United States General Accounting Office

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Report to the Chairman, Committee on Science, Space and Technology

April 1987

SPACE OPERATIONS

NASA's Use of Information Technology

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United States
General Accounting Office
Washington, D.C. 20548

Information Management and Technology Division

B-226577

April 17, 1987

The Honorable Robert A. Roe
Chairman, Committee on Science, Space, and Technology
House of Representatives

Dear Mr. Chairman:

In response to a July 1, 1986, request from the former Chairman (see appendix I), we are providing an overview of the information technology[1] that is critical to the missions of the National Aeronautics and Space Administration (NASA). As requested, this report discusses NASA's planning, development, and use of information technology for three areas: the Space Transportation System (STS), the Space Station, and unmanned space explorations. (For details, see appendixes II-IV, respectively.)

NASA's use of information technology is significant. In fiscal year 1986, NASA allocated about $784 million for this technology, about 10 per cent of the agency's total $7.8 billion budget. During fiscal years 1987 through 1991, NASA plans to spend about $4.1 billion on new information technology projects, approximately 70 percent of which will support STS, Space Station, and unmanned space programs. (Appendix V contains additional information on NASA's planned acquisitions.)

In performing our review, we examined pertinent management, technical, and contract information provided by NASA. We also held discussions with NASA representatives responsible for the direction of the information technology support for the agency's space programs. We conducted our work at NASA headquarters in Washington, D.C., and at selected NASA field locations, including Goddard Space Flight Center, Jet Propulsion Laboratory, Lyndon B. Johnson Space Center, John F. Kennedy Space Center, and the White Sands Test Facility. Where possible, we have updated the information in this report through February 1, 1987. Details on our scope and methodology can be found in appendix VI.

Additional work is necessary before we can reach final conclusions, or make recommendations, on the topics discussed in this report. However,

[1]For purposes of this review, we have defined information technology as computers (hardware and software), sensors, robotics, and telecommunications systems that NASA uses to support its mission

as requested during progress briefings with your office, we have identified several issues related to STS, the Space Station, and unmanned space explorations that the Committee may wish to pursue.

Space Transportation System

STS information systems architecture, both the hardware and software that support the system's operations, merits close attention, as the space program continues to recover from the loss of the Challenger in 1986. According to NASA officials, the existing architecture is obsolescing, thus possibly limiting flight rates and potentially becoming an even larger obstacle to operational efficiency as NASA attempts to perform more complex missions in the future. NASA has several modernization projects under way, but additional work is needed to determine if these projects fully address the obsolescence problem.

STS' overall operational performance depends not only on the number of shuttle orbiters and the time it takes to refurbish them between flights, but also on the efficiency and effectiveness of three key mission operations: flight planning, flight readiness, and flight control. According to NASA officials, much of the STS software and hardware used to support these operations was originally designed for the 1960s Gemini and Apollo projects, whose missions were operationally different from those of STS. These officials have also said they recognize that the existing hardware and software architecture that supports current operations may be nearing the end of its useful life, has limited spare equipment, and requires extensive time to modify from flight to flight. A 1986 NASA flight rate capability study[2] points out that, depending upon the mission complexity, existing flight planning and software development and production operations may not be able to support the flight rates that NASA currently plans. As STS mission tasks become more complex (for example, constructing, assembling, and servicing the Space Station), architectural obsolescence could become an obstacle to efficient and effective operations. As a result, according to NASA officials, operations costs could rise, or the number and type of missions that could be flown could be limited, or both.

NASA has several projects to update selected automated data processing systems supporting mission operations. In addition, NASA's Johnson

[2] Mission Operations Directorate: Flight Rate Capability Study, Johnson Space Center, September 1986.

Space Center has projects that are exploring the use of advanced automation to improve the effectiveness and efficiency of certain flight control operations. However, the obsolescence issue may need further attention. To illustrate, although NASA has progressed in developing a long-range architecture plan for financial and administrative information systems, the agency has not developed an integrated long-range plan for flight planning, readiness, and control systems that identifies (1) current performance shortfalls, including obsolescence issues, and (2) modernization plans for addressing these issues.

In January 1987, NASA announced that it was taking steps to place greater emphasis on long-range operational planning and system design for STS operations overall. In view of this, NASA and the Committee may wish to address several key questions, including:

- To what extent, and at what cost, can the existing STS hardware and software support the number and complexity of missions currently planned?
- To what degree can existing hardware and software support an effective and efficient assembly and servicing of a space station? and
- What opportunities exist for using advanced automation and information technologies to improve STS' operations, and what is NASA's plan to incorporate these new technologies?

Space Station

According to NASA representatives, the Space Station is one of the most challenging projects that the agency has ever undertaken. The agency intends to move rapidly toward awarding contracts for the detailed design and development phases. At the same time, it hopes to contain initial development costs. Successful development of the station will require NASA to solve many critical issues over the life of the Space Station project. According to NASA officials, determining the level of advanced automation that will be needed to run the station efficiently and effectively, while containing development costs, represents a major issue. NASA documents indicate that acquiring the benefits of advanced automation will require complex research and development in information technology.

During this review, we noted concerns by the scientific community and NASA representatives that the agency's automation plans and advanced information technology efforts are not progressing as quickly as the agency's efforts to design and build the Space Station. As a result, the station may include only limited advanced automation, making initial operations expensive. Further, studies show that if NASA does not design the station so that it can incorporate advanced automation over time, subsequent redesign of the station could be extremely costly.

One organization that has voiced concern about the Space Station is the Advanced Technology Advisory Committee. This committee was created by law[3] to identify and recommend Space Station systems that should use advanced automation and robotics[4] technology. The advisory committee noted in a 1985 report[5] that, although the station would not initially have significant on-board automation, it was critical that the station's design be flexible enough to accommodate future automation enhancements. The advisory committee explained, however, that much complex research and development of several advanced information and communication technologies had to be addressed long before they could be used for either the station's initial or later configurations. A recent advisory committee report[6] stated that, although NASA's planned use of robotics looked promising, planning for some kinds of advanced automation technology was not progressing quickly enough to significantly influence station design. To underscore its concern, the committee noted that the results of the automation work to date had not been incorporated into the design control documents, which were to be used for the detailed design and development contracts. The advisory committee believed that NASA's constraint to design the station to an initial target cost, without giving balanced consideration to operational (life-cycle) costs, was the primary inhibitor of automation planning for the station.

On the basis of its concerns, the advisory committee recommended that NASA (1) set aside funds for advanced automation or (2) consider both the estimated life-cycle costs and the initial development costs when evaluating the proposals submitted by contractors competing for the station's detailed design and development contracts. Without NASA's commitment to one of these alternatives, the committee reported that it expected to see limited advanced automation on the initial station; an excessively costly process to incorporate evolutionary growth in

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

[4]Advanced automation and robotics can be defined as the use of machines, either computers or robots or both, to perform pre-designated tasks largely without human intervention.

[5]Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy, NASA-TM87566, March 1985.

[6]Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy-Progress Report 3, NASA-TM89190, October 1986.

advanced automation; a station that would be operationally expensive; and a station that could not support autonomous operations.

In responding to these concerns, NASA has stated that it will ensure that the final requests for proposals for the detailed design and development contracts will address the importance of automation and robotics. To give automation and robotics a more significant role in station design, the agency said that it had appointed a Division Director in the Office of Space Station with direct responsibility for this area.

Our preliminary review of the four draft requests for proposals issued by NASA for the detailed design and development contracts supports the advisory committee's basis for concern about the design control documents. For example, two key automation requirements documents developed to date were not properly updated or, except for one instance, were not included as documents that would be binding on the contractors who will do the detailed design of the Space Station's information system architecture. At the time we prepared this report, NASA had delayed issuing the final proposal requests. Thus, we could not determine whether NASA had changed the requests to incorporate the advisory committee's recommendations.

We also noted other concerns about information technology for the station. For example, the report from a 1980 NASA-sponsored study[7] pointed out that, unlike its pioneering work in other areas of science and technology, the agency's use of computer science and machine intelligence for advanced automation had been conservative and unimaginative and was 5 to 15 years behind the leading edge of technology. Also, NASA officials have expressed concern that tools and procedures that will guide contractors in developing high-quality software for the station may not be ready when needed. Finally, a 1985 Office of Technology Assessment study[8] conducted for the Congress expressed concern that, unless NASA funds automation research and development at levels substantially greater than currently projected levels, the Space Station would not include significant automation and its eventual evolution beyond initial capabilities would be hampered.

NASA has taken some action to address these concerns, including intensifying, in 1985, its program for research and development of the use of

[7] Advanced Automation for Space Missions, University of Santa Clara, Santa Clara, California, September 1980.

[8] Automation and Robotics for the Space Station: Phase B Considerations, An OTA Staff Paper, 1985

automation and robotics technology. Funding for this program has increased from fiscal years 1985 through 1987, with additional funding requested for 1988.

NASA may soon be making important trade-off decisions that could significantly affect the cost and operational capabilities of the station, possibly for its estimated life span of 30 years. In light of the large investment that the Space Station will likely require, NASA and the Committee may wish to consider addressing several key questions, including:

- If NASA remains committed to its cost and timeframe goals for designing and developing the station, will it have to use a "minimal risk approach," which would involve, in large part, the use of existing technologies for most station systems?
- If a minimal risk approach is taken, will this force NASA to rely primarily on proven, existing information technology that may be seriously outdated by the time the station is placed in operation?
- Will NASA be incurring the risk of building a less effective station with excessive operating costs and extensive dependence on ground stations for its long life?

Unmanned Space Exploration

In addition to its manned space missions, NASA has a goal of extending scientific knowledge about space through unmanned exploratory missions to survey Earth, the rest of our solar system, and the universe. Information technology is used to support three major areas of unmanned space exploration: telecommunications, space science data management, and spaceflight control operations. NASA has ongoing programs to improve operations in these areas. However, we noted concerns by the scientific community and NASA representatives about the capacity of telecommunications systems to meet planned future needs; NASA's processing, distribution, and archiving of science data; and the efficiency of spaceflight control operations.

In telecommunications, NASA initially planned to rely on a space network of three satellites (two active and one spare) to relay data between all low earth orbiting spacecraft and ground stations through the early 1990s. One satellite is currently in orbit, and two more are planned to be launched when the shuttle resumes flights. NASA documents indicated that the two active satellites may not be adequate to handle the substantial telecommunications needs of STS, the Space Station, and all other low earth orbiting spacecraft. This could result in significant losses of scientific data. Furthermore, the agency's networks for transferring data among different NASA locations may not be able to handle the increasing demands being placed on them and could add to the potential telecommunications shortfall.

NASA officials told us that the agency will continue to assess the requirements for the space network and update its plans, if necessary, to launch two additional satellites to support the Space Station. However, our review of the payloads for all planned shuttle flights through 1994 did not show launches for the two additional satellites.

Concerning space science data management, NASA has been criticized in the past by the scientific community for its performance in processing, distributing, and archiving space science data. Although NASA is attempting to respond to some of these concerns by funding "pilot" data management systems and acquiring additional computing resources, the agency's efforts may not go far enough. Scientists now expect space data to be generated at a far greater rate by the end of the decade than has ever been produced in the past. For example, NASA program managers for the planned Earth Observing System estimate that the system will have to receive, process, and store 10 trillion bits of data per day. To illustrate the magnitude of this number, if the data were stored on standard magnetic tape (6,250 bits of data per inch of tape), there would be enough tape to encircle the earth each day. While no one, to our knowledge, has proposed using magnetic tape to store this data, considerable advances must still be made to accommodate the projected massive storage needs.

Regarding spaceflight control operations, NASA's Solar System Exploration Committee, Subcommittee on Mission Operations and Information Systems, has expressed concerns about the duplication of effort in establishing multiple mission control centers for unmanned satellites and probes instead of consolidating these efforts. In an effort to partially address this concern, the Jet Propulsion Laboratory is planning to establish a consolidated deep space flight operations center. However, we have not yet seen evidence that NASA has identified what technical risks would be involved in the consolidation project.

Considering the significant financial and human investments that are being made by NASA and the scientific community in the unmanned space area, NASA and the Committee on Science, Space, and Technology may wish to consider addressing several key questions, including:

- What specific action is NASA taking to ensure that its space and ground-based telecommunications systems will be able to handle the massive amounts of scientific data that it anticipates processing in the near future?
- What plans does NASA have to ensure that its ground facilities will be able to adequately communicate, process, distribute, and archive such volumes of data from satellites and other systems, like the planned Earth Observing System, in a high quality manner?
- Although NASA is taking steps to make space flight operations control more efficient by establishing the space flight operations center, what other alternatives are available in conjunction with the center? For example, is there potential for using advanced automation in on-board satellite systems to alleviate some of the burden of managing routine functions that are now controlled from the ground? Also, how would the use of advanced automation, along with more efficient ground operations, reduce overall life-cycle costs?

Agency Comments and Our Evaluation

NASA stated that, in large part, our report presented a correct picture of the agency's use of automated information technology in support of space operations. Nevertheless, NASA believed there were several areas that were not properly addressed in the report. Specifically, the agency stated that our report did not adequately address the current and planned ground support systems used to support NASA missions. NASA also stated that we had made an incorrect assumption about the final space network configuration for the Space Station era. Finally, regarding the Advanced Technology Advisory Committee's concerns about the use of automation and robotics for the Space Station, NASA provided us with additional information that it believed accurately represented the agency's views regarding the Committee's report and resulting actions that NASA has planned or has taken.

Regarding our description of ground support systems, our report is intended to be an overview of information technology critical to NASA's space missions. It is not intended to be a comprehensive survey of all space-related information technology projects being pursued by the agency. We note on numerous pages in the report that NASA has modernization projects under way in several information technology areas, including ground support systems. We did not believe it was appropriate for this overview to include detailed descriptions of every information technology project. However, we did consider all projects mentioned by NASA in its comments on the draft report in our review.

Concerning the space network configuration, the information in our draft report was accurate, based on the information we reviewed. For example, both NASA documents and officials indicated that the space network configuration considered for the early to mid-1990s included two active telecommunications satellites and one spare. NASA's manifest for shuttle flights planned from the time flights resume through 1994 verified this configuration. Specifically, the manifest did not show plans to launch the two additional satellites that the agency included in its 1986 long-range plan. We made several additions and technical corrections in appendix IV to better reflect NASA's long-term plans for the space network. However, we believe the issue regarding the agency's plans for space and ground telecommunications systems is still valid for discussion because of other constraints raised by NASA's long-term plans.

Finally, the information that NASA provided us regarding the Advanced Technology Advisory Committee concerns was considered in preparing our draft report.[9] We included several references in appendix III about the agency's planned or ongoing actions to address the committee's concerns.

NASA also raised several technical and editorial points about our draft report, which we have addressed. The agency's points and our comments are included in appendix VII.

As arranged with your office, unless you release its contents earlier, we plan no further distribution of this report until 30 days from its issue date. We will then send copies to interested parties and make copies

[9]Letter dated December 10, 1986, from NASA's Administrator to the Honorable Edward P. Boland, Chairman, Subcommittee on HUD and Independent Agencies, House Committee on Appropriations. This letter is included in our report as enclosure 2 of appendix VII.

available to others upon request. Should you need additional information or have any questions on the contents of this document, please contact Dr. Carl R. Palmer, Associate Director, on 275-4649.

Sincerely yours,

Ralph V. Carlone

Ralph V. Carlone
Director

Contents

Abbreviations

ATAC	Advanced Technology Advisory Committee
CODMAC	Committee on Data Management and Computation
GAO	General Accounting Office
JPL	Jet Propulsion Laboratory
NASA	National Aeronautics and Space Administration
OTA	Office of Technology Assessment
STS	Space Transportation System

Request Letter

DON FUQUA, Florida, CHAIRMAN

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July 1, 1986

Hon. Charles A. Bowsher
Comptroller General
U.S. General Accounting Office
Washington, DC 20548

Dear Mr. Bowsher:

The Committee on Science and Technology intends to continue to broaden its oversight of NASA's information technology and automation activities critical to its space missions. NASA has long been heavily dependent on information technology for its space mission effectiveness. Indeed, NASA is the largest federal user of information technology for civilian purposes. Highly complex, information and automation technology is at the heart of all of NASA's space missions--from unmanned space exploration to Shuttle operations to its proposed space station. Further, NASA's investment in increasingly complex information and automation technology is growing. As a result of all this, NASA faces tremendous challenges in effectively developing and applying the technologies necessary for all its programs and especially for the Space Station program.

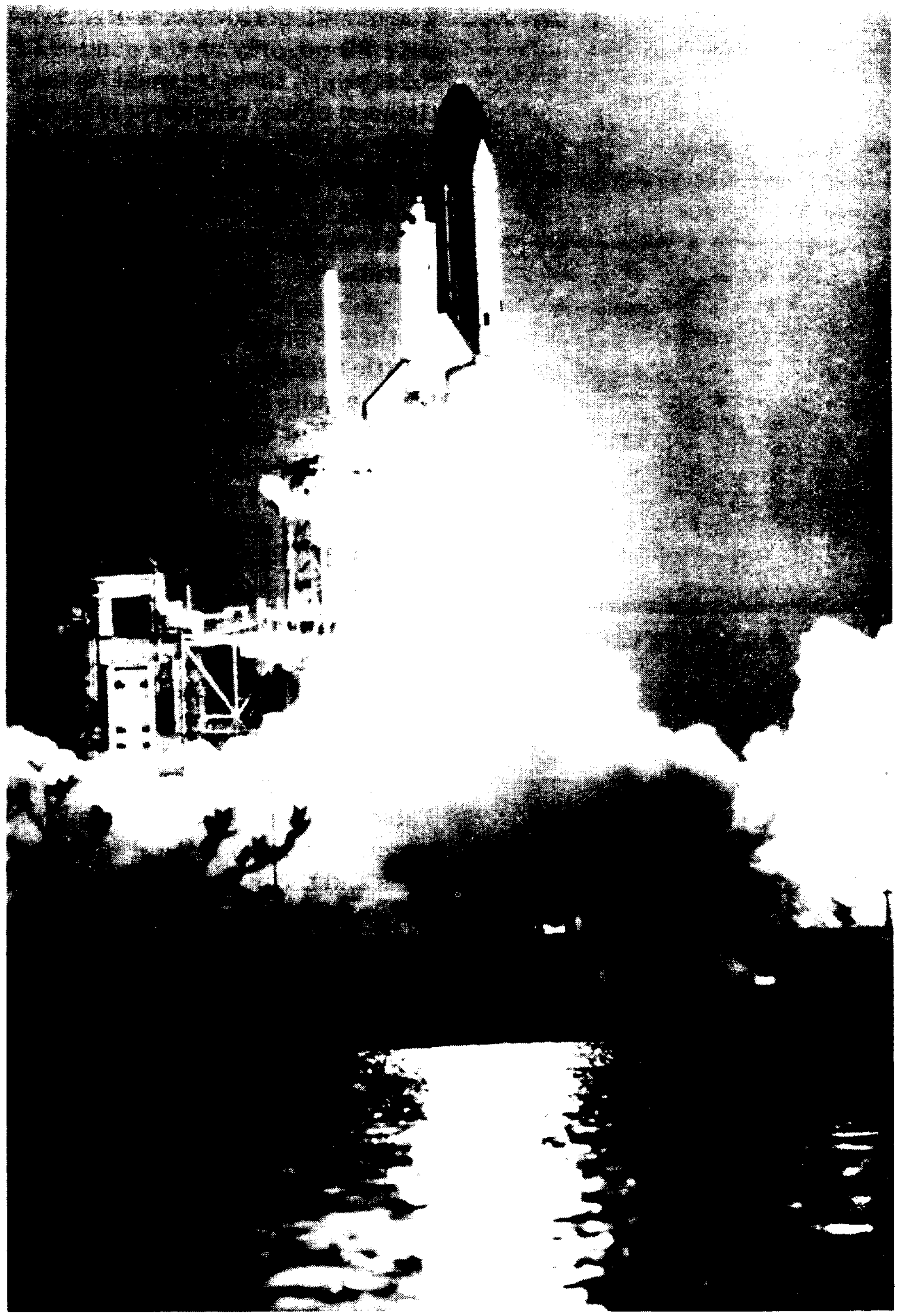
The Committee is interested initially in information in three areas: NASA's planning and development of ADP and automation technology for the Space Station, especially expert systems and automation technology useful to reduce operations costs; NASA's modernization of information technology for the Shuttle program; and NASA's information technology for unmanned space exploration. The Committee would like a summary overview on the above areas by January 1987. Recognizing this short timeframe, the overview should focus on providing information that will give the Committee a general understanding of NASA's information technology and automation investment for the above areas. If you have any questions, please contact Dr. Radford Byerly (225-7858) of the Committee staff.

Sincerely,

DON FUQUA
Chairman

DF/Bvt

Space Transportation System



Source: NASA

The overall performance of NASA's Space Transportation System depends not only on the number of shuttle orbiters and the time it takes to refurbish them between flights, but also on the efficiency and effectiveness of key mission operations. The effectiveness and efficiency of these operations, in turn, are dependent on how well supporting hardware and software systems work. According to NASA officials, the existing overall architecture of these hardware and software systems is obsolescing and may limit the effectiveness and efficiency of mission operations.

As the STS program continues to recover from the loss of the space shuttle Challenger in January 1986, architectural obsolescence could become quite significant, particularly as STS mission tasks become more complex (for example, the planned assembly and servicing of a space station). Although NASA has several modernization projects under way, additional work is needed to determine if these efforts fully address the obsolescence issue.

STS: An Overview

NASA developed STS to reduce the cost of space operations and provide easy access to space for commercial enterprises, foreign governments, the Department of Defense, and other government agencies. In addition to the shuttle orbiter, external fuel tank, and solid rocket boosters, STS includes computer hardware and software that support key mission operations, such as flight planning, flight readiness, and flight control. Table II.1 lists the large, complex hardware and software, which are manufactured by several companies, that currently support these operations and the major information systems/facilities that use the hardware and software. The software needed to support STS mission operations consists of approximately 25 million lines of software code and is written in at least six languages.

Overall management of the STS is the responsibility of NASA's Office of Space Flight. The STS planned budget for fiscal year 1987 is about $4.95 billion, of which $2.1 billion is appropriated for a new orbiter. Of the remaining $2.85 billion, NASA spends approximately $840 million annually for mission operations. A description of these operations follows.

Table II.1: Hardware and Software Supporting Mission Operations

Mission operations	Hardware used	Software/languages used
Flight planning		
—Flight design	—Unisys 1100s —Perkin Elmer 32/42 —Hewlett Packard 9000s	—4.7 million lines of code —Fortran 66, Fortran 77
—Crew activity	—DEC/Vax 11/750s and VS100s	—57,000 lines of code —Fortran 77
—Remote manipulator	—Hewlett Packard 9000s	—22,000 lines of code —Fortran 77 —Fortran V
Flight readiness		
—Software development	—Amdahl 5870 and 800 user terminals	—1.3 million lines of code —PL1, HAL 360, ADF, and assembly code
—Software production	—IBM 3033s —IBM 3084 —AT&T 6300 PC terminals —IBM SPF terminals	—2.3 million lines of code —PL1, Unix and C
—Mission simulation	—Unisys 1100s —IBM AP101s —Perkin Elmer 832s and 352s	—1.6 million lines of code —Fortran V —Assembly code
Flight control		
—Launch processing	—ModComp II/45s —Honeywell 66/80s —Honeywell DPS 8/70s	—13 million lines of code GOAL (custom language)
—Mission control	—IBM 3083s —IBM 3081	—1.8 million lines of code —Fortran IV —PL1 —Assembly code
—Shuttle on-board	—IBM AP101s	—Over 580,000 lines of code HAL (custom language) —Assembly code

Flight Planning Operations and Systems

Flight planning operations produce the trajectories and schedules for crew and mission activities that are feasible, consistent, and satisfy mission operational requirements. Flight planning systems include the flight design system, the crew activity planning system, and a planning system for the remote manipulator system.

The flight design system is used to analyze and design each mission's flight plan, including ascent/descent analysis and design, on-orbit flight design, attitude and pointing (that is, orbiter position) planning, and analysis of the effects of the orbiter's flight path on such consumable items as fuel, water, oxygen, and batteries.

The crew activity planning system develops, analyzes, and schedules all activities that the orbiter crew will perform in flight, including routine activities, such as eating and sleeping, as well as the more complex non-routine activities, such as maneuvering or deploying payloads. The system also produces a plan that the crew takes on board.

The planning system for the remote manipulator system is used to plan and evaluate the operation of the orbiter's remote manipulator, a 50-foot-long mechanical arm mounted in the orbiter's cargo bay, which is used in such space operations as satellite retrieval.

Flight Readiness Operations and Systems

Flight readiness operations produce the software necessary for each flight, support the training for each flight through simulation, and modify the mission control system for each flight. Flight readiness systems consist of the software development system, the software production system, and the mission simulation system.

According to a NASA official, the software development system modifies and adds new computer logic and equations to enhance shuttle operational capabilities. For example, the system is implementing a recently recommended change to improve shuttle safety by including an additional abort capability.

The software production system complements the software development system by modifying the vehicle, payload, and avionics data that are unique for each mission and by producing an overall software package for each flight. Specifically, the system collects and integrates the type of actual flight data, from both the shuttle and its payloads, that is to be monitored and the process for doing so. The system then uses this requirements data to produce a tape that will format telemetry data and integrate it with other shuttle data to produce a complete flight software package for the on-board computers. According to a NASA official, the software production system also produces software products that modify the mission control computers that will process and route the telemetry data and modify the workstations that display selected telemetry data to specific flight personnel.

The mission simulation system trains flight and ground crew members in handling both normal and contingency operations they may face in each flight stage: prelaunch, ascent, on-orbit (for example, payload deployment), descent, landing, and abort. The system conducts integrated simulations in conjunction with the mission control system. These simulations are a complete rehearsal of an actual shuttle mission, including the exchange of data and voice communications between the shuttle mission simulator and the mission control center. Figure II.1 shows an operator station for the shuttle mission simulator. Thousands of simulated flight conditions can be set or reset from these stations.

Flight Control Operations

Flight control, from prelaunch to orbit to landing, centers around the launch processing system, the mission control system, and the shuttle on-board system. The launch processing system at the Kennedy Space Center performs pre-flight checkout and monitoring of the space shuttle vehicle and controls its launch. This includes monitoring critical measurement data and displaying it in "real-time"[1] to different operator consoles in the launch control center at Kennedy, which, in turn, can relay commands directly back to the shuttle vehicle. Overall, about 40,000 temperatures, pressures, flow rates, turbine speeds, voltages, switch positions, and other parameters are monitored several times per second.

The Johnson Space Center uses the mission control system to perform real-time command and control of shuttle flights from launch through landing, to flight crew egress. Once the shuttle clears the launch tower at Kennedy, control of the mission switches instantly from launch control at Kennedy to mission control at Johnson. The mission control system also supports preflight and non-flight activities, such as flight simulations, launch pad tests, communications network tests, and software testing and validation. (Figure II.2 shows a mission controller console for the mission control system at Johnson.)

[1] Real-time applications control an ongoing process and deliver outputs not later than the time when these are needed for effective control.

Figure II.1: Shuttle Mission Simulator Control Center

Source: NASA

In its real-time mode, the system processes command, trajectory, communication and telemetry data; displays the data to flight controllers; processes and transmits controller commands to the orbiter; and displays the responses received from the orbiter. A digital television subsystem displays to the flight controllers the data computed on board the shuttle, as seen by the crew. In analyzing potential failure conditions, flight controllers will often use some of the 250 analysis programs that are kept on off-line computers due to loading limitations on the mission control system. The screens in front of each operator display thousands of different measurements that must be monitored constantly during a flight.

Figure II.2: Controller Console for Mission Control System at Johnson Space Center

Source: NASA

The on-board computers are involved in the control and monitoring of almost every phase of shuttle operations, from vehicle testing at the orbiter manufacturer's plant through ascent, orbit, re-entry, and landing. A set of five of these computers constitutes the orbiter's avionics (that is, aeronautic and electronic systems). Four computers are arranged as a redundant set, with each computer running the avionics software independently and simultaneously. Any one of these four computers may be designated as the flight control computer that actually controls and flies the shuttle. The four redundant set computers are linked as a "voting set." Each computer "votes" on the accuracy of the other three computers' computations. If the computers detect an error in one of the machines, they send a message to the mission commander, who may then deactivate the faulty machine.

The avionics software essentially flies and controls the orbiter. Functions include guidance, navigation, and control during each flight phase (that is, ascent, orbit, re-entry, and landing), and during contingency phases, such as abort. The backup flight software runs on the fifth onboard computer and can provide guidance, navigation and control during ascent, orbit, re-entry, landing or abort should the primary avionics software fail.

Concerns About Current Operations and Systems

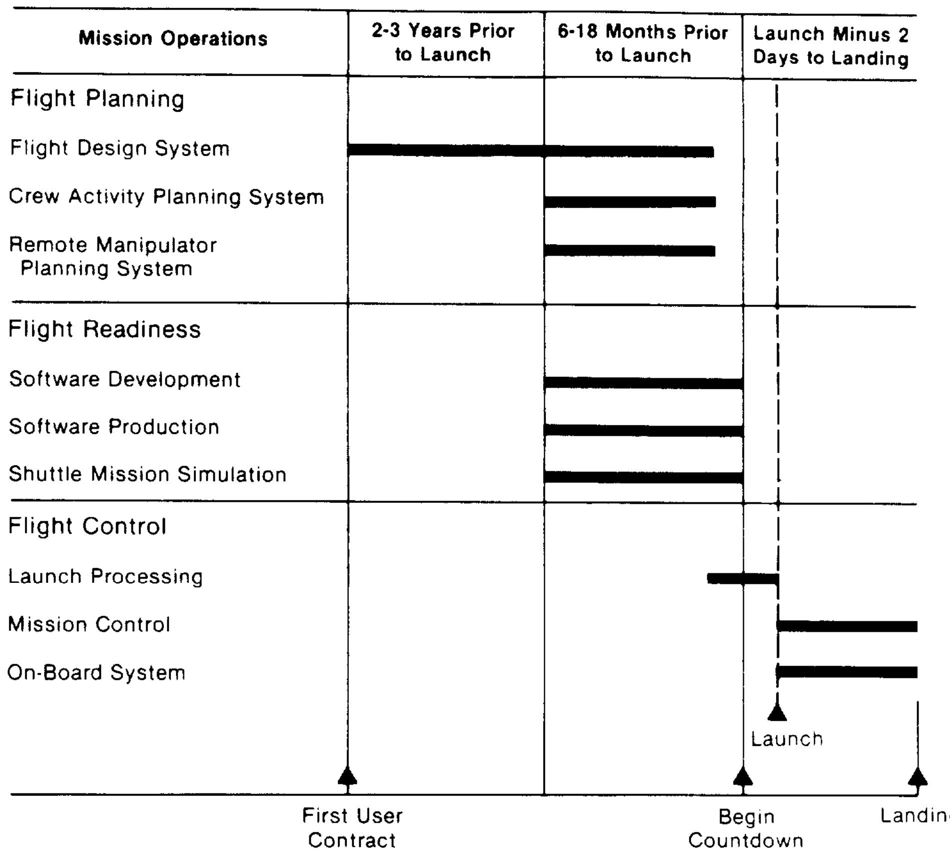
The existing operations and systems have been used to plan and develop 25 missions to date.[2] We noted concerns that current mission operations are not as effective or efficient as they could be. According to NASA officials, the growing obsolescence of the current information system architecture is an underlying constraining factor to the overall performance of flight planning, flight readiness, and flight control operations. This obsolescence could force up mission operations costs, or limit the number and complexity of missions that can be flown, or both.

Operations Concerns

On the basis of the STS experience to date, the planning, readiness, and control operations can take 2 or more years for a mission, depending upon the mission's complexity. (Figure II.3 shows a timeline for an individual mission.) Mission complexity is affected by several factors. For example, complex missions could involve a unique ascent/descent profile; a payload not flown before; extra vehicular activity; multiple payloads where the payloads have not previously flown together; rendezvous or multiple orbit changes; or the use of the remote manipulator system.

[2]This includes flight number 51L, the Challenger, that was lost after launch in 1986.

Figure II.3: Mission Timeline



Flight planning can start as early as 2 to 3 years prior to launch and not be finalized until 4 months prior to launch. It can take up to 5 months to finalize flight plans after they have been generated. A September 1986 flight rate study[3] by Johnson indicates that, depending upon the mission complexity, existing flight planning and software development and production operations may not be able to support the flight rates that NASA currently plans for the next several years. NASA officials recognize that the time required for initial flight-to-flight reconfiguration and then later reconfiguration due to payload or flight plan changes needs to be decreased.

[3]Flight Rate Capability Study, Mission Operations Directorate, Johnson Space Center, September 1986.

Unique parameters of the flight software have to be modified, or newly developed, from flight to flight. This includes modifying orbiter software, simulation software, launch software, and mission control software. For example, the requirements data for just a single new pressure measurement would include noting data limitations, identifying on-board wiring configurations, describing on-board and ground display formats, and specifying the method of communicating the data between the orbiter vehicle and the ground. This is complicated by the fact that each orbiter is wired differently and that existing data bases may not include all data needed for each flight, requiring authorized Johnson personnel to manually input this requirements data. In addition, just to integrate the telemetry data tape with the shuttle data tape to produce a total software package for on board the shuttle requires 5 weeks. According to a Johnson official, this 5-week period will most likely be further lengthened to accommodate safety measurements.

System Architecture Concerns

According to several NASA officials, the current information systems architecture is a primary constraining factor to overall operational efficiency and effectiveness. While some major system components (primarily hardware) are 1970s and 1980s technology, the overall system architecture carries over many parts from Gemini and Apollo (1960s vintage) and was not designed for rapid, low-cost reconfiguration for high flight rates and/or increasingly complex missions.

The architecture design for the Gemini/Apollo information systems was based on the assumptions that the missions to be supported would have a long interval between flights (2-6 months), that the spacecraft to be supported would be relatively simple (compared to the shuttle), and that the total duration of the project would not be so long that the technology would become obsolete within the project's lifetime. The long mission interval meant that mission operations could be highly "labor intensive"—flight controllers could be expected to put in a couple of 50-60 hour work weeks during a flight without performance degradation, if they could have some time to recuperate and train before the next flight was scheduled. Also there would be ample time to reconfigure the software and hardware between missions. According to NASA officials, based on the then state-of-the-art technology, the labor intensive operations were the most cost-effective.

Hardware obsolescence was one area of concern identified by NASA officials. For example, according to NASA, the manufacturer of current Univac 1100/44 computers will discontinue maintenance support in

1990. Hardware obsolescence generally means lower reliability and increased operations and maintenance costs. Computer capacity shortages in all operational areas was another area of concern. Computer capacity shortfalls can constrain the flight rate and can also impede off-line, real-time flight support, such as slower response time, and preclude the addition of new capabilities, such as better simulation models, which can improve crew training and increase flight safety.

In addition to hardware obsolescence and capacity problems, NASA officials expressed concern over the lack of user friendly software and the use of nonstandard operating systems and software. This makes software maintenance and modification very complex and implies larger personnel and training costs. Kennedy officials believe that the launch processing system software may become obsolete by 1992, making it impractical to continue using the system. The Kennedy system is reportedly a more modern system than Johnson's mission control center.

While it may be easy to recognize that hardware must eventually be replaced, it is more difficult to recognize that software also reaches the limits of its original design and the technology used to implement it. While there are no absolute rules on when to rebuild rather than maintain the existing system, the National Bureau of Standards has issued guidance[4] on this issue. Basically the Bureau identified several system characteristics which, if they exist, make the system difficult to maintain and potentially a candidate for redesign. These include the questions of whether (a) the system is a "mega-system" consisting of one, or several, very large (thousands or tens of thousands of lines of code) programs; (b) the code is over 7 years old; (c) the code was written for prior generation hardware; (d) more than one programming language is used; (e) low-level languages, particularly assembly code, or unique languages are used; (f) very complex program structure and logic flow are involved; (g) there is difficulty in keeping maintenance programmers and analysts; and (h) the documentation is inadequate or out of date. NASA's STS software meets many of these criteria.

A 1981 Mitre study[5] on the obsolescence of air traffic control operations software offers insight into software obsolescence and its potential impact. Mitre concluded that the existing air traffic control software,

[4] Guidance on Software Maintenance, National Bureau of Standards Special Publication 500-106, December 1983.

[5] The Obsolescence of National Airspace System Software, MITRE Corporation, WP-81W00412, August 1981.

which was developed in the early 1970s, was becoming obsolete and was not likely a suitable foundation for incorporating advanced automation. Mitre pointed out that the application code was written in a mixture of assembly code and a high-level, but obsolescent, language, which made the system difficult to maintain and modify.

According to Mitre, patches and modifications had caused the code to become very convoluted. Therefore, the Mitre study concluded, it would be extremely difficult to design software for advanced automation functions that would perform within the constraints of the current air traffic control software. Mitre also pointed out that these characteristics were not peculiar to just the air traffic control software but are believed to be a natural condition of any large software system that is used over a number of years without extensive restructuring.

There are some functional and operational similarities between the air traffic control operations software and the shuttle operations software. For example, similar to the STS operations software, air traffic control software performs real-time flight planning and flight control functions. STS operation software code, some of which dates back to the mid 1960s, is written in several unique and potentially obsolete languages. According to NASA officials, Johnson software has also been modified many times.

NASA's Current Modernization Plans

NASA has approved several projects for upgrading selected components of STS information systems and is examining the use of advanced automation to improve selected areas of mission operations. However, additional work is needed to determine if these projects fully address the growing obsolescence of the overall flight planning, flight readiness, and flight control operations and systems. For example, NASA does not yet have a single long-range architecture plan that integrates overall STS information systems used from the beginning of a mission to the end of a mission and that focuses on the obsolescence issue and how NASA is going to address it.

NASA has identified projects for upgrading various equipment components of the flight simulation, mission control, and on-board systems. These projects are divided into time phases. The initial phases focus on upgrades to alleviate short-term hardware obsolescence and capacity shortfalls. For example, NASA is currently upgrading the capacity of the mission simulation system. The agency has also replaced the central processors of the mission control system in order to improve reliability and reduce operation and maintenance costs. Later phases, if approved and funded, would replace the existing flight controller displays with higher-performance workstation technology that is intended to improve controller productivity and make controller training easier. At the time of our review, the later phases for the mission simulation system were not sufficiently advanced and were being studied further.

Some projects at Johnson are exploring the use of advanced automation software, such as expert systems to improve the efficiency and effectiveness of mission operations. According to a NASA handbook,[6] an expert system is a computer program that performs at the level of a human expert in solving specific, rather than general, problems in specific situations.

Given the design of existing mission control systems, it is unclear as to how much automation can be incorporated in these systems. NASA officials have expressed concern that the design of existing operational software does not allow easy incorporation of new advanced automation features. A Johnson official estimated that only 10 to 15 percent of mission control operations could be automated, because of the existing mission control system design. We found no detailed NASA analysis that addresses the potential obsolescence of operational software at Johnson and Kennedy, or its impact on the integration of advanced automation features into the current or a future systems architecture.

In an effort to incorporate advanced automation into operations, Johnson staff have developed a language or tool to embed expert systems, which are written in specialized software languages, into conventional software and computers. Johnson has used this tool to develop four STS software applications, but none of these applications have yet been used on an actual flight. This new tool may potentially ease the integration of expert system software into existing software for some STS functions.

In October 1985 Johnson prepared a Statement of Policy for Integrated Data Processing—a top-level data processing policy to guide the development of a long-term automated data processing plan. The document includes broad policy statements regarding integrated information system architectures, but does not include an implementation plan and has not been formally adopted by the center. Based on Johnson's

[6] Expert Systems Handbook, Mission Support Directorate, Mission Planning and Analysis Division, NASA, July 1986.

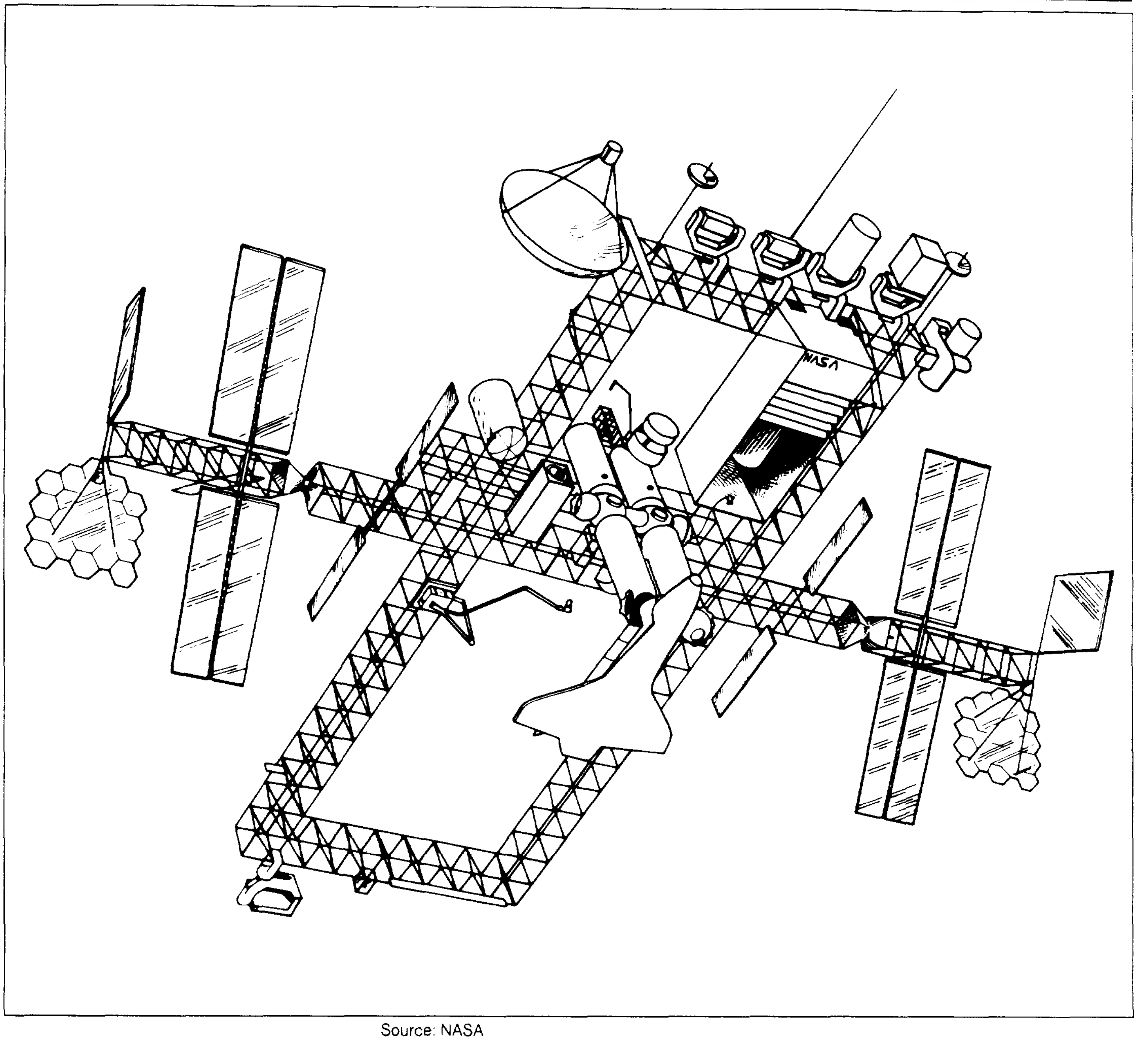
recently published information technology plan required by the Office of Management and Budget, it appears that Johnson has applied this policy primarily to financial and administrative systems and not to flight planning, flight readiness, and flight control operational systems.

Johnson's Inspector General recommended in a September 1986 audit report that the center director formally adopt the policy statement and formally recognize both a Planning Council and Steering Committee for Integrated Data Processing that had been proposed in the 1985 policy statement. An interim Integrated Data Processing Steering Committee is studying how to implement the Inspector General's recommendations.

In January 1987, NASA announced that it was taking steps to place greater emphasis on long-range operational planning and system design for STS operations overall. In view of these steps, NASA and the Committee may wish to address several key questions, including:

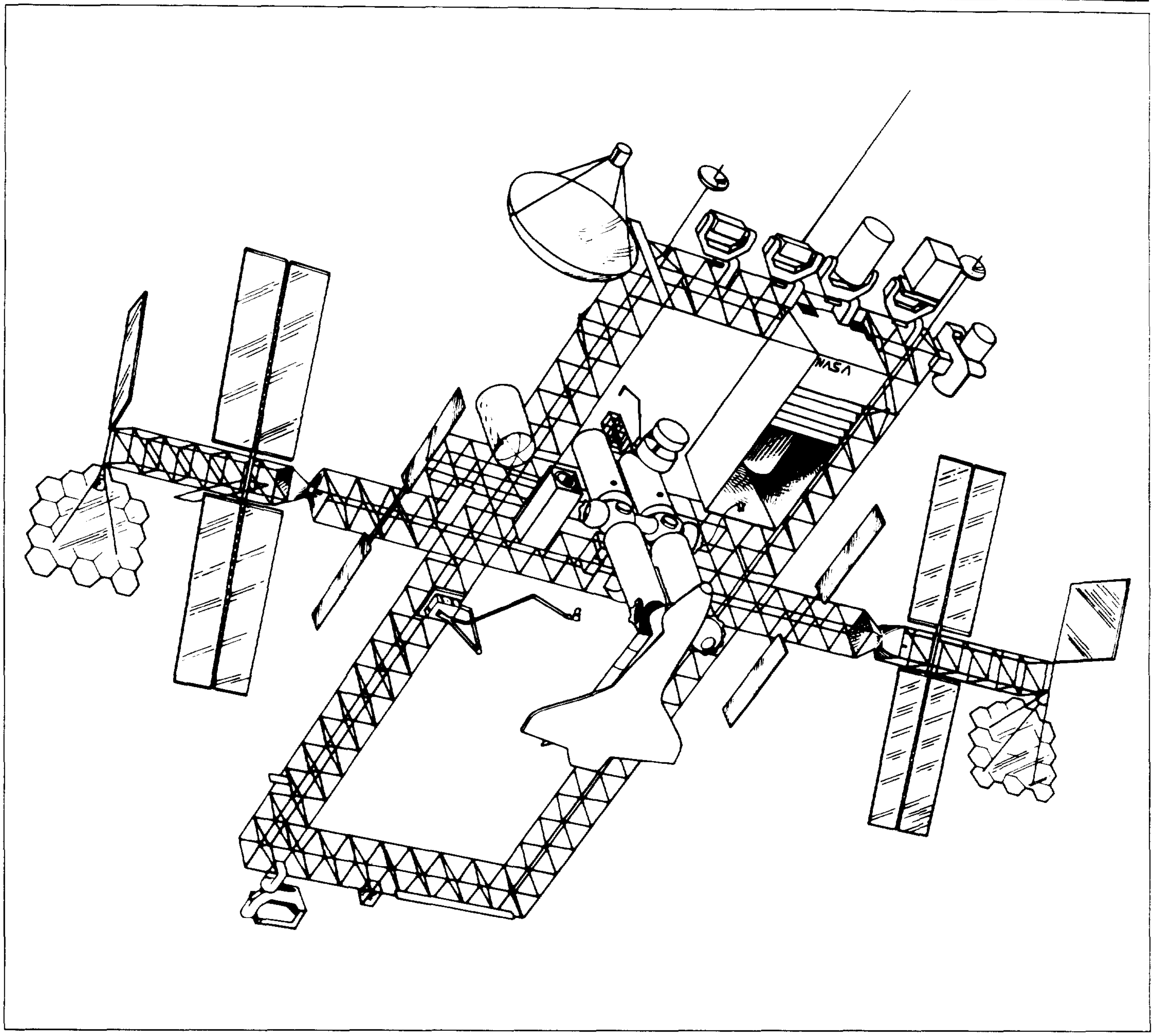
- To what extent, and at what cost, can the existing STS hardware and software support the number and complexity of missions currently planned?
- To what degree can existing hardware and software support an effective and efficient assembly and servicing of a space station? and
- What opportunities exist for using advanced automation and information technologies to improve STS' operations, and what is NASA's plan to incorporate these new technologies?

Space Station



Source: NASA

Space Station



Source: NASA