Space Technology for the New Century

Committee on Advanced Space Technology, National Research Council

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SPACE TECHNOLOGY FOR THE NEW CENTURY

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Preface

In the early twenty-first century, the U.S. government and commercial space industry plan to launch a wide variety of spacecraft for astronomy, remote sensing, communications, crewed and robotic exploration, and other activities. Advanced space technologies will be required for spacecraft to be less expensive and more capable than current ones. Some of the technologies will be developed by the U.S. Department of Defense or by commercial industry, but others—particularly those required for the National Aeronautics and Space Administration's (NASA's) unique science and exploration missions—will not be developed by any other agency or company and will have to be developed by NASA.

In the spring of 1996, NASA asked the National Research Council (NRC) to examine the nation's civil space technology needs for the post-2000 time frame and identify the technologies that NASA should develop to meet those needs. The NRC was asked to gather information about future technology requirements, consider innovative technologies that may enable new capabilities, determine which technologies would benefit from long lead-time research and technology development (R&T), and suggest ways for NASA to work more effectively with industry, universities, and other government agencies to conduct this R&T. (The complete charge to the committee is reprinted in Appendix A.) The committee was not asked to consider technologies for human support in space because those were the focus of another NRC report, Advanced Technology for Human Support in Space (1997).

The NRC asked its Committee on Advanced Space Technology to conduct this study. The committee did not work alone, however, and would like to thank the many organizations (listed in Appendix B) that provided us with white papers or met with us to discuss future space activities and technologies. We would also

like to thank Carl Allen, Roger Angel, Gary Bennett, Vincent Chan, Ben Clark, Mike Duke, Eliezer Gai, Henry Helvajian, Deborah Jackson, Stephen Lukachko, Ernest Robinson, Joe Sovie, K.R. Sridhar, Jim Trainor, Michael Wehner, and the staff of the Harvard-Smithsonian Center for Astrophysics for their help.

This report has been reviewed for the NRC by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank Aaron Cohen, Texas A&M University; France Cordova, University of California, Santa Barbara; Harold Forsen, National Academy of Engineering; Robert Frosch, Harvard University; Jack Kerrebrock, Massachusetts Institute of Technology; Henry Pugh, The Boeing Company; James Wertz, Microcosm, Inc.; and Peter Wilhelm, Naval Research Laboratory, for their participation in the review of this report. All of these individuals provided many constructive comments and suggestions, but the responsibility for the final content of this report rests solely with the authoring committee and the NRC.

Unlike other reports in the past decade that have looked at NASA's technology development program, this report is based on the assumption that NASA budgets will continue to be constrained and that limited funding will be available for technology development. Although research into advanced technology inherently carries a significant risk of failure, the research areas proposed in this report have a high potential to yield significant results with relatively small amounts of funding.

It is important to note that the technologies discussed in this report are not the only technologies NASA should develop. Some technologies that are not highlighted in this report may turn out to be even more critical for future space activities. The committee believes that the best approach for NASA is to invest in a portfolio of technologies that will be valuable in a wide range of future scenarios. By highlighting these technologies and suggesting ways NASA can best develop them, we hope we have performed a useful service for NASA and the nation.

DANIEL HASTINGS, *chair*

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Executive Summary

The National Aeronautics and Space Administration (NASA) is responsible for developing advanced space technologies that will lower the cost and improve the performance of existing space activities and enable new ones. Although NASA has recently proved adept at incorporating modern technologies into its spacecraft, the agency currently supports relatively little work in long-term space technology development. To enable ambitious future space activities and to achieve its long-term goals, NASA needs to engage in space research and technology development (R&T) in critical areas needed for the long term.

NASA requested that the National Research Council (NRC) examine the nation's space technology needs in the post-2000 time frame and identify high-risk, high-payoff technologies that could improve the capabilities and reduce the costs of NASA, other government, and commercial space programs. The NRC was also asked to suggest how NASA can work more effectively with industry and universities to develop these technologies. To accomplish these ends, the Committee on Advanced Space Technology, under the auspices of the Aeronautics and Space Engineering Board, undertook a systematic process of information gathering and technology assessment.

KEY TECHNOLOGIES

One outcome of this process was a list of six key technologies that the committee believes NASA should support with low-level (about $3 million to $5 million a year for each technology for three to five years) R&T funding. All six are high-risk, high-payoff technologies—there is no guarantee that they will prove to be viable, but if they are, they could greatly reduce the cost or increase the capabilities of future space activities. This list does not include all of the high-risk, high-payoff technologies NASA should pursue. The six technologies were extracted from a larger list by filtering out technologies that would not be enabling for future missions, were already under development elsewhere, or would have required more than low-level funding to produce major improvements. In three to five years, NASA—or a group sponsored by NASA—should re-examine potential space technologies and technology requirements to rewrite or modify this list. The six chosen technologies represent a small but broad investment portfolio that appears to hold high promise for large future benefits at the cost of a small investment today.

Wideband, High Data-Rate Communications over Planetary Distances

Wideband, high data-rate communications over planetary distances could enable live transmissions of high-resolution images from robotic rovers, orbiters, and astronauts on missions to other planets. Although several U.S. Department of Defense agencies and some private companies are currently working on wideband, high data-rate communications, NASA will need to take the lead in developing technologies—including high-precision spatial acquisition and tracking systems and high-efficiency lasers—to support such communications over planetary distances.

Precisely Controlled Space Structures

Structures in a weightless environment—especially structures that are unique to space—pose difficult control challenges. These challenges must be met to enable the next generation of instruments for space-based astronomy and to support the development of very large antennas for communications and remote sensing. NASA is uniquely suited to conduct this type of research in areas such as controlling deformable reflectors and formation flying of spacecraft to create distributed sensors.

Microelectromechanical Systems for Space

Microelectromechanical systems (MEMS) could enable the development of small, relatively low-cost spacecraft devices and subsystems with very low mass, volume, and power consumption. MEMS could be used to enhance conventional spacecraft or to create miniature spacecraft that could enable a broad range of new space activities. Although a vigorous government and industry-supported MEMS research effort is under way, little of this work is aimed at space applications. Low-level NASA funding in areas such as spacecraft bus technologies and NASA-unique sensors could therefore lead to significant advances.

Space Nuclear Power Systems

Advanced space nuclear power systems will probably be required to support deep space missions, lunar and planetary bases, extended human exploration missions, and high-thrust, high-efficiency propulsion systems. A major investment will eventually be needed to develop advanced space nuclear power sources, but low level R&T investments can make the systems that are eventually developed more efficient, less expensive, and safer. Currently, limited work is being done on advanced space nuclear power to enable ambitious future space activities. Unless NASA supports R&T in areas such as innovative conversion methods or innovative packaging and integration, future space nuclear power systems will probably be more expensive and less efficient.

Low-Cost, Radiation-Resistant Memories and Electronics

Radiation in the space environment can damage sensitive electronics, disrupt signals, cause single-event phenomena, and degrade microelectronic devices. Low-cost, high-capacity, low-mass, radiation-resistant memories and electronics are not currently available. NASA's support is needed to lay the groundwork for major improvements in radiation-resistant memories and electronics. NASA R&T support should focus on exploratory research in low mass shielding, reducing the frequency of and improving recovery from single-event upsets, and the use of radiation-resistant materials.

Extraction and Utilization of Extraterrestrial Resources

The capability to extract and utilize space resources can significantly improve the performance and lower the costs of planetary exploration, reduce the cost of constructing and shielding human habitats, and enable and accelerate the development of new generations of in-space capabilities. Virtually no other organization is working in this field, so NASA must support R&T in certain areas, such as planetary material handling, materials processing technologies, and systems design and engineering to optimize process efficiencies.

COOPERATIVE DEVELOPMENT OF KEY TECHNOLOGIES

Finding the most effective ways to develop new technologies is as important as choosing which technologies to pursue. The committee examined how NASA currently manages technology development and how the agency could work more effectively with industry and academia to develop advanced space technologies.

The committee found that NASA's new approach to decentralized R&T management is appropriate but faces challenges in providing support for advanced R&T on cross-cutting technologies or technologies that will pay off only in the long term. For NASA's new approach to work, the Office of the Chief Technologist will require strong and continued support from NASA senior leadership.

Although the agency has been successful in conducting cooperative R&T, NASA has often had difficulties conducting cooperative R&T with universities and private companies. To ensure that the most capable people and resources are involved in its R&T, NASA must involve both industry (including small businesses) and academia in its R&T programs. The Office of the Chief Technologist should work with the NASA centers to organize cooperative programs among NASA centers, universities, and industries to leverage NASA's investment in new technology. NASA should also develop a "fellows" program to place superior employees into universities for periods of one to two years and support subsequent collaborative efforts after they have returned to the agency.

1

Introduction

Advanced space technologies are needed to enable many potential space activities and to reduce the cost and improve the performance of others. The National Aeronautics and Space Act of 1958, which created the National Aeronautics and Space Administration (NASA), directed the agency to conduct the nation's civil space activities to contribute materially to "the preservation of the role of the United States as a leader in aeronautical and space science and technology..." (Space Act, 1958). Subsequent national space policies have reaffirmed NASA's responsibility for the development of advanced civil space technologies (The White House, 1989, 1996).

In the agency's early years, NASA—often working through private contractors and university grants—developed many technologies for use in its space missions. A 1987 report by the National Research Council (NRC), however, found that "since the Apollo program, little has been done to enhance or develop the basic technologies that will enable future missions or provide the nation with a variety of options for the space program" (NRC, 1987). Since the late 1980s, NASA's space technology program has continued to evolve as agency priorities have shifted in response to changes in the larger environment.

One change in NASA's environment has been the rapid growth in the availability of technologies from outside NASA that are applicable to space uses. These new technologies are being developed by the rapidly growing commercial space industry and the U.S. Department of Defense (DOD), which has made its new technologies available to NASA and the commercial sector with increasing frequency. Rather than producing new space technologies, NASA has often used technologies developed outside the agency. Technology developers outside NASA, however, are generally not focused on achieving the agency's long-term goals.

Budget constraints have also had a major impact on NASA since the late 1980s. The agency has recently responded to constrained budgets by developing small spacecraft that incorporate modern technologies, increasing the number of missions and reducing the cost of transportation to orbit. These efforts, however, are intended to yield clear benefits in the relatively near term—the agency currently supports very little work on long-term space technology development.

If NASA is to continue its drive for more capable and cost-effective missions into the twenty-first century, it will need advanced and innovative technologies—some of which may require years to develop and mature. The commercial space industry and other government agencies could provide some of these technologies, but some critical technologies will require long lead-time NASA research and technology development (R&T) to ensure that they are available when required. NASA also will have to develop a plan and mechanism to support advanced technology development for the long term if it intends to be a source of technology for industry and other government programs in the new century.

The NRC Committee on Advanced Space Technology examined future technology needs and opportunities to create a technology development portfolio of six enabling space technologies that would maximize the impact of the small amount of technology development funding that NASA is expected to be able to provide in a constrained budget environment. In this report, the six enabling space technologies are examined in detail, and key areas for future NASA support are identified. Suggestions are also offered for improving NASA's approach to space technology development, focusing primarily on how the agency can work more effectively with industry and academia.

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2

Study Approach

NASA asked the NRC to examine the nation's space technology needs for the post-2000 time period and identify high-risk, high-payoff technologies that could improve the capabilities and reduce the costs of NASA, other government, and commercial space programs. The NRC was also asked to suggest how NASA could work more effectively with private companies and universities to develop these technologies. To accomplish these ends, the NRC's Committee on Advanced Space Technology undertook a systematic process of information gathering and technology assessment.

IDENTIFYING KEY TECHNOLOGIES

The committee took two approaches to identifying promising technologies. One was to predict civil space activities that would be conducted in the post-2005 time frame and determine the technologies that would be necessary to enable them. The other was to examine a range of potential space technologies and try to determine whether they would enable new space activities.

The committee gathered information about potential space activities and enabling technologies from a wide range of sources. These included past reports on space technologies by the NRC, Space Technology to Meet Future Needs (NRC, 1987) and Technology for Small Spacecraft (NRC, 1994); NASA documents, including the agency's last Integrated Technology Plan (NASA, 1991) and more recent publications, such as Mission to the Solar System: Exploration and Discovery (JPL, 1996) and the NASA Strategic Plan (NASA, 1997); and reports by other advisory groups, including Advanced Technology for America's Future in Space (SSTAC, 1992) and New World Vistas: Air and Space Power for the 21st

Century (AFSAB, 1996). The committee also made extensive outreach efforts to gather the opinions of numerous organizations in the space field.

The committee asked more than 30 organizations active in the space arena—from NASA centers to industry groups to space advocacy organizations—to prepare white papers describing: (1) the kinds of space activities the United States will need to conduct in the post-2000 time frame to be a leader in civil and commercial space; (2) new technologies that would be enabling or helpful for these activities; (3) who they believe would develop these technologies; and (4) whether they believed that the development of these technologies would benefit from long lead-time, low-level concept studies and R&T supported by NASA. The organizations that responded are listed in Appendix B. Additional information was gathered from a similar survey of the space industry conducted by the Air Force Scientific Advisory Board and during visits by committee members to organizations active in the space field.

From these sources of information, the committee compiled a list of approximately 50 representative future space activities and 200 potential technologies. Appendix C contains the committee's list of representative future space activities. Appendix D contains the list of technologies grouped into categories, such as power, propulsion, and thermal control.

To narrow down the list of technologies, the committee was divided into five panels, one for each of the major areas of civil space activities expected for the post-2005 period. The five areas were:

- study the galaxy and universe
- study and explore the Solar System
- study the Earth
- provide other services to users on Earth
- space operations and infrastructure

Each panel then examined the lists of promising technologies and determined whether the technologies would be enabling, helpful, or unimportant for some or all of the activities in their area. Figure 2-1 is a greatly simplified version of the matrix used by the committee in this exercise. The full matrix contained all of the technologies and activities listed in Appendices C and D and was filled in by each of the panels. A short list of potential key technologies, including the technologies ranked highest by each panel, technologies that were enabling for multiple different classes of future activities, and technologies that had been strongly and repeatedly suggested during the committee's outreach, was then prepared. This list appears in Box 2-1.

Three filters were then applied to refine the list of key technologies. The first filter eliminated technologies that were not enabling for at least some activities or were not broadly applicable. Enabling technologies were defined as those that either made feasible space activities that would otherwise be infeasible or that dramatically reduced the cost or time required to perform a space activity—by two-thirds, for example. In this way, technologies that were merely incremental

ACTIVITIES

TECHNOLOGIES	Study the Galaxy and the Universe	Explore the Solar System	Study the Earth	Provide Services to Users on Earth	Space Operations and Infra-structure
Communications					
Earth-Based Systems					
Guidance and Control					
Information Technologies					
Launch					
Materials					
Power					
Propulsion					
Robotics					
Sensors					
Systems and Electronics					
Structures					
Thermal Control					
Working in Space					

FIGURE 2-1 Technology Assessment Matrix.

improvements to current technologies were eliminated. The second filter eliminated technologies that are already receiving large amounts of development funding, including funding from NASA, other U.S. government agencies, and private industry. (Funding for technology development outside of the United States was not considered unless U.S. organizations were expected to be able to use the technology.) The third filter eliminated technologies that might have been very important but would not have benefited significantly from low-level, long lead-time NASA funding. All three filters were intended to create a technology development portfolio that would yield the most benefits from a small amount of NASA funding.

After these filters were applied, a short list of key technologies emerged. The list was examined to ensure that the technologies were applicable across a wide range of future space activities and not just to one kind of activity. The committee then investigated each technology in more depth to determine the particular areas that would benefit most from long lead-time development funding. Finally, draft write-ups of each technology were critiqued by experts in the relevant technical areas and revised in response to their comments. The results are presented in Chapter 3.

BOX 2-1
Initial List of Key Technologies

- Antimatter propulsion
- Autonomous systems
- Beamed power
- Data compression technologies
- Deployable structures
- Digital systems processing
- Electric propulsion
- Extraction and utilization of extraterrestrial resources
- Flywheels
- Higher-efficiency solar power generation
- Improved antennas (phased arrays, high power, high frequency)
- Improved thermal control systems
- Lower cost launch and transfer vehicles
- Low-cost/low-power imaging sensors
- Low-cost, radiation-resistant memories and electronics
- Microelectromechanical systems for space
- Precisely controlled space structures
- Space nuclear power systems
- Task-capable telerobots
- Wideband, high data-rate communications over planetary distances

IMPROVING NASA'S TECHNOLOGY DEVELOPMENT PROCESSES

The committee's approach to determining how NASA can work more effectively with industry and academia to develop advanced space technologies was based heavily on the committee's expertise and experience but also included significant outreach. The organizations that were asked to provide white papers on technology were also asked to suggest ways for NASA to work more effectively with other agencies, universities, and private companies on early technology R&T. Numerous responses were received and were used by the committee to develop findings and recommendations. The committee also reviewed numerous past reports that have commented on NASA technology development (CBO, 1994; NRC, 1983, NRC, 1993; NRC, 1995).

The committee also met with NASA leaders to discuss the agency's current methods of technology development, focusing on cooperative efforts with academia and industry. The committee initially met with the Associate Administrator of the Office of Space Access and Technology (OSAT) John Mansfield. After OSAT was dissolved, the committee met with NASA Associate Deputy

Administrator Michael Mott. Finally, the committee met with NASA Chief Technologist Samuel Venneri and Deputy Chief Technologist Gregory Reck, near the end of the study. The committee's findings and recommendations in this area are presented in Chapter 4.

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3

Key Technologies

The committee was asked to determine which high-risk, high payoff technologies have the greatest potential for improving the capabilities and reducing the costs of NASA, other government, and commercial space programs in the 2000 to 2020 time period and to determine which of these new technologies could benefit most from NASA-supported, low-level, long lead-time R&T. In this chapter, a diverse portfolio of six technologies is recommended. Determining the exact amount of funding is beyond the scope of this report, but the committee's working assumption was that funding for each technology of about $3 million to $5 million a year for three to five years would be sufficient to create a high probability of significant advances. The committee is aware that NASA is already supporting work on some of these technologies and endorses those investments.

This list of key technologies is not static. Nor does it represent all of the high-risk, high-payoff technologies NASA should pursue. Rather, it is a snapshot of six key technology areas that at this moment appear to hold great promise of yielding large future benefits for small investments today. Regular surveys of technology needs for future space activities, as well as of promising new space technologies, will be necessary to update this list.

The procedures the committee used to select the key technologies are described in Chapter 2. Narrowing the list of technologies was a difficult task, and many valuable technologies that met some, but not all, of the committee's criteria had to be left off. For example, improved thermal control systems will be valuable for a wide range of spacecraft, but large amounts of commercial funding are being invested to develop technology in this area as heat dissipation becomes more of a problem for high-power communications satellites. Another example, task-capable telerobots, will be crucial to future space exploration, and perhaps to space station operations, but another $3 million to $5 million a year would only advance the state of the art in this field incrementally.

Perhaps the most important suite of technologies that are recognized as critical but are not included in the list are technologies that would reduce the cost of access to space, including both Earth-to-orbit and intra-orbital transportation. Launch costs currently represent a large fraction of the total cost of most space activities, and reducing these costs will not only be beneficial for current activities, but will also enable new kinds of space activities. Reducing the costs of launch vehicles could also help U.S. companies regain a larger share of the growing international space launch market.

Process improvements and innovative applications of existing technologies can help to reduce launch costs, but major reductions in the costs of expendable launch vehicles will require dramatic reductions in engine and structure costs. Low cost, reusable launch vehicles may require even more advanced technologies. Although the committee wholeheartedly supports technology development to reduce launch costs, it believes the low-level, long lead-time R&T recommended in this report will not have a significant timely effect on space transportation capabilities. These six key technologies are described below.

WIDEBAND, HIGH DATA-RATE COMMUNICATIONS OVER PLANETARY DISTANCES

Description

Communications over planetary distances are now conducted over radio frequencies. Higher frequency carriers could enable the rapid transfer of much larger amounts of data. Wideband, high data-rate communications might be conducted by high frequency microwave transmissions or optical transmissions based on laser technology. Challenges to be overcome include detecting weak signals over distances of hundreds of millions of miles and maintaining extremely precise pointing accuracies.

Importance

Wideband, high data-rate communications over planetary distances would enable the real-time transmission of high-resolution images. For example, a robotic rover using this technology could transmit high-definition, live, hyperspectral stereo imagery to Earth as it traveled over the surface of Europa. In the event of an accident, astronauts on the way to Mars could rapidly transmit detailed video of damaged components or injuries, providing technical experts and doctors on Earth with data that could be critical to helping the crew. A Jupiter orbiter equipped with this technology could provide nearly continuous high-resolution movies of the turbulent Jovian atmosphere.

The same technologies that would to enable wideband, high data-rate communications over planetary distances could also be used for Earth-orbiting spacecraft, allowing them to use lower-power lasers or smaller receivers for intersatellite links. These communications technologies could also prove to be superior to current technologies from a cost and weight perspective and would certainly not encounter the problems of congestion associated with many radio frequencies in the near-Earth region.

Rationale for NASA Involvement

NASA is the only organization in the United States that has both an interest in planetary exploration and the capability and will to fund technology development to support planetary exploration. Although the European Space Agency, the National Space Development Agency of Japan, the DOD, and U.S. companies are all working on optical communications, they have focused on Earth-to-orbit applications. Planetary distances are four to five orders of magnitude greater than Earth-to-orbit distances. Consequently wideband communications over planetary distances will require technologies unlikely to be developed for Earth-orbit applications. If wideband, high data-rate communications over planetary distances are to be realized, NASA will have to take the lead. Industry support in this area will be limited to responses to NASA procurements for the foreseeable future.

Key Areas for NASA-Funded Research

The basic technologies for wideband high data-rate communications in space have already been developed. However, there are still barriers to high data-rate communications over extremely long distances. The broad key technology areas for NASA investment are listed below:

- high-precision spatial acquisition and tracking systems (maintaining the extreme pointing precision required for long-distance communication may require highly stable structures and high-precision mirrors)
- high-efficiency, high-brightness lasers for lightweight, low-power, long-range optical communications
- technologies to reduce the mass and power requirements of communication systems, including nonmechanical, beam-steering technology, such as optical phased-arrays, and low drive voltage modulators
- the development of architectures to reduce the cost of facilities that receive signals on (or near) Earth, including innovative Earth and space-based receivers

PRECISELY CONTROLLED SPACE STRUCTURES

Description

Structures in a weightless environment, especially structures that are unique to space—including gossamer structures and distributed structures—pose difficult control challenges. The field of precisely controlled space structures involves high-accuracy measurement and control of the geometrical configurations, attitudes, and positions of single and multiple space structures. Actuators with a large dynamic range and mechanisms that can control geometrical configurations ranging in size from meters to nanometers will be required, as will technologies for high performance vibration damping and thermal isolation.

Importance

Continued scientific exploration of our galaxy and the universe for the purpose of expanding knowledge through optical, infrared, and x-ray astronomy requires increasingly precise measurements and stable control of large space-based mirrors, antennas, and interferometric baselines. Astrometry, for example, requires measurements of the positions of structures over tens of meters to accuracies of tens of picometers, deployment accuracies of millimeters, and maintaining vibrations to nanometer amplitudes for frequencies above 10 Hz. Nulling for exoplanet detection requires precision deployment and control of up to 150-meter structures to accuracies of several centimeters, with final operating temperatures of approximately 30 Kelvin. Multiple thin-mirror infrared telescopes with diameters of a meter or more operating at approximately 30 Kelvin need to be stable to tens of nanometers for long periods of time. Applications like these will require advanced precision control capabilities.

New technologies to meet these requirements may include highly damped structural members, passive and active vibration control, precise thermal control and low thermal expansion materials, “smart” (active) structural elements, and distributed vehicles that can perform precision free-flying. Once developed, these technologies might also be useful for controlling large antennas on communication satellites, pointing Earth-sensing satellites with precision, and controlling large gossamer solar arrays, radiators, and tethers.

Rationale for NASA Involvement

Although the DOD and companies that build satellites are interested in somewhat larger space antennas and mirrors than are currently available, they are not investing in the development of technologies for much larger, precisely controlled space structures. NASA-funded research will be needed in areas where NASA requirements will be more exacting than DOD requirements.

Precision control of space structures is an inherently space-oriented, cross-cutting technology that will incorporate a variety of basic disciplines (damping/elasticity, dynamics, materials, cryogenics, microelectromechanical systems [MEMS], computational structural mechanics, piezoelectricity) and a wide range of physical applications (mirrors, antennas, deployable structures, precise actuators). This technology supports the kinds of generic engineering space research for which NASA is responsible. NASA is capable of undertaking this R&T by virtue of its experience with various aspects of control-structures interaction (CSI).

Key Areas for NASA-Funded Research

The broad key technology areas for NASA investment in R&T on precisely controlled space structures are listed below. Close coordination with the DOD should be maintained to ensure that work is not being duplicated.

- extending nanometer-precision metrology to long baselines (which will enable the operation of very large interferometers)
- figure control of deformable reflectors by mechanical, thermal, and piezoelectric techniques (which could lead to dramatic decreases in the weight of primary mirrors)
- vibration isolation and structural damping technologies for dimensional stability and to simplify the acquisition of metrology data
- thermal control of structures, including sunshades and insulation (particularly at cryogenic temperatures)
- long-term maintenance of precise antenna-pointing attitudes to simplify system operations
- long-term measurement and control of the relative positions and attitudes of spacecraft flying in formation (which would enable very long-baseline interferometry, potentially with baselines of thousands of kilometers)
- system optimization studies of launch, deployment, and control of large elastic structures

MICROELECTROMECHANICAL SYSTEMS FOR SPACE

Description

MEMS involve the synthesis, integration, and application of materials, processes, and devices in the submicron to millimeter size range. MEMS development-based materials and fabrication methods are already being used to produce miniature gears, inertial sensors (gyroscopes and accelerometers), pressure and acoustic sensors, digital distributed surface controls, pumps, valves, and switches (for microwave, optical and radio frequency communications). MEMS and nanoelectronic technologies can be combined into application-specific, integrated microinstruments (ASIMs) and can be further integrated to create subsystems.

Importance

MEMS technologies could enable the development of small, relatively low-cost spacecraft devices and subsystems—including sensors and communications, navigation, power, thermal, and propulsion subsystems—with very low mass, volume, and power consumption. On conventional spacecraft, MEMS technologies could increase mission survivability by enabling the use of more redundant systems with a relatively small increase in weight and power requirements. If spacecraft mass can be reduced, missions to the outer planets could be launched from smaller launch vehicles at higher velocities. MEMS could also provide distributed control and sensing capabilities to enhance and enable large, lightweight, or deployable space structures.

MEMS technologies could also be integrated to create entire miniature spacecraft, which could be deployed in large numbers to function as a sparse-array, synthetic-aperture radar or to take distributed measurements of Martian surface temperatures or the atmosphere of Titan. The combination of redundancy, flexibility, and potential low cost to launch distributed systems (because no connecting structures are required) could enable a broad range of new space activities. Miniature spacecraft could also be launched singly as secondary payloads to conduct simple missions—such as measuring a single atmospheric variable for a limited period of time. Alternative launch options, such as cannons or other gun launchers (e.g., rail guns, coil guns, light gas guns, ram accelerators) may be feasible for miniature spacecraft.

Rationale for NASA Involvement

MEMS R&T programs supported by multiple government agencies and industry are developing concepts and processes for a broad range of applications. The MEMS field is growing rapidly and is currently largely driven by ground-based commercial and defense expectations. Except for work at NASA's Jet Propulsion Laboratory, little of this R&T is aimed at space applications (although the Aerospace Corporation has explored applications of ASIMs for space systems).

The space environment poses unique challenges and opportunities for small systems (often based on fundamental characteristics, such as surface-to-volume ratios and radiation damage) that can be very different from the challenges faced by terrestrial systems. The limited efforts at space applications by the government and industry appear to be concentrated on "payload" or micro-electronic devices. Little work is being done on spacecraft bus technologies (such as power, thermal, structure, and propulsion). By focusing on these technologies and leveraging existing MEMS technology and infrastructure, NASA could provide a service for all space efforts, as well as enable a wide range of future space activities.

Key Areas for NASA-Funded Research

The broad key technology areas for NASA investment in MEMS R&T are listed below:

- sufficient investments in bus technologies that are not being developed by other organizations to take full advantage of miniaturizing space systems
- "payloads" that are NASA space-mission-unique and (unlike such items as miniature accelerometers) are not likely to be available from commercial ventures
- solutions to problems specific to space missions, including surviving in unique environments (particularly the radiation and vacuum environments), comparatively low production rates, and controlling distributed formations of small satellites

SPACE NUCLEAR POWER SYSTEMS

Description

Almost all space activities require a supply of conditioned electrical energy. Near-Earth spacecraft generally use arrays of photovoltaic solar cells linked with chemical storage batteries to provide power. However, solar power systems may not be feasible for many deep space missions, lunar and planetary bases, extended human exploration missions, or for powering high-thrust, high-efficiency propulsion systems. Advanced space nuclear power systems—including various types of reactors and radioisotope thermoelectric generators (RTGs)—will probably be required. Developing these systems will require major funding, but low-level research into improving conversion efficiency and developing demonstrably safer nuclear power sources through the use of new materials and designs could greatly improve the technical efficiency and lower the cost of the nuclear power sources that are eventually developed.

Importance

Nuclear power sources are typically compact, produce power reliably for many years, are relatively unaffected by the external environment (e.g., radiation belts, Martian dust storms), and do not require exposure to sunlight. Solar power systems, on the other hand, are generally not compact, are affected by the external environment, and require exposure to sunlight. Moreover, their efficiency drops rapidly as the distance from the sun increases. Batteries or other energy storage devices, although they are compact and insensitive to the external environment, cannot produce power for long durations. Nuclear power will be a critical technology for many future space activities (probably including lunar bases and outer-planet missions) for which solar power will not be feasible (AIAA, 1995).

The NRC has stated in a previous report that "nuclear power eventually will be essential for lunar and Mars bases" (NRC, 1990). Advanced radioisotope power sources with conversion efficiencies well above today's 5 to 10 percent efficiencies would enable smaller, more capable outer planet probes. High-power advanced reactors could power either high specific-impulse electric propulsion systems for deep-space missions or high-thrust thermal propulsion systems to enable shorter crewed missions to Mars or the asteroids. Lower-power reactors, which present an extremely low radiation hazard during launch, could power sensors and communications systems onboard deep space probes.

Rationale for NASA Involvement

Unlike solar arrays and battery technologies, for which commercial interests will continue to drive R&T, space nuclear power has no commercial R&T program to enable ambitious future space activities. Some research on thermionic conversion is being conducted by the DOD, but it is not aimed at supporting NASA missions. Unless NASA supports R&T on advanced nuclear power for space, the required technologies will probably not be available for future space missions (see Box 3-1).

It is important to note that low level R&T alone will not be sufficient to enable space nuclear power systems—major investments will eventually be needed to develop advanced space nuclear power sources. The R&T investments should, however, make the advanced space nuclear power systems that are eventually developed more efficient, less expensive, and safer. Low-level investments

BOX 3-1
Nuclear Power?

The committee is well aware that political constraints may make R&T on advanced space nuclear power systems unpopular. However, the committee could not ignore the fact that space nuclear power will be a key enabling technology for future space activities that will not be able to rely on solar power.

The development of advanced nuclear power technologies for space has received little funding in the past decade. If NASA does not invest now in the long-term R&T that could lead to future high-efficiency, safer, nuclear power sources, future mission planners and spacecraft designers will be deprived of potentially valuable design options that could improve safety and performance and reduce the costs of future space activities.

in this area may also help to ensure that expertise in space nuclear power is available when major investments are eventually made.

Key Areas for NASA-Funded Research

The broad key technology areas for low-level long lead-time NASA investment in nuclear power sources for space are listed below:

- innovative conversion to electricity, including advanced static conversion (e.g., thermoelectric, alkali metal thermal to electric [AMTEC], thermophotovoltaic) and dynamic conversion of heat to electricity (e.g., Brayton, Rankine, Stirling conversion)
- innovative packaging and integration, including the development of small, safe, modular, nuclear power packages that can be added incrementally to increase power levels
- innovative materials, including components that can operate in high temperatures and high radiation environments
- innovative power management, including the use of supplementary devices (such as ultracapacitors) that can store energy and release it quickly for high power, and power management schemes that can reduce output power requirements

LOW-COST, RADIATION-RESISTANT MEMORIES AND ELECTRONICS

Description

The Earth's atmosphere and magnetic field protect electronics on the Earth's surface from the harsh radiation environment in space. Various types of radiation in the space environment, including trapped radiation, solar particle events, and galactic cosmic rays, can damage sensitive electronics, disrupt signals, cause single-event phenomena, and degrade microelectronic devices. This problem is especially severe in regions, such as the Earth's Van Allen belts and Jupiter's magnetosphere, where the radiation environment is particularly harsh. Low-cost, high-capacity, low-mass, radiation-resistant memories and electronics are not currently available.

Importance

Many future space activities, including high-resolution imaging and deep-space missions with onboard mission planners and autonomous operations, will require the storage of large volumes of data. These memories, as well as electronic devices and subsystems, will be subjected to long-duration exposure to the space radiation environment. Radiation-resistant electronics would reduce the need for redundancy in some systems, as well as allow spacecraft operations in the Van Allen belts and other high-radiation areas.

Rationale for NASA Involvement

Industry has developed some radiation-resistant processors, and several small companies have been developing shielding concepts. The U.S. Department of Energy, the DOD, and other organizations have also invested in R&T on radiation-resistant electronics. However, most of this work is focused on the immediate future rather than long-term benefits. Very little exploratory research has been funded in this area since the late 1970s. NASA's key niche should be supporting the investigation of truly fresh ideas that may not result in immediate payoffs but would enable low-cost, high-capacity, low-mass, radiation-resistant memories and electronics in the longer term.

Key Areas for NASA-Funded Research

The broad key technology areas for NASA investment in low-cost radiation-resistant memories and electronics R&T are listed below. Emphasis should be on exploratory research that could have large payoffs in the post-2005 time frame:

- improving logic and storage elements to improve recovery from single-event upsets
- logic and storage elements with higher linear energy transfer (LET) thresholds that are less susceptible to single-event upsets.
- innovative low-mass shielding that is more effective and lighter than current shielding (which would enable spacecraft to use advanced, off-the-shelf microprocessors, which would be a huge improvement over currently available systems)
- use of radiation-resistant materials, including silicon-on-insulator and silicon-on-sapphire circuitry or other radiation-resistant materials, for electronic circuitry

EXTRACTION AND UTILIZATION OF EXTRATERRESTRIAL RESOURCES

Description

The capability to extract and utilize space resources, particularly from the Moon, Mars, and near-Earth asteroids, would provide an alternative to transporting certain products from Earth into space. This technology area includes exploring for resources; mining and refining raw materials; processing, manufacturing, and storing materials derived from raw resources; transporting materials to their point of use; and identifying potential uses or customers. Technology development in this area would focus on extraction, processing, and storage, although advances in other areas, such as power, automation and robotics, and space transportation, will also be required for many applications.

Importance

The in situ production of propellant from extraterrestrial resources could significantly increase the performance and lower the costs of planetary exploration missions that require the return of people or hardware to Earth. The extraction of propellants from the Martian atmosphere, for example, could dramatically cut the cost of round-trip missions to Mars by reducing the amount of fuel that would have to be to be lifted from Earth.

Using extraterrestrial resources could also make these missions safer. For example, in situ processing could be used to produce reservoirs of oxygen, nitrogen, and water that could support a crew in the event of the failure of life support systems. In the long term, in situ resource utilization will be essential for self-sustaining human settlements in space.

Extraterrestrial resources could also be used for shielding or constructing human habitats. Surface materials, such as the lunar regolith, might be much cheaper than materials delivered from Earth, particularly for applications that require large masses of material (such as radiation shielding for lunar surface habitats). If in-space transportation for bulk material from the Moon or nearby asteroids became cost effective, it could also enable and accelerate the development of new generations of government and commercial in-space capabilities that require large masses of material, such as large space stations—or hotels or power stations—beyond low Earth orbit.

Rationale for NASA Involvement

No other agency or commercial company (with the exception of the limited efforts of one Japanese construction company) has shown an interest in the extraction and utilization of extraterrestrial resources. NASA should develop this technology both to support its own missions and to lower the barriers to the future commercial use of space resources.

Key Areas for NASA-Funded Research

The broad key technology areas for NASA investment the extraction and utilization of extraterrestrial resources are listed below:

- robotic systems, teleoperation, and autonomous failure detection and repair systems for mining, moving, and preparing planetary materials for processing (current NASA-supported R&T toward extracting useful products from the Martian atmosphere has made progress, but very little work has been done on handling solid planetary materials, including ices)

- materials processing technologies at various levels, including chemical reactors—particularly energy-efficient, high production-efficiency reactors—and water and carbon dioxide electrolysis systems, including high temperature systems
- systems design and engineering, particularly thermal control and thermal management systems, to optimize process efficiencies
- manufacturing technologies with high throughput that are simple, effective, and have minimal repair and maintenance requirements or manufacturing systems that can be fabricated from in situ materials
- self-erecting systems, in which small systems, probably multiple interacting systems, use simple manufactured pieces to assemble much larger structures
- cryogenic storage technology for produced propellants, including lightweight tanks, efficient cryocoolers, and insulators

RECOMMENDATIONS

Recommendation 1. NASA should initiate a program to support low-level research and development (about $3 million to $5 million a year for each technology area for three to five years) in the six technology areas described in this chapter. The agency should also consider designating these technologies as topic areas in solicitations for existing programs.

Recommendation 2. In three to five years, NASA—or a group sponsored by NASA—should re-examine promising technologies and technology requirements and modify the portfolio of key technologies, if necessary.

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4

Cooperative Development of Space Technologies

Finding the most effective means of developing new technologies is as important as choosing which technologies to develop. If the task of technology development is not given to the right people, the results could be disappointing. If the approach is not well organized, valuable technologies could be overlooked rather than incorporated into spacecraft. This chapter examines how NASA currently manages technology development and suggests how the agency could work more effectively with industry and universities to develop advanced space technologies.

NASA'S CURRENT APPROACH

In the past, many NASA resources were oriented toward operations. New programs tended to be evolutionary rather than revolutionary, and technology development was centralized to ensure that R&T critical to NASA's future was being addressed and given budgetary priority. NASA's technology development program had its own budget and its own associate administrator. Once a technology had been developed by the technology organization, it was offered to the agency's mission developers for use in space missions.

NASA's current technology organization reflects the fundamental shift in the agency's vision and direction under the present administrator's efforts to reinvent NASA (see Box 4-1). The agency's four enterprises (Human Exploration and Development of Space, Earth Science, Space Science, and Aeronautics and Space Transportation Technologies) are now being challenged to establish performance requirements for missions that can only be met by incorporating new

BOX 4-1
Changes in NASA's Technology Organization

The lead organization responsible for space technology development at NASA has undergone a number of transformations since the late 1980s. The Office of Aeronautics and Space Technology (OAST) became the Office of Aeronautics, Exploration and Technology (OAET) in 1990. In 1992, OAET turned into the Office of Advanced Concepts and Technology (OACT), which became the Office of Space Access and Technology (OSAT) in 1994. OSAT was dissolved in 1996. The responsibility for space technology development now rests with NASA's mission enterprises, as advised and coordinated by the Office of the Chief Technologist.

technologies. Each enterprise is responsible for acquiring or developing the required technologies.

The four-person Office of the Chief Technologist is responsible for overseeing agency-wide technology development (NASA, 1997). The chief technologist and his staff are responsible for monitoring NASA's technology development to ensure it is in line with overall agency goals. The chief technologist's influence is based on his relationship with the NASA administrator. With the administrator's support, the chief technologist can veto enterprise budgets that do not have enough R&T funding.

NASA management also plans to shift agency priorities by shifting the agency's focus from developing space systems and conducting flight operations to engineering R&T that will enable future space systems. As NASA's new Strategic Plan states, the agency "will focus on what we do best by reestablishing NASA's role as a research and development agency" (NASA, 1997).

Assessment of the New Technology Development Process

Decentralization

NASA's new approach of decentralizing control of technology development seems to be in keeping with the agency's goals of pushing frontiers and defining missions that have challenging requirements. This model has many similarities with the approach commercial organizations have taken to successfully managing technology development when time-to-market is critical, by placing a premium on developing highly relevant technology and efficiently produced products.

However, NASA's task is broader than simply developing technologies and rapidly incorporating them into products. The agency's statutory charge of expanding human knowledge in space, improving space vehicles, and preserving the leadership of the United States in space science, technology, and applications (Space Act, 1958) requires that NASA also pursue R&T that goes beyond the immediate requirements of the enterprise missions. Because NASA enterprises are necessarily mission-oriented, however, their primary charters do not require them to support R&T that leads to the development of technologies that are broadly useful across a wide variety of future space activities (including commercial space activities) or technologies that will pay off over the long term.

Finding. NASA's new approach to decentralized R&T management is appropriate to the agency's new vision but may not sufficiently support advanced R&T on cross-cutting technologies or technologies that will pay off only in the long term.

Office of the Chief Technologist

The chief technologist does not have a large budget or staff. Therefore, a key to the success of the decentralized R&T approach, including NASA's ability to develop the kinds of long-range technologies discussed in this report, will be the interest shown by the NASA administrator and the authority he grants the chief technologist to act on his behalf. For NASA's new approach to work, the administrator will have to support the chief technologist as the agency's "technology conscience" who ensures that the R&T conducted by the enterprises is in keeping with the overall strategic plan of the agency.

In this enterprise-driven model, the associate administrators of the enterprises must be responsible and accountable for pushing the state of the art in technology for future missions and for protecting resources budgeted for R&T. Unless the enterprise organizations budget and protect R&T resources, the committee believes those funds would almost certainly be used as discretionary reserves to solve the inevitable problems that arise in mission area programs. (The history of research, both in the private sector and government, is rife with examples of the vulnerability of research budgets during times of fiscal constraints.) NASA centers performing research—the center directors in particular—will have to be both R&T advocates and the first line of defense in protecting resources earmarked for R&T.

We believe that the process would be much less vulnerable if the Office of the Chief Technologist were given explicit authority to initiate and fund research projects within the enterprises and to protect some projects from fiscal attack. The modus operandi now relies heavily on creative tensions, good will, and consensus; but the commitment to R&T, especially to generic, long-term research, may not be strong enough to survive without institutional protection.

Finding. For NASA's new technology development approach to work, the chief technologist will need strong, continuous support from the NASA enterprises, the center directors and, most important, the NASA administrator.

Emphasizing Engineering Research and Technology Development

NASA management's plan to increase the agency's focus on engineering R&T for future space systems (and reduce the agency's focus on space system product development and flight operations) has the potential both to improve the agency's ability to conduct long-term R&T of the type described in Chapter 3 and to increase cooperative R&T with academia and industry. However, strong organizational barriers could hinder an orderly, gradual, and graceful change.

One potential barrier could arise from internal competition for limited agency funding. Space flight operations and development will inevitably encounter problems that require additional funding to resolve. Because NASA will probably be operating under budgetary constraints for the foreseeable future, there may be strong pressure to resolve these near-term problems by diverting funding from longer-term R&T that will not pay off for years. The pressure is likely to increase if R&T funding is designated for researchers in universities and private companies rather than to researchers at NASA centers.

The culture at some NASA centers might pose additional barriers to the agency's transformation. The agency's flight centers (Marshall, Goddard, and Johnson), for example, have strong operational mind-sets and have historically relied on older technology for their flight programs. These centers have often resisted new ideas from outside the NASA community, or even from other NASA centers. Plans to increase cooperative R&T or to reorient funding from space systems development and operations to R&T will have to take these historical factors into account.

COOPERATIVE PROGRAMS

Government agencies, private companies, and universities operate on different time scales, bring different assets to bear on problems, and have different motivations. Understanding these differences is essential to developing successful cooperative strategies for advanced space technology development.

Private companies necessarily focus on the near term. Because failure to implement a new technology affects the bottom line, they tend to be conservative about using their own funding to explore new technologies, and they only implement technologies that have a high probability of success and payback in the near term (less than five years). The advantages private companies offer include experienced workers, the ability to dedicate resources rapidly to a task, and experience with fast-paced projects. Private companies are willing to participate in cooperative projects as long as they can realize a profit.

NASA approaches R&T very differently for many reasons. Rather than trying to make a return on investment, NASA must maintain a high level of support from Congress, taxpayers, and the president. Thus, the agency is encouraged to plan for the long term and on a grander scale than industry. The agency may also be forced to distribute funding geographically rather than to where it would be most useful from a technical standpoint. Government regulations (as well as budgetary considerations) have also hampered NASA's efforts to revitalize its workforce.

NASA has many experienced people, as well as the ability to implement and test new ideas and technologies. But the agency has also encountered difficulties in the past in conducting cooperative space R&T. A major reason is that the NASA centers have traditionally focused on space operations rather than on sponsoring fundamental space engineering research in universities and in the aerospace industry. (This is in contrast to NASA's aeronautics R&T, which is largely conducted in close coordination with academia and industry.) NASA program managers at the working level often see university researchers as competitors for funds for individual projects. In addition, some NASA centers have reputations for using the outside community as sources for ideas that they then develop internally, which has led to mistrust.

Universities operate quite differently from both private companies and NASA. Universities essentially provide no funding of their own for R&T but do educate students and provide high-quality researchers. University researchers are motivated by the desire to produce innovative work, the requirement to train new generations of students, and the need for funding. Universities thus often work on more theoretical issues, developing far-reaching ideas unencumbered by the need to show a profit. Researchers typically represent diverse disciplines, and individual faculty members may have great expertise because of their long-term specialization in a single area. Universities also have innovative students and many new technologies from outside the traditional space enterprise.

Cooperative programs must take the special characteristics of universities into account. For example, training graduate students to perform state-of-the-art research tends to require that research schedules be coordinated with the time it takes graduate students to complete their studies. The desire of university faculty members and research groups to engage in cutting-edge work means they are generally less suited than private companies to work on narrowly defined problems with highly focused objectives.

To gain the maximum benefit from cooperation with industry and academia, NASA must recognize the strengths and weaknesses of each and design cooperative programs that take these characteristics into consideration. NASA must also monitor its own practices carefully to ensure that it does not discourage university and industry researchers from cooperating with NASA.

Finding. NASA, universities, and private companies each have unique qualities that they can contribute to space R&T programs. To take advantage of these qualities and ensure that the most capable people and resources are involved in NASA's R&T, the agency must include industry (including small business) and academia in its R&T programs.

Building Cooperative Programs

By opening up its space R&T to the larger aerospace community, NASA will be able to fund a large number of projects with a limited budget, harness the brain power and creativity of universities, and take advantage of industrial expertise. Coalitions of university, industry, and NASA center personnel could also become a powerful combination of stakeholders in shaping future programs.

To reap these benefits, however, NASA's cooperative efforts will have to be well designed. Experience from other cooperative programs between various combinations of government agencies, private companies, and universities has shown that success requires that certain conditions be satisfied. These include:

- common objectives
- economic and intellectual advantages to each participant
- mutual trust
- contributions proportional to the benefits received
- commitment to seeing projects through to completion

If these conditions are not met, productivity will be limited, as some of NASA's recent cooperative R&T efforts have shown. Although individual principal investigator grants, for example, have many good points, they have often treated university faculty members as "workers for hire" and have not taken advantage of a university's inherent capability for innovation. University space engineering centers that once involved many students and faculty members in coherent efforts proved to be rigid and unresponsive to changes in technical focus and have all been closed down. The centers for the commercial development of space have involved several companies in NASA-funded work but have not been successful in attracting a significant amount of non-NASA funding into NASA efforts at space commercialization.

Examples of successful government/academia/industry R&T programs abound, however. The Defense Advanced Research Projects Agency (DARPA), for example, has for many years conducted a successful cooperative R&T program. Another example that shows the benefits of unconventional government/university cooperation in R&T is the Landsat program. Box 4-2 describes how the Landsat program was established in response to an unsolicited proposal from academia.

Two potential approaches to cooperative space R&T are outlined below. Although these are not the only promising approaches NASA could adopt, the committee believes they are very likely to improve the quality of NASA's space R&T. The key to both approaches, and to any other approach to improving NASA's

BOX 4-2
The Landsat Example

In the early 1960s, the idea was suggested of using spacecraft to monitor the Earth's resources. From the initial idea, which originated outside of NASA, three universities came together to create what eventually became the Landsat program (Landgrebe, 1997). NASA's role was to fund and monitor the universities rather than to direct them. Instead of telling university personnel to "take pictures of the Earth's surface and research picture processing methods to analyze them," NASA allowed them to devise their own approach. University personnel hit upon the idea of identifying the contents of individual image pixels based on measurements in 12 to 18 spectral bands—the so-called multispectral approach—which was much simpler and less expensive then existing alternatives, although before the fact it had appeared unlikely to succeed.

space R&T, is taking advantage of the full potential of the nation's technical and intellectual resources. NASA's space R&T must be conducted not just within NASA but in a spirit of true cooperation with the U.S. aerospace community. NASA will have to seek partnerships aggressively with both private companies (including small businesses) and universities to achieve this goal.

Potential Cooperative Approach 1: Technology and Personnel Transfer

One way NASA could tap into the intellectual vigor of universities would be to initiate a vigorous program of sending distinguished NASA scientists and engineers to work at universities for periods of approximately one year. To enhance the prestige of these appointments, these scientists and engineers would be designated NASA fellows. While at the universities, they would work with teams of faculty and students on NASA-funded research. These integrated teams would study new concepts and explore the application of new technologies to the NASA mission, drawing from the wide range of technologies—including technologies from outside the space arena—available at the university. As viable concepts were found, the NASA fellows would make substantial efforts to transfer the technology to the NASA enterprises, both personally and by arranging for the students they had worked with to work in NASA centers. Finally, returning NASA personnel would be given some discretionary funds for a period of a few years to continue their collaborative work.

This approach could yield a number of benefits. It would provide NASA with new technologies and new ideas. NASA researchers would be exposed to new technologies and would develop working relationships with university faculty members. University students would have an opportunity to work on "real-world" problems and establish relationships that could lead to future employment or collaboration. Finally, participation in this program might be an incentive to NASA's best and brightest researchers to stay with the agency. Once the program proved viable, it could be broadened so that NASA fellows could work at industrial research laboratories that conduct forward-looking R&T.

Potential Cooperative Approach 2: NASA-Funded University/Industry R&T

The Office of the Chief Technologist could sponsor R&T projects (in some or all of the areas recommended in this report) that would be accomplished cooperatively by private companies and universities. An announcement of opportunity for research in the six key technology areas would be developed by the Office of the Chief Technologist. A joint university/industry team would propose the concept to NASA, along with the required budget. Winning proposals would be selected by peer review groups comprised of NASA, university, and industry representatives. The participant from industry—someone with expertise in the technology area—would be funded to review the project, brainstorm concepts for further exploration, remain involved throughout the project, and review the analyses, findings, and results. The industry expert would, of course, understand that the technology might not be applied for several years and that the project would not be constrained by the need to solve current problems quickly.

This approach also has numerous advantages. First, NASA would benefit from high-quality research involving both university innovation and industry expertise. University researchers would have an opportunity to work on relevant and challenging projects and to collaborate with industry experts. In the process, students would be exposed to space-related engineering R&T and would be better prepared to work in the field after graduation. Industry, which would only have to invest time, would be able to form links with possible future employees and to gain early experience with promising technologies. The peer review by representatives from NASA, industry, and universities would help to ensure open competition, prevent overly close relationships from forming between NASA and particular university groups, and result in R&T that is forward looking but directed towards future real-world applications.

RECOMMENDATIONS

Recommendation 3. The Office of the Chief Technologist should work with the NASA centers to organize cooperative programs among NASA centers, universities, and private companies (including small businesses) to leverage significantly NASA's investment in new technology.

Recommendation 4. NASA should develop a fellows program to send superior employees to universities for periods of one to two years and support their follow-on collaborative efforts after they return to the agency.

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APPENDICES

APPENDIX A

Statement of Task

The study committee will examine the nation's space technology needs for the post-2000 time frame and identify areas where early R&T could result in the creation of an enabling technology "pipeline" that could be tapped for future activities. Emphasis will be placed on identifying high-risk, high-payoff technologies that initially can be pursued within a constrained budget environment. Technologies to be considered will apply to NASA missions and to other civil and commercial uses of space. Specifically, the committee will:

I. Characterize the space missions likely to be conducted in the post-2000 time frame in order to understand possible technology needs.

II. Assess which technologies have the greatest potential for improving the capabilities and reducing the cost of NASA, other government, or commercial space programs in the 2000–2020 time frame.

III. Determine which of these new technologies could benefit greatly from NASA long lead-time research and development and which are already being developed, or are likely to be developed, by the commercial space industry or by other government agencies.

IV. Suggest how NASA can be more effective in working with industry and universities to develop these technologies.

APPENDIX B

Organizations that Submitted White Papers to the Committee

The following organizations replied to the committee's request for white papers on advanced space technologies for the next century: the Aerospace Corporation; the American Astronautical Society; the American Institute of Aeronautics and Astronautics; the American Society for Gravitational and Space Biology; the Applied Physics Laboratory; the Charles Stark Draper Laboratory; the Defense Advanced Research Projects Agency; the Federal Aviation Administration; the Jet Propulsion Laboratory; Lawrence Livermore National Laboratory; Los Alamos National Laboratory; NASA's Ames Research Center, Goddard Space Flight Center, Langley Research Center, Lewis Research Center, Johnson Space Center, and Stennis Space Center; the National Center for Advanced Technologies; the National Space Society; the Office of Commercial Space Transportation; Phillips Laboratory; the Planetary Society; NASA's Advanced Concepts Office; the Space Frontier Foundation; the Space Studies Institute; and the Universities Space Research Association.

APPENDIX C

Representative Future Space Activities

Study the Galaxy and the Universe

Acquire better observations across the electromagnetic spectrum

- gamma and x-ray imaging and spectroscopic follow-on investigations
- deployment of single-element optical instrumentation at 1 to 10 meter scales
- space- and lunar-based radio and optical interferometer deployment at 10 to 100 meter scales
- coupled space-Earth interferometer systems
- study the interstellar medium with a submillimeter telescope
- investigate cosmic microwave background
- advanced infrared and near/far ultraviolet missions
- cosmic ray identification and energy measurement campaigns

Survey cosmic rays and interstellar gas as samples of extra-solar matter

- interstellar probe
- probe for 1,000 astronomical unit scale distances

Carry out basic new tests of gravitational theory

- detect and understand gravitational waves

Search for life beyond our solar system

- detect and image planets in other solar systems
- search for signals from extraterrestrials

Study and Explore the Solar System

Conduct unmanned missions to objects in the solar system to investigate near-planet space environments, atmospheres, surfaces, and interiors

- fly-by missions
- orbiters and observational platforms
- landers and rovers with and without sample return
- direct atmospheric probes and aerobots
- fleets of microprobes, microlanders, and microrovers
- terrestrial surface sensor networks

Study interaction among Sun, Earth, and heliosphere

- stereoscopic sun observations
- near-field solar probe to understand solar structure and dynamics
- explore coupling between solar radiation and Earth's atmosphere, magnetosphere, and plasmasphere
- study solar plasma transport and energization, including solar wind sample return and investigation of coronal mass ejections

Conduct human missions to explore the Moon, Mars, and the asteroids

Establish long-term human presence in space

- low-Earth orbit (LEO) and beyond-LEO space habitats
- lunar and Martian bases

Study the Earth

Establish better understanding of global processes through remote sensing

- investigate seasonal, interannual, and long-term variability in:
  — land cover and use
  — atmospheric chemistry and dynamics from troposphere to mesosphere
  — the dynamics of the ocean and the cryosphere
  — interactions among biospheric systems
- natural hazard prediction and management
- geodesic missions
- weather prediction
- environmental and infrastructure management
- resource identification and management

Provide Other Services to Users on Earth

Provide communications services to users on Earth

- mobile communications
- direct broadcast communications
- fixed-service communications
- geographic information systems

Expand navigation services to launch vehicles and spacecraft at all altitudes

Space Operations and Infrastructure

Preserve the near-Earth environment

- expanded space debris tracking system
- space debris cleanup

Utilize off-Earth resources for terrestrial and space activities

- tests of robotic utilization of local resources
- surface mining of planets and small bodies (e.g., asteroids, comets)

Study the effects of microgravity

- biological processes
- effects of microgravity on humans
- physical processes
- fluid mechanics and transfer
- combustion
- chemical processes

Create new services

- spacecraft staging, assembly, and refurbishing services
- point-to-point transport on Earth via space
- space-based power depots for use in terrestrial activities and transmission to spacecraft and planetary bases
- manufacturing (materials and pharmaceuticals) in space
- space tourism
- disposal of hazardous materials
- space-based cultural/entertainment activities

APPENDIX D

Technologies Assessed by the Committee

Communications

- broadband, high-power, high data-rate, redundant systems
- communications system-on-a-chip
- high-dielectric constant patch antennas
- high-frequency (> Ka band) antennas
- high-power (broadcast) antennas
- high-power, solid-state transponder systems
- phased-array antennas
- up-down transmission technologies, including raindrop compensation
- wideband (i.e., optical) communications

Earth-Based Systems

- automated and semi-automated processing of image data
- autonomous ground control
- development of space systems using nanotechnology
- image storage and dissemination
- integrated design systems
- large-scale information management and simulation
- low-cost operations
- paperless designs
- rapid system prototyping tools using multimedia capabilities
- verification and validation approaches and databases for commercial off-the-shelf technologies

Guidance and Control

- advanced attitude-control technologies
- all star-tracker attitude-reference system
- avionics-on-a-chip (multichip module)
- coordinated operation of spacecraft fleets
- fault-tolerant electromechanical actuators
- high-accuracy, low-mass star trackers and gyros
- interferometric fiber-optic gyros (IFOGS)
- low-cost, reliable, position-tracking and telemetry systems (with built-in collision avoidance)
- micromechanical sensors
- miniature momentum-exchange devices
- modular avionics
- precision spacecraft pointing
- redundant (multistring) solid-state avionics
- use of Global Positioning System for guidance and control

Information Technologies

- artificial intelligence systems
- automatic fault recovery
- autonomous systems
- data compression technologies
- data fusion
- digital systems processing
- distributed functions among spacecraft
- effective human-machine interfaces
- high-density, fiber-optic sensor networks
- high-density, low-cost command and data handling with open architecture
- high-temperature electronics
- hundred-fold increase in processing capability
- integrated vehicle health-monitoring systems
- low-cost, high-capacity, low-mass, radiation-resistant, solid-state memories
- neural nets
- neuro-engineering systems
- onboard image processing
- onboard mission planning capability
- parallel computer processor architectures
- radiation-hardened electronics
- sequencing systems
- system standards to expand software reuse

Launch

- < 3,000 lb. thrust scale pump-fed liquid rocket propulsion
- air-augmented/breathing rockets
- automated ground processing
- clean solid propellants
- electromagnetic launch/assist
- environmentally compatible boosters
- gel propellants
- high-energy density chemical propellants
- high-energy liquid propellants
- high thrust-to-weight engines
- hybrid launch vehicle
- hypersonic airplane first stage
- integrated solar upper stage
- laser propulsion for ground-to-orbit launch
- lightweight integrated vehicle structures
- lightweight launch vehicle structures
- lightweight propellant tanks
- low-cost, reliable cryogenic propulsion
- lower-cost launchers
- mass drivers
- modular launch vehicle
- oxygen/kerosene rocket-based combined cycle engines
- reusable oxygen/kerosene rocket engines with thrust-to-weight ratios greater than 100
- single-stage to orbit launchers

Materials

- advanced coatings
- advanced composite materials
- advanced composites manufacturing and processing
- atomic oxygen-resistant coatings for solar cells
- high-temperature materials for rocket engines
- lightweight, high-strength, high-temperature materials for launch vehicles
- low-mass, high-reflectivity composites (for telescope mirrors)
- organic coatings (instead of hermetically sealed containers)
- silicon carbide structures

Power

- advanced solar power
- arc-proof, environmentally durable solar arrays

- beamed power
- compact electrical power supplies
- flywheels
- high-conversion efficiency, low-mass solar arrays
- high-efficiency, high-power, low-mass power generating systems
- high-power sources at millimeter wavelengths
- higher-energy density batteries
- integrated energy conversion/energy storage concepts
- large-capacity energy storage systems
- large gossamer fresnel lenses for concentrating solar energy
- lithium ion batteries
- long life, lighter, cheaper regenerative fuel cells
- long-term, compact nuclear-electric systems
- long-term nonphotovoltaic power sources
- low-cost, high-efficiency solar arrays
- low-cost power storage devices
- low-mass, high-capacity, low-cost power storage
- more efficient long-term solar power conversion
- nuclear power sources
- power conversion
- power management and distribution-on-a-chip
- smart power-management systems
- sodium sulfur batteries
- solar cells with different bandgap energies with better than 40 percent efficiency
- thin-film solar arrays

Propulsion

- antimatter propulsion
- concentric combustion chamber engine
- electric propulsion
- high-energy density matter propulsion
- high-energy density storable propellants
- high-performance, less expensive, more producible electric propulsion
- high thrust-to-weight engines
- laser propulsion
- magnetic sail
- nontoxic storable bipropellants
- nuclear fusion propulsion
- nuclear propulsion
- nuclear-thermal rocket
- propulsion for 50 kg spacecraft

- rockets using native propellants
- solar sail
- solar-thermal propulsion
- tethers for momentum exchange/electromagnetic maneuvering
- xenon thrusters

Robotics

- curious, autonomous, adaptive probes
- mobile robots
- partially self-replicating robots
- rovers
- small robots for planetary mining, manufacturing, assembly
- telerobotics

Sensors

- active sensors using synthetic aperture radar and high-frequency microwaves
- free-flying, synthetic-aperture radars and interferometers
- high-power local oscillators
- high-resolution, stereoscopic Earth sensing systems
- high-sensitivity, room temperature mid-infrared detector arrays
- highly-integrated, multifunctional atmospheric sounders
- hyperspectral focal planes
- infrared interferometer (for planet detection)
- large-aperture, deployable, optical telescopes with active alignment
- large-format, low-noise, long-wavelength, direct-detection sensors
- low-cost, low-power imaging sensors
- low-mass, low-power radars
- low-noise heterodyne mixers
- microcalorimeters for high throughput spectroscopy
- microsensors
- microwave technologies
- multiband phased arrays
- multispectral sensors
- remote sensing signal chain miniaturization
- smaller autonomous instruments
- solid-state sensor systems with high spectral and spatial resolution
- space-based lidars

Spacecraft Systems and Electronics

- almost monolithic small spacecraft
- highly integrated multifunction modules

- integrated instruments
- integrated low-power electronic microsystems (communications, guidance)
- integrated power and propulsion bus
- microminiaturization
- miniaturized electronics
- multichip modules and chip-on-board technologies
- optical buses
- superconducting devices

Structures

- active interferometric system technologies, such as active delay lines and space-qualified precision metrology
- adaptive membranes and space fabrication techniques for large optics
- adaptive structures
- deployable structures
- gossamer films in multi-km sizes
- inflatable structures
- lightweight composite spacecraft
- lightweight debris shielding
- lightweight structures
- microelectromechanical systems (MEMS)
- multifunctional structures
- spinning spacecraft (for gravity)
- structures to reduce vibrations on crewed platforms
- technologies and processes for deploying "quiet" structures to precise dimensional tolerances
- tethers

Thermal Control

- advanced coatings for thermal control and electrostatic discharge control
- electrochromic radiator surfaces
- electronics able to function at high temperatures
- electronics able to function at low temperatures
- electronics cooling with direct immersion heat pipe
- graphite/aluminum radiator panels
- improved heat-rejection technologies
- long-life cryocoolers
- low-mass, low-power cryocoolers
- multichip modules with integral thermal control
- nuclear heat sources
- rugged thermal protection for reentry
- spacecraft that can approach the sun

Working in Space

- aerocapture/aerobraking
- autonomous landing
- chemical processing of off-Earth resources
- construction with off-Earth resources
- lasers for debris shielding/removal
- lightweight, high-efficiency cryogenic liquefaction
- long-term cryogenic fluid storage in space
- planetary surface transportation technologies
- remote (cryogenic) fluid transfer and handling
- remote robotic rendezvous, docking, and other operations
- space traffic management systems
- structures for planetary surfaces
- surface/subsurface sample acquisition
- terraforming technologies