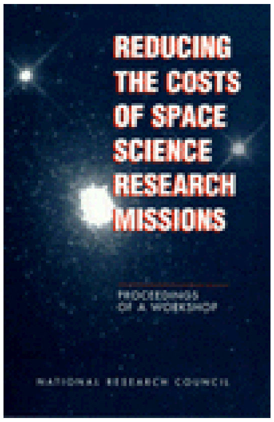

Reducing the Costs of Space Science Research Missions: Proceedings of a Workshop

Joint Committee on Technology for Space Science and Applications of the Aeronautics and Space Engineering Board and the Space Studies Board, National Research Council

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THE NATIONAL ACADEMIES
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REDUCING THE COSTS OF SPACE SCIENCE RESEARCH MISSIONS

PROCEEDINGS OF A WORKSHOP

Joint Committee on
Technology for Space Science and Applications
of the Aeronautics and Space Engineering Board
and the Space Studies Board

Commission on Engineering and
Technical Systems

Commission on Physical Sciences,
Mathematics, and Applications

National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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1

Introduction

Most space science missions initiated in the late 1970s and during the 1980s relied on large, complex spacecraft that carried a broad array of scientific instruments. These large spacecraft required long lead times for development, and cost and schedule overruns were common, often due to changing or poorly understood requirements (NRC, 1994). As the 1990s progressed, space science budgets were increasingly constrained due to pressures on the federal budget and within the National Aeronautics and Space Administration (NASA). In response, NASA has initiated several new programs, such as the Small Explorer and the Earth System Science Pathfinder programs, with limited, clearly defined scientific goals that can be met by instrumentation flown on less complex, lighter weight spacecraft (Baker et al., 1991; NRC, 1995b).

A strategy to build and launch scientific missions within three years after program initiation has improved NASA's ability to respond to research opportunities. To conform to current budget constraints, space science proposals now are evaluated almost equally on cost, scientific merit, and technical requirements. Unless there appears to be an overriding scientific justification, lighter-weight, less complex (i.e., "small") spacecraft are generally preferred because they are individually less expensive. Several efforts have been made to determine whether the cumulative results of small spacecraft missions can provide the quality of science that is offered by the larger missions of the past, to identify the primary sources of savings, and to assess whether additional cost savings can be made. Three National Research Council (NRC) reports, *Technology for Small Spacecraft* (NRC, 1994), *The Role of Small Missions in Planetary and Lunar Exploration* (NRC, 1995b), and *Managing the Space Sciences* (NRC, 1995a), have addressed some of the issues in question.

2

Approach

The Aeronautics and Space Engineering Board (ASEB) and the Space Studies Board (SSB) of the NRC, recognizing that the costs of space science research missions were of concern to both the space science and the space technology communities, jointly initiated, organized, and conducted a workshop, under NASA sponsorship, to identify ways to reduce the cost of space science missions. The workshop steering committee was given a Statement of Task that detailed a list of technologies to be considered for their impact on system cost (See Appendix A). Rather than convene a symposium, the committee elected to put together a workshop in which four working groups, working independently, would respond to statements-of-work for two hypothetical mission descriptions. Expanding on the Statement of Task, the chairs of the workshop steering committee charged the workshop participants to "break out of the ordinary" and seek innovative approaches to reducing space science research costs. This charge is detailed in Box 2-1.

Each working group was composed of invited participants who were selected for their expertise in space science, advanced space technology, systems engineering, program management, cost and risk analyses, and aerospace policy. They came from industry; academia; government agencies, including NASA and the Department of Defense; and the legislative branch of government. Already familiar with the impetus of the past few years to reduce the size and cost of space science missions, the participants attempted to assess some of the trade-offs between mission goals, technical requirements, costs, and risks that are common to space mission systems engineering and operations (see Table 2-1).

The workshop was held at the NRC's Beckman Center in Irvine, California on October 16–18, 1996. After introductory presentations, participants spent the

BOX 2-1 Message from the Chairs

The workshop will focus on alternative and innovative approaches for reducing cost in future space science missions and the potential effect of these approaches on risk and performance . . . considering many factors.

Over the past 20 to 25 years, we have all heard many "mantras" proposed as solutions to cutting the cost of space missions, both scientific and military. We all know that controlling mission requirements, simplifying and controlling interfaces, adopting multiyear procurement strategies, and using other management techniques should reduce overall mission costs. We all also know that nothing works—we still end up with large, complex, and sophisticated satellite systems that, we believe, cost too much and take too long to develop.

We have asked all of you to participate and to assess this problem, using the rich variety of your individual backgrounds and experience. We want to use this workshop as a team-building effort to focus on whether the costs of space science missions can be reduced by the application of various methodologies, or if we are, as an industry, doing things basically the right way and major cost reductions are not achievable.

Instead of assembling to hear a series of papers on techniques of cost reduction, we decided to divide you, the invited participants, into four groups and present each group with the challenge applying these techniques and designing a low(er)-cost satellite system. During the opening session of the workshop, participants will be provided with background briefings on cost-reduction techniques and a road map of current space technologies.

We hope you and your group will break away from the ordinary and do some creative thinking to solve the problems that continue to limit the number of missions because of high cost. For example, if your group identifies a solution that meets requirements with a system configuration that cuts costs but increases the risk of failure, can you convince management (the customer and Congress) that the elevated risk is acceptable? If your group works diligently, applying every identified technique and technology to meet specified requirements and to stay within cost limits, and you honestly believe this is impossible, we want to know how you reached this conclusion and what you believe the major factors are that prohibit cost reduction.

The final report of this workshop will include the four system design solutions and associated findings, as reported by each systems engineer on Friday morning (October 18). Materials utilized to help reach the design solution will be included, at least by reference, in the document.

We intend that the findings contained in the final report should provide insight into the process by which things really could be changed. We believe that people should resolve to work together to make changes outside of their current sphere, to ensure scientific return on investment, and to maintain reasonable costs for scientific space missions.

TABLE 2-1 Major Points Identified by Working Groups

Effect of policy mandates	Inflexible policies, such as launch vehicle restrictions, may preclude mission savings. National policies and political mandates that impose requirements for scientific missions should consider long-term scientific goals.
National space science mission	Rivalry within an agency can preclude cost savings by focusing on competition rather than priorities. An articulated national policy and plan with near- and long-term goals can enhance public acceptance and congressional support.
Clear definition of requirements	Clear objectives and priorities with associated rationale are essential to reducing mission costs. An integrated team approach that involves scientists, spacecraft designers, and operations personnel promotes realizable mission requirements and potential cost savings. Defining the level of quality required, or how much "science" is enough, is fundamental to holding down the costs of missions and avoiding unnecessarily restrictive requirements. The trade-off of science performance per total program dollar ought to be thoroughly addressed before a cost cap is established. The rationale for various program and mission requirements ought to be published along with the requirements so that further decisions will be made in light of the underlying philosophy and rationale.
Programmatics and acquisition strategies	Affordable space science is achievable if the program manager has the authority over decisions, such as choice of launch vehicle, make or buy, contracting for services, and participating in joint programs with other agencies. Stable, multiyear funding can contribute to program success by allowing a program to realize savings from end-to-end program planning. Concurrent engineering can prevent problems and reduce costs through the maximum (and timely) exchange of technical, management, and cost information. Cost trade-off studies at the program level should consider technology and hardware from the growing commercial space infrastructure. Revisions in the Federal Acquisition Regulations to facilitate multiyear funding are highly desirable.
Risk-informed decisions	Risks ought to be stated clearly, and risk mitigation plans ought to be identified early.

TABLE 2-1 *Continued*

Risk-informed decisions—*continued*	Risk assessments should examine not only technical risks but also programmatic risks. Innovation in technologies and design will only be realized in a climate of mutual trust with acknowledgment that space missions are inherently risky and that, despite all precautions, some losses will occur.
Inclusion of advanced technology	The cost savings achieved by launching a small spacecraft on a less expensive launch vehicle may be offset by the cost of technology miniaturization and packaging. Some important studies cannot be performed by small spacecraft because physical limits mandate the use of a large instrument. Economies of scale may be achieved with large spacecraft. Consideration ought to be given first to existing technology (worldwide) and then to new technology that will reduce cost, enable new or better capabilities, or facilitate scientific results. Because ground control and data retrieval costs can exceed the costs of space hardware and launch, mission life-cycle costs could be reduced through on-board systems that increase satellite autonomy. Utilizing standardized mechanical and electronic architectures at the interface level—as opposed to the spacecraft bus level —can reduce costs substantially without overly constraining design options.

remaining two days assessing trade-offs and cost and risk constraints for the hypothetical missions. Mission scenarios—a Mars mission, titled “Mars 2001,” and an Earth-observing mission, titled “Windstar”—were presented by individuals from the Jet Propulsion Laboratory and the NASA Goddard Space Flight Center. Each mission had a modest budget and was examined independently by two working groups.

As the working groups discussed potential designs and strategies for the two missions, they considered the following questions: (1) What are the impediments to reducing the cost of space science missions? (2) What areas have the greatest potential for cost reduction (e.g., operations, management, procurement, etc.)? (3) What practices have proved effective in accomplishing stated objectives at lower costs? (4) Have smaller (i.e., lighter weight, less complex) spacecraft proved to be cost effective in meeting objectives? (5) What are the hidden costs associated with leaner programs that could have a long-term impact on performance? Stimulated by the discussions, the groups arrived at findings concerning potential sources of cost reduction. This report summarizes the overall findings from the workshop and includes the major conclusions of the working groups.

The workshop steering committee would like to thank the invited participants for their thoughtful contributions (see Appendix B for the list of participants), especially Eberhardt Rechtin, Liam Sarsfield, Wiley Larson, Frank Redd, Donna Shirley, and Lester Thompson for their presentations and many helpful insights.

3

Summary of Findings

The workshop participants concluded that the challenge in reducing space science mission costs is that there is no one "prescription" that can be applied to the wide variety of circumstances associated with the public funding of science. This report summarizes two days of discussions and the findings of the four working groups. A synopsis of each working group's findings is included in Appendix D. The invited papers in Appendix C contain much of the data used by workshop participants in their analyses. The workshop participants also had access to the results of many previous studies and workshops that had addressed the issue of cost reduction for space science research; these materials are listed in Appendix E.

The workshop results are categorized under the major topics of policy, the national space science mission, mission requirements, programmatics and acquisition strategies, recognition and management of risk, and the influence of new technology. These topics are addressed in descending order of importance and influence on the cost of space science research missions as agreed by the workshop participants.

EFFECT OF POLICY MANDATES

Behind all missions is a fundamental belief that public investment in creating new knowledge is a worthwhile objective. Science missions usually begin with the basic objective of advancing scientific knowledge rather than enhancing national prestige or promoting societal benefits. This approach to mission objectives, preferred by scientists, may not demonstrate clearly the value of the public investment to nonscientists or provide a basis for articulating national space science policy.

Mission definitions are influenced strongly by national policy as defined by the executive and legislative branches of the federal government. Interpretation of the policy by the procuring agency, particularly the definition and acceptability of risk, can affect the mission definition. Also at play may be parallel agendas in government agencies, the Congress, or the scientific community. Perhaps the foremost example was the short-lived national policy of the early 1980s that the Space Shuttle would be the sole U.S. launch system and that expendable launch vehicles would no longer be available for scientific payloads (NSDD, 1981, 1982).

Often policies that have a worthwhile objective result in unintended consequences when they are applied inflexibly. Examples include policy decisions affecting launch vehicle selection, such as the Space Shuttle policy mentioned above or restricting the use of non-U.S. launch vehicles. This policy can have a negative effect on mission cost. In this context, the consensus of the workshop and of the steering committee was that "buy American" policies frequently preclude mission savings that might be otherwise achievable.

All four working groups believed that when national policies and political mandates impose requirements on individual scientific missions, there must also be serious consideration of longer-term scientific goals. Only then can there be major reductions in mission costs.

UNDERSTANDING THE NATIONAL SPACE SCIENCE MISSION

An articulated national policy and plan that identifies both near-term and long-range goals for the gradual exploration of space and the enhancement of the body of space science knowledge can provide a framework for increased public acceptance of and congressional support for the science program (NRC, 1995a). The scientific community shares responsibility with government for developing space science goals and for educating the public on the benefits of the scientific knowledge to be gained. The executive branch articulates these scientific goals within the broader framework of a national policy and recommends the adoption of an implementation plan that can satisfy the goals within realistic cost and schedule constraints.

In times of decreasing budgets competition between agencies for funds is to be expected. However, competition often continues at the intra-agency level, which may have a negative impact on both cost and productivity. The workshop participants strongly believe that agency heads will have to work harder to eliminate internal rivalry and achieve agency consensus on priorities to achieve cost savings.

CLEAR DEFINITION OF REQUIREMENTS

Clear objectives and priorities with associated rationale are essential to reducing mission costs. Early in the process, objectives and their relative priorities are translated into mission or spacecraft requirements. Mission success or failure can be the result of decisions made in the first few days of mission definition (Rechtin, Appendix C). Requirements are not always well thought out, logically consistent, or communicated to all team members (Rechtin, Appendix C). "Good" science ought to be the primary requirement of any space science mission and the basis for the definition of success. The workshop participants stressed that science can be overwhelmed by technical and programmatic decisions if the scientists are not included in the decision-making process. This may have an impact on both cost and product.

Realizable science mission requirements can be promoted by an integrated team approach that actively involves scientists, spacecraft designers, and operations personnel in the requirements definition process. The team should also be given the authority to make necessary trade-offs throughout the project in order to achieve the scientific objectives within the budget constraints (NRC, 1995b). As noted in *Managing the Space Sciences* (NRC, 1995a):

> The synergism of talents that is possible in team environments has proven equally effective with flight projects. The necessary compromises and mutual learning among scientists and engineers can best be realized in these team settings where everyone understands the enabling value of new technologies and recognizes that science and technology are mutually supportive in ensuring the vitality of the space sciences (p. 63).

One of the workshop groups noted that "requirements without rationale are overly constraining—and constraint usually translates to increased cost." Arbitrary requirements can take the form of preselection of the launch vehicle, the spacecraft bus, the payload, the data rate, or the management and operations structures (NRC, 1995b). For example, rather than articulating the basic scientific goal to be realized by the mission, a typical space science research announcement may specify the type of instrument to be flown, as well as the information that it must gather (e.g., a specific instrument to take a specific measurement). Other workshop participants expressed the view that mission success can be defined "when there is mutual agreement that a complete, passable set of acceptable criteria has been developed for a plausible system." Workshop participants also expressed the view that, in many industries affected by declining budgets, the definition of "acceptable" versus "best" is a key element in reducing cost. Defining how much quality is needed, or how much "science" is enough, is fundamental to holding down mission costs and avoiding unnecessarily restrictive requirements.

Requirements of a program to deliver space science research at a reduced cost may include a "cost cap."[1] However "For a cost not to exceed $150 million,

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[1] For example, cost caps have been included in the following: the Discovery Program Announcement of Opportunity (AO), dated September 20, 1996, which shows a FY97 "cost constraint" of $193 million; the Earth System Science Pathfinder missions AO, dated July 19, 1996, which has a $140 million "cost cap"; and the Medium-Class Explorer missions AO, dated March 27, 1995, which has a $70 million "cost cap."

what is the best science that can be done?" is very different from the question, "What is the cost of the best, focused science that can be done to address this area of research or to answer this question?" The former question may lead to mission requirements that preclude the "best, focused science" of the latter. And neither approach addresses the issue of the total science delivered versus the total costs over the life of a program.

Workshop participants expressed the concern that, although the cost cap seems an obvious route to "smaller, faster, cheaper" science missions, the trade-off of science performance per total program dollar is not addressed adequately. Although space science has always been limited by the availability of funds, certain types of scientific objectives, such as those requiring large optics, cannot be accomplished within an across-the-board cost cap. The working groups concluded that an arbitrary cost cap may lead not to the best science, or even to the best science for the dollar, but to the best science that fits the amount of money available.

The tendency to overspecify when defining requirements can lead to a point design that is focused on satisfying the requirements rather than achieving mission goals. Overspecification can prevent developers from proposing more than one solution to achieve desired scientific mission goals. The U.S. Department of Defense (DOD) has recently adopted what was regarded by workshop participants as an enlightened procurement strategy of providing potential contractors with specifications of technical need, allowing the respondents to define a system that meets the need, and promoting the highest degree of flexibility, including nontraditional solutions such as "buy, not build" (Wertz and Larson, 1996; Rechtin, Appendix C).

Once the rationale has been established for the various program and mission requirements, it should be published along with the requirements so that further decisions will be in keeping with the underlying philosophy and rationale. Further down the road, this can mean that changes will be less likely to have unintended consequences.

PROGRAMMATICS AND ACQUISITION STRATEGIES

In addition to good engineering principles, the administration and oversight of a program need to include early definition of an operations concept, thoughtful procurement strategies, and concurrent engineering techniques (i.e., an integrated approach to designing, building, and operating a spacecraft). In Technology for Small Spacecraft (NRC, 1994), it was noted that the initial phase of a mission is important in establishing cost-control methods and limits prior to decisions regarding the use of new and existing technology, systems engineering and operations, and management style. Mission schedule and duration, overall mission funding, and the use of commercially developed and supported technologies are also key early decisions that have an impact on cost (NRC, 1994). These decisions should be made in the early conceptual and definition phase before commitment to a spacecraft configuration and design approach is made.

Flexibility in decision making and fiscal stability contribute to effective program management. Lower cost space science is achievable if program managers have the authority to make decisions such as choice of the launch vehicle, whether to make or buy, contracting for services, and whether to participate in joint programs with other agencies (e.g., DOD, international). The workshop consensus was that stable, multiyear funding can contribute greatly to program success. If the program has adequate funding throughout its life, savings can be realized by end-to-end planning.

The working groups emphasized the importance of developing and articulating an operations concept in the early study phase of the program and updating it as the project moves toward building operational hardware. A validated operational concept makes possible analyses of options and decisions on allocating tasks to ground and space elements, defining products, and data flow.

In describing an end-to-end design, development, and procurement policy, one of the working groups noted that decisions made without an overall understanding of mission goals and objectives are counterproductive. A policy to require programs to make sensible trade-offs before design, development, and operational decisions are made is important for both the government and the space science community (NRC, 1995b).

Workshop groups observed that, in many cases, the spacecraft, payload, and launch vehicle teams working on designing a mission virtually “throw their work over the transom” to the manufacturing teams rather than coordinating their efforts. Concurrent engineering can prevent problems and reduce costs through the maximum (and timely) exchange of technical, management, and cost information (NRC, 1995b). In addition, the working groups believed that the inclusion of the scientist or principal investigator on these teams is instrumental to balancing scientific and technological trade-offs.

Cost trade-off studies at the program level could also consider technology and hardware from the growing commercial space infrastructure. For example, infrastructure costs, such as launch, mission ground control, and retrieval and distribution of scientific data—the life-cycle costs—can often be lowered significantly by using commercially available products and services instead of duplicating them in-house. The recent DOD experience of introducing commercial off-the-shelf elements into military specification systems is also relevant (Wertz and Larson, 1996; Sarsfield, Appendix C).

Although concerns over government procurement systems are not new, participants believed it was worthwhile to rearticulate them in light of the current government emphasis on eliminating bureaucratic waste. Revisions in the Federal Acquisition Regulations could facilitate multiyear funding to meet the demands of rapid deployment and cost control. This was successfully demonstrated as a cost-savings strategy in the development of the Global Positioning System

(NRC, 1995b). Workshop participants agree that such revisions are highly desirable for programs involving space science missions.

RISK-INFORMED DECISIONS

Failures in science missions can result from a variety of causes, such as a spacecraft failure (Mars Observer), a launch failure (Mars '96), or a budgetary problem (Comet Rendezvous/Asteroid Flyby). In some cases, mission capabilities can be seriously degraded by simple mechanical failures that occur after launch (for example, the Galileo high gain antenna). The current NASA Strategic Plan states that the space science program can accept higher levels of risk in order to lower mission costs (NASA, 1996). Although program managers are ostensibly encouraged to apply new techniques and advanced hardware and software, they and spacecraft engineers are often reluctant to put their program and their careers at risk by using new technologies. They prefer to minimize risk and mitigate against failure by relying on older, proven technologies and occasionally by overengineering the spacecraft. Innovation in technologies and design can be realized only in a climate of mutual trust, with acknowledgment by all parties, including Congress and the procuring agencies, that space missions are inherently risky and that, despite all precautions, some losses will occur.

Some risks inherent in space missions are unique. Plans that do not recognize and articulate these risks make it extremely difficult to assign proper value to space science investments. The consensus of the workshop and this committee is that risks should be stated clearly and that risk mitigation plans be identified early. The risk mitigation plans may both define the acceptable level of risk in a given mission and establish methods for addressing risk throughout the program. The working groups believed that risk assessments could be expanded to include not only technical risks but also programmatic risks (e.g., changes in national policy and congressionally mandated budget cuts, schedule delays, and unforeseen expenses). Risk-informed decisions are possible when there are clear mission goals and when a well understood risk evaluation framework is in place.

INCLUSION OF ADVANCED TECHNOLOGY

The major cost drivers in spacecraft are size, weight, and power. The continual search for and recent emphasis on space technology that will support the development of lighter weight, smaller systems have resulted in a diverse inventory of space-qualified technologies (Wertz and Larson, 1996). Workshop participants noted that small spacecraft missions in such programs as Discovery, Pathfinder, and Explorer can be considered forerunners. In NASA's recent generation of small satellites, the agency has taken advantage of past technology investments, including investments by the Strategic Defense Initiative Organization, the Ballistic Missile Defense Organization, and industry. In addition, NASA's New Millennium program is intended to fill the need for new technology testing and application (Redd, Appendix C). However, the reduction of budgets dedicated for technology research and development budgets raised general concern among workshop participants about the future of research and development in this area.

Workshop participants pointed out that even though a small spacecraft may be launched on a less expensive launch vehicle than a large spacecraft, the cost saving may be offset by the cost of technology miniaturization and packaging, as well as by capital investments for tooling, new facilities, and training and certification. Miniaturized technology in the space science context connotes costly investments in research and development. Thus, small spacecraft with scientific capabilities comparable to their larger counterparts may not always be cheaper, even including savings in launch costs. Multiple spacecraft in constellations may distribute the risk among several spacecraft and launch vehicles but may not actually cost less than a large spacecraft with the same scientific capability (NRC, 1994).

The working groups also agreed that smaller spacecraft should not necessarily be expected to deliver the same science for less money. There are two factors that may prevent an improvement in the cost-benefit ratio when reducing the size and cost of space science research. The first is that some instruments cannot be reduced in size within current funding constraints. For example, to obtain a specific optical resolution, the mirrors or lenses on a space telescope must meet or exceed the size set by the diffraction limit and the technology available at the time. Thus, some important studies cannot be performed by small spacecraft because of physical limits and a lack of funds for new technology development. Second, economies of scale may be achieved on large spacecraft. That is, the science performance-cost ratio may be higher for large spacecraft than for small spacecraft, despite higher launch costs (Sarsfield, Appendix C). One participant noted that if the "best" science involves sending ten instruments to a planet, then co-locating all ten on one platform may well be cheaper than sending them on ten small spacecraft.

A widespread concern is the transition of available advanced technology into operational missions. Project managers are reluctant to specify non-space-qualified subsystems for their missions because of the risk of failure. Funding for proof of concept and space qualification has been, and remains, difficult to obtain. The upcoming availability of the International Space Station for engineering research may help alleviate the problem of space qualification in some areas. (This is discussed in detail in the 1996 NRC report, *Engineering Research and Technology Development on the Space Station.*) In general, because technology advances require significant up-front investment in research and development, workshop participants believe that consideration ought to be given first to existing technology (worldwide) and then to new technology that will reduce cost, enable new or better capabilities, or facilitate scientific results (Redd, Appendix C).

Workshop participants noted that utilizing standardized mechanical and electronic architectures at the interface level—as opposed to the spacecraft bus level—can reduce costs substantially without overly constraining design options. Standardization can significantly reduce nonrecurring engineering and design expenses while permitting the development of unique or specialized instruments. Flexible designs within standard architecture and interface formats can allow early integration of hardware, software, and computers.

The ground-based infrastructure required for satellite control and mission data retrieval represents a major component of mission costs over the life cycle of the program. The participants noted that ground control and data retrieval costs can exceed the costs of space hardware development and launch. Therefore, savings in launch costs may represent a small fraction of the total mission cost. Workshop participants noted that a mission's ground control and, thus, life-cycle costs could be reduced by on-board systems that increase satellite autonomy (NRC, 1994). Although technologies to support both simple autonomous operations (e.g., routine, repetitive processes, such as orbit and attitude determination) and more complex operations (such as problem detection, identification, and resolution) are advancing, autonomous satellite operation has not achieved the degree of acceptance that will be necessary to realize major cost savings. This is directly related to the problem of risk acceptance (discussed above).

In addition to the use of more advanced technologies, possible cost-reduction strategies include out-sourcing, using available commercial installations, and consolidating program facilities to realize economies of scale (Larson, Appendix C; Sarsfield, Appendix C).

4

Concluding Remarks

The conclusions, reached by each group independently, were remarkably similar. More important, the conclusions indicate that future reductions in space mission costs might be achieved through fundamental changes in policy and decision processes. The major points of each section are summarized in Table 2-1. There was a consensus that agencies involved in space missions now have to concentrate on how their policies for requirements development, mission definition, and system acquisition affect mission costs. The impressive cost reductions in the past several years are largely a result of agencies focusing on engineering or adopting technology that was already in the research pipeline. Progress in the next several years must come from changes in how agencies make basic decisions and conduct operations. These changes have the potential for even greater cost savings, but most participants at this workshop appreciate the difficulties associated with agency-level changes.

Although advanced technology has enabled smaller, faster, cheaper programs in the recent past at both NASA and DOD, all of the working groups agreed that orders-of-magnitude cost savings do not result simply from better technologies. Cost reductions result from a combination of well defined policy, thoughtful rationales for requirements, well developed program planning, facilitation of using advanced technology, and appropriate procurement strategies.

5

References

Baker, D.N., G. Chin, and R.F. Pfaff, Jr. 1991. NASA's Small Explorer Program. Physics Today 44:44–51.

NASA (National Aeronautics and Space Administration). 1996. Strategic Plan. Washington, D.C.: NASA.

NRC (National Research Council). 1994. Technology for Small Spacecraft. Panel on Small Spacecraft Technology, Committee on Advanced Spacecraft Technology, Aeronautics and Space Engineering Board. Washington, D.C.: National Academy Press.

NRC. 1995a. Managing the Space Sciences. Committee on the Future of Space Science, Space Studies Board. Washington, D.C.: National Academy Press.

NRC. 1995b. The Role of Small Missions in Planetary and Lunar Exploration. Committee on Planetary and Lunar Exploration, Space Studies Board. Washington, D.C.: National Academy Press.

NRC. 1996. Engineering Research and Technology Development on the Space Station. Committee on the Use of the International Space Station for Engineering Research and Technology Development, Aeronautics and Space Engineering Board. Washington, D.C.: National Academy Press.

NSDD (National Security Decision Directive) 8. 1981. Space Transportation System. Washington, D.C., November 13.

NSDD 42. 1982. National Space Policy. Washington, D.C., July 4.

Wertz, J.R., and W.J. Larson. 1996. Reducing Space Mission Cost. Torrance, Calif.: Microcosm Press and Dordrecht, The Netherlands: Kluwer Academic Publishers.

APPENDICES

APPENDIX
A

Statement of Task

The Aeronautics and Space Engineering Board (ASEB) and the Space Studies Board (SSB) will form a steering committee from their Joint Committee on Technology for Space Science and Applications, along with other members, to develop a workshop to explore the major contributing factors regarding space science mission costs. The steering committee will be composed of members of the ASEB and the SSB Joint Committee on Technology for Space Science and Applications, and the two boards will maintain oversight of the activity.

The workshop will focus on alternatives and innovative approaches for reducing cost in future space science missions and their likely effects on risk and performance. Factors that will be considered include, but are not limited to, issues regarding the use of new technology versus proven space-qualified technology; use of military specification versus screened commercial parts; life-cycle costs including on-board processing versus ground processing; approaches to test and verification; spacecraft relationship to launchers, including designing to standard shroud size and capsulation; trade-offs between several small versus fewer large missions; upgradability issues including preplanned product improvement versus "goldplating"; the use of piggyback payloads; improving scheduling and its impact on costs; and back-up hardware issues.

The steering committee will meet after the workshop to reach agreement regarding the findings of the workshop and prepare an appropriate overview. Formal recommendations are not anticipated.

APPENDIX
B

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APPENDIX
C

Papers Submitted by Opening Session Presenters

CONTENTS

Remarks on Reducing Space Science Mission Costs

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INTRODUCTION

These remarks have two objectives. The first is to highlight the areas of greatest opportunity for cost reduction. To do that, I will need to distinguish between system-level and component-level opportunities, because by far the greatest ones are at the system level. True, a 25-cent transistor can ruin a billion dollar flight, but the use of that transistor came from a value judgment of the acceptable risk level for the system as a whole. The availability of most component-level opportunities, as it turns out, depends on prior system-level judgments. The possibilities list in the Aeronautics and Space Engineering Board challenge posed to the working group includes some of both. (This list is contained in the Statement of Task in Appendix A.) I will add three more: the definition of success, the use of software to reduce hardware and mission costs, and the use of ultraquality parts to reduce testing costs.

The second objective is to suggest a dozen or so guidelines—heuristics—for reducing or avoiding costs.

SYSTEM-LEVEL POSSIBILITIES

By far the most important decisions that affect cost—as well as performance and schedule—are made in the very beginning of a project. As a well-tested heuristic states:

> In architecting a new aerospace system, by the time of the first design review, performance, cost and schedule will have been predetermined. One might not know what they are yet, but to first order, all the critical assumptions and choices will have been made that determine those parameters.

A number of studies of past projects have concluded that 75–90 percent of the end cost was determined up front. Thereafter, unless there was a major mistake, the most that was affected later was between 10–25 percent. This is not small, but is typically within the uncertainty of the initial cost estimates. So what are the system-level parameters? An amended list of possibilities follows. They are more or less in decreasing order of potential cost reductions.

Modified List I
System-Level Opportunities for Cost Reduction

- The definition of success.
- The client's acceptable risk level; for example, the utility of back-up hardware and prototypes.
- The nature of the effort. Is it a single project or a product line (a continuing program); for example, is it a few large or many small spacecraft, an upgrading, or a planned product improvement?
- Life-cycle costs and their annual cost profiles.
- Improving schedule to reduce costs.
- Upgrading or block changes?

Every one of these requires a value judgment by the client; that is, what is worth doing, what is acceptable, what is good, and what is not. But the client cannot make value judgments, even relative ones, a priori without some idea of what is feasible.

The Definition of Success

For example, ask a typical client prior to conceptual design, "What is most important: cost, performance, or schedule?" And the answer is most likely to be either "Yes" or "It depends." The determination of what is feasible is largely up to the architect, who, of course, cannot make that technical determination without value judgments by the client as to what is wanted! A truly chicken and egg dilemma.

Therefore, the name of the game in the beginning, when cost is being determined to better than an order of magnitude, is a *joint* process between client and architect to create a conceptual design that is *both* desirable and feasible. A client who insists on defining the mission and its cost up front is likely to get neither in the end.

Therefore, to really reduce costs, the mission and its cost must be adjustable. There is a powerful heuristic that defines the initial ground rules:

> **Don't** (either the client or the architect) **assume that the original statement of the problem is necessarily the best, or even the right one.**

So when is the right one stated? When has success been defined? In realistic terms, it is when there is mutual agreement that a complete, passable set of acceptance criteria have been developed for a plausible system. Only then is it even worth talking about costs.

It may surprise you, but clients do not really deal in costs, they deal in *worth,* which has psychological, political, social, and personal dimensions in addition to the financial. If you do not believe it, talk to your real estate or automobile dealer! The only thing worse than the client starting with a fixed, immutable definition of success is having a fuzzy one, say a set of performance goals. Predictably, the clients will be disappointed, the builders frustrated if not bankrupt, costs will come in seriously out of line, and only lawyers will be happy. So decide on the set of acceptance tests early and as a guideline, "Keep It Simple Stupid!" For the scientists here, what you are willing to accept very strongly affects systems costs. That last 10 percent in capability or elaborate detail can be a back breaker.

An important thing to remember about cost reductions is that they come in different flavors. Some are true deletions of activity or equipment. Some are avoidances of overruns, cost uncertainties, and failures. Some are preplanned savings in foregoing options and eliminating contingencies based on better-than-expected progress to date.

But with all the best intentions, the estimated costs may still be too high. So downsize the mission. More exactly, **Scope! Scope! and Re-scope!** Make sure that the project is not so far-reaching that success is inherently costly. Carefully define what is necessary and no more. If in doubt, cut!

Once that is done, aggregate similar problems and partition the subsystems carefully. In partitioning, choose the elements so that they are as independent as possible, that is, elements with low external complexity and high internal complexity. For example, look for the reasons behind "contingency costs," determine the degree to which the system as a whole benefits from them, and then partition wherever possible to eliminate them. Many are due to suboptimizations that different structuring could eliminate.

Cost Risk

So far, so good. Then there is the question of cost *risk*.

What *variation* in cost is acceptable? What are the "tolerance limits" of the nominal cost? How much "insurance" is required to keep that risk in bounds? What are the sources of that risk (poorly characterized commercial off-the-shelf [COTS], immature technology, accident-prone launch vehicles, Congress . . .)? There are a number of ways to reduce cost risk without increasing cost. It is a profitable opportunity to exploit. One powerful heuristic is: **Simplify**!

If possible, have an alternate, simpler, competitive mission ready in the wings, preferably one with a similar cost-to-benefit ratio. That is, one of less cost and of acceptably less benefit. It is surprising what a bit of competition will do to keep costs within bounds. One common alternate to a new system is a somewhat less capable upgrade of the old one. Another is a completely different system that essentially accomplishes the same purpose. The longer a competitive alternative is available, the lesser is the cost risk for the mission as a whole.

The Nature of the Effort

A critical value judgment is the level of commitment to the project that follows the current one. Is the current project a single, one-time project or part of a long-range program? Parenthetically, in the early 1960s Congress committed to a one-of-a-kind Apollo lunar mission, not to a continuing manned flight program, to the long-lasting frustration of NASA and considerable expense to the country. As an example, planetary flights in general tend to be one of a kind if for no other reason than that specific mission opportunities are so far apart in time (and often so different) that to do the next mission at a minimal cost requires major changes in system architecture and technology. On the other hand, Earth satellites, for both national security and scientific purposes, tend to be multidecade programs exploiting a common architecture.

Unfortunately, perhaps, but for understandable reasons, Congress very seldom commits to long-range programs, only to projects. An unstated assumption to the contrary can be very costly. There are a number of ways to "hedge" those costs: design in options such as the "scars" for airliner stretching, or partition the system into relatively autonomous components. Define success in reachable, intermediate steps.

Life-Cycle Costs

Life-cycle costs, while theoretically worthwhile, all too often run afoul of the governmental reality of annual appropriations. More than one project has had cost overrun badly because its year-to-year funding did not match efficient implementation. The government does not run on life-cycle costs. It runs on cash flow. No cash, no flow. *Designing* on the basis that minimal life-cycle costs will "automatically" generate annual appropriations almost never works. Annual appropriations come from continuing needs and go to "programs" that satisfy them—communications, weather, surveillance and, most recently, navigation.

The principal value of life-cycle costs is that it enforces a consideration of operations costs, particularly the costs of testing and failure. It is unfortunate but true that most cost estimates in proposals are based on everything going according to a (life-cycle) plan. This is a near impossibility. It is not yet common practice to try to reduce cost by improving quality, though life-cycle cost strategies mandate it. In short, **quality makes money.**

Improving Schedules to Reduce Costs

From time to time assertions have been made that project costs can be saved by optimum scheduling. For example, NASA in its early years maintained that a specific Apollo schedule would result in the least cost, with greater costs on either side of it. In another case, an Air Force manager decided that the way to reduce cost was to shorten the schedule and enforce it, regardless. Another insisted that tightening schedules always increased costs. Unfortunately, data from many projects do not support the one-to-one relationship assumed by any of these strategies. There are too many other factors involved, among them erratic cash flow, changes in procurement regulations, technological mismatches, unexpected events in lengthy projects, responsive management, and so on.

A more profitable area for cost reduction through scheduling is likely to be the timing of projects *relative to each other*. Permitting every project or program to have its own funding profile over time results in peaks and valleys in the sum of all of them. Timing them relative to each other, for steady cash flow for example, means that not every project can be scheduled for the same time, much less when it wishes. There have to be years of the planetaries, years of the orbiting telescope, years of Earth observation, years of manned flight. If all parties understand and agree, more or less, to such macro-scheduling, and can *plan* for it, the frustrations, tragedies, and costs of "no new starts" and the miseries of missed opportunities might be considerably reduced. Galileo is only one example of many in the terrible 1980s for planetaries. To work, of course, each project must stay within its cost boundaries and, if not, take the consequences.

And then there is cost *allocation*. For example, to achieve a reasonable balance between mission effectiveness and launch success rate, the ratio of spacecraft to launcher costs should be between 4 and 5 to 1. Higher than that risks the loss of a very high-value spacecraft due to a relatively cheap, relatively unreliable launcher. Lower than that invests too much in a support function (launching) that has little to do with the final mission of exploration, communication, intelligence, etc. One thing for sure, changing launch vehicles in midstream is very expensive. Some common causes are spacecraft weight growth or misestimation, launch vehicle fleet grounding, failure to meet a deadline, etc.

Upgrading or Block Changing?

The effectiveness of upgrading as a way of cost reduction—as opposed to block changes—depends on where in the upgrading S curve the item is. Continually upgrading relatively mature hardware is likely to be *less* cost-effective than is continually upgrading rapidly evolving software. Note too that software upgrading can be, and has been, done remotely in flight—a major advantage for long-duration flights. On the other hand (all new) block changing of hardware is more straightforward than block changing software because the latter is more dependent on backward compatibility. The system-level value judgment here is the value to the client of being able to upgrade (or downsize) the mission, both before and after launch, and to exercise built-in options depending on the situation at the time.

It might seem that such flexibility would automatically be welcomed. But although the natural inclination of design engineers is for plenty of options, the natural inclination of operators and clients is almost the opposite—no changes at all unless components have checked out ahead of time. What is it worth to the *client?* Better not prejudge.

COMPONENT-LEVEL POSSIBILITIES

Modified List II
Component-Level Opportunities for Cost Reduction

- The use of software to reduce hardware and mission costs.
- The use of ultraquality parts to reduce testing costs.
- New technology versus space-qualified technology.
- Military specification versus screened commercial parts (COTS, pro and con).
- Piggyback payloads, etc.

I will address here only the first component.

Using Software to Reduce Hardware and Mission Costs

Where are the opportunities for using software to reduce costs? The most apparent opportunity is to use "smart" systems, both on the ground and in flight. For many missions, software can increase dramatically the mission's *worth* per dollar spent, even to the point where previously anticipated flights are not needed. And that, if planned in time, can be a real cost reduction.

Another possibility is to replace hardware with software in the interests of greater reliability and lower cost. Clearly the ratio of hardware to software, expressed as costs, has changed dramatically in the last decade from a cost ratio of 10:1 to 1:2. Part of this change is justified on mission effectiveness grounds; "smart" systems are not only more valuable, they cost less at the margin. Very soon software will be at the center of all real-time, software-intensive systems. Earth satellites and planetary spacecraft are certainly examples.

However, as software becomes a larger and larger part of mission costs, it becomes, and should become, a primary target for cost reduction. The question is how. It is a complex and controversial subject, perhaps better for a subsequent workshop. But from my point of view, the answer lies in new software architectures, reusable mission-certified modules, and progressive, integrated modeling.

For example, proponents of reusing software modules claim great savings. However, industry experience with COTS equipment and software has been mixed. On the one hand, the lack of knowledge of the details of a COTS component increases system risk, just as it did in the case of space lubricants whose composition was proprietary and unreleaseable. COTS "standards" can create otherwise unnecessary constraints on systems design. Supplier support for specialized hardware and consumer software may evaporate with time or if the COTS is modified in any way. As the heuristic states, "COTS is COTS," period.

On the positive side, the use of COTS *ought* to reduce development time (and costs), and in a world of "time to market" economics, time is money. All things considered, it would seem the better part of wisdom to use only COTS coming from the same or similar programs and subject to the same acceptance tests.

HEURISTIC GUIDELINES FOR COST REDUCTION[1]

- Simplify! Keep it simple, stupid! (KISS).
- Efficiency is inversely proportional to universality.
- Scope! Scope! Scope!
- Success and risk are defined by the beholder, not the architect.
- In architecting a new program, all the serious mistakes are made in the first day.
- In architecting a new system, by the time of the first design review, performance, cost, and schedule have been predetermined. One might not know what they are yet, but to first order, all the critical assumptions and choices have been made that will determine those key parameters.
- Do not assume that the original statement of the problem is necessarily the best, or even the right one.
- The most dangerous assumptions are the unstated ones.
- Any extreme requirement must be intrinsic to the system's design philosophy and must validate its selection. Everything must pay its way onto the airplane.
- In partitioning, choose the elements so that they are as independent as possible, that is, elements with low external complexity and high internal complexity. Choose a configuration with minimal communications between the subsystems.
- "Proven" and "state of the art" are mutually exclusive qualities.
- Complex systems will develop and evolve within an overall architecture much more rapidly if there are stable intermediate forms than if there are not.
- In any resource-limited situation, the true value given a service or product is determined by what one is willing to give up to obtain it.
- The bitterness of poor performance remains long after the sweetness of low prices and prompt delivery are forgotten.
- Quality makes money.

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[1] Rechtin, E., and M. Maier. 1997. The Art of Systems Architecting. Boca Raton, Fla.: CRC Press.

Perspectives on Small Spacecraft: Results of a Recent RAND Workshop[1]

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OVERVIEW

Small spacecraft are becoming an increasingly important element of civil space policy. RAND is currently studying small spacecraft missions and their future in space science missions. This briefing provides a review of this on-going study and highlights from a recent RAND workshop covering trends in the development of small spacecraft. This material is presented as an in-process briefing. Results discussed here are preliminary and are provided in support of ongoing intellectual discourse on methods to reduce the cost of space science missions.

BACKGROUND OF THE STUDY

The purpose of RAND's current work on small spacecraft is to review current and future programs to assess the efficacy of various development approaches and to gain insight into the performance of small spacecraft. In preparing the course of study, three key questions were established to guide the review of programs:

- What role are small spacecraft playing in civil space programs?
- What strategies have proven especially effective in reducing cost and increasing performance of small spacecraft?
- What role does advanced technology play in the process of building small spacecraft?

At the conclusion of the study, policy options will be synthesized and recommendations prepared regarding future directions for small spacecraft programs.

The study focuses on NASA science spacecraft with a dry mass of under 500 kg. Some analysis of DOD unclassified programs is also included. Although the definition of what constitutes "small" is arbitrary, the 500 kg. limit captures the programs that are generally considered small within both NASA and DOD. Occasionally larger programs are referred to for comparative purposes.

THE ROLE OF SMALL SPACECRAFT

Small spacecraft have become important policy tools. We already rely on small spacecraft to meet many of our national objectives in space and this trend is likely to continue. Small programs offer opportunities for international cooperation, in civil space most notably, but also possible future military cooperation in

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[1] From *Cosmos on a Shoestring*. Washington, D.C.: RAND Critical Technologies Institute. MR-864-OSTP (in press). Reprinted with permission.

communications and remote sensing. As missions become smaller these programs will also carry an increasing burden of helping the U.S. maintain a skilled aerospace workforce.

On the economic side, small spacecraft currently represent a sizable national investment. Figure C-1 provides an estimate of NASA spending in FY96 for (1) all spacecraft research programs, and (2) for small spacecraft programs within the scope of this study.[2] Cost breakdowns are provided in five areas; hardware (development of flight systems), launch systems, operations, research and analysis (R&A), and personnel. Approximately $4B is spent on spacecraft research programs within NASA, with $1B devoted to small spacecraft missions.

Small spacecraft are also of economic importance because they provide a means of conducting science at lower cost. They can be built faster requiring less engineering and testing; as a result they are cheaper. They also provide platforms for testing cost reduction strategies that have implications for programs of all sizes.

Competitiveness is another economic advantage inherent in small spacecraft. Built on faster timelines, small spacecraft are better able to approach the state-of-the-art. Since scientific objectives have remained ambitious spacecraft developers have been forced to aggressively pursue technology to increase performance.

One of the most important characteristics of small spacecraft, however, centers around a set of technical advantages. Firstly they are responsive to scientific needs. The ability to return results in 24 to 36 months is especially important in the realm of space science. Before budgets shrank spacecraft had already started to become leaner, a trend initiated by the demands of the science community:

> "Rapid, elegant response is imperative . . . science is not best served by exclusive emphasis on major missions."
>
> *Crisis in Space and Earth Science*
> NASA Space and Earth Advisory Committee, 1986

> "Efficient conduct of science and applications missions cannot be based solely upon intermittent, very large missions that require 10-20 years to complete. Mission time constants must be commensurate with the time constants of scientific understanding, competitive technological advances, and inherent changes in the systems under study. . . . NASA's new initiative for smaller, less expensive, and more frequent missions is not simply a response to budget pressures; it is a scientific and technical imperative."
>
> *Improving NASA's Technology for Space Science*
> NRC, 1993

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[2] This is a crosscut of the NASA budget prepared using RAND's RaDiUS (Research and Development in the United States) data base, which contains detailed budget information on the federal budget. Spacecraft costs are a summation of development costs for flight segments within the respective crosscuts. Launch costs include vehicle procurement and spacecraft-to-vehicle integration costs. Operational costs represent an aggregate of individual mission operations and data analysis (MO&DA) costs, construction of facilities (COF), and ground segment line items. Research and analysis (R&A) is a simple accumulation of these identified line items. Personnel costs are estimated as a fixed percentage of overall research and program management (R&PM) accounts.

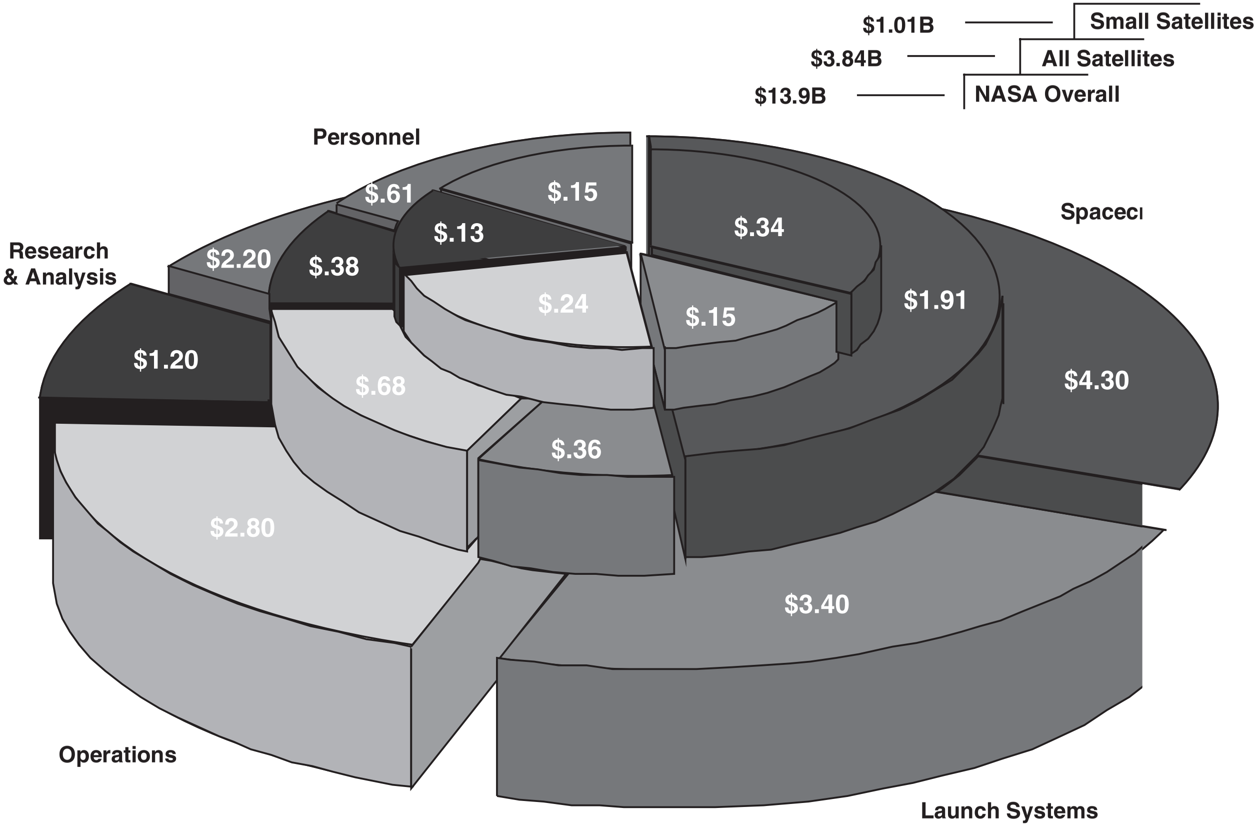

FIGURE C-1 NASA spending on small spacecraft.

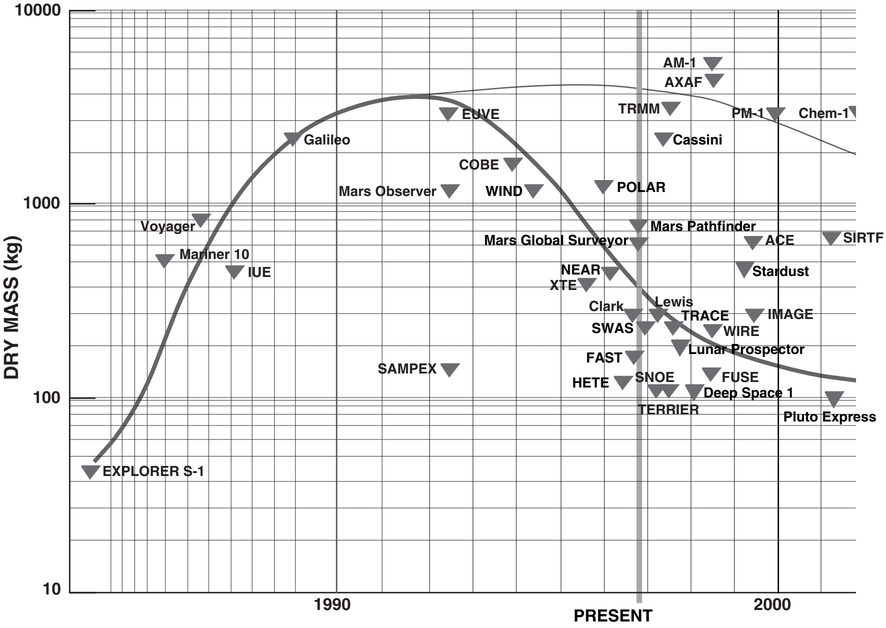

FIGURE C-2 Historical spacecraft mass trends.

Since the late 1980's there has been an evolutionary movement back to smaller missions. The Explorer program, NASA's oldest spacecraft series, evolved to Delta-Class missions, and then returned to smaller spacecraft with the formation of the Small Explorers (SMEX) Program. The shift to smaller missions is shown in Figure C-2. The mass of research spacecraft has dropped dramatically in recent years. The large missions remaining on the chart are, for the most part, legacy programs that were initiated prior to sharp budget reduction.

Risk is another technical factor that can weigh in favor of small spacecraft. There is certainly less financial exposure on a given mission and there is a proven track record of success for small spacecraft. With less at stake there is a tendency to believe that higher levels of risk-taking are acceptable on small missions. This is an area where additional analysis is needed. It is not clear whether future budgets can support a proliferation of small spacecraft. If additional initiatives are not forthcoming each small spacecraft will remain as important as their larger predecessors.

ANALYSIS OF SMALL SPACECRAFT PROGRAMS

Smaller spacecraft are certainly faster and cheaper to build, but whether they are better is open to some debate. The content of NASA's science program has

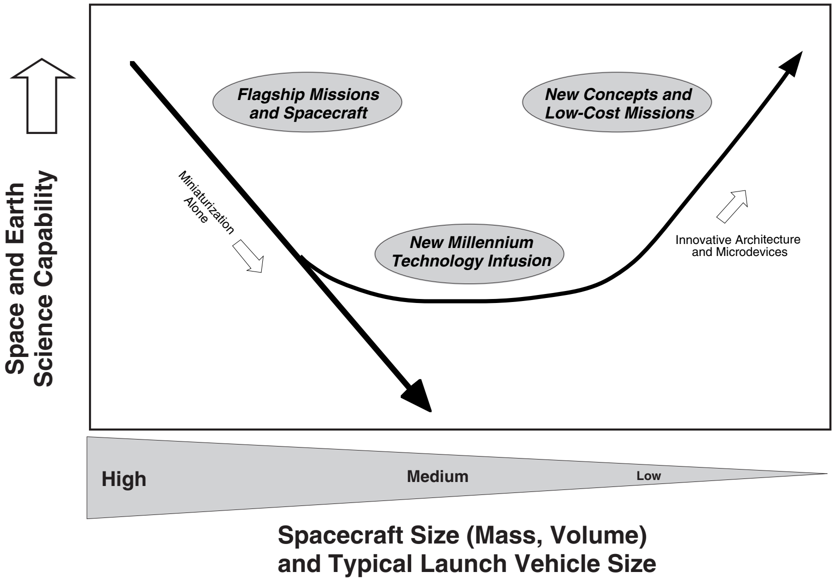

FIGURE C-3 The importance of technology in future small missions.

been reduced a good deal in recent years. Missions have been canceled (CRAF, OSL), deferred (Solar Probe), stretched (AXAF), downsized (SIRTF, FUSE), or turned off. It seems clear that the current generation of small spacecraft cannot maintain the pace of science without dramatic increases in system performance. Figure C-3 reflects NASA's reliance on new technology as the principal means of expanding the capability of small spacecraft, both to remain within anticipated budgets and to provide increasing scientific returns.[3] There are indications that small spacecraft can deliver big science. An example is the Small Explorer Wide-Field Infrared Explorer (SMEX-WIRE) which, at 250 kg., will observe sources 500 to 2000 times fainter than the Infrared Astronomical Satellite (IRAS), which was launched in 1983 weighing 1100 kg.[4]

Although small spacecraft are indeed cheaper in an absolute sense, they can cost 2 to 3 times as much per kilogram when compared with larger spacecraft. Figure C-4 presents an assessment of spacecraft development cost relative to, and as a function of, dry mass. The figure includes the cost to manage, design, develop and test the spacecraft and instrument, and excludes any launch, ground support equipment, and operational costs. The chart shows that many small spacecraft, in a relative sense, are more expensive than larger ones. The chart also

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[3] Space Science for the 21st Century, NASA Office of Space Science, August, 1995, p. 25.

[4] Minutes of the NASA Astrophysics Subcommittee, September 1994.

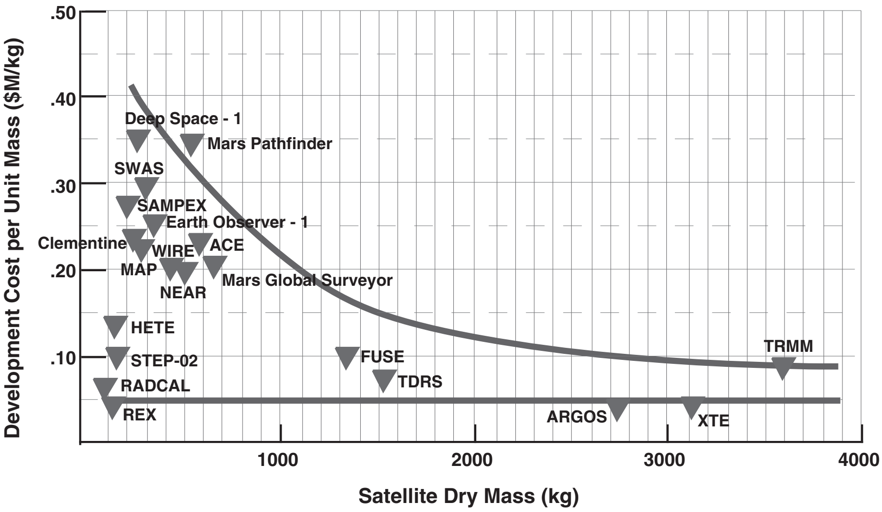

FIGURE C-4 Spacecraft cost per kilogram comparison.

shows that some small spacecraft programs demonstrate a linear relationship between mass and relative cost. The principal reason for the higher relative cost of many small spacecraft is the complexity inherent in trying to integrate compact systems, advanced technology, and redesigned instruments into a smaller package. Future analysis will seek to normalize the cost of complexity in these missions and perform a more revealing comparison.

As part of the study, detailed cost estimates were prepared for twelve NASA small spacecraft.[5] Based on current mission data, Figure C-5 depicts a breakdown of costs for an average NASA small spacecraft mission. It is not remarkable that small spacecraft should cost less to develop that larger ones. The question remains: how much have “faster, better, cheaper” initiatives impacted mission cost? The SMEX program provides an excellent data point. The Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX) mission was the first in the Small Explorer (SMEX) series and an early demonstration of the movement to smaller spacecraft. It was, however, a spacecraft that was built according to more or less traditional practices, before designing to lowest cost became a mission priority.[6] In FY’96 dollars the total mission cost for SAMPEX, including estimates of civil servant labor costs, was approximately $81M. The follow-on

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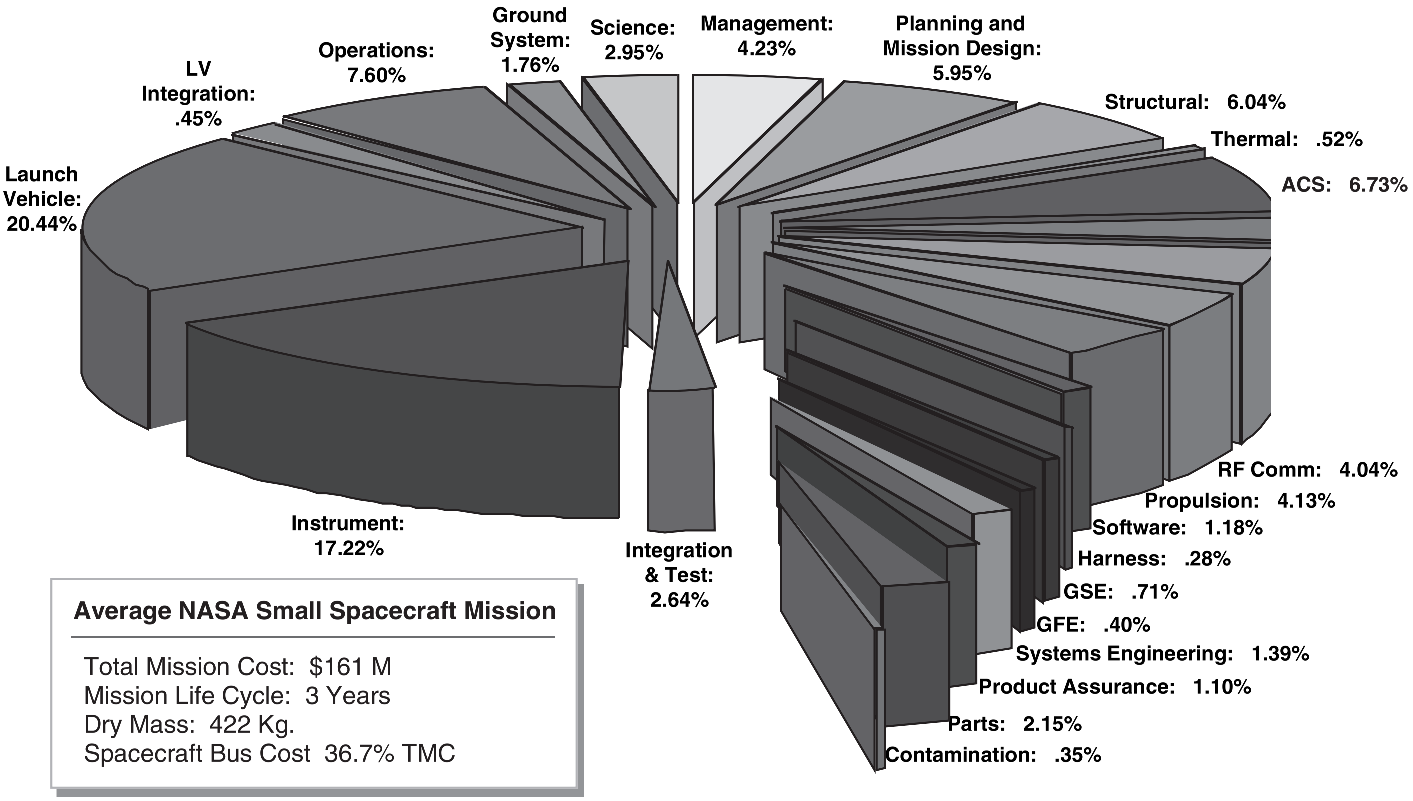
[5] Detailed cost data was provided by the respective NASA program offices: Discovery, NMP, Explorer, and Surveyor, for missions in the 500kg category. Each program provided information against a standard cost template which included estimates of civil servant resources and government furnished equipment.

[6] O. Figueroa, *SAMPEX*, in Wertz and Larson, *Reducing Space Mission Cost,* 1996.



Average NASA Small Spacecraft Mission

Total Mission Cost: $161 M
Mission Life Cycle: 3 Years
Dry Mass: 422 Kg.
Spacecraft Bus Cost 36.7% TMC

FIGURE C-5 Distribution of TMC cost elements for current small spacecraft.

SMEX spacecraft, the SMEX-Lite missions, will take advantage of all that has been learned at NASA GSFC. They are projected to have a TMC of $65M, including launch and civil servant costs, more than a 20 percent reduction.

Although real savings have been realized from the advanced practices being used to build the current generation of spacecraft, there are some reasons for concern. In the drive to reduce mission cost it is essential not to overlook hidden costs which can cause:

Lessons not to be learned—in small spacecraft programs there is usually little time or money to document team experiences. Travel funds are in short supply, discouraging the communication and cooperation required to vitalize new programs and train new people.

Poor working environments—there is danger of creating "spacecraft sweatshops" with working conditions that exhaust and demoralize project personnel. Many of the projects examined in the study reported problems with employee fatigue, stress-related ailments, and retaining key staff. On flight projects it is not uncommon to see employee timesheets in excess of 70 to 80 hours per week, much of it representing uncompensated time. To some degree this is a fact of life in space development programs, but in past programs such extremes were usual only in the integration, test, and launch phases. The concern now is that excessive workload is now appearing throughout the development cycle. Compounding this problems is the pressure to further reduce schedule.

Loss of margin—most small spacecraft are being built with very small design and operation margins in an effort to save cost. Small margins lead to elimination of redundant strings, with a subsequent loss of opportunity to fly advanced designs. Lean margins can also drive *up* non-recurring engineering costs, since it can be difficult to design systems with little margin. Mission designers must also prepare and verify spacecraft operational sequences that exhibit very little room for error. Another downside is that opportunities for commonality/standardization are frequently foregone because there is not enough money or technical performance left to develop them.

Limited profitability—many commercial developers complain that small spacecraft are not profitable undertakings. Small spacecraft builders often operate as 'skunk works' within a larger corporation. Their viability is increasingly tenuous in a low-profit environment. Capital equipment funds for tooling, new facilities, training and certification, are also hard to come by.

These costs, though difficult to quantify, are, nonetheless, real. Failure to account for them will inevitably affect long-term quality and performance.

RAND WORKSHOP RESULTS

A workshop to examine trends in the development of small spacecraft was sponsored by RAND in mid-August of 1996 in Washington, D.C. The purpose of the workshop was to bring together engineers, managers, and policy-makers to discuss progress in a forum held without attribution. The results of the workshop are summarized into five areas; cost trends, reducing TMC, commonality, technology, and policy.

Cost Trends

- Emergence of small spacecraft:
  - Driven not just by budget.
  - Small missions are responsive to change (political, economic, and scientific).
  - Small spacecraft philosophy impacts all aspects of management and engineering—a new paradigm.
- Measurement of costs:
  - Should be public to inspire competition.
  - Should be inclusive of all costs (including overruns).
- Overall trends:
  - Subsystems and, in some cases, the whole spacecraft are now commodities.
  - Cultural change to a new, smallsat paradigm has not yet occurred within NASA.

Reducing TMC

- Impact of commercial systems:
  - Direct purchase of COTS buses will allow some missions to substantially cut TMC.
  - Commercial suppliers are betting on demand pull to increase sales.
- Technical approaches:
  - Replace traditional Phase A-E with in-process, as-needed reviews.
  - Maintain a level of documentation rigor appropriate for small spacecraft.
  - Avoid “we’ll fix it in I&T”, focus on firm requirements and upfront engineering.
- Management approaches:
  - Team size and schedule are the principal determinants of cost.
  - Trust “contractor best methods” (for established entities)—corporate reputation is at risk and infrastructure is in place.
  - Process improvement is at least as important as new technology in bringing down TMC.
  - Hidden costs often lie within programs (poor profits, employee overload, creative bookkeeping . . .).

Spacecraft Commonality

- Future planetary and space physics missions are moving to higher levels of instrument/bus integration—a move away from purchase of commercial buses.
  - — However, future constellation missions seem ideally suited to bus purchases.
  - — Scaleability of future spacecraft will allow downward and upward propagation of new designs.
- Communications and operations:
  - — Internet-based team integration and operations is an emerging reality.
  - — Efforts to encourage working-level communication and cooperation (colloquia, personnel exchange . . .) are a wise investment.
- Articulating requirements:
  - — Matching technology solutions to spacecraft requirements requires continuing conversation—road maps often prevent this.

Technology Trends

- Retiring risk of new technology:
  - — Demonstrator missions don't fly the high risk technologies.
  - — Risk should be tied to the requirements of the spacecraft designer, realistic budget/program portfolio, and government performance-based planning (GPRA).
- Planning technology programs:
  - — NASA technology programs should follow the USAF "mission-pull" model.
  - — Save a portion of the technology budget for projects unrelated to future missions—strong R&D base.
  - — Technology roadmaps bear no relation to budgets.
  - — NASA should understand commercial investment in space technology and not compete—identify unique requirements.
- Future technology programs:
  - — The loss of SDIO/BMDO technology funding will constrain the performance of future small spacecraft.
  - — Commercial IR&D programs are the big spenders.

Space Policy

- Future budgets:
  - — Budget constraint will be a long-term phenomenon.
  - — No more "bet it all, lose it all."
- Political support:
  - — Effort needed to educate Congress on the need for occasional high-risk technology missions.

  - High risk in selling promise ("order of magnitude reduction in . . .") in this environment.
- Metrics:
  - Stop counting "what we spent," measure "what we did."
  - Technology programs should be peer reviewed by the people that use the technology.
  - Ask NASA's customers to evaluate performance, not NASA.

CONCLUSION

The purpose of this NRC workshop is to explore new ways to reduce mission cost. Significant effort has already been directed at the challenge of simultaneously reducing cost and increasing performance. As a result both government and industry have discovered ways to accomplish significant results.

It is likely that additional cost savings will be more difficult to extract. Fundamental changes are required in our approach to conceptualizing spacecraft, and new techniques and processes must be defined to manufacture and operate them. Fortunately, technology advances at a steady enough pace to ensure that new solutions lie around every corner.

In embracing new approaches it is essential to integrate risk management more thoroughly into mission planning and implementation. Greater reliability should be synonymous with increased performance. Spacecraft of the next millennium should not only be less expensive, but also longer-lived and ever more reliable.

Achieving these objectives will require careful planning and wise investment of limited resources. The results of this workshop will no doubt help outline the next steps.

LIST OF ACRONYMS

ACE	Advanced Composition Explorer
AM	ante meridiem (the AM-1 is NASA's Earth Observing System Satellite with a 10:30 a.m. descending node)
AXAF	Advanced X-Ray Astrophysics Facility
BMDO	Ballistic Missile Defense Organization
Chem	Earth Observing System Chemistry Satellite
COBE	Cosmic Background Explorer
COTS	commercial-off-the-shelf
EUVE	Extreme Ultraviolet Explorer
FAST	Fast Auroral Snapshot Explorer
FUSE	Far Ultraviolet Spectroscopic Explorer

GSFC	NASA Goddard Space Flight Center
HETE	high energy transient experiment
I&T	integration and test
IMAGE	imager for magnetopause-to-aurora global exploration
IR&D	in-house research and development
IUE	International Ultraviolet Explorer
MAP	Microwave Anisotropy Probe
NEAR	Near Earth Asteroid Rendezvous
PM	post meridiem
REX	radiation experiment
SAMPEX	Solar, Anomalous, and Magnetospheric Particle Explorer
SDIO	Strategic Defense Initiative Office
SIRTF	Space Infrared Telescope Facility
SNOE	student nitric oxide experiment
STEP	Space Test Experiment Program
SWAS	Submillimeter Wave Astronomy Satellite
TDRS	Tracking and Data Relay Satellite
TERRIERS	tomographic experiment using radiative recombinative ionospheric EUV (extreme ultraviolet) and radio source
TRACE	Transition Region and Coronal Explorer
TRMM	Tropical Rainfall Mapping Mission
WIRE	Wide-Field Infrared Explorer
XTE	X-Ray Timing Explorer

Influence of Technology on Space Mission Costs

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INTRODUCTION

The consideration of new technology for introduction into space mission planning can influence cost, risk, and performance in many significant ways. The evaluation of this influence requires a system-level assessment of these factors as technology trade-off investigations are conducted to compare off-the-shelf and new technology solutions. Planners must beware of temptations to reach for new technology to solve excess cost problems. The space design graveyard is littered with the remains of those who have tried.

New technology *can* present possibilities for space mission cost reduction by:

- introducing cheaper components (e.g., advanced electronics)
- introducing less complex components (e.g., self-contained thrusters)
- achieving higher performance
- reducing volume, mass, and power requirements
- enabling cost and performance trade-offs

These factors may allow additional cost reductions that may be realized from reduced ground test requirements, lower-cost launch options, shifting requirements from one subsystem to another, and from reduced system complexity. In estimating potential reductions, however, it is crucial that cost projections include accurate assessments of the nonrecurring costs associated with technology development, validation, and qualification. The ability to estimate these costs accurately is a strong function of the maturity of the technology.

The necessity for space qualification introduces added complexity into assessing costs associated with introducing new technology into a space mission. Can a new technology be qualified on the ground using simulations of the space environment or must it actually be flown in space? The answer to that question may depend on who is answering it. Finding an agreement between the technology developer and the space mission director is often very difficult. Typically the developer considers the technology ready for flight before the mission director does. If there is a disagreement, funding must be provided to conduct the necessary testing to enable the technology transition.

There is a useful discussion of the influence of technology on space mission costs in *Reducing Space Mission Cost* (see Ch. 3 in Wertz and Larson, 1996).

This book also contains some excellent case studies that include the effects of the use of new technology. The decision to consider the use of new technology is a critical one that is wrapped up in the original mission design philosophy. The Near Earth Asteroid Rendezvous (NEAR) design philosophy allowed the use of new technology only when it could be shown to directly reduce mission cost. "New technology was used when it was necessary for the execution of the mission and not because it was neat to do so" (Maurer and Santo, 1996). The first of NASA's Discovery missions, the NEAR spacecraft was launched on February 17, 1996. It was completed under cost ($108 million versus a ceiling of $150 million) and ahead of schedule (27 months versus the goal of 36 months). New technologies employed under the guiding philosophy included (1) the use of gallium arsenide solar arrays, (2) the use of a solid-state recorder, (3) the use of a sodium iodide crystal inside a bismuth germinate crystalline shield for rejection of the interplanetary background in the gamma ray spectrometer, (4) the use of a scaled down but more reliable version of the Clementine laser range finder, and (5) the use of software autonomy rules for use during long cruise portions of the mission (Maurer and Santo, 1996).

In summary, the decision to introduce new technology into a space mission involves intelligent, thorough cost/risk trade-off assessments that must be conducted at the system level. These assessments must include accurate estimates of the nonrecurring costs associated with development and space qualification. An up-front mission philosophy that governs trade-off decisions (e.g., the NEAR philosophy) should be articulated. In all cases, available off-the-shelf technologies must be included in the trade-off considerations.

SPACE QUALIFICATION

Consideration of the use of new technology in a space mission must address the level of space qualification necessary to reduce the risk to an acceptable level. "Unfortunately, there is no universally accepted definition of what makes a particular component 'space qualified'" (Wertz and Larson, 1996:66).

At best one would hope that the component had actually operated to required performance levels in the space environment. To achieve this the components must either have been flown as an operational component or have been operated as part of a space technology demonstration experiment. Even then one has to be concerned with the number and breadth of the testing. Ground testing in simulated space environments can reduce space qualification costs if the simulated environments are sufficient to qualify the component. The cost/risk trade-offs in seeking an acceptable level of space qualification are part of the reason it takes so long to get some of the promising new technologies into space.

In some instances formal technology transfer programs have been devised to develop a planned movement of technology from the laboratory into space. NASA's New Millennium Program (NMP) is one of these. Implementation of this program has led to the establishment of a group of Integrated Product Development Teams that are examining technology needs for future space missions. One of the products of these teams is a collection of technology roadmaps that chart planned technology development versus identified technology need dates. A series of planned technology demonstration flights are integrated into the NMP to provide flight opportunities in the space environment. Much of the information in the following sections is taken from the *1995 New Millennium Program Technology Roadmaps* (NASA, 1995). Other sources are the Tenth Annual American Institute of Aeronautics and Astronautics/Utah State University (AIAA/USU) Conference on Small Satellites (1996) and other media sources. The presented information is by no means exhaustive. More detailed information can be found in the original sources. The technology information is keyed to availability dates of 2001, to support the Mars 2001 mission, and 2004 to support Earth observation missions.

SPACE ELECTRONIC SYSTEMS

The general goals for space electronics systems are (1) reduction of electronics subsystems mass, volume, and power requirements; (2) increased use of commercial components; and (3) fault-tolerant on-board computing to enable onboard data processing and autonomous spacecraft control and operation. The latter goal is intended to introduce large cost savings by a reduction of ground operations personnel requirements. Specific goals versus current state of the art for 1999 are (1) a reduction in semiconductor feature size from 0.7 to 0.4 microns, (2) an increase in processor million instructions per second (MIPS)/W from 1.8 to 14, (3) a decrease in processor mass from 1000 to 100 grams, (3) an increase in memory storage from 0.1 to 500 Mbits/gram, and (4) an increase in power electronics output from 16 to 250 W/cm^3 and 0.01 to 6 W/kg. Again, details are provided in the *New Millennium Program Technology Roadmaps*. Some flight validation will take place on the first technology demonstration flight, Deep Space 1, in late 1997 (NASA, 1995).

Additional technology considerations in designing space electronics systems include decisions on the use of space-qualified parts and the required levels of radiation hardening. During 1965–1980, special process, testing, and documentation requirements were introduced to provide electronics parts that were “space qualified.” These parts are usually much more costly than their commercial counterparts. Specification of space-qualified parts reduces the risk of failure at the expense of significantly increased costs. These costs can sometimes be avoided by combining the use of commercial, high-reliability parts with fault-avoidance design. Wertz and Larson (1996:295–300) present a good discussion of the use of derating, environment protection, screening, and fault-tolerant design.

Required levels of radiation hardening are mission dependent and must be considered in the design. Choices of electronic systems, components, and parts must conform to radiation-hardening requirements. Modern electronics parts with high-density integration tend to be less tolerant to radiation effects than older ones. The sensitivity to radiation drives trade-off decisions among parts and component selections and shielding designs.

An example of space computer development trends was described by Gaona (1996) in the recent Tenth Annual AIAA/USU Conference on Small Satellites. Gaona described a Sandia-developed, radiation-hardened computer that uses the NASA Goddard R3000 “Mongoose” for its central processing unit. The computer uses a high-reliability 32-bit processor and is capable of 10 MIPS at 480 Mbits/s while consuming only 1.2 W.

ELECTRICAL POWER

The NMP emphasis in power technology improvements focuses on silicon versus gallium arsenide solar cell cost versus performance trade-offs. Included in the technology roadmaps are multiband gap planar photovoltaics that project 26 percent efficiency, flight tested and qualified by 1999, and a SCARLET concentrator array that will achieve 1.5 times the present state-of-the-art efficiency at one-half the cost. The SCARLET Concentrator will fly on the NMP Deep Space 1 mission (NASA, 1995).

For power storage the NMP emphasis is on lithium-solid polymer battery technology. A space prototype providing 150 Whr/kg at “low” cost is planned for availability by 1998 (NASA, 1995). Nearer-term options include nickel metal hydride and lithium ion technologies. Emphasis in the AIAA/USU Conference on Small Satellites was on nickel hydrogen performance improvements (approximately 55 Whr/kg) (Machlis, 1996; Caldwell et al., 1996).

STRUCTURES AND MECHANISMS

The primary effort in improving structures and mechanisms has been on reducing mass and increasing stiffness through the use of new materials. The introduction of graphite/epoxy into spacecraft structures has already happened (e.g., the use of graphite/epoxy in the recently launched Mars Global Surveyor reduced the mass to one half that of the Mars Observer). Outyear technology possibilities include the use of inflatable structures that could be 2–10 times lighter, 10 times smaller in stowable volume, and 20 times less expensive than current approaches. Space-qualified inflatable structures will not be available until after 2000 (NASA, 1995).

Exciting developments in multifunctional structures (MFSs) are just now emerging. MFS concepts envision the integration of electronics and thermal functions onto lightweight structural components. Successful integration will eliminate cables, electronic boxes, and connectors from the spacecraft. Electronics will be bonded directly to the load-carrying thermal structural panel. MFS concepts promise a doubling of current payload mass fractions.

COMMUNICATIONS

The combination of smaller, low-power spacecraft with sophisticated, high data-rate sensors is aggressively driving the need for higher performance communications systems. The NMP communications roadmap identifies key capability needs such as (1) miniature deep-space communications systems, (2) extremely large bandwidth systems for near-Earth missions, and (3) capabilities for in-space interconstellation communications. Needed technology developments include:

- extremely high bit-rate transponders
- high throughput on-board transponders
- phased array antennas
- high data-rate radio frequency transmitters
- low-mass, low-power integrated circuits

Schedule details are found in the NMP Roadmaps (NASA, 1995). The major thrusts are in deep space systems are Ka Band (32-GHz) systems, highly miniaturized transponder/transmitters, highly efficient power amplifiers, and lightweight, deployable antennas. Near-Earth thrusts include high data-rate transmitters incorporating data compression techniques and phased array antennas (NASA, 1995).

Optical communications systems offer some significant advantages over radio frequency. These include reduced size, aperture gain, and unlimited bandwidth. The NMP roadmaps indicate initial availability in 1997–1998 (NASA, 1995).

ATTITUDE DETERMINATION AND CONTROL

The penetration of nearly all space missions by small spacecraft has driven attitude determination and control (AD&C) technology very hard. The primary drivers are the need for low-mass, low-volume components. Fortunately, the reduced mass and inertia of small satellites allows the use of very low torquing systems.

In the area of attitude determination, significant progress has been made in attitude sensing technology. Some new sensing devices are already in use; some are very near. Examples of these are small, lightweight star sensors enabled by charge-coupled device arrays and increased on-board computing capability; low-cost, turned-rotor gyros; high-precision magnetometers; and differential Global Positioning System attitude sensing. Miniature electromechanical systems technology envisions accelerometers and gyros on-a-chip that will revolutionize attitude sensing and control. New low-force torquing devices are being introduced into spacecraft attitude control system design very quickly. Such devices include magnetic torquers, arc jet electric propulsion (on the shelf), ion thrusters (baselined for flight on Hughes communications spacecraft and the NMP Deep Space 1 mission), pulsed plasma thrusters, and self-contained thrusters using evaporation and sublimation techniques.

The development of AD&C hardware is on a very steep slope with new devices appearing every day. Software developments enabled by increased on-board computing capacity are also significant factors in increasing AD&C capabilities. The combination of increased on-board computing capacity, reliable small sensors, and robust control software is a major factor in enabling future spacecraft autonomy. Autonomy, in turn, will generate large decreases in operations costs by reducing manpower requirements.

CONCLUSION

The potential introduction of new technology into spacecraft programs includes strong interactions among cost, performance, and risk factors that require intelligent trade-off analyses before commitment to a decision. Significant spacecraft technology developments are on the horizon that will allow incorporation of new capabilities into space mission design at potentially lower cost. The readiness of these developments depends on the required levels of space qualification and the costs associated with achieving these levels. Programs such as the NASA New Millennium program are designed to provide the planning and resources to enable the technology transition activities required to provide space-qualified hardware and software for future space missions. The impact of future technology development on future space mission costs and performance will be significant.

REFERENCES

Caldwell, D.B., C.L. Fox, and L.E. Miller. 1996. Powering small satellites with advanced NiH_2 dependent pressure vessel (DPV) batteries. In Proceedings of the Tenth Annual American Institute of Aeronautics and Astronautics/Utah State University (AIAA/USU) Conference on Small Satellites. Logan, Utah: Utah State University, Center for Space Engineering.

Gaona, J.I., Jr. 1996. A radiation-hardened computer for satellite applications. In Proceedings of the Tenth Annual AIAA/USU Conference on Small Satellites. Logan, Utah: Utah State University, Center for Space Engineering.

Machlis, M.A. 1996. On orbit NiH_2 battery performance and problem solving on the Apex spacecraft. In Proceedings of the Tenth Annual AIAA/USU Conference on Small Satellites. Logan, Utah: Utah State University, Center for Space Engineering.

Maurer, R.H., and A.G. Santo. 1996. The NEAR Discovery mission: lessons learned. In Proceedings of the Tenth Annual AIAA/USU Conference on Small Satellites. Logan, Utah: Utah State University, Center for Space Engineering.

NASA (National Aeronautics and Space Administration). 1995. New Millennium Program Technology Roadmaps. Washington, D.C.: NASA.

Wertz, J.R., and W.J. Larson, eds. 1996. Reducing Space Mission Cost. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Summary of Techniques for Reducing Space Mission Costs

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The objective here is to capture useful strategies for reducing the cost of space missions and to provide the information to industry and government program managers to implement. There are several approaches to reducing space mission costs, and the key is to carefully select and implement an integrated combination of the approaches for a program. Potential cost reduction approaches include the following:

- use policy issues that affect cost to reduce cost
- limit the acquisition process to a shorter time
- manage the requirements process
- develop and employ cost-effective mission concepts
- emphasize reducing costs while managing the program
- incorporate the design, development, and test of spacecraft to reduce cost
- emphasize mission operations and ground infrastructure concepts
- consider technology to reduce cost

SUMMARY OF POLICY ISSUES THAT CAN AFFECT COST

Develop and implement Department of Defense (DOD) and NASA integrated plans and architectures. Build credibility for your program in the executive and legislative branches of government. Build a strategic road map that provides a common frame of reference. Make dual use of information, hardware, software, and programs among DOD, NASA, and industry. By merging selected NASA and DOD capabilities (for example, weather), cost can be reduced.

Implement an accounting system for mission operations by making the developer and operator responsible for cost of operations and by making as much of operations as possible direct costs. Continue by making users and operators accountable for funding and system cost.

Improve the acquisition process to facilitate cost reduction by increasing procurement stability to reduce wasted effort and by increasing funding stability to reduce the cost of developing systems by a significant percentage. Use incremental funding where appropriate. Set up an organizational structure and acquisition process to facilitate trading on requirements and eliminate all noncritical requirements. Consider implementing stringent cost control methods such as canceling programs for 15–30 percent cost overruns or six-month schedule overruns.

Eliminate any unnecessary military standards and specifications, and facilitate the use of commercial best practices. Increase the dollar limit for noncompetitive contracts, and make users and operators accountable for funding and system cost. Then provide incentives for government and contractors to reduce cost—don't penalize your program team for taking calculated risks.

MANAGE THE REQUIREMENTS PROCESS TO FACILITATE REDUCING COST

Identify and implement a process for managing requirements that provides the user or customer what they need; however, generate fiscally responsible requirements, and make a concerted effort to identify the truly difficult and costly requirements. Bundle program requirements to facilitate affordable systems. Establish a timely process to trade on the requirements and negotiate acceptable compromises by motivating key players in government and industry to identify tough requirements and provide options to change or meet them.

Develop better integrated mission concepts, document them, and be willing and able to negotiate by integrating space into the everyday lives of users and operators. State your program requirements in a more constructive fashion by describing what is needed, not how to provide it, by including ranges of performance and by stating the rationale or reason for requirements—the goal is to communicate.

DEVELOP COST-EFFECTIVE MISSION CONCEPTS

Recognize and facilitate different classes of missions and payloads, select the proper class of mission and payload, then implement accordingly. Perform up-front space mission engineering to develop innovative mission concepts using air, space, land, and sea resources, but implement them conservatively. The most important cost savings occur while deciding how to meet operational requirements, not how to implement a set of technical specifications. Do trades among mission elements early, as they provide the best opportunity for reducing cost. Examples include data processing, orbit insertion, propulsion, and autonomy.

Make maximum use of cost-effective commercial products—look for commercial capabilities first, then remember that large missions can be done by using several large or many small spacecraft—many trade-offs exist. Technical risk and cost may increase when you put all of your eggs in one basket, for example, dollar per bit may be lower for one large integrated spacecraft, and the consequence of failure is also larger. Use a "design-to-cost" approach and adjust the mission concept, requirements, and design to meet a life-cycle cost goal.

EMPHASIZE MANAGING PROGRAMS

Carefully select an experienced program leader and give him sole responsibility and accountability for development, test, and operations; then support him or her. Use committees to gather sage advice, wisdom, and good ideas but don't make decisions by committee—when things go wrong, it turns out no one can remember being at the meeting!

Select your program leadership based on the type of program and desired attributes for a specific program (large or small, technical or not, hands on, motivation, and skill mix). Build competitive hardware; do not focus on paper studies. Actively use prototyping and simulation where appropriate. Minimize documentation and reviews. Only develop and maintain necessary documentation. Zero-base documentation works, but it is painful. Explore using existing contractor documentation and augment, if necessary, and reuse generic documentation.

Track cost and schedule in near real time—work the problems in real time and don't accept schedule slips. Encourage mutual trust between the government and contractor team—integrated product teams can work well. Facilitate easy communication among all players. Determine the appropriate approach for government interaction with contractors (small government and contractor program office—separate or joint). Use concurrent design and fabrication judiciously and avoid jointly funded programs.

Manage the requirements and design change process with an iron fist once you have selected the proper philosophy (in any event do not allow changes on changes to go unchallenged). Government program managers can save time and money by using contractor/contracting officers to procure hardware, software, and services as well as some facilities. Be wary of reducing contract funding by 10 percent each year because it causes a very destructive phenomenon. Consider canceling lower-priority activities and leave others unchanged.

A compressed schedule can reduce overhead of a "standing army." It forces your program to move rapidly and can reduce cost. A tight schedule can be a wonderful excuse to expedite procurement.

Reducing the budget should result in reduced capability. If not, you are reducing program margin and increasing risk. Use increased spacecraft margins to reduce cost because it provides more flexibility and makes the system more robust during the development and operations phases. It can also reduce operations, engineering, and manufacturing costs. Make maximum use of cost-effective commercial products by looking for commercial capabilities first. Use of commercial off-the-shelf items should be strongly encouraged. Share cost among nations, organizations, and companies. This may reduce the cost of one piece, but be sure that the overall cost will be higher. More interfaces usually imply more complexity and higher cost.

INCORPORATE SPACECRAFT DESIGN, DEVELOPMENT, AND TEST STRATEGIES

Develop and use standard interfaces where possible. Automate appropriate spacecraft functions to reduce life-cycle cost. Automating the wrong ones will drive costs up. We know that automating things such as anomaly detection can work, but anomaly resolution has been less successful. Automating some functions on the spacecraft to ease operations cost has, in some cases, had the opposite effect.

Consider weight-optimized, smaller spacecraft versus fewer larger spacecraft to reduce launch cost. This may drive spacecraft cost up. Develop designs that are robust to known or anticipated changes (historically based). Shoehorning software into a computer and increasing the speed at which a code operates is one of the most expensive things we can do. Mass, power, and throughput must be robust. Make considered, maximum use of existing capabilities and infrastructures if they are cost effective.

Use the 80 percent rule in developing multiuser systems; but trying to be all things to all users drives the cost through the roof. Don't sacrifice on integration and test; however, it is possible to eliminate some development and performance tests if qualification tests are used. Emphasize validation and testing from day one.

INCLUDE MISSION OPERATIONS AND GROUND INFRASTRUCTURE CONCEPTS

Develop and use standard interfaces, protocols, and procedures. Software and procedure reuse coupled with up-front participation can reduce cost significantly. Automate appropriate functions to reduce cost and enhance reliability. Eliminating one low-cost operator and replacing him, or her, with a high-cost software maintainer is not cost effective in many cases. Use automation to enhance reliability and reduce life-cycle cost. Carefully consider data flow to minimize organizations and steps. Review data push and data pull approaches. The data pull approach has the potential to reduce the cost of data. Implement an accounting system for mission operations and make the developer and operator responsible for the cost of operations. Make as much of operations as possible direct costs. Allow adequate spacecraft margin needed for expensive analysis during development and operations. This makes the spacecraft more operable and less expensive to operate. Check mission and spacecraft operability prior to committing to mission and spacecraft design. Periodically revisit the design throughout development.

IDENTIFY TECHNOLOGY

Focus on technologies that provide savings in the "-ilities"—producibility, testability, reliability, and operability—are prime. Fly operational demos in addition to tech demos—the philosophy and approach may be different. Technologies to reduce mission operations cost include autonomous orbit determination and maintenance, on-board data processing and health monitoring, standardized communication interfaces, use of spacecraft command language, and on-board solid-state memory. Technologies to reduce the cost of space missions include those that improve up-front development of mission concepts, operations planning, and systems engineering. For example, miniaturization of electronics, solar electric power generation, and electric propulsion, autonomous navigation of spacecraft, the Global Positioning System, or other technologies.

SUMMARY

We share many of the same problems; however, we can work together to solve many of them. We've seen many useful approaches and many examples of how to reduce cost, but the strongest approach is to select a combination of approaches that suit a program's particular needs.

Mars Exploration Program Strategy: 1995-2020[1]

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and
DANIEL J. McCLEESE
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ABSTRACT

In the wake of the failure of the Mars Observer mission in 1993 a long-term program of robotic exploration of Mars was established. The themes of the Mars Exploration Program are to understand Life, Climate and Resources on Mars, with these themes tied together by the common thread of Water. The Mars Exploration Program comprises at least one Discovery mission (Mars Pathfinder), the Mars Surveyor Program, plus sample return missions and other missions to prepare for possible human expeditions to Mars. The program will launch (on average) two missions every 26 months. The missions launched between 1996 and 2001 will include a lander and an orbiter at each opportunity, launched on the Delta family of launch vehicles. International participation is an important factor in the program, and relationships are being established with Russia, Europe and Japan. The program is severely cost constrained, with missions costing about $150M apiece or less, including launch and operations.

THE "WATER STRATEGY"

The Mars Exploration Program will continue the exploration of the red planet which has fascinated humankind for thousands of years. Robotic spacecraft began visiting Mars in 1965, and landed on the surface in 1976. Mars was found to be a planet of stark contrasts. The surface features range from ancient, cratered terrain like Earth's moon, to giant volcanoes and a canyon as long as the United States is wide. The atmosphere is less than 1 percent as dense as Earth's, but there are constant polar caps with reservoirs of water ice. Close-up, Mars resembles an earthly desert like California's Mojave, but there is evidence that water once flowed and cut channels on the surface.

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NASA Administrator Dan Goldin and NASA Associate Administrator for Space Science Wes Huntress have agreed on a strategy for the exploration of Mars for the next 10 years. The strategy is to explore and study Mars in three areas:

- evidence of past or present life
- climate (weather, processes and history)
- resources (environment and utilization)

Mars will be our first footfall in the search for life beyond Earth. We began our search for life on Mars using the tools of astronomy. As we extend our reach with new astronomical tools in search of planets and life in other solar systems, Mars remains our touchstone for understanding planetary evolution different from Earth's. Robots and humans will go to Mars to explore intensively. We seek the markers of life from which we will learn how to find and study hospitable worlds. Using both remote presence and physical contact, our skills will be honed and our reach lengthened sufficiently to understand whether we occupy a unique place in the universe or one of many such places scattered throughout it.

If life ever arose on Mars it would almost surely have been connected with water. And understanding the water-connected processes which led (or didn't lead!) to life on Mars will help us understand the potential for life elsewhere in the Universe. The climate and resources themes are also connected with the search for water on Mars. When and where was water present in the past, and what is its current form and amount? We know from previous missions that the Martian polar caps include water ice as well as frozen carbon dioxide. The Viking and Mariner 9 orbiter images show evidence of past great floods (the Pathfinder lander is planning to land in such an area) and of dry rivers and lake beds. Where did the all the water go?

Water is key to climate both on Earth and Mars, and understanding the history of the Martian climate will help us understand better the Earth's climate change processes.

Water will also be a major resource for future human exploration of Mars, and if we understand how Mars evolved (including discovering the sources and sinks of water, past and present) we may be able to locate reservoirs of water for human use.

A SERIES OF MISSIONS TO BUILD UP "WATER" KNOWLEDGE

Our exploration of Mars for greater understanding of life, climate and resources will focus, in large part, on the study of water and its role in the history of the planet. How do we go about finding out about water on Mars? Dr. Daniel McCleese of JPL, the Mars Exploration Program Scientist, and Dr. Steven Squyres of Cornell, the head of the Mars Science Working Group, led that group to define a strategy for the "water search." They looked at how small Mars orbiters, landers, "networks" of landers, and sample returns could be combined in a logical progression of missions that will build up an understanding of how water has existed and is existing on Mars today.

Small orbiter missions will search for accessible water (we know that ice is accessible at the poles, but are there reservoirs underground or in the soil?). They'll search for ancient sediments and hydrothermal deposits (dry lake beds and hydrothermal vents). They'll provide data needed to understand the present Mars climate and study how water escapes from the atmosphere into space. The orbiters will also study the surface of Mars and identify good landing sites for the landers, and provide radio links between the landers and the Earth.

Small lander missions will search for carbonates and evaporites that could only have formed in the presence of water. Landers can investigate water reservoirs in detail: for example, they can measure the amount of water which is in the soil, or examine the polar ice caps (using drilled core samples and electro-magnetic sounding) to see how, when, and how much ice was laid down. Investigation of surface chemistry and how the rocks and soil have "weathered" will tell us about the past climates. And the landers may find organic compounds or even evidence that tells us whether life was ever present on the surface of Mars; and if not, why not.

"Networks" of more than a dozen very small landers scattered over the planet could be used as weather stations to study Martian weather and the circulation of its atmosphere. If the network landers also have seismometers on board, and if they detect "Marsquakes," that information will tell us about what Mars is like deep in its interior, and how the interior has evolved over time. Mobility will be important for understanding the Martian surface and accessing features of particular interest, so missions involving long range rovers and balloons are being studied.

Finally, sample return missions can bring rocks and soil to laboratories on Earth for analysis by our most sophisticated instruments (too large and massive to send to Mars) which can tell us about the chronology of the planet's evolution, and may even allow us to detect compounds which could have led to life, or which are evidence of past life. (The odds of being able to select a rock with a fossil, however, are very low, even if fossils exist on Mars.)

BASELINE MISSION SET

All of these missions must be done within the very tight cost constraints of the Mars Exploration Program. The entire program over the next 10 years will be conducted for about one-third the cost of the Viking missions which orbited and landed on Mars twenty years ago. Each mission will cost about the same as a major motion picture, and the total cost of the first 10 missions to Mars will be about that of a single major military aircraft.

The Mars Science Working Group laid out a "strawman" strategy for fitting the science goals into a set of missions which can gradually build up our knowledge of Mars over the next 10 years. This set of missions has evolved over the past year to that shown in Figure C-6. Figure C-6 shows the Mars launch opportunities from 1996 through 2005. The bottom half of the chart is the "U.S.- Only" component of the program, while the top half is actual or potential augmentation by international partners. The "baseline" missions are clear, with possible alternative missions or augmentation shaded. The numbers in parentheses are, respectively, the development cost, operations cost, and approximate launch costs of each year's mission set.

Mars Pathfinder will be the second mission in the series of NASA's Discovery program of planetary exploration missions. It was launched in December 1996 on a McDonnell Douglas Delta II 7925 rocket (capable of throwing about 1000 kg to Mars). Mars Pathfinder will fly directly to Mars and plunge into the atmosphere at 17,000 mph without going into orbit. Using a combination of a heat shield, parachute, rockets and airbags, Pathfinder will land on the surface in an ancient flood plain which is expected to be littered with a wide variety of rocks. Pathfinder will image the Martian terrain in 13 different colors, monitor the weather, and deploy a small rover to explore the region around the lander and measure the composition of the surface.

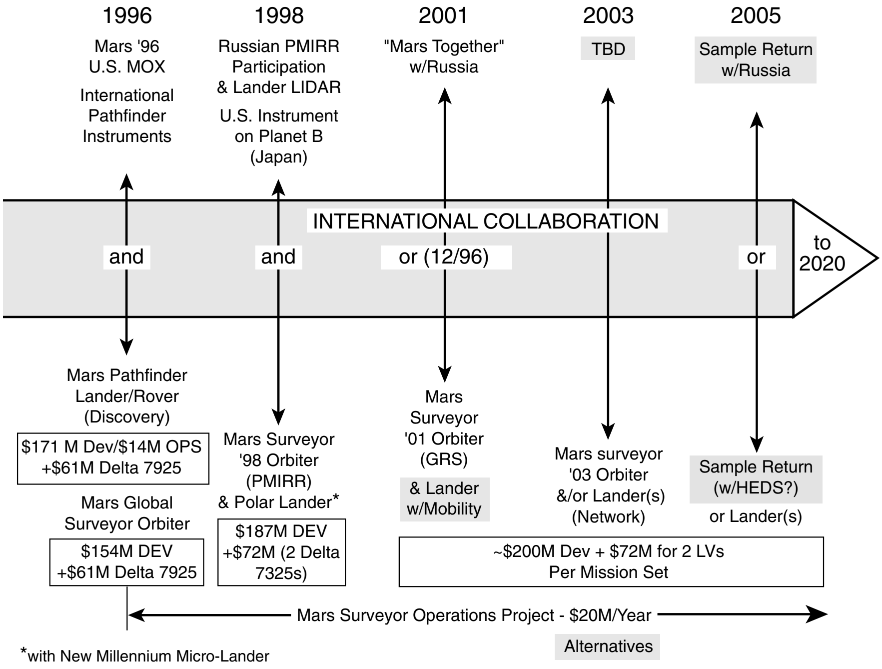

FIGURE C-6 Mars Exploration Program strategy.

Mars Global Surveyor, which was launched in November 1996 (also on a Delta II 7925), will go into orbit around Mars in September 1997. It will use "aerobraking," skimming through the upper part of the thin Martian atmosphere, to go from a long, looping orbit into a circular polar orbit. Mars Global Surveyor will scan the surface of Mars for a full Martian year (about two Earth years) using 6 of the 8 instruments that were originally flown on Mars Observer (which was lost in 1993—the first planetary spacecraft failure in 27 years).

Mars Global Surveyor is the first of a series of missions called the Mars Surveyor Program. This program will fly two missions to Mars every opportunity (about every 26 months), and, with Pathfinder, is pioneering the "better, faster, cheaper" approach to planetary missions. Through competitive procurements, Lockheed Martin Astronautics of Denver, Colorado, has been selected as JPL's industrial partner for Mars Global Surveyor, and for at least the subsequent set of Surveyor missions to be flown in 1998.

In late 1998, Mars Surveyor '98 will launch an orbiter and a lander on a Delta 7325 "Med-lite" launch vehicle. (The Med-lite will only throw about 565 kg to Mars, but is expected to cost considerably less than a Delta 7925.) The orbiter will carry a Pressure Modulator Infrared Radiometer (PMIRR) to map atmospheric temperature, water vapor, and dust over a full Martian year. This instrument was also previously flown on Mars Observer. The lander launched in 1998 will come to rest near the south pole of Mars and will carry a payload, including a robotic arm, which will excavate Martian history by trenching down through thin layers of dust (and possibly ice) deposited in the layered terrain. The polar lander will also chemically analyze the soil, including a search for organic molecules.

The final element of the lost Mars Observer payload (a gamma ray spectrometer) will search for water in 2001 on the Mars Surveyor '01 orbiter. Also to be launched in '01 is a lander which may explore the ancient highlands of Mars in areas where water is thought to have once flowed. The 2001 lander may analyze rocks to determine the ancient history of the climate and geology of Mars. The 2001 orbiter will be launched on a Delta 7325, but the lander may be launched on a new "Delta-lite" configuration which will reduce the lander's mass allocation. The 2001 mission may be conducted in partnership with the Russians, with the orbiter being launched on a Russian Molniya. This "Mars Together '01" launch would also include one or more Russian landers. A Russian lander could include a large rover, or perhaps two "small stations" of the Russian Mars '96 mission type.

In 2003, the Mars Surveyor Program is exploring a partnership with the European Space Agency (ESA) to launch three U.S. landers carrying international payloads. These landers, plus a communication orbiter, provided by ESA, would be launched on a European rocket (Ariane 5). This joint NASA/ESA mission is called InterMarsNet. The landers would explore the interior of the planet using seismology to detect "Marsquakes," study geochemistry at three sites, and act as weather stations. In addition, a separate United States mission may be flown, perhaps deploying a "network" of complementary and very small weather stations around the planet.

Mars Surveyor '05 mission may be the first in a series of missions to return samples from the Martian surface. Another possible sample return target is the Martian moon, Phobos. The Russians are especially interested in a Phobos sample return mission. Sample return missions, in general, will probably require violating some of the constraints of the Mars Surveyor program. They may be too expensive to be completely funded by the Mars Surveyor Program, and/or they may require violating the "two-launch" per opportunity rule. Therefore, these missions may be in partnership with the Russians and/or Europeans. A continuing program of robotic missions, including the return of samples, over ten years or so will pave the way for future human exploration.

NEW TECHNOLOGY INFUSION

More instruments can be carried, or more landers and orbiters sent, if new technology improvements can be introduced into the U.S. spacecraft to make them smaller, lighter and cheaper. The Mars Pathfinder mission has introduced a new flight computer, based on the commercial IBM/Loral RS6000 computer, which will be the basis for the computers of a number of future planetary missions. This provides an enormous increase in computational power. Pathfinder is also utilizing a commercial operating system for its computer, and has pioneered a concurrently engineered flight/ground data system which has greatly reduced costs. Pathfinder has also pioneered a low cost entry and landing approach, of which all but the final airbag impact system is being baselined for future Mars missions. Mars Global Surveyor is utilizing a composite structure for the spacecraft, although its electronic systems and instruments are inherited from Mars Observer.

A program called "New Millennium" is currently being planned to develop and demonstrate the next generation of space technologies to reduce costs and improve performance for both planetary and Earth missions. The Mars Exploration Program will be a "customer" for this new technology, and some of the New Millennium demonstrations may "piggyback" on Mars missions. For 1998 the feasibility of the Mars Surveyor '98 lander carrying one or two New Millennium "microlanders" to Mars is being studied.

Investment strategies are being developed by the Mars Exploration Program at JPL in partnership with Lockheed Martin, the New Millennium Program, and NASA's Office of Space Access and Technology (OSAT). Technology investment is required to shrink the '01 and '03 landers so that they are compatible with the limitations imposed by the Delta-lite launch vehicle, and the even more stringent limitations of the InterMarsNet mission. With the current InterMarsNet concept the U.S. landers must mass no more than 415 kg each, which means that the landers must decrease 150 kg from the 565 kg in 1998. Key technology advances are required to accomplish this mass reduction, while hopefully maintaining or increasing the payload fraction. These advances center around the electronics: an advanced flight computer and memory, a small deep space transponder (X-band), light weight batteries, a high efficiency solid state power amplifier, advanced power electronics, and an inertial fiber-optic gyroscope.

In addition, because of the harsh environment on the surface of Mars, technology advances in temperature tolerant electronics and light weight insulation are required to enable long-term lander missions. The Pathfinder rover has pioneered an approach to light weight insulation using silica aerogel, however phase change materials are expected to be necessary for future missions.

The Pathfinder landing ellipse is about 70 by 150 km and its rover can only travel a few hundred meters. The lander mission in 2001 is expected to require much more accurate landing (< 50 km landing ellipse) and considerable mobility (10s of km) to enable access to ancient lakebeds which may hold clues to the climate history of the planet. Advances in sample collection and storage, and in sample return technology (such as utilization of the atmosphere to manufacture fuel) will be required to enable low cost sample return by 2005.

PREPARATION FOR HUMAN MISSIONS

Each of the robotic missions in the Mars Exploration Program will be gathering information needed to plan future human missions to Mars. The robots will find and scout safe and interesting human landing sites, characterize the atmosphere and surface environments so that human missions can be designed properly, look for water and other resources needed by humans, and develop technologies (such as very low mass electronics) which will be important for human space flights to Mars.

Over the next couple of decades the robotic part of the Mars Exploration Program will result in a detailed understanding of Mars, which is of interest not only to scientists but to understanding more about the Earth's environment, and eventually, for future human exploration.

NASA is currently developing a long range "road map" for the human exploration of Mars. The road map builds upon the capability of the international space station to understand how people can live and work in space. Trips to Mars will utilize new launch vehicle technologies currently just beginning development, including re-usable and expendable rockets. The use of commercial technologies such as advanced electronics will greatly reduce the cost of human exploration of Mars. A current goal of this road map is to enable the first human Mars mission in 2018.

Humans on Mars, in partnership with robots, will explore the planet in more detail than robots alone can. Human presence may be required to finally answer the question of whether Mars has or once had life, and humans will seek to understand the implications of the answer to that question for the possibility of life elsewhere in the universe. Humans will utilize the resources of Mars to investigate how the planet can be made more easily habitable for future generations. And finally, our grandchildren may become citizens of Mars.

APPENDIX
D

Summary of Working Group Reports

BARBARA C. CORN
Steering Committee Co-Chair

The four working groups spent a day and a half reviewing the requirements of their assigned space science missions and preparing their findings in viewgraph form for the final morning's presentation. Working Groups 1 and 2 were asked to examine the cost-savings potential of options for implementing an interplanetary mission, Mars 2001. Groups 3 and 4 were asked to work on an Earth-observing exemplar, the Windstar experimental satellite. Each group took a somewhat different approach to the problem of reducing space science mission costs. The groups' findings are summarized below.

WORKING GROUP 1

Andrew Christensen, chair

Assigned Mars 2001 as their task, Group 1 began their study by examining the general considerations for cost savings as they applied to the classical systems engineering process.

They emphasized that, during the mission definition phase, each project should develop a clearly defined set of mission goals, an explicit definition of the criteria for mission success, and an agreed-on definition of "acceptable" science. During this early study phase, the project management should formulate an operational concept that will be updated continuously for the life of the program. Taken together, the defined mission goals and operational concept provide the framework for project risk evaluation.

Cost-reduction goals are met either by competition or by use of strong financial incentives. A long-term development and contractual relationship between the government and a supplier is not in the best interests of the government unless the supplier has an incentive to reduce cost. If cost reduction is a major objective of future government contracts for access to space, significant changes in acquisition strategies are required, including stronger consideration of overall past performance of the contractor during proposal evaluation. Avenues should be sought that will permit proposals from government–industry teams to take advantage of the experience and expertise found in government laboratories. Performance-based contracts that focus on end-item cost rather than the individual cost elements of labor, hardware, travel, and other direct costs are under consideration by NASA, but will require changes to the Federal Acquisition Regulations.

The working group cited multiyear funding and allowing NASA more autonomy in managing its own finances as important steps in achieving cost reduction. Close cooperation between engineering and science was also strongly emphasized.

The view was expressed that the U.S. Department of State should bear its share of the costs of international projects, in keeping with the degree of political gain anticipated and to separate these costs from the true cost of space exploration. NASA project management should participate actively in Memorandum of Agreement definition rather than have agreements dictated. Experience gained regarding the performance of international partners and NASA's own performance in meeting international agreements should be retained for performance evaluation, and NASA should be provided assistance in bridging the cultural gaps that cause miscommunications and hinder development of a close operating team.

The working group then turned its attention to examining systems engineering principles as applied to their assigned project, the Mars 2001 mission. It was the general consensus that the mission, as presented, was too tightly defined to permit any potential cost savings that might be achieved through opportunistic events. Indeed, the success of the entire project of Mars exploration is jeopardized by the dependence of each succeeding element on the success of the previous one. Premature decisions as to launch vehicle and developer were also constraining and the source of funding ambiguous.

Not enough attention had been paid to the long-term benefits of investment in concurrent development of an infrastructure for the exploration of Mars, as depicted in Table D-1.

WORKING GROUP 2

Thomas Heinsheimer, chair

Working Group 2 observed that the scenario for the Mars 2001 mission, as defined today, is overly constrained as to objectives, equipment choices, contractors, and architecture. As currently defined, it excludes most of U.S. industry from competing and limits the use of much new low-cost technology. The rigidity of the definition does not permit responding to evolving objectives.

TABLE D-1 Mars Program Infrastructure Candidates

Candidate Infrastructure	Benefit to Mission or Program	Program Risk/Lien
Long-life surface beacon, passive corner reflector, or active radio beacon	Surface reference point for location/navigation by future surface rovers, airplanes, balloons, landers Simple test of ability to sustain long-term surface operations (dust, other environmental issues)	Little or none
Mars GPS[a]	Precise navigation aid for surface and in-air operations	More elements for operations to manage
Areosynchronous communications relay orbiter	Reduce antenna size and power requirements for landers by supplying downlink relay	More complex data downlink path, subject to significant degradation by failure of the link Increase in data volume demand could exceed relay's as-built capacity
In situ propellant manufacture	Decouples propulsion requirements and sizing for outbound and return transfers Early use of indigenous resources increases knowledge base for human exploration to come	More ATD[b] effort Increased risk for first implementing mission, unless it is a technology demonstrator
Surface power utility	Reduce or eliminate need to build power generation/collection into every surface explorer; global coverage if implemented as power beaming from orbit May increase power available to surface investigations	Significantly more ATD dollars to bring to operational status
Reusable mission elements	Amortize development costs over multiple uses, longer lifetimes	Probably increases need for autonomous operation

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[a] GPS Global Positioning System

[b] ATD advanced technology development.

Piggyback/Dedicated?	Technology Readiness	Cost-Reducing Potential
Piggyback with science mission	Most technologies ready now Long-life arrays and secondary batteries may be required	Minimal cost-reducing potential, and minimal value added *by itself,* although this may be an essential element for later missions
Probably dedicated	Ready now	Unknown
Could be a combination; assured global coverage requires dedicated launches Could boost science orbiter up to synchronous orbit	Now or near-term	Lowers system costs for future landers or atmospheric vehicles Added up-front cost to emplace, but could be implemented gradually
n.a.	Near to mid-term	Lowers cost of some hardware elements Adds development and operations complexity Overall mission impact not clear Overall program impact potential is very high
Dedicated	Mid- to long-term	Increased program investment Lower per-mission costs and/or more flexibility and capability for science Overall program impact potential is very high
n.a.	Varies by element	Moderate reductions in hardware development and fabrication Probably applies to selected missions

Specifying the Delta-lite launch system has the unintended consequences of indirectly limiting the top weight and implicitly dictating the cost of the spacecraft, thus limiting the applicability of new low-cost technology. Commonality with the Mars 1998 mission is encouraged as having the lowest *perceived* risk and the lowest *perceived* development costs. The government has constrained the ability to trade instrument costs against spacecraft and launch vehicles, and minimal dollars are available for the development of key instruments.

After citing examples of potentially more cost-effective options that had been precluded by the imposed constraints, the working group suggested a better approach to meeting mission requirements that would include

- creation of a new, single, open procurement
- application of acquisition reform principles (i.e., tell potential offerors “what” is required, not “how” to do it)
- expansion of the architectural tradespace
- encouragement of broad participation by the science community

The benefits of this approach would be the elimination of constraints, the use of the latest low-cost technologies, exploitation of new launcher competitions, and the ability to respond to evolving goals for the exploration of Mars. Drawbacks would include, of course, the costs of a new procurement and the risks inherent in programmatic uncertainties.

In the context of the mission, the group encouraged consideration of the following:

- Opening the 2001 and 2003 flights to single integrated bids, thereby creating a “commercial critical mass” worth bidding on. Source selection should be based on “best value” science, and all funds available should be specified to eliminate “buy-ins.”
- Creating a science-based statement of operational objectives based on top-level Mars science objectives to open the architectural tradespace to an innovative mix of spacecraft and launchers, to broaden science competition and participation, and to provide incentives for instrument development.
- Encouraging the formation of Discovery-style teams made up of participants from science, industry, and universities.
- Selecting the implementation team based on the best plan rather than the best gadget.

WORKING GROUP 3

J. Eugene Farr, chair

The five primary factors for achieving low-cost Earth-orbiting space science missions were addressed. The working group chair prefaced his presentation of the first factor, the policy environment, with the observation that these are important truths that should be promulgated through government and industry. He further noted that the opening presenters and the working groups are all agreed on their importance. Provided with the Earth-observing scenario for the Windstar mission, the working group first identified the factors they believed critical for the achievement of a low-cost Earth-orbiting space science mission and then applied these factors as a template to the Windstar mission. The group completed its assignment with an examination of the costs of the mission.

The group defined a good policy environment by the following characteristics and conditions:

- stability—a bad *stable* policy is sometimes better than a good *unstable* one—fluctuating budgets and policy changes are examples of instabilities that negatively impact program costs
- sensitivity to and involvement of the public and the science community—NASA has a clear mandate to publicize space science to ensure that the public truly agrees that NASA is promoting national interests
- information (public relations) on projects
- clear statement of policy
- policy incorporating research strategy and thrusts
- policy tied to defined national theme or mission
- allowance for and encouragement, but not mandate for, international and Department of Defense cooperation and cost sharing
- program flexibility in choosing launch systems, operations structure, technologies, etc.; selection of the best for the program

Project selection objectives should be focused on what is *needed*, not on what is *desired*. A decision process that goes from policy through objectives to project specifics should include all parties with an interest, including end users of the data. Synergism between different science measurements and projects hosted on one vehicle should be included in the decision making. The goal should be to achieve the best *architecture* for the mission, not the *smallest* size. The project should be considered in light of other ongoing activities, and cost and technical risks should be evaluated.

Acquisition strategy considerations included the suggestion of an overall examination of all projects in concert with the U.S. budget for space science. This would result in the deletion of some projects, but would provide funding stability for those retained. Keen attention should be directed to the up-front systems engineering process when both the basic technical and the managerial structure of the program is chosen. Faulty decisions made in this phase will result in driving up the costs of the entire project.

Instrument alternatives should be subjected to test and analysis prior to selection, and technologies should be examined for readiness. The importance of multiyear funding as a cost savings was echoed again by the findings of this group. Other factors were discussed, such as early establishment of the funding profile, elimination of unnecessary documentation and procurement requirements, provision of incentives for government project managers, "buy versus own," and independence of the science community from government and contractors.

Care should be given to adhering to proven principles of program management and systems engineering. Clear definition of requirements; development of a risk management plan that includes cost, schedule, and performance criteria; avoidance of the "not invented here" syndrome; and attention to development and maintenance of the plan to transition to an operational system are examples of these principles.

The group then applied its factors as a template to evaluate the Windstar scenario. The mission goals fit within policy as stated in NASA's Mission to Planet Earth, but the objectives of ocean vector wind measurements were unclear and should be re-evaluated. Many technology options, such as a wide variety of launch vehicles, available communications systems, and existing buses, could result in considerable savings, but do not appear to have been considered. The working group completed its study with the application of an existing cost model.

WORKING GROUP 4

Liam P. Sarsfield, chair

Working Group 4 began with an analysis of the Windstar mission requirements, performed an analysis of potential cost-reduction options for Windstar, and then concluded with broader space science mission cost-reduction suggestions.

By assuming that a new instrument is required and that a traditional approach to designing small missions will be employed, the mission definition precluded a thorough test of the cost-reduction process. In this sense, the Windstar mission as presented was overconstrained and "too real."

Three distinct mission objectives were identified: a science requirement, a technology requirement, and an operational requirement. It was noted that, although the science requirement may be sufficient in itself, the other two would not stand alone. The working group also noted that, as the number of objectives increases, the number of cost-reduction options decreases.

Although the spacecraft and payload were overspecified, the group analyzed Windstar spacecraft characteristics to develop cost-reduction options within the constraints. The major cost elements were specified as the spacecraft, the instrument, launch costs, and five years of operational costs. The group also included instrument advanced technology development and a contingency budget. The group identified the most important factors in reducing Windstar mission costs as instrument advanced technology development, leverage of commercial systems, alternative launch vehicle options, and maximum use of existing infrastructure.

Applying their experience in these areas, the working group developed

TABLE D-2 Cost-Reduction Options

Cost Reduction Options	Science	Technology	Operational
Off-the-shelf bus	X	X	X
Data purchase	X		
Airborne assets	X	X	
Low-cost launch vehicle	X	X	X
Re-fly existing instrument	X		
Place instrument on communication satellite	X	X	X
Earth-based wind sensors	X		
Resource requirements	X	X	X
Outsource ground segment	X	X	X

bracketed estimates for costs of each element. Options, from re-flying an existing instrument to using Earth-based or airborne sensors, were evaluated for their applicability to each of the requirements. Although many options for performing the required science at a lower cost appeared feasible, only a handful of options applied to all three sets of requirements. The most widely applicable options were use of an off-the-shelf bus, use of a low-cost launch vehicle, piggybacking the mission on a communications satellite, outsourcing the ground segment, and reevaluating the requirements. The Working Group did find the potential for significant cost reduction in the Windstar mission, although wide variability in bus costs, launch costs, and the cost of operations forced the high end of the bracket well over the NASA $100 million mark (see Table D-2 and Figure D-1).

- Dry Mass: 225 kg
  - Instrument: 100 kg
  - Bus: 125 kg
    - Structure: 30 kg
    - Power system: 20 kg
    - ACS: 35 kg
    - Propulsion: 15 kg
    - C&DH: 25 kg
- Power (BOL): 400 W
  - Instrument: 300 W
  - Bus: 100 W
- Thermal: passive
- Pointing accuracy/knowledge
- Communication rate = 3 Mbps downlink
- On-board storage = 3 Gbytes

FIGURE D-1 Windstar spacecraft characteristics.

The working group concluded with general thoughts on reducing the cost of space science research. They echoed the other working groups' finding that requirements without rationales are overly constraining.

A great deal of progress has already been made toward reducing the cost of spacecraft. The greatest future cost leverage will be obtained in reducing overhead and infrastructure costs. The group found that ground operations, data analysis, and distribution systems are all areas of potential future savings. They also agreed that the "cost of quality" or process issues should be addressed in all elements of space missions and infrastructure and suggested full cost accounting as a possible metric.

Finally, the working group suggested that all aspects of a program should be optimized as a system. Consideration of life-cycle costs should be broadened to ensure that potential cost savings in future missions are not lost in decisions made today.

APPENDIX
E

Selected Bibliography

Alkalai, L., and M. Underwood, eds. 1995. µElectronics Systems IPDT Technology Roadmap. Pasadena, Calif.: New Millenium Program Office, NASA Jet Propulsion Laboratory.

Arno, R.D. 1996. Sorting Reason from Rhetoric in Small Spacecraft Policy, a Strictly Unofficial Assessment. Working paper presented to the Workshop to Reduce Space Science Mission Costs, Arnold and Mabel Beckman Center, Irvine, California, October 16–18.

Baker, D.N., G. Chin, and R.F. Pfaff, Jr. 1991. NASA's Small Explorer Program. Physics Today 44(Dec):44–51.

Bearden, D. 1994. Small Satellite Cost Model (SSCM) Study. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Beins, J.C. 1994. Aircraft Direct Operating Cost Study: Advanced Subsonic Technology. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Book, S.A. 1993. Do Not Sum "Most Likely" Cost Estimates. Briefing presented to the 27th Annual DOD Cost Analysis Symposium, The Aerospace Corporation, El Segundo, Calif., September 7–10.

Book, S.A., and P.H. Young. 1994. General-Error Regression for USCM-7 CER Development. Briefing presented to the 28th Annual DOD Cost Analysis Symposium, Leesburg, Va., September 21–23.

Chromik, C. 1994. Lessons Learned: Tooling for Composite Airframe Structures. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Cyr, K.J. 1994. The Role of Cost Analysis on Manned Spacecraft Development. Society of Automotive Engineers Technical Paper Series 901863. Presented to Aerospace Technology Conference and Exposition, Long Beach, Calif., October 1–4.

Dean, E.B. 1994. Inserting Economics into Multidisciplinary Design Optimization. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Dean, E.B. 1994. Proposed Metrics for the High Speed Research Program. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Dixon, B. 1994. Overview of Resource Analysis Office (RAO). Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Eller, E., D. Roussel-Doupre, R. Weiss, and O. Bruegman. 1996. New ideas for affordable space missions. Aerospace America 34(4):26–31.

Fleeter, R. 1996. Some thoughts on optimizing the cost of space projects. Launchspace Magazine 1(3):14–15.

Fryer, C. 1994. Risk Management: RAO Instrument Risk-Cost Model. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Gallagher, M.A. 1994. Multi-Variable Instrument Cost Model (MICM) Enhancements. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Garrick, B.J., et al. 1987. Space Shuttle Probabalistic Risk Assessment, Proof-of-Concept Study, Auxiliary Power Unit and Hydraulic Power Unit Analysis Report. Prepared for the National Aeronautics and Space Administration. Washingon, D.C.: McDonnell Douglas and PLG, Inc.

General Accounting Office. 1992. Space Missions Require Substantially More Funding than Initially Estimated. Report to the Chairman, Subcommittee on Investigations and Oversight, Committee on Science, Space and Technology, U.S. House of Representatives. NSAID-93-97. Washington, D.C.: U.S. General Accounting Office.

Gunning, D. 1994. Overview of Goddard Space Flight Center Parametric Manpower Model. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Heller, S., G. Ball, and J. Olivieri. 1994. Instrument Cost Growth and Lessons Learned. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Hoeser, S. 1990. The cost impacts of true spaceships. Journal of Practical Applications in Space 1(4):1–38.

Isakowitz, S. 1991. International Reference Guide to Space Launch Systems, 2nd ed. New York: American Institute of Aeronautics and Astronautics.

James, L.D. 1993. DOD Space Systems: Reducing the Cost. Maxwell AFB, Ala.: Air University Press.

Johnson, N. L., and Rodvold, D. M. 1994. Europe and Asia in Space: 1993–1994. Colorado Springs, Colo.: Kaman Sciences Corporation.

Jones, K.M. 1994. Ground Systems Cost Model, Version 1.1. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Kaplan, S., et al. 1993. Probabalistic Schedule and Cost Risk Analysis for KSC Shuttle Operations. SBIR Contract No. NAS10-11984, PLG-0934. Kennedy Space Center, Fla.: NASA.

Korsmeyer, D.J. 1994 Automation Life-Cycle Cost Modeling. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Lalli, V. 1996. SARGE: Standard Assurance Requirements and Guidelines for Experiments. Cleveland, Ohio: NASA Lewis Research Center.

Laue, H.H. 1995. Towards Improved Cost-Effectiveness on Spacecraft Operations. Paper presented at 46th International Astronautical Congress, Oslo, Norway, October 2–6.

London, J.R. 1994. LEO on the Cheap. Maxwell AFB, Ala: Air University Press.

Lusignan, B.B. 1996. An International Single Stage to Orbit. Center for International Cooperation in Space, Stanford University. Working paper presented to the Workshop to Reduce Space Science Mission Costs, Arnold and Mabel Beckman Center, Irvine, Calif., October 16–18.

Lusignan, B.B. 1996. The Mars Surface Robot Marsokhod. Center for International Cooperation in Space, Stanford University. Working paper presented to the Workshop to Reduce Space Science Mission Costs, Arnold and Mabel Beckman Center, Irvine, Calif., October 16–18.

Man, G.K., ed. 1995. NASA New Millennium Autonomy Technology Roadmap. Autonomy Integrated Product Development Team D-13479. Pasadena, Calif.: NASA Jet Propulsion Laboratory.

Milsted, M. 1994. Office of Space Flight Contractor Rates and Escalation Assessment. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Musser, G.S. 1995. Faster, Better, Cheaper. Interview with Domenick J. Tenerelli. Astronomical Society of the Pacific, from the Internet.

NASA (National Aeronautics and Space Administration). 1995. OSMA Training Presentation: Design for Reliability. Cleveland, Ohio: NASA Lewis Research Center.

NASA. 1996. Communications Systems Integrated Product Development Team (IPDT) Roadmap, Version 2.0a. New Millennium Program. Pasadena, Calif.: NASA Jet Propulsion Laboratory.

NASA. 1996. Instrument Technologies and Architectures Technology Roadmap. New Millennium Program. Pasadena, Calif.: NASA Jet Propulsion Laboratory.

NASA. 1996. Modular and Multifunctional Systems Integrated Product Development Team (MAMS IPDT) Technology Roadmaps. New Millenium Program, D-13447, Version 3-14-96. Pasadena, Calif.: NASA Jet Propulsion Laboratory.

NASA. 1996. Standard Assurance Requirements and Guidelines for Experiments. Cleveland, Ohio: NASA Lewis Research Center.

NASA News and Information Service. 1995. NASA's Discovery Program. Information Brochure, July.

NRC (National Research Council). 1994. Technology for Small Spacecraft. Panel on Small Spacecraft Technology, Committee on Advanced Space Technology, Aeronautics and Space Engineering Board. Washington, D.C: National Academy Press.

NRC. 1995. Managing the Space Sciences. Committee on the Future of Space Science, Space Studies Board. Washington, D.C.: National Academy Press.

NRC. 1995. A Scientific Assessment of a New Technology Orbital Telescope. Task Group on BMDO New Technology Orbital Observatory, Space Studies Board. Washington, D.C: National Academy Press.

NRC. 1995. The Role of Small Missions in Planetary and Lunar Exploration. Committee on Planetary and Lunar Exploration, Space Studies Board. Washington, D.C.: National Academy Press.

NRC. 1995. A Science Strategy for Space Physics. Committee on Solar and Space Physics and the Committee on Solar-Terrestrial Research, Space Studies Board. Washington, D.C.: National Academy Press.

NRC. 1996. Engineering Research and Technology Development on the Space Station. Committee on Use of the International Space Station for Engineering Research and Technology Development, Aeronautics and Space Engineering Board. Washington, D.C.: National Academy Press.

NRC. 1996. Review of NASA's Planned Mars Program. Committee on Planetary and Lunar Exploration, Space Studies Board. Washington, D.C.: National Academy Press.

National Space Development Agency of Japan. 1996. ADEOS: Advanced Earth Observing Satellite. Information brochure.

Olivieri, J.M. 1994. A Simplified Approach to High-Level Performance-Based Cost Estimating Relationships. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Pate-Cornell, E., and P.S. Fishbeck. 1993. PRA as a management tool: organizational factors and risk-based priorities for the maintenance of the tiles of the space shuttle orbiter. Reliability Engineering and Systems Safety. 40:239–257

Pate-Cornell, E., and P.S. Fishbeck. 1993. Probabilistic risk analysis and risk-based priority scale for the tiles of the space shuttle. Reliability Engineering and System Safety. 40:221–238.

Prince, A. 1994. Parametrics in Cost Proposal Preparation and Evaluation. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Redd, F.J., ed. 1996. Proceedings of the 10th Annual AIAA/Utah State University Conference on Small Satellites. Logan, Utah: Utah State University, Center for Space Engineering.

Sarsfield, L. 1996. Federal Investments in Small Spacecraft, Interim Report. DRU-1494-OSTP. Washington, D.C.: RAND Critical Technologies Institute.

Schoenfelder, T.E. 1994. One Pagers: An Overview of the Concept. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Sefcik, R. 1994. Estimating Costs of In-House Projects. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Sefcik, R. 1994. Estimating Joint US/Russian Projects: Lessons Learned from the Solar Dynamics on Mir Project. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Smith, K. 1994. Overview of MSFC Modeling Activities. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Stancati, M. 1996. Cost Estimation and Programmatic Risk Assessment. Working paper presented to the Workshop to Reduce Space Science Mission Costs, Arnold and Mabel Beckman Center, Irvine, Calif., October 16–18.

Taylor, D. 1994. Cost Data Exchange with the Air Force. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Twigg, L.T. 1994. NASA Langley Research Center Cost Estimating Office Organization Status. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.

Ullrich, P. 1996. Sciencecraft: New Millennium Approach. Presentation to the Joint Committee on Technology, National Research Council, May 31.

Wertz, J., and W. Larson. 1996. Reducing Space Mission Cost. Boston: Kluwer Academic Publishers.

Winiewicz, C.M. 1994. Kennedy Space Center's Ground Operations Cost Model. Briefing presented to the 1994 NASA Cost Estimating Symposium at NASA Lyndon B. Johnson Space Center, Houston, Texas, November 7–10.