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Report to the Chairman, Subcommittee on Space Science and Applications, Committee on Science, Space, and Technology, House of Representatives

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SPACE OPERATIONS

NASA Efforts to Develop and Deploy Advanced Spacecraft Computers

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The Honorable Bill Nelson
Chairman, Subcommittee on Space Science
and Applications
Committee on Science, Space,
and Technology
House of Representatives

Dear Mr. Chairman:

On February 29, 1988, we briefed your office on the results of our preliminary work on the National Aeronautics and Space Administration's (NASA) development and deployment of spacecraft computers. At that time we agreed to continue our work and report on (1) the capabilities of NASA's existing spacecraft computers; (2) NASA and Defense programs to develop advanced, general-purpose, space-qualified computers; and (3) the type of primary computer system NASA plans to use in the Data Management System on-board the space station.

This report provides that information and discusses the challenges that NASA faces in building and deploying computers for its spacecraft. The report notes that by the time a NASA spacecraft is launched, the computers inside the craft are outdated. Generally, it takes 8 to 20 years from the time computer technology is available on the ground to when it is deployed in space. Various reasons exist for this situation. We noted that if NASA could shorten this lag time, it could significantly increase spacecraft capabilities for collecting scientific data and possibly decrease the costs of future missions.

The report recommends that NASA's Administrator should consider further strengthening the agency's ongoing activities by establishing an independent expert panel to comprehensively examine the process by which advanced spacecraft computers are developed and deployed, and determine the further steps that could be taken to shorten the process.

As arranged with your office, unless you publicly release the contents of this report earlier, we plan no further distribution until 30 days after the date of this letter. At that time, we will send copies to other appropriate congressional committees; the Administrator, NASA; the Secretary of Defense; the Secretary of Energy; and make copies available to other interested parties upon request.

This work was performed under the direction of Samuel W. Bowlin, Director for Defense and Aeronautics Mission Systems. Other major contributors are listed in appendix IV.

Sincerely yours,

Ralph V. Carlone

Ralph V. Carlone
Assistant Comptroller General

Executive Summary

Purpose

On-board computers are critical to a spacecraft's safety and mission. Developing more advanced spacecraft computers is important to future space missions that call for increased automation, robotics, and data processing to prolong spacecraft life, reduce ground-control costs, and expand scientific capabilities.

The House Science, Space, and Technology Committee, Subcommittee on Space Science and Applications, asked GAO to provide information on (1) the performance capabilities of the National Aeronautics and Space Administration's (NASA) existing spacecraft computers, (2) ongoing NASA and Department of Defense programs to develop and deploy advanced spacecraft computers, and (3) NASA's plans for space station computers.

Background

Spacecraft computers must operate in a harsh environment. They must be hardened against radiation and high-energy particles that exist outside the earth's atmosphere; be able to operate under extreme temperatures; be small, lightweight, and use small amounts of electricity; and have highly reliable hardware components and software.

The process by which computers are designed, manufactured, and tested to meet space mission requirements is known as space-qualification. Space-qualification requirements make spacecraft computers much more difficult to design, manufacture, and test than ground-based computers.

Results in Brief

By the time a NASA spacecraft is launched, the computers inside the craft are outdated. Generally, it takes 8 to 20 years from the time computer technology is available on the ground to when it is deployed in space. Various reasons exist for this situation. If NASA could shorten this lag time, it could significantly increase spacecraft capabilities for collecting scientific data, and possibly decrease the costs of future missions.

NASA recognizes the problem. The question is whether it is possible to develop and deploy newer, more powerful computers quickly enough to support ambitious plans for future missions.

Principal Findings

Computers in Today's Spacecraft Are Based on 1960s and 1970s Technology

Spacecraft computers being used today are based on 1960s and 1970s technology. They operate more slowly and have smaller memories than currently available commercial microcomputers. Thus, computers used in offices today are much more powerful than those found on NASA spacecraft, including the shuttle. Spacecraft mission and operational capabilities are limited to those that can be supported by the older and slower, on-board computers.

Several Factors Cause Technology Gap

Several factors contribute to the 8-to-20 year gap in spacecraft computers. First, it is difficult to space-qualify computers. It is not simply a matter of installing a computer in the spacecraft. Computers have to be modified to withstand a harsh space environment, including exposure to radiation, high-energy particles, and extreme temperatures.

Second, it takes several years to design, build, test, and launch a spacecraft. Because a spacecraft's computer system is such an integral part of the design, NASA chooses a computer system early in development.

Third, spacecraft safety and mission success depends on the reliability of on-board computers-they usually cannot be repaired in space. Therefore, NASA managers tend to be conservative in selecting older computers that have proved reliable rather than newer, less proven, but more powerful computers.

Fourth, launch delays contribute to the age of spacecraft computers. Sometimes, after the computers are selected and installed, spacecraft launch dates are delayed by several years. For example, the Galileo spacecraft was scheduled for a 1982 launch and was designed using 1975 computer technology. Because the Galileo launch has been delayed to 1989, its computer technology will be 14 years old by its 1989 launch.

Spacecraft Computer Research and Development Efforts

NASA and Defense are researching and developing spacecraft computers. Also, the Department of Energy, through its government-owned, contractor-operated Sandia National Laboratories, is developing advanced, space-qualified computer technologies.

GAO was told that NASA, in order to "leverage" its funds and avoid duplication of effort, is looking to the success of ongoing Defense and Energy programs involving the research and development of general-purpose, radiation-hardened microprocessors to help meet some of its future space mission needs. Recently, NASA began funding its own research in advanced spacecraft computer technologies. This effort includes developing computer architectures, hardware components, and software technologies that are needed to incorporate into NASA spacecraft the general-purpose microprocessors being developed by Defense.

Space Station Computers

NASA is also trying to incorporate newer technology in the space station. If NASA is successful, the station's primary computer, the Data Management System, will use 1985 technology, which is similar to that used in some of the newest commercial microcomputers. NASA is still analyzing whether or not these computers will need to be radiation-hardened or shielded for the station. However, the time lag problem will still remain. Even if NASA is successful in using recent, commercially available microprocessors, that technology will be 10-years old if the station is launched in 1995, as planned.

Recommendation

Solving this complex problem will not be an easy task and the solutions could be costly. Yet, the nation's leadership in space depends on NASA's ability to implement advances in many technologies, including incorporating more up-to-date computer systems in its programs.

GAO recommends that the NASA Administrator consider further strengthening the agency's ongoing activities by establishing an independent expert panel to comprehensively examine the process by which advanced spacecraft computers are developed and deployed, and determine ways to shorten the process. At the discretion of the Administrator, members on the panel could be gathered from appropriate federal agencies, the scientific community, and private industry.

Agency Comments

NASA agrees that its space-qualified, general-purpose computer hardware is based on 8-to-20-year-old technology. NASA confirmed that significantly reducing this time would result in cost and performance benefits for selected, highly automated future missions, but believed it would be unreasonable to expect to reduce the technology gap below the 4 to 6 years required to space qualify computers.

NASA said the report adequately describes its efforts to develop general-purpose, space-qualified microprocessors but understated its efforts in the broader field of spacecraft computer research and development. NASA listed some examples of these efforts. GAO recognizes that NASA must develop and deploy many advanced technologies to support future missions. However, GAO focused its review on the development of space-qualified microprocessors, the principal part of most computers, because of (1) the complexities associated with space-qualifying this part, and (2) its integral relationship to the processing speed and capacity of on-board computers. GAO believes that these factors will significantly affect NASA's ability to accomplish future mission objectives.

NASA did not specifically comment on GAO's recommendation. However, a NASA official told GAO that there was general agreement with the spirit of the recommendation, namely that more needs to be done in this important area. The official stated that the NASA Administrator would make a decision on the recommendation once the report was issued. An evaluation of the agency's March 6, 1989, comments on the report (appendix II) is included in chapter 5.

Contents

Abbreviations

CRAF	Comet Rendezvous and Asteroid Flyby
CSTI	Civil Space Technology Initiative
DMS	Data Management System
EOS	Earth Observing System
GAO	General Accounting Office
GVSC	Generic Very High-Speed Integrated Circuit (VHSIC) Spaceborne Computer
IBM	International Business Machines Corporation
IMTEC	Information Management and Technology Division
JPL	Jet Propulsion Laboratory
MIPS	Millions of Instructions Per Second
NASA	National Aeronautics and Space Administration
RH32	Radiation-Hardened 32-bit Processor
SA3300	Sandia Application 3300 Family
SDI	Strategic Defense Initiative

Introduction

Existing National Aeronautics and Space Administration (NASA) and Department of Defense spacecraft depend on space-qualified, on-board computer systems to operate, control, and maintain spacecraft and spacecraft payloads. Space-qualification of computer systems is the process of designing, building, and testing systems or subsystems to verify that they can successfully operate in the expected space environment. Space-qualified computers must: (1) be hardened against the radiation and high-energy particles that exist outside the Earth's atmosphere; (2) be able to operate under extreme temperatures; (3) be small, lightweight, and use small amounts of electricity; and (4) have reliable hardware components.

Among other functions, spacecraft computers currently help operate and control craft temperature, power generation and distribution, communications, and payload instruments. Computers also help navigate and control the attitude (pointing) of the spacecraft. In future space missions, spacecraft computers are expected to perform these as well as more advanced functions, such as advanced automation and robotics, and large-scale, on-board processing of scientific data.

Space missions may be categorized into two types: near Earth and deep space. Near-Earth missions include orbital and suborbital missions that may be manned or unmanned. Deep-space missions travel out of the Earth's orbit to investigate interplanetary space, other planets, the sun, or other phenomena. Each of these space missions presents different problems for spacecraft designers and operators. Spacecraft computers on interplanetary and polar orbit missions may have to withstand more radiation and bombardment by high-energy particles than spacecraft computers on an equatorial, near-Earth orbit, where there is a relatively benign radiation environment. Astronauts have been able to use modified commercial lap-top computers on the space shuttle. According to a NASA official at the Johnson Space Center, NASA programmed these lap-top computers to do a number of things, such as operate experiments and display experimental data. However, we were also told that these portable computers do not meet all the space-qualification requirements for mission-critical, shuttle computers and are not therefore used to operate the shuttle.

The Congress, in the National Aeronautics and Space Act of 1958,[1] made NASA responsible for developing and applying technologies for use in space. This legislation also directs NASA to coordinate space research and

[1] Public Law 85-568, July 29, 1958.

development with other federal agencies, in particular the Department of Defense. In addition to NASA, Defense and the Department of Energy are also working to develop and deploy space-qualified computers.

Defense funds the development of space-qualified computers and uses them for spacecraft, such as navigation, weather, and communications satellites. Energy, through its contractor-operated Sandia National Laboratories, also develops advanced, space-qualified computer technologies for Defense and NASA spacecraft.

Objectives, Scope, and Methodology

In February 1988, the House Science, Space, and Technology Committee, Subcommittee on Space Science and Applications, asked us to report on NASA's plans to develop and deploy advanced, space-qualified computers. Specifically, we agreed to provide information on (1) the performance capabilities of NASA's existing spacecraft computers, (2) ongoing NASA and Defense programs to develop advanced, general-purpose, space-qualified computers,[2] and (3) the type of primary computer system NASA plans to use in the Data Management System onboard the space station.

To obtain this information, we relied in part on several recent studies performed by agency advisory groups.[3] We did not attempt to verify in detail the data and conclusions the studies present, and we did not independently validate actual costs during our review. In addition, we reviewed previous GAO and Congressional Budget Office studies of NASA and Defense space programs and federal research and development policies.

To obtain information on the capabilities of existing space-qualified computers and government efforts to develop and deploy advanced, space-qualified computers, we reviewed NASA, Defense, and Energy plans, program descriptions, and budgetary documents. Specifically, we reviewed (1) programmatic and budget information for NASA and

[2]We focused our work on the development of space-qualified microprocessors—semiconductor chips that constitute the principal part of a computer. Other key computer components that must be space-qualified include memory chips and input/output devices.

[3] Space Technology To Meet Future Needs, National Research Council, National Academy Press, 1987; Report By The SSTAC Ad Hoc Committee on On-board Processing and Data Management Technology, Space Science Technology Advisory Committee, July 1987; Report of the Defense Science Board 1987 Summer Study on Technology Base Management, Defense Science Board, Office of the Under Secretary of Defense For Acquisitions, Dec. 1987; and Aerospace Safety Advisory Panel Annual Report For 1987, Aerospace Safety Advisory Panel, National Aeronautics and Space Administration, 1988.

Defense technology development plans and specific space-qualified computer development programs, including Energy programs; (2) NASA, Defense, and Energy program office descriptions and status reports for specific space-qualified computer development programs; and (3) NASA and Defense plans for future space missions and their plans for developing new technologies for those missions. We did not independently verify this information.

We interviewed officials from NASA headquarters, NASA's Ames Research Center, the Jet Propulsion Laboratory (JPL), NASA's Lyndon Johnson Space Flight Center, the Office of the Secretary of the Air Force for Acquisitions, the Air Force Space Technology Center, Air Force Space Division, the Air Force Rome Air Development Center, Defense's Advanced Research Projects Agency, Energy's Sandia National Laboratory, General Electric's Astro Space Division, and the Atlantic Aerospace Electronics Corporation.

We conducted our work at: (1) NASA headquarters in Washington, D.C.; (2) JPL at Pasadena, California; (3) the Air Force's Space Division at El Segundo, California; (4) the Air Force Space Technology Center at Albuquerque, New Mexico; and (5) Energy's Sandia National Laboratory at Albuquerque, New Mexico.

To obtain information on the type of primary computer system NASA plans to use on the space station, we interviewed NASA officials at NASA headquarters in Washington, D.C.; NASA's Lyndon Johnson Space Center in Houston, Texas; NASA's Ames Research Center in Moffett Field, California; and the Jet Propulsion Laboratory in Pasadena, California.

We obtained written NASA comments on a draft of the report on March 6, 1989. An evaluation of these comments (appendix II) is included in chapter 5. We also gave Defense an opportunity to comment, because of certain Defense activities mentioned in the report. Defense chose not to provide comments. We conducted our work from February 1988 through December 1988, in accordance with generally accepted government auditing standards.

A Technology Gap Exists Between Ground-Based and Spacecraft Computers

Computers now used in NASA spacecraft have performance capabilities that are 8 to 20 years behind systems available on the ground. Factors that contribute to this technology gap include (1) the challenges of developing and modifying computer systems so that they are capable of withstanding the harsh environment of space, (2) the long spacecraft development cycle, (3) the reliance of spacecraft development managers on using proven computer technology in spacecraft, and (4) launch delays, sometimes of several years, during which time the on-board computers become even older.

NASA tailors the functions of its spacecraft to those that can be supported by the relatively small memories and slow processor speeds of the on-board computers. The question is whether NASA can develop and deploy newer, more powerful computers quickly enough to support its ambitious plans for future missions.

Limited Spacecraft Computer Capabilities

NASA spacecraft now in space or awaiting launch use computers with comparatively slow processor technologies, some of which were commercially available as early as the 1960s and early 1970s. Spacecraft computers also have relatively small random access memories, which further limit their capabilities.

A report by the Space Systems Technology Advisory Committee[1] stated that existing space-qualified computer technologies lag two to four generations[2] behind commercial computer technologies. Some common personal computers are readily available with far more computational power than existing spacecraft computers. However, unlike personal computers, space-qualified computers must operate in a fault-tolerant and highly reliable manner in the harsh environment of space.

Existing space-qualified computers use 4-bit, 8-bit, and 16-bit microprocessors. Microprocessors are semiconductor chips that constitute the principal part of a computer. Generally, larger bit architectures operate faster and can access more memory than smaller bit architectures. Some

[1] Report by the SSTAC Ad Hoc Committee On On-board Processing And Data Management Technology, Space Systems Technology Advisory Committee, July 1987.

[2] Categorizing computers into "generations" is an informal system of differentiating computer systems as significant technological advances are made; for example, computers using vacuum tubes in one generation, those using transistors in the next, and those using integrated circuits in the next.

currently available, commercial personal computers use 32-bit microprocessors. (See appendix III for additional information on microprocessor architectures.)

Table 2.1 shows the age and selected operational characteristics of on-board computers used on several important existing or planned NASA missions.

Table 2.1: Performance Characteristics of On-Board Computers for Several NASA Spacecraft

	Selected Current and Planned Missions				
	Original Shuttle	Galileo	Upgraded Shuttle	CRAF[a]	Space Station
Age					
Launch date	1981	1989[b]	1990	1995	1995
Date computer selection made	1971	1978	1984	1990	1988
Date technology became commercially available	1964	1975	1979[c]	1982	1985
Difference between launch date and date available (in years)	17	14	11	13	10
Performance Characteristics[d]					
Microprocessor architecture	16 bit	8 bit	16 bit	16 bit	32 bit
Performance, in MIPS	0.4	0.1	1.2	<1	4
Random access memory, in kilobytes	104	384	256	128 or 256	4000[e]

[a]Comet Rendezvous and Asteroid Flyby (CRAF).

[b]Galileo was originally scheduled for launch in 1982.

[c]Date architecture introduced in Defense systems.

[d]For comparison purposes, an International Business Machines (IBM) PS-2/Model 80 microcomputer became commercially available in 1985, that had a 32-bit architecture, random access memory of 16,000 kilobytes, and a processor speed of 4 million instructions per second (MIPS).

[e]Has 16,000 kilobyte capacity, but will be limited to 4,000 due to electrical power limits on the space station.

The limited capabilities of these on-board computers resulted in NASA spending additional effort in finding ways to accomplish its mission objectives. For example, an official at Johnson Space Center told us that because of the shuttle computer's small random access memory, NASA had to develop three different software systems for launch and flight operations on shuttle missions, and these systems had to be loaded manually by the astronauts. Furthermore, the official explained that shuttle software development and maintenance was inefficient and expensive, partly because three different systems were being used. For additional information on several NASA spacecraft, including how the capabilities of the on-board spacecraft computers have affected the space shuttle orbiter and Galileo missions, see appendix I.

Reasons for the Technology Gap

There are several reasons for the technology gap between spacecraft and ground-based computers, including (1) the requirement to use space-qualified computers in the difficult space environment (as compared to the relatively benign Earth environment); (2) the long spacecraft development cycle; (3) the reliance of spacecraft program managers on proven technology; and (4) launch delays, sometimes of several years, during which time the computers age even more. The importance of these factors varies greatly from mission to mission, depending on spacecraft design, mission objective, and conditions in space.

Space-Qualification Process

The demands of space-qualification make spacecraft computers much more difficult to design, manufacture, and test than ground-based computers. Spacecraft computers must be hardened against the radiation and high-energy particles that exist outside the Earth's atmosphere, and must be designed to operate in extremely hot and cold temperatures. Because of size, weight, and power limitations on-board spacecraft, spacecraft computers must also be small in size, lightweight, and have low electrical power requirements. Since spacecraft computers are often inaccessible for servicing, they must be fault-tolerant and incorporate highly reliable hardware and software. The space qualification process takes time. For example, as further discussed in chapter 3, Energy's Sandia National Laboratory is developing a set of advanced 16- and 32-bit space qualified microprocessors called the SA3300 family. Even using existing commercially developed microprocessors as a basis for its advanced systems, a Sandia official estimated it will take about 5 years to design, build, and test the new 3300 family of space-qualified microprocessors and associated computer hardware.

The process of space-qualifying a computer depends on the operational characteristics of the mission. For example, space-qualifying computers for use on missions to Jupiter, which has a high radiation environment, must operate correctly despite these high levels of radiation and high energy particle bombardment, whereas space-qualifying computers for use in low, Earth-orbiting missions do not face as harsh an environment. Also, some spacecraft have more limited space available for computers, and some missions have more stringent data processing requirements than others.

Long Spacecraft Development Cycle

Part of the technology gap is due to the long spacecraft development cycle. The development cycle generally necessitates a firm decision, or "lock-in," for the spacecraft computer architecture about 5 years before planned launch. NASA project managers told us they prefer to have space-qualified computer hardware available 5 years before mission launch in order to develop, test, and integrate the spacecraft subsystems to produce a complete working spacecraft. As discussed above, space-qualification requirements can vary from mission to mission so that even though a computer may have been space-qualified for one mission, its use on a different type of mission may require more testing and evaluation.

The length of the spacecraft development cycle also varies from mission to mission. Although it may be possible to shorten the development cycle, or insert new computer technologies later in the cycle, some lag time will always occur because of the time required to design, build, test, and launch spacecraft.

Using Proven Technology and Other Considerations

Researching and developing microprocessors is important because these devices determine, in large part, a computer's capabilities. The spacecraft project manager's choice of a particular microprocessor at the time of design lock-in depends on a number of factors, including the project manager's reliance on computer technology that has already been space-qualified. At the time of design lock-in, project managers must make a choice. They may choose to use recently developed computer technology that may not yet be space-qualified, or they may use older, proven technology.

Each choice involves trade-offs. Selecting more advanced space-qualified computers for the spacecraft can result in higher hardware development costs, yet may lower the overall life-cycle costs of space missions through lower software development and maintenance costs. However, delays or cancellations of advanced computer research and development programs can delay the availability of new technology. Furthermore, the process of space-qualifying advanced computers adds schedule risks and complexity to the project.

On the other hand, using older, on-board computers with limited capabilities may decrease the overall capabilities of the spacecraft. The Director of the NASA Office of Aeronautics and Space Technology, Division of Information Sciences and Human Factors, believes that using proven technology creates a large computing "penalty," given the rapid pace of advances in computer technology. Further, using less-capable computers can result in more difficult and costly programming and software maintenance, and lead to higher life-cycle project costs.

NASA project managers usually relied on proven technology that had already been space-qualified and flown, for their on-board computers. However, using older, proven technology increased the length of the technology gap. Computers that had already been space-qualified and flown at the beginning of the spacecraft's design phase were already several years older than hardware that was just becoming space-qualified at design lock-in.

Another factor affecting the delay was the difficulty in moving promising technologies from the research and development laboratories to operational spacecraft, according to NASA advisory groups and program officials. Although no specific examples were mentioned, the Space Systems Technology Advisory Committee said that too often good technologies developed under NASA's Office of Aeronautics and Space Technology, which is NASA's primary research component, had not been utilized in major NASA programs. The committee added that this problem was caused, in part, by a lack of funding to transfer technology from the research laboratories to operational use. The committee suggested that NASA operational personnel sponsor some of NASA's research and technology programs. Joint sponsorship between NASA's research and operational components would split the cost of conducting technology demonstrations and encourage the transition of new technology into operational spacecraft. Another important aspect of joint sponsorship would be the increased confidence of the program manager in the technology developed.

On the basis of the committee's report, NASA said it was considering ways to improve the transition of advanced computer technologies from research and development to operational spacecraft as part of its Civil Space Technology Initiative (CSTI) project. Because the CSTI project began in fiscal year 1988, it is too early to tell if the program will successfully address the concerns raised by the advisory group. Additional information on CSTI is included in chapter 3.

Launch Delays

Launch delays of NASA missions are another factor contributing to the technology gap between ground-based and space-based computer systems. Delayed launches mean that the spacecraft computers are even older than anticipated by the time they get into space. For instance, the Galileo mission to Jupiter was approved in 1977, and scheduled for a 1982 launch. Because of launch delays, Galileo is now scheduled for a 1989 launch, a 7-year delay. (See appendix I for additional information on the Galileo mission.) In addition, upgrading spacecraft computers during launch delays involves costly trade-offs. Galileo personnel said that replacing one of the Galileo computer systems with an improved processor was considered during the most recent delay. However, since the software had already been written, the cost of reprogramming for a new processor outweighed the benefits gained by replacing the system.

Effects of the Technology Gap on Future NASA Missions

Many of the operational capabilities planned for future space missions, such as expanded, on-board processing of mission data and advanced automation and robotics, depend on the availability of advanced, space-qualified computers. NASA studies and the National Research Council report indicated that these kinds of capabilities hold the promise of lengthening the operational life of spacecraft, providing large increases in scientific data from space projects, and controlling the costs of future space missions. Without advanced, space-qualified computers, these benefits may not be fully achieved.

Future space missions are planned to be longer and more complex than previous missions, creating a need for more reliable and capable spacecraft computers. General-purpose, space-qualified processors with speeds of 10 to 25 million instructions per second will be needed to implement these capabilities, as reported in a JPL technical paper sponsored by NASA. As shown in table 2.1, the original shuttle microprocessor architecture had a speed of 0.4 million instructions per second, while the speed of the planned microprocessor for the space station's primary computer system will be 4 million instructions per second.

Scientific papers published by JPL and the National Research Council estimated that the amount of data collected on future missions will be much greater than in the past, and spacecraft computers with greater on-board processing capabilities will be needed to operate and manage increasingly complex spacecraft, instruments, and data. The National Research Council report cites NASA's planned Earth Observing System (EOS) as an example of a future spacecraft that will produce large amounts of data at high rates and will need significant advances in on-board data processing capabilities. (See appendix I for additional information on the EOS spacecraft and its mission.) On-board processing of mission data could also reduce the volume of data transmitted to Earth, which would reduce the large demands on space-to-ground telecommunications systems.

JPL program officials told us that greater on-board computer processing speed and memory would allow for more efficient use of scientific instruments, and could increase the scientific return on investment of a given mission. Greater on-board memory capability would also allow greater use of high-level programming languages, JPL officials said. This increased capability could reduce the cost of software development, as software developers will not have to write programs in assembler language to compensate for the small memory available on existing space-qualified computers. Also, by using standard, high-level programming languages, computers can be upgraded with less rewriting of software. For example, the high cost of rewriting software was a major factor in the decision not to upgrade Galileo spacecraft computers during the launch delay.

The National Research Council and NASA studies also stated that the application of automation and robotics technologies on board spacecraft will require advanced spacecraft computers. However, these advanced, space-qualified computer processors are not currently available. For example, a two-armed robot operating in space would require a computer with a processing speed of about 18 million instructions per second, according to a JPL robotics program official. Current space-qualified, general-purpose processor speeds are below one million instructions per second.

The National Research Council and NASA studies state that applications of automation and robotics in the future are expected to expand the capabilities of space missions and reduce costs to NASA. The advantages include increasing the ability of spacecraft to operate autonomously (that is, with less ground support), increasing crew member productivity, reducing hazards to human life in space, and enabling new missions to other planets. A JPL study performed for NASA estimated that automated operations may reduce ground support costs by as much as 10-fold, as compared to performing the missions without advanced automation and robotics technologies. Automation and robotics will also be critical to servicing vehicles and instruments in space.

One example of how future missions can be affected by the technology gap is seen in the Mars Rover and Sample Return mission, which is currently in an early stage of planning. A Mars Rover project official envisions that an unmanned vehicle would be launched around 1998 and land on Mars. The rover would move across the Martian surface, periodically collecting samples. How much autonomy can be built into the rover, and therefore, how far it can travel in a given period, depends largely on the rover's computers. According to JPL officials, the rover's computers are being planned on the basis of constrained project budgets and the limited availability of advanced, space-qualified computer hardware. As a result, the original concept for a highly autonomous or semiautonomous rover may be scaled back to a nearly teleoperated design, JPL officials said. This more limited, teleoperated design would require instructions from Earth each time the rover moves 15 to 100 feet. If it is scaled back, the rover would travel about 4 miles in 235 days on the Martian surface while a semiautonomous rover would travel as much as 25 miles in 235 days, JPL officials said. (See appendix I for additional information on the Mars Rover mission.)

Efforts to Develop and Deploy Advanced, Space-Qualified Computer Technologies

The Departments of Defense and Energy have ongoing programs to develop general-purpose, radiation-hardened microprocessors. We were told that NASA, in order to "leverage" its funds and to avoid duplication of effort, is looking to these ongoing Defense and Energy research and development programs to help meet some of its future mission needs. Also, in fiscal year 1988 NASA began to fund its own research in advanced spacecraft computer technologies through the Civil Space Technology Initiative (CSTI) project, which among other things, will reportedly build on the radiation-hardened microprocessors under development by Defense.

Various forms of interagency coordination exist between NASA and Defense. NASA and Defense officials stated that both agencies could benefit from improved coordination in their efforts to develop and deploy advanced, space-qualified computers, and they have recently taken steps to do so.

NASA Programs to Develop Advanced Spacecraft Computers

A 1987 National Research Council report stated that NASA had not been funding enough space research and technology development for the last 15 years, including the area of advanced, space-qualified computers.[1] The Council concluded that NASA's preoccupation with short-term funding for operational programs, such as the space shuttle, had left the agency with a technology base that was inadequate to support future space missions. Advanced, space-qualified computers was one of the technologies identified in the report as critical for accomplishing future space missions.

A 1987 report by the Space Systems Technology Advisory Committee identified specific advanced computer technologies that NASA needs for future missions, including general- and special-purpose, radiation-hardened computers.[2] In its December 1987 response to this report, NASA agreed that a greater emphasis was needed in developing advanced computer systems and said that many of the committee's recommendations had been incorporated into the CSTI project, which began in fiscal year 1988. For the longer term, NASA said it was evaluating the possibility of a joint Defense-NASA program to develop a next generation, space-qualified, 32-bit, general-purpose microprocessor.

[1] Space Technology To Meet Future Needs, National Research Council, National Academy Press, 1987.

[2] Report by the SSTAC Ad Hoc Committee On On-board Processing And Data Management Technology, Space Systems Technology Advisory Committee, July 1987.

We were told that in order to "leverage" its funds and to avoid duplication of efforts, NASA is looking to ongoing Defense and Energy programs involving the research and development of general-purpose, radiation-hardened microprocessors to help meet some of its future mission needs. Also, as discussed in chapter 4, NASA plans to use an International Business Machines (IBM), 32-bit, commercially-available microprocessor for the space station's primary computer system. Moreover, in fiscal year 1988, NASA began funding its own research in advanced spacecraft computer technologies, such as developing computer architectures, hardware components, and software technologies needed to incorporate the advanced microprocessors that Defense is developing. This research is being conducted primarily under CSTI. NASA's funding of the CSTI project for fiscal years 1988 and 1989 amounted to $114.2 and $121.8 million, respectively.

The CSTI project focuses on three research and development areas: (1) space transportation, (2) operations, and (3) science. A NASA official explained that within these areas, NASA is conducting three advanced computer technology research and development efforts that expend about 10 percent of CSTI's annual funding:

- JPL is developing a next-generation, high throughput, spaceborne computer capable of supporting the EOS platform. This computer, known as MAX, will utilize components developed by Defense.
- The Langley Research Center is developing advanced, general-purpose, high-data-rate, spaceborne computer technology for space data processing and storage, also based on Defense-developed multiprocessors.
- The Ames Research Center is developing the Spaceborne VHSIC Multiprocessor System for the space station's thermal control subsystem. The system is designed to incorporate Defense-developed microprocessors, and is intended to be a joint effort between NASA and Defense.

In addition to the CSTI project, NASA started the Pathfinder program in fiscal year 1989, which is intended to continue CSTI's advancement of technological capabilities. According to NASA officials, the program's objective is to develop those emerging technologies that make possible new and enhanced missions and system concepts. They estimated that NASA funding for the first year of the Pathfinder program amounted to $40 million, of which about $115,000 was allocated to the area of computer technology development.

As the CSTI project and Pathfinder program are just beginning, it is too early to tell how successful they will be in advancing the performance capabilities of NASA spacecraft computers.

Defense and Energy Programs to Develop Advanced Spacecraft Computers

With the growth of the Strategic Defense Initiative (SDI) program in the 1980s, Defense eclipsed NASA in space-related funding, and in research on space-qualified computers. Defense funds the development of and uses space-qualified computers for various types of spacecraft, such as navigation, weather, and communications satellites. Defense's SDI sponsors the development of advanced, space-qualified computer technologies for the space-based elements of SDI. As discussed below, some space-qualified computer technologies sponsored by SDI will provide capabilities that are also needed by NASA. Defense is also providing research results and funding for part of NASA's CSTI project.

The generic very-high-speed integrated circuit spaceborne computer (GVSC) and the radiation-hardened 32-bit processor (RH32) programs, both of which the Air Force is managing, are examples of Defense programs that NASA may use, according to NASA officials. The GVSC microprocessor is being considered for NASA's planned Mars Rover vehicle, according to a Rover project engineer. NASA program officials also told us that NASA is planning for the eventual use of the Air Force's RH32 microprocessor in the space station's automated thermal control system. Chapter 4 provides additional information about NASA's planned application of the RH32 microprocessor on the space station and appendix I provides additional information on the Mars Rover vehicle. (See pages 28 and 37.)

The Department of Energy, through its Sandia National Laboratories, also conducts programs to develop advanced, space-qualified computer technologies for various federal agencies. The Sandia Center for Radiation-Hardened Microelectronics was formally established in 1980 with sponsorship by NASA, Energy, the Air Force, and the National Security Agency. Much of Energy's work in space-qualified computers is funded by Energy and Defense. Its primary goal in developing microelectronic devices is to provide radiation-hardened electronic components for Defense weapons systems. However, Sandia is also developing space-qualified computer components for NASA.

Sandia is developing a set of advanced 16- and 32-bit, space-qualified microprocessors and supporting chips called the SA3300 Family, sponsored primarily by Defense. NASA is planning to use the Sandia 16-bit, space-qualified microprocessor in future NASA spacecraft, such as the Comet Rendezvous and Asteroid Flyby (CRAF) mission, according to CRAF project officials at JPL. The CRAF project manager told us that NASA provided $275,000 of the total $25 to $30 million spent by Sandia to develop its SA3300 16-bit microprocessor. These funds were provided at the end of fiscal year 1986. (See appendix 1 for additional information about the CRAF mission.)

Table 3.1 below lists ongoing Defense and Energy programs specifically intended to develop advanced, general-purpose, space-qualified microprocessors. Total development costs for these programs are estimated to be $84.9 to $89.9 million.

Table 3.1: Advanced, General-Purpose, Space-Qualified Microprocessor Development Programs

Dollars in millions

Program Name	Microprocessor Architecture	Agency	Total Costs[a]	Fiscal Years Start	Fiscal Years End
General Purpose Very High Speed Integrated Circuit Spaceborne Computer[b]	16 bit	Defense	$36.5	1985	1989
Radiation Hardened 32-bit Processor	32 bit	Defense	$23.4	1988	1991
Sandia Application 3300	16 & 32 bit	Energy	$25 to $30	1985	1989
Totals			**$84.9 to $89.9**		

[a]Figures are agency program office estimates.

[b]This project is developing a microprocessor and the associated components needed to make a computer.

Coordination of NASA and Defense Efforts

Various forms of interagency coordination now exist. For example, technical managers who are involved in developing NASA computer systems periodically attend meetings and conferences with Air Force computer development staff. Also, Defense staff and contractors gave presentations on Defense's GVSC computer development program at NASA headquarters to obtain an exchange of information on the program.

NASA and Defense officials stated that both agencies could benefit from increased cooperation in their efforts to develop and deploy advanced, space-qualified computer technologies. NASA can often use the results of Defense's relatively large investments in developing advanced, space-qualified computers in its space programs. On the other hand, NASA's longer experience in defining and meeting requirements for space-qualified computers could help Defense's technology development and deployment efforts. NASA advisory groups believe that by working together, in selected joint technology development programs, NASA and Defense can combine and capitalize on the strengths of each agency.

The importance of successful coordination is illustrated by the results of one government computing meeting—the first of its kind—held in November 1987. This meeting involved agency management, program office, and technical personnel from the agencies involved in developing and deploying advanced microelectronics technologies, including advanced, space-qualified computer technologies. Officials who attended this meeting told us it helped to improve coordination among federal agencies, by an exchange of technical and programmatic information at the technical and program management levels, and by bringing together most of the agencies involved in this work.

One result attributed to this meeting was the decision by Defense to consolidate, at least for the initial design and test phase, three Defense programs into one to develop the next-generation spaceborne computer processor, which became known as RH32. Also, a NASA development manager who first learned of RH32 at the meeting, decided to explore the eventual use of Defense's RH32 program, in order to provide the advanced, radiation-hardened microprocessor needed in future modifications to the space stations' thermal control system. The NASA project manager told us that NASA, the Defense Advanced Research Projects Agency, and the Air Force are now sharing information on advanced applications of RH32.

Although the government computing meeting was an example of successful interagency coordination, the Defense official who sponsored the meeting indicated the future of such meetings is uncertain because effective coordination depends upon the commitment of participating personnel, and can be adversely affected by personnel changes in projects. In addition, he and several other Defense and JPL officials noted that good coordination is difficult, requires resources, and is not often high among agency priorities. Further, agency personnel do not always perceive close coordination with other agencies and programs to be in their best interests because they sometimes believe that their program budgets may be jeopardized by visibility of other programs engaged in similar work. In a recent report, the Congressional Budget Office noted that the previous history of cooperation between NASA and Defense has alternated between cooperative and competitive relations.[3]

[3] The NASA Program in the 1990's and Beyond: A Special Study, Congressional Budget Office, May 1988.

The report stated in part that "In the context of the effectiveness of NASA spending, the relationship with the Department of Defense remains . . . most critical."

Existing coordination efforts between NASA and Defense have had mixed success, according to NASA and Defense officials. For example, the NASA/Air Force Space Technology Interdependency Group was dormant for about 2 years, until a meeting was held in April 1988. The group is designed to encourage cooperation between NASA and Air Force space technology programs, monitor ongoing cooperative programs, and avoid duplication of effort. In its response to the Space Systems Technology Advisory Committee report, NASA stated that the group's reactivation would help assure regular meetings between Defense and NASA data systems communities.

Space Station Computers

In January 1984, President Reagan announced a national commitment to develop a permanently manned space station. Some of NASA's objectives for the station are to provide

- a national laboratory in space;
- a permanent observatory;
- a servicing facility for satellites and space vehicles;
- a transportation node between low earth orbit and higher orbits;
- an assembly facility for satellites, vehicles, and other large structures;
- a storage facility; and
- a staging base for missions beyond earth orbit.

In 1984, as part of its appropriations for the space station,[1] the Congress directed NASA to research the use of advanced automation and robotics technologies to increase the space station's efficiency, and to enhance the nation's scientific and technical base to promote more productive industries on Earth. Operating automation and robotics systems in space will require development and deployment of advanced, space-qualified computers.

The Space Station's Primary Computer System

IBM has been selected to provide the primary computer system for the space station. The system, called the Data Management System (DMS), is the baseline data processing system for the space station, and many of the station's computer subsystems feed into and use the DMS. IBM is proposing to build the DMS computer system using a 32-bit computer microprocessor, the Intel 80386, which IBM and other manufacturers use in some of the newest commercially-available microcomputers. A report issued by NASA's Aerospace Safety Advisory Panel in 1987 expressed concern that NASA would choose a 16-bit computer architecture for the space station, while 32-bit processor architectures would be the industry standard, even before the station was placed in orbit.[2] NASA's plans to use the Intel 80386 32-bit microprocessor appear to address this concern. However, the Intel 80386 microprocessor is not radiation hardened.

Because of the space station's low orbit, its radiation environment is expected to be relatively benign and therefore may not require the use of a radiation-hardened microprocessor in the DMS. However, radiation

[1] Public Law 98-371(98 Stat. 1227), July 18, 1984.

[2] Aerospace Safety Advisory Panel Annual Report Covering Calendar Year 1986, Aerospace Safety Advisory Panel, National Aeronautics and Space Administration, Feb. 1987.

periodically produced by solar activity could potentially affect the DMS computers, according to a NASA official. NASA is therefore examining ways to shield the DMS computers from the high-energy particles released by solar flares, in lieu of developing and using a radiation-hardened microprocessor. According to the Assistant Chief of Johnson Space Center Avionics Division, NASA has not yet decided whether it needs to radiation-harden or shield the Intel 80386 microprocessor as part of the space station program.

While the IBM computer system will initially be used in DMS and other key systems, other computers may eventually be used for other functions. For example, a NASA official developing the automated thermal control system said that a planned Defense space-qualified computer system, the RH32 (discussed in chapter 3), may eventually be used for this system. According to the program manager, eventual use of the RH32 microprocessor will facilitate higher processing speeds over the Intel 80386 microprocessor. Specifically, the Intel microprocessor is expected to operate at 4 million instructions per second (MIPS), as compared to the RH32 microprocessor, which is expected to operate at 20 MIPS. NASA will be making final technology decisions for the remaining systems in the station over the next several years, if the design and development of the station proceeds as initially planned.

Conclusions and Recommendation

Conclusions

By the time a NASA spacecraft is launched, the on-board computers are outdated. This situation exists for several reasons. First, modifying computers to withstand the harsh environment of space is difficult. Second, as an integral component of the spacecraft, the computer system is chosen early in the development process to allow sufficient time to integrate the system into the spacecraft. Third, because of the importance of safety and reliability, NASA managers use older, more reliable, but less powerful systems than are offered by newer technology. Finally, launch delays of months or years render the on-board computer systems farther out of date. As a consequence of such outdated systems, spacecraft functions are slower and more limited than might be possible with more advanced technology. These older systems in turn may reduce the amount of scientific data-gathering that can be accomplished.

The significance of the technology gap has been noted by the scientific community and NASA advisory groups. The National Research Council identified the development of advanced space-qualified computers as critical to accomplishing future NASA missions. The Space Systems Technology Advisory Board identified the specific technologies that NASA will need for future missions. NASA advisory groups believe that better coordination between Defense and NASA is in order, and could capitalize on the strengths of each agency.

Future space missions planned by NASA contain ambitious requirements, such as expanded on-board processing of mission data and advanced automation and robotics. Given the continuing rapid advances in computer technology, if NASA can shorten the time it now takes to modify such advanced technology for space use—even by a few years—the potential benefits may be substantial, in terms of extending the operational life of the spacecraft, significantly increasing the amount of scientific data that can be obtained, and controlling the cost of space missions.

NASA recognizes the benefits to be gained by using advanced spacecraft computer technologies and has taken several steps to address various aspects of the problem. NASA is considering ways to improve the transition of advanced computer technologies from research and development into operational spacecraft as part of its CSTI project. Additionally, the NASA/Air Force Space Technology Interdependency Group was reactivated in April 1988 to improve the coordination and exchange of information about NASA and Defense programs. In order to "leverage" its funds and avoid duplication of effort, NASA is looking to the success of ongoing Defense and Energy programs involving the research and development of general-purpose, radiation-hardened microprocessors to help meet some of its future space mission needs. NASA's reliance on Defense and Energy for the development of advanced microprocessors could save NASA millions if that technology is ready when NASA needs it. Also, overall performance capabilities of spacecraft computers may be enhanced if programs like CSTI and Pathfinder are successful, and if using more up-to-date microprocessor technology in the space station proves successful.

The extent to which these separate actions will reduce the time lag that presently exists remains to be seen. For example, even if NASA is successful in using recent commercially available microprocessors for the space station's primary computer system, this technology will be 10 years old if the station is launched, as planned, in 1995.

Solving this complex problem will not be an easy task, and the solutions could be costly. Nevertheless, the nation's leadership in space depends on NASA's ability to implement advances in many technologies, including incorporating more up-to-date computer systems in its programs.

Recommendation

Accordingly, we recommend that the NASA Administrator consider further strengthening the agency's ongoing activities by establishing an independent expert panel to comprehensively examine the process by which advanced spacecraft computers are developed and deployed, and determine the further steps that could be taken to shorten the process. At the discretion of the Administrator, members on the panel could be gathered from appropriate federal agencies, the scientific community, and private industry.

Agency Comments and Our Evaluation

On March 6, 1989, NASA provided comments on our report (see appendix II). NASA agreed with our finding that its space-qualified, general-purpose computer hardware is based on 8-to-20-year-old technology, and stated that the report provided a fair review of its efforts to develop space-qualified microprocessors. NASA also stated that the report properly identified the primary factors for the technology gap and that significantly reducing the technology gap would bring cost and performance benefits for selected, highly automated future missions. NASA believes, and we concur, that several of the factors that cause the technology gap will persist. The agency believes the gap could not be reduced significantly below the 4 to 6 years required to space-qualify computers.

While recognizing the importance of developing space-qualified microprocessors, NASA believed our report should also recognize that other research and development efforts are important in developing and deploying advanced spacecraft computers. Further, NASA believed the report understated its efforts in the broader field of spacecraft computer research and development, which included the development of system architectures, hardware, software, data storage systems, and special-purpose computers. For example, the agency pointed out that we did not include a discussion of two special-purpose computers planned for EOS, or discuss the high-capacity, spaceborne optical data storage system.

As we mentioned in chapter 1, our work focused on the development of space-qualified microprocessors used in general-purpose, spacecraft computers. We focused on the development of this component, the principal part of most computers, because of (1) the complexities associated with space-qualifying it, and (2) its integral relationship to the processing speed and capacity of on-board computers—factors that we believe will significantly affect NASA's ability to accomplish future mission objectives.

During the course of our work we did identify a number of projects related to the overall development of spacecraft computers and their supporting technologies. We recognized that in fiscal year 1988, NASA began funding its own research in advanced spacecraft computer technologies, such as developing computer architectures, hardware components, and software technologies needed to incorporate advanced microprocessors, under its CSTI project. We mentioned the overall scope of the CSTI effort, as well as three specific projects. We did not include information about all projects under CSTI because some projects were recently initiated and it is too soon to tell if they will have any impact on reducing the technology gap.

NASA did not comment on our recommendation. However, a NASA official told us that an internal working group had met to discuss the report and its recommendation. He told us the group was in general agreement that more needs to be done in this important area, but stated that the NASA Administrator would need to make a decision on the recommendation once the report had been issued, and the agency had additional time to evaluate the message and study the nature and extent of any alternative actions.

Spacecraft Computer Case Studies

This report discusses the technology gap between ground-based and spacecraft computers, and the effect on past and possible effect on future NASA missions. This appendix describes in more detail the dynamics of developing, selecting, and implementing computers for NASA spacecraft. Specifically, this appendix presents case studies of (1) the space shuttle; (2) the Galileo spacecraft; (3) the Comet Rendezvous and Asteroid Fly-by Mission; (4) the Earth Observing System (EOS), which will be part of the space station; and (5) the Mars Rover Mission.

Space Shuttle Orbiter Computers

The space shuttle was first flown in 1981; the computer system was chosen for it in 1971. The shuttle uses AP-101 processors, originally a defense avionics version of IBM model 360/370 technology, which was developed commercially about 1964. According to the NASA Johnson Space Center Assistant Chief of the Avionics Division, microprocessor chips were not available in 1971, and shuttle managers chose what they felt was the best option at the time. This official described several problems and limitations imposed by shuttle computers. For example, because the computer's random access memory is small, NASA had to develop three different software systems for launch and flight operations on shuttle missions, and these systems had to be loaded manually by the astronauts. Furthermore, according to the official, shuttle software development and maintenance is inefficient and expensive, partly because three different systems are being used.

A Johnson Space Center avionics official explained that in the early 1980s, a shuttle computer upgrade project was undertaken to address memory limitations of the existing computers and meet new shuttle operational requirements. The upgraded shuttle computers will use an improved version of the original shuttle computer processors, and larger random-access memories, the official said. The new processor, which will run at a speed of slightly more than 1.2 millions of instructions per second (MIPS), compared to 0.4 MIPS for the existing processors, became available in 1979 and is used in the B-1 bomber avionics system. The new processor will enable the shuttle computers to meet new operational requirements, such as deployment of a new Inertial Upper Stage booster rocket, and permit more programs, such as shuttle abort sequences, to be stored in the on-board computers.

According to a Johnson Space Center avionics official, NASA will consider upgrading the shuttle's on-board computers in the 1990s using Intel

80386 32-bit microprocessors that are available now in personal computers. NASA will evaluate its experience using the Intel 80386 microprocessor in space station computers, in considering its later use on the shuttle.

Galileo Spacecraft Computers

The Galileo spacecraft is currently awaiting launch. The primary objectives of Galileo's mission are to investigate the chemical composition and physical state of Jupiter's atmosphere and satellites and to study the structure and dynamics of Jupiter's magnetic field. The mission was first approved in 1977 and scheduled for launch in 1982. However, the launch was delayed and is now scheduled for 1989.

In 1978, NASA decided to use RCA 1802 8-bit microprocessors for Galileo's Command and Data System. A commercial version of this microprocessor was first available in 1975. This microprocessor was chosen because it was radiation-hardened, consumed little power, and was one of only three processors available to the project that could meet Galileo's mission requirements, a Galileo project official said. The limited capabilities of this processor have caused problems for Galileo. According to a Galileo engineer, the processor's relatively slow speed and its limited memory caused problems writing efficient and maintainable software, and increased costs. A more advanced computer would have allowed for expanded mission objectives such as acquiring and relaying more pictures faster, and allowing more autonomous operations, the engineer said.

The Galileo spacecraft launch has been delayed several times. While waiting for launch, some of the computer memory chips have been updated with chips that can withstand higher radiation levels. However, the capability of the chips is still limited compared to commercial capabilities. An overall system upgrade to more advanced computer technology was considered during one of the launch delays, a Galileo official said. But NASA decided not to upgrade Galileo spacecraft computers because too much reprogramming, testing, and integration would have been required.

Comet Rendezvous and Asteroid Flyby Spacecraft Computers

The CRAF spacecraft is scheduled, as of October 1988, for launch in 1995. NASA plans for CRAF to fly by at least one asteroid, orbit a comet, and insert a scientific device into a comet's nucleus. CRAF project officials at the Jet Propulsion Laboratory want to avoid the expensive software development that the Galileo spacecraft experienced. As a result, CRAF is planning to use Sandia's SA3300 16-bit microprocessor for CRAF's computer system. According to CRAF officials, Sandia's microprocessor is based on a commercial microprocessor first available in 1982. According to these officials, while scientific objectives could be reached with a less advanced computer, development would be more difficult and the cost and risk of not meeting CRAF mission objectives would increase. According to CRAF officials, even at this early stage of the project, other NASA managers consider them to be incurring undue risk in waiting for the SA3300 16-bit microprocessor that is still being developed. According to these CRAF officials, Sandia plans to complete development of the computer chip set close to the design review/lock-in date for CRAF spacecraft subsystems.

Earth Observing System Spacecraft Computers

NASA's planned EOS is scheduled for a 1996 launch on the initial Polar Orbiting Platform, which is part of the space station program. The mission's objective is to understand what changes are occurring in the Earth's environment. The mission will generate a greater volume of data faster than any previous mission, and will require significant advances in spacecraft computer capabilities. According to a National Research Council report, in order to reduce the telecommunications requirements of the EOS mission to manageable levels, and to ease the demand on NASA's ground-based data processing, new high-rate, on-board data processing computers must be developed. This on-board processing could dramatically reduce the life cycle costs of the EOS mission, according to an analysis performed by JPL information systems officials. Further, once developed, these capabilities can be applied to future NASA missions.

Since EOS is scheduled to operate for 15 years, regular servicing visits to check instruments, replace batteries, and replenish spacecraft supplies are expected every 2 or 3 years. According to the National Research Council, in order to avoid interrupting scientific observation or losing instruments between repairs on EOS, the Polar Orbiting Platform must be able to analyze its own status, detect problems, activate back-up systems, or devise alternatives to malfunctioning systems. While the original mission plans called for manned servicing of the Polar Orbiting Platform, manned servicing may not be feasible since there may not be a polar-orbiting shuttle available during the planned time frame of the EOS mission. Instead, according to mission planners, they are considering using an expendable launch vehicle to service the spacecraft with robotics. Robotic servicing could require significantly advanced computers to control and operate the robots.

Mars Rover and Sample Return Spacecraft Computers

The proposed Mars Rover Sample Return mission is in an early stage of planning. According to a Mars Rover project official, this project envisions an unmanned mobile vehicle, known as the Mars Rover, to be launched around 1998 and landed on Mars. Originally, NASA envisioned a highly autonomous robotic rover capable of self-navigation over long distances on the Martian surface, taking samples without guidance from Earth. However, such a vehicle is considered well beyond state-of-the-art technology. On the other hand, the robot will need some autonomy. It is considered impractical to teleoperate, that is, control each movement of the rover from Earth, because it can take each command signal, including a spacecraft response, up to 40 minutes to travel round trip.

Between the extremes of full autonomy and teleoperation, NASA is considering two different ways of navigating the rover on Mars—semiautonomous control and computer-aided remote driving. The semiautonomous rover would have computers on-board so it could plan its route along the surface autonomously. This would allow the rover to travel an estimated distance of 25 miles in 235 days and collect 100 to 125 samples.

The other alternative, computer-aided remote driving, is closer to the teleoperation approach. Pictures from the rover are sent to earth and viewed by a human operator who designates a safe path for the rover to follow. Depending on the terrain, the rover might travel 15 to 100 feet between Earth commands. This mode of operation would allow the rover to travel approximately 4 miles in 235 days and collect 80 samples, which is less than the stated requirement for 100 samples.

According to a rover project official, a 1998 launch would mean a space-qualified computer would have to be selected by 1992. Given the pace of development of advanced space-qualified computers, the Defense GVSC project (see table 3.1) is viewed as the most probable source of radiation-hardened parts for the rover. The GVSC project includes development of a 16-bit microprocessor. According to the rover data systems manager, the performance of the computer is a limiting factor on the rover's autonomy, and lack of usable hardware is a clear constraint.

Agency Comments

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of: RC

MAR 6 1989

Mr. Ralph V. Carlone
Assistant Comptroller General
Information Management and
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United States General Accounting Office
Washington, D.C. 20548

Dear Mr. Carlone:

The National Aeronautics and Space Administration (NASA) appreciates the opportunity to review and comment on the General Accounting Office (GAO) draft report entitled, Space Operations: NASA Efforts to Develop and Deploy Advanced Spacecraft Computers (GAO/IMTEC-89-17, Code 510318). While the report is an accurate reflector of NASA's efforts in the limited field of space-qualified microprocessors, it understates our efforts in the field of space qualified computer systems. These activities are addressed in the enclosed comments.

NASA has provided editorial changes and comments to Steve Schwartz of your staff.

Sincerely,

C. Howard Robins, Jr.
Associate Administrator
for Management

Enclosure

NASA Comments on GAO Draft Report: SPACE OPERATIONS: NASA Efforts to Develop and Deploy Advanced Spacecraft Computers Dated February 10, 1989

One of the purposes of the draft report is to provide information on "ongoing NASA and Department of Defense programs to develop and deploy advanced spacecraft computers." The report, however, is focused primarily on the development of space-qualified microprocessors. While this is an important element, it should be recognized that other research and development elements are also important in developing and deploying advanced spacecraft computers. Within the limited scope of space-qualified microprocessors, the draft report does provide a fair review of the status of NASA efforts. However, the report understates NASA's efforts in the broader field of spacecraft computer research and development, which includes development of system architectures, hardware, software, data storage systems and special-purpose computers. These all contribute to the development of advanced spacecraft computing capabilities important for future space missions.

The Office of Aeronautics and Space Technology (OAST) is responsible for NASA research and advanced technology development. The report did not discuss our ongoing efforts to develop special purpose computers for the High Resolution Imaging Spectrometer and the Synthetic Aperature Radar instruments planned for the Earth Observing System, or the high capacity spaceborne optical data storage system. In addition, we continue to actively study spacecraft data system architectures to guide our research efforts and support advanced mission planners. In order to expeditiously develop general purpose spacecraft computers for operational programs, NASA has chosen in the near term to concentrate on developing multi-computer architectures and software operating systems which utilize space-qualified general purpose computer hardware developed by the Department of Defense (DOD) and the Department of Energy (DOE). While problems may arise from NASA dependence on DOD/DOE hardware such as potential program delays or cancellation of divergence of NASA technical requirements, this strategy is the most cost effective approach.

NASA does not dispute the report finding that space-qualified general purpose computer hardware is based on 8 to 20 year-old technology. We agree significantly reducing this gap would bring cost and performance benefits to selected highly automated future missions. The report properly identifies the primary factors for this technology gap as the need to qualify computers for the space environment, the long mission development cycle, the use of proven technology and launch delays. Several of these factors will persist and it is unreasonable to expect to see the technology gap reduced significantly below the 4 to 6 years required to space qualify computers.

Robert Rosen
Deputy Associate Administrator for
Aeronautics and Space Technology

Microprocessor Architecture

A microprocessor is a semiconductor chip or chip set that contains many small and interconnected microelectronic circuits that perform the principal functions of a computer. Microprocessors were developed in the early 1970s. Before the development of microprocessors, the principal functions of a computer were performed by a set of separate electronic devices, such as transistors, that were connected together to form a processor. Microprocessors are much smaller than processors. Today, the terms "processor" and "microprocessor" are often used interchangeably.

Microprocessors are characterized by their operating speeds, the size of the data units (or word-length) they can input and output, the size of the data units that can be manipulated inside the chip, their physical design, and their supporting devices. The combination of these characteristics determines the performance capabilities of a microprocessor.

Microprocessor architectures have typically been designed to manipulate data units of 4-bits, 8-bits, 16-bits, and most recently 32-bits. For example, a microprocessor designed to operate on data in 8-bit word-lengths is called an 8-bit microprocessor.

Bit-slice microprocessor architecture refers to a class of microprocessors constructed by linking together separate processing units known as slice elements. A computer of any word size can be constructed in this manner. The resulting microprocessor has an architecture that is determined by the bit-size of the slice elements and the number of slice-elements used. For example, a microprocessor composed of two 4-bit/slice elements would be an 8-bit microprocessor.

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Glossary

Automation	The operation of autonomous and self-regulating machinery, which can perform specialized, preprogrammed tasks using computers as the central element in the system.
Autonomy	The ability of a system (e.g., a robot) to act independently of human operators.
Bit	The smallest unit of storage and information in a binary system within a computer. The term is an abbreviation of the term binary digit, which refers to either of the two digits 0 and 1 used by computers to represent numbers, characters, and instructions.
Byte	A unit of information within a computer, usually composed of eight bits.
Parallel Processor	A computer design using more than one processor simultaneously.
Radiation-Hardening	The process of designing, building, and testing computer components, such as semiconductor chips, to withstand the destructive effects of radiation and energy particles encountered in space.
Robot	A general-purpose system, with a great degree of autonomy, through which a computer senses its environment, plans and decides its actions, and performs mechanical manipulations and data handling, sometimes to a degree normally done by humans.
Space-Qualification	The process of designing, building, and testing a system or subsystem, such as a computer or computer component in a spacecraft, to verify that it meets all the requirements of a space mission, including successfully operating in the expected space environment.

Teleoperator	A system that uses telecommunications to enable humans to activate and control systems in remote places.
Tele-Robot	A robot that is controlled from a distance by an operator via telecommunications.