiFS Project maintained a healthy working relationship with Orbital Sciences Corporation (OSC) and the instrument vendor, Hughes/Santa Barbara Research Center, even though there were some serious problems with the launch vehicle, spacecraft and sensor resulting in a four-year launch delay. OSC also overran their budget, but not at government expense. While the whole process was very stressful for all parties, it did result ultimately in the provision of quality data. It is worth noting, however, that a less harmonious relationship between both parties could well have led to contract cancellation.

Even though SeaWIFS was technically a data buy from the private sector, the project would not have been a success without the engineering support from NASA's Goddard Space Flight Center (GSFC). Considerable support was provided by GSFC engineers in areas such as the power system, attitude control system, navigation system, component quality control. Although there was some heritage in ocean color remote sensing from the proof of concept Coastal Zone Color Scanner, the fact that SeaWiFS was a totally new sensor employing a novel lunar calibration underscored the need for expert engineering support from an organization like NASA Goddard.

As part of the ocean color data buy arrangement, NASA was also responsible for science data processing, on-orbit sensor calibration, and product quality control. Key to the success of the research quality of the data was the sustained participation of the science community, a project office staffed by experienced scientists with a vested interest in the mission, and development of the necessary infrastructure that did not exist when the project started. *In any such public-private partnership going forward this range of activities needs to be supported and sustained*.

Most of the infrastructure (including staff, which is critical) that we put in place under SeaWiFS remains in place today and has been expanded to support development of successor instruments, including MODIS[4] and its successor, VIIRS,[5] which is currently manifested on Suomi National Polar-orbiting Partnership, or Suomi NPP. VIIRS is also a key instrument on NOAA's JPSS[6] system going forward. This is relevant to the topic of routine or sustained observations where the science or support to societal benefit areas requires the data stream to be stable, continuous and calibrated for years to decades. If such long-term data records and related research is the goal, then a long-term commitment is required.

Maintaining consistent and traceable time series between missions with, for example, different sensor designs and different orbits presents many challenges. It is not clear how this can be accomplished by a public-private partnership given that every mission is competed and executed independently. This problem is magnified by the need for reprocessing all data sets using standardized algorithms and calibration methodologies. Developing close working relationships and sharing data with other space agencies has always been NASA's policy. NASA has also made data freely available. Under commercialization, these relationships and policies would need to be maintained. The private sector (U.S. and international) tends to consider code, sensor design information, and test data as proprietary—potentially a huge stumbling block to data consistency and continuity.

In order for OSC to market ocean color data, NASA did not have free and open access to the data. Overall, the data access agreement for research worked well—that is researchers had to register and verify they were only using the data for research and not for commercial purposes. Even though most of the research with SeaWiFs data was done in a delayed mode, we were able to provide real-time data in support of research cruises/field campaigns. Going forward any public-private partnership will need to develop a cost model based on data latency and resolution.

3. **Provide a summary of prior National Academies work relevant to NASA Earth observations and partnerships with commercial entities.**

The Academies has published several reports that touch on the issues of this hearing, including *Resolving Conflicts*

[4] MODIS (or Moderate Resolution Imaging Spectroradiometer) is a key instrument aboard NASA's Terra (originally known as EOS AM-1) and Aqua (originally known as EOS PM-1) satellites.

[5] Currently flying on the Suomi NPP satellite mission, VIIRS (Visible Infrared Imaging Radiometer Suite) generates many critical environmental products about snow and ice cover, clouds, fog, aerosols, fire, smoke plumes, dust, vegetation health, phytoplankton abundance and chlorophyll. VIIRS will also be on the JPSS-1 and JPSS-2 satellite missions.

[6] The Joint Polar Satellite System (JPSS), the Nation's next generation polar-orbiting operational environmental satellite system, is a collaborative program between NOAA and its acquisition agent, NASA. JPSS was established in the President's Fiscal Year 2011 budget request as the civilian successor to the restructured National Polar-orbiting Operational Environmental Satellite System (NPOESS).

Arising from the Privatization of Environmental Data (2001); *Toward New Partnerships In Remote Sensing: Government, the Private Sector, and Earth Science Research* (2002); and *Assessing the Requirements for Sustained Ocean Color Research and Operations* (2011).[7] Of particular note, *Toward New Partnerships* and *Assessing the Requirements for Sustained Ocean Color Research and Operations* include an examination and lessons learned from NASA's Science Data Buy (SDB) for SeaWiFS, a data buy for which, as previously mentioned, I am quite familiar with as I was the SeaWiFS source selection official while serving as head of NASA Goddard's Laboratory for Hydrospheric Processes.

Here, I would like to touch briefly on two specific challenges that need to be addressed for commercial entities to become viable partners in NASA's Earth science research and applications programs.

Full and Open Access to Data:

For obvious reasons, a commercial entity entering into a partnership to provide NASA observations must have a business model that promises a tangible financial return. Typically, whether the entity is producer or distributor, they will require restrictions on access to data. However, as noted in *Toward New Partnerships*, full and open access to data and the opportunity both to replicate research findings and to conduct further research using the same data are critical to scientific research.

In the case of SeaWiFS, which generated ocean color data of commercial and scientific value, the contract between NASA and the data provider, Orbital Sciences Corporation (OSC), had NASA retaining all rights to data for research purposes, and ORBIMAGE, a spinoff of OSC, retaining all rights for commercial and operational purposes. The contract included an embargo period of 2 weeks from collection for general distribution of data to research users to protect ORBIMAGE's commercial interest. Notably—and the key to making this arrangement practicable in my view—the commercial value of ocean color data to the fishing industry dissipates rapidly while the scientific value is not impacted substantially by short delays in data distribution.

With respect to access and utilization of its science data, NASA has, as a matter of longstanding policy and practice, archived all science mission data products to ensure long-term usability and to promote wide-spread usage by scientists, educators, decision-makers, and the general public. NASA has called attention to this policy in particular with respect to Earth science data, stating, "Perhaps the most notable endeavor in this [open access] regard is the Earth Observing System Data and Information System (EOSDIS), which processes, archives, and distributes data from a large number of Earth observing satellites and represents a crucial capability for studying the Earth system from space and improving prediction of Earth system change. EOSDIS consists of a set of processing facilities and data centers distributed across the United States that serve hundreds of thousands of users around the world."[8]

Ensuring the Quality of the Data and Maximizing the Nation's Return on Investment

In *Assessing the Requirements for Sustained Ocean Color Research and Operations*, it is noted that, "Building and launching a sensor are only the first steps toward successfully producing ocean color radiance and ocean color products. Even if the sensor meets all high-quality requirements, without stability monitoring, vicarious calibration, and reprocessing capabilities, the data will not meet standards for scientific and climate-impact assessments." The report goes on to note that: "To a large extent, success of the SeaWiFS/MODIS era missions can be attributed to the fact that they incorporated a series of important steps, including: pre-flight characterization, on-orbit assessment of sensor stability and gains, a program for vicarious calibration, improvements in the models for atmospheric correction and bio-optical algorithms, the validation of the final products across a wide range of ocean ecosystems, the decision going into the missions that datasets would be reprocessed multiple times as improvements became available, and a commitment and dedication to widely distribute data for science and education (e.g., Acker et al.,[9] 2002a; McClain,

[7] NRC. 2001. *Resolving Conflicts Arising from the Privatization of Environmental Data*. The National Academies Press, Washington, D.C.; NRC. 2002. *Toward New Partnerships In Remote Sensing: Government, the Private Sector, and Earth Science Research*. The National Academies Press, Washington, D.C.; and NRC 2011. *Assessing the Requirements for Sustained Ocean Color Research and Operations*. The National Academies Press, Washington, D.C.

[8] See "Access and Utilization of NASA Science Data: Stewardship for the Integrity and Preservation of Science Data as a Worldwide Resource," available online at: http://www.nasa.gov/open/plan/science-data-access_prt.htm.

[9] Acker, J.G., R. Williams, L. Chiu, P. Ardanuy, S. Miller, C. Schueler, P. Vachon, and M. Manore. 2002a. Remote sensing from satellites. *Encyclopedia on Physical Science and Technology* 14(3): 161-202.

2009;[10] Siegel and Franz, 2010[11])."

The report's conclusion, which I strongly endorse, is that SeaWiFS' success in producing high-quality data was due to the commitment by NASA to all critical steps of the mission, including pre-flight characterization, on-orbit assessment of sensor stability and gains, solar and lunar calibration, vicarious calibration, atmospheric correction and bio-optical algorithms, product validation, reprocessing, and widely distributed data for science and education.

It is my understanding that the organizers of this hearing, the Space and Environment Subcommittees of the Committee on Science, Space, and Technology of the U.S. House of Representatives have a particular interest in the potential role of public-private partnerships in sustaining Earth science measurements beyond the nominal lifetime of the mission/instrument that provided a first demonstration of capability/proof of concept. Here I wish to note the particular challenges that would need to be met—whether by NASA or in partnership with a private entity—with respect to trend detection and the creation of data records that can be used to inform decision makers.

Monitoring over long time periods is essential to detecting trends, whether for solar radiance, land-cover change, or ozone destruction. Long-term monitoring is also necessary to understand critical processes that are characterized by low-frequency variability. Because changes on a wide range of time and space scales affect Earth, it is not possible to determine *a priori* and with certainty the types of observations that should be made and the appropriate sampling strategy. An observing system may very well reveal unexpected phenomena such as the large-scale, low-frequency El Niño/Southern Oscillation of sea surface temperature as is happening right now in the tropical Pacific Ocean, and scientific opportunities are lost if the observing strategy cannot adapt accordingly.[12]

A Finding in *Towards New Partnerships* gives further detail on the challenge in creating an observing system capable of trend detection. There it is stated, "Continuity of remote sensing observations over long periods of time is essential for Earth system science and global change research, and it requires that scientists have access to repeated observations obtained over periods of many years…As scientists expand their use of data from both public and private sources, problems may arise in combining remote sensing data from multiple sensors with different capabilities and characteristics." These statements are consistent with an earlier report from the Academies, where it is noted, "It takes a special effort to preserve the quality of data acquired with different satellite systems and sensors, so that valid comparisons can be made over an entire set of observations. There are few examples of continuous data records based on satellite measurements where data quality is consistent across changes in sensors, even when copies of the sensor design are used. Sensor characterization and an effective, ongoing program of sensor calibration and validation are essential in order to separate the effects of changes in the Earth system from effects owing to changes in the observing system…Data systems should be designed to meet the needs for periodic reprocessing of the entire data set. An aggressive, science-driven program to ensure long-term data quality and continuity is very important."[13]

4. What processes and policies are needed to identify if public private partnerships should be used and when, and how they should be evaluated? What, if any, are the next steps for Congress?

Drawing on the lessons learned from the past, the most important next step is to establish a series of best practices to guide future public private partnerships for Earth remote sensing. In my experience, the following are characteristics of successful partnerships between NASA and a private-entity:

- The establishment of an appropriate insight/oversight model with the commercial partner.
  - What worked well for the SeaWiFS science data buy was the arrangement where NASA maintained insight, but not oversight, of the project. "Insight" is a monitoring activity, whereas "oversight" is an exercise of authority by the Government. SeaWiFS was a cost-sharing collaboration between NASA and Orbital Sciences Corporation (OSC) wherein NASA Goddard specified the data attributes and bought the research rights to these data, maintaining insight, but not oversight, of OSC. The SeaWiFS Project at GSFC was responsible for the calibration, validation, and routine processing of these data. OSC provided the spacecraft, instrument,

[10] McClain, C.R. 2009. A decade of satellite ocean color observations. *Annual Review of Marine Science* 1: 19-42.
[11] Siegel, D.A. and B.A. Franz. 2010. Oceanography: A century of phytoplankton change. *Nature* 466: 569-570.
[12] See Chapter 10, "Issues, Challenges, and Recommendations," in NRC 2000. *Issues in the Integration of Research and Operational Satellite Systems for Climate Research: Part I. Science and Design*. National Academies Press, Washington, D.C.
[13] Ibid.

and launch, and was responsible for spacecraft operations for five years at a fixed price, while retaining the operational and commercial rights to these data. In order to protect OSC's data rights, the release of research data was delayed, unless near-real time access is necessary for calibration and validation activities.[14]

- NASA access to algorithms and instrument characterization; NASA access to and reuse of data; and the establishment of an appropriate data archive.
  - Turning data into information of value to both a commercial entity *and* to the science community--now and in the future--requires detailed knowledge of how the raw data are generated, the algorithms that are used to process the data and generate higher-level data products, and control of how the data are archived. Taking these steps ensures the quality of the data and enables it to be characterized in a way that permits it to be combined with similarly well-characterized data from different instruments. It also facilitates future reprocessing in light of new knowledge and newer algorithms.
- Need for science teams as part of a plan to maximize the utility of the data
  - The establishment of a science team early in the development of a NASA Earth observation mission is a familiar and well-grounded recommendation. Once established, early science efforts (e.g. on prototype systems and/or synthetic datasets) can contribute directly to engineering and systems analyses. They can also optimize algorithms through competition (e.g. retrieval algorithms, extrapolations, etc.); provide a conduit to the user community; and provide timely notice to the research community, which would rapidly expand the user base. In addition, they can exploit the science perspective for system refinements (i.e. for follow-on missions), validation, and error detection.[15]
- Technical readiness as a measure of what observation methodology may be ripe for a public private partnership.
  - In the case of Earth imaging there is over six decades worth of heritage on the design of such sensors. This has provided the opportunity for significant core competencies to be developed in the private sector thus enabling public private partnerships. Those technologies that are mature are likely the ones that may be most amenable to a public private partnership. Conversely, the more novel the technology or newer the data stream may well require more government involvement to draw on a wider base of expertise for sensor characterization, calibration, validation, and science data processing and reprocessing.
- Commercial demand and market for the data is key to cost savings to the government.
  - If the government is the sole user of the data, there is little incentive for a public private partnership. In the example of SeaWiFS, the cost to the government was reduced by OSC's intent to sell the real-time data to the commercial fishing industry. Transition across basic research to applied research to the development of products and applications is not easy and not fast. However, the extent to which this can be accelerated in support of a range of societal benefit areas, including, for example, agriculture, transportation, fishing, recreation, and land use, will determine the non-governmental demand for the data and potential cost savings to the government.

I hope that even these brief comments demonstrate that obtaining the kinds of data required by scientists for critical Earth science applications and for credible forecasts of the future state of the Earth system requires careful attention from the design of an instrument to the plan for continuity to stewardship of the data. Yet, the science community operates in a way that typically differs dramatically from that of the commercial remote sensing industry. Public-private partnerships offer an alternative—and potentially less costly—method to acquire Earth observations. However, with SeaWiFS as a guide, a successful public-partnership may be realized only in limited circumstances and only with careful attention to the particular needs of both profit-making entities and the scientific community.

[14] For a fuller discussion, see McClain, C.R., Feldman, G.C., and Stanford B. Hooker. *An overview of the SeaWiFS project and strategies for producing a climate research quality global ocean bio-optical time series*. Deep Sea Research II, 51, 5-42, 2004.

[15] See Appendix D, "The Role of Science Teams," in NRC. 2000. *Ensuring the Climate Record from the NPP and NPOESS Meteorological Satellites*. The National Academies Press, Washington, D.C.

7
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