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Technology Needs for Air Force Autonomous Spacecraft

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16 March 1982

Interim Report

Prepared for

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Headquarters, Space Division
Los Angeles, California 90009

Through an agreement with

National Aeronautics and Space Administration

by

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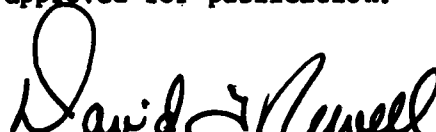
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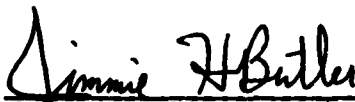
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TECHNOLOGY NEEDS FOR
AIR FORCE AUTONOMOUS SPACECRAFT

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SECTION 1

PURPOSE

The purpose of this document is to report on an assessment of the current state-of-the-art and ongoing technology programs to determine their applicability toward achieving spacecraft autonomous operation and to identify critical technologies needing development to enhance the cost effectiveness of achieving autonomous operation. The specific purposes of the technology needs assessment task were to:

- (1) Identify known mission requirements that might drive autonomy needs.
- (2) Review technology-trends forecasting to help identify future expectations.
- (3) Identify technology needs to meet autonomy requirements of the late 80's.
- (4) Prioritize these technologies relative to their criticality toward meeting the needs of autonomous spacecraft.

The basis for this assessment was various Air Force, NASA, and university technology forecasts and requirements studies (References 1 through 11), and the set of goals defined in "Goals for Air Force Autonomous Spacecraft" (Reference 8) as a part of Phase I of the Jet Propulsion Laboratory's (JPL) Autonomous Spacecraft Project (ASP).



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SECTION 2

BACKGROUND

The Air Force Office of Scientific Research commissioned JPL in March 1980 to coordinate a workshop on the feasibility of Autonomous Spacecraft Maintenance (ASM). The workshop study group, composed of experts from industry, academia, and NASA, identified critical issues related to ASM technology development. The group met in three workshops during 1980 and studied state-of-the-art spacecraft design, fault-tolerant computers, and ASM implications on the design. A final report was prepared covering these assessments, as was a research agenda and technology implementation plan (Reference 7).

Concurrently, during the Summer of 1980, the Space Division of the United States Air Force initiated planning for a spacecraft autonomy program intended to provide a sound technology base for significantly upgrading the autonomous capability of defense satellites by the end of the decade. The broad goal established for this program was to increase mission readiness by:

- (1) Enhancing spacecraft survivability against onboard failures.
- (2) Enhancing spacecraft survivability against hostile acts.
- (3) Reducing spacecraft dependence on ground stations, thereby enhancing the capability for system reconstitution if the ground stations were disabled.
- (4) Achieving an early satellite health- and ephemeris-maintenance capability by Fiscal Year 1987 (FY87), with spacecraft launched after this date capable of performing missions for unattended periods on the order of six months.

An additional goal for this program was to utilize the enhanced autonomy of spacecraft to increase the cost effectiveness of ground operations.

During the Fall of 1980, JPL initiated the first phase of a project for Space Division with the purpose of applying planetary spacecraft autonomy technologies and procedures for military satellite use.

The Jet Propulsion Laboratory's role as NASA's lead center for solar system exploration has produced an experience base in autonomous spacecraft designs. These designs are a consequence of the fact that flights to planets in the outer reaches of the solar system require very long flight times,

communication distances, and round-trip communication times. These characteristics require spacecraft designs that can take care of themselves when they are not in close touch with parent ground stations.

As a result of this experience, Space Division asked that JPL assess the technology base for autonomous spacecraft and provide recommendations on technology needs as a part of the Autonomous Spacecraft Project Phase I effort (Project Definition Phase). This report is one of the outputs of Phase I.

SECTION 3

SUMMARY

The technology needs were examined for Air Force Autonomous Spacecraft based on autonomy goals, mission drivers, and a technology forecast. The study concluded that spacecraft near-term autonomy goals could be accomplished using current technology supplemented by several key developments, none of which require a major technological breakthrough. The highest priority technology needs identified were in the areas of autonomous system methodology, high-speed and fault-tolerant computers, autonomous navigation sensors and algorithms, mass data storage, and autonomous function control.

The following observations are made relative to these five categories:

- (1) There is a need for developing a set of design rules and methodology for autonomous systems and redundancy management.
- (2) The main technology needs for high-speed fault-tolerant computers are the development of VLSI design methodology for custom chips and a series of building-block modules to use with existing microprocessors and memory devices.
- (3) Autonomous navigation systems need to be developed using more accurate and reliable sensors and new computing algorithms.
- (4) Mass data-storage systems require the development of rad-hard bubble-memory input/output components to provide nonvolatile storage of audit trace information and software data storage for fault recovery and diagnosis.
- (5) Autonomous function control needs to be developed in several subsystem areas to enable operation which is relatively autonomous under the supervision of a redundancy-management computer. Examples are:
 - (a) A more autonomous attitude control and stabilization system.
 - (b) A battery state-of-charge indicator to provide autonomous adjustment of charging rate and reconditioning.

In addition, reliability improvement programs are needed for traveling-wave tubes (TWT), optical sensors, and electromechanical subsystems such as gyros and tape recorders. Radiation hardening is of particular importance, and will be needed for VLSI and optical sensors.

SECTION 4

ASSUMPTIONS AND CONSTRAINTS

4.1 ASSUMPTIONS

In performing this assessment, it was assumed that the current state-of-the-art of technology had been applied in the design of existing spacecraft systems and that there was adequate subsystem and component reliability to meet the basic mission lifetime by appropriate use of redundancy. The approach taken was to define the technologies needed for autonomous operation and overlaying them upon existing sound spacecraft design.

Both the USAF and NASA have technology-improvement programs for basic spacecraft and payloads which are independent of autonomy needs. Mission-lifetime requirements may have been met by incorporating certain selected spare subsystems which could be switched by onboard logic or by ground command. Thus, the assessment assumed that high-quality electronic components had been selected, that appropriate screening, selection, and testing techniques had been used to construct subsystems, and that good worst-case circuit-design approaches and failure-mode effects analysis techniques were used. In the case of some subsystems, such as TWT's and electromechanical devices, these assumptions were believed to be optimistic. The required reliability improvement programs are identified in Subsection 9.6.

4.2 CONSTRAINTS

4.2.1 Payload Considerations

The assessment was restricted to nonpayload functions except where overlaps between payload and nonpayload functions occurred. Nonpayload functions are those provided by the spacecraft, and its ground support system, to the payload; i.e., a stable platform, power, thermal control, and an alternate communication channel. Requirements placed on the spacecraft by the payload were identified and considered in the assessment, and payload/spacecraft interfaces were defined; however, no consideration was given to automating payload functions.

4.2.2 External Threat Considerations

Space Division and JPL agreed that, for the time scale under consideration, it was not necessary to provide the capability for the spacecraft to autonomously avoid external threats. The assessment did, however, consider recovery from failure modes which could have been caused by several factors, including threat effects.

4.2.3 Consideration of Design Features not Related to Autonomy

The assessment did not consider performance improvement options such as reductions in mass, improvements in performance, improvements in pointing accuracy, or extensions of design lifetime; however, autonomy additions could be expected to improve reliability and extend lifetime.

SECTION 5

ASSESSMENT APPROACH

The overall approach to the technology needs assessment task was to:

- (1) Utilize the previously established set of goals for autonomous spacecraft operation.
- (2) Identify the mission drivers which placed specific demands on the spacecraft performance and lifetime.
- (3) Determine the current state-of-the-art of major subsystems and make a forecast of the technology trends over the next decade.
- (4) Survey the technical discipline support personnel and ASP Project personnel to identify the critical areas of technology needed to be developed in order to meet the mission drivers in Item (2) above.
- (5) Prioritize the technology needs according to established criteria.

5.1 ASP GOALS

One of the first tasks of the ASP Project was to establish a set of "working" goals in order to guide the design and development efforts of the project. These goals are intended to provide a common understanding of the engineering objectives of the Air Force's autonomous program effort and to provide a set of autonomy-related performance goals at the system and functional level. The results of this task were published in Reference 8. A summary of the Goals Document is included herein as part of Section 6.

5.2 MISSION DRIVERS

A preliminary list of known mission drivers was prepared to help identify requirements imposed on the spacecraft by the mission and payload. These mission requirements are shown herein as part of Section 7.

5.3 JPL SURVEY

After establishing the goals and mission drivers and after completing a preliminary assessment of the autonomy characteristics of the DSCS III spacecraft, a survey was taken of JPL technical discipline support personnel and the participants in the ASP Project to identify the critical technologies needed to provide autonomy. This material is presented in Appendix C of this report.

5.4 TECHNOLOGY FORECAST

A composite of several recent technology forecasts is summarized in Section 8. This forecast was based on a sample of a large number of unclassified Air Force and NASA-funded studies along with planning studies from Air Force contractors. This is not believed to have caused serious omissions since spacecraft-related technology work is typically unclassified.

5.5 TECHNOLOGY PRIORITIZATION

An examination of the technologies which are needed to support autonomy and the predicted changes in the state-of-the-art over the next five-to seven-year period were used to develop a prioritized list of technology programs which should be undertaken in the next few years. After a preliminary ranking by the ASP design team, the Project staff and the author did a final ranking and grouping of the material in Appendix C. A discussion of these technologies is included in Section 9 of this report.

SECTION 6

AUTONOMY GOALS AND REQUIREMENTS

The ASP design methodology task established a set of goals to reduce spacecraft dependence on ground stations and also to enhance survivability against onboard failures and hostile acts. Policy and implementation goals were provided to form a structured approach to quantifying broad autonomy requirements.

Policy goals cut across all classes of spacecraft and missions to achieve autonomy. The focus for policy goals is to:

- (1) Reduce ground interaction for periods of up to six months.
- (2) Maintain spacecraft integrity (autonomous features should not decrease performance or induce adverse effects).
- (3) Ensure transparency of the autonomous features as seen by the spacecraft data user (the spacecraft must always be capable of receiving ground commands and execution of autonomous functions should have little impact on the data stream).
- (4) Manage onboard resources (expendable resources should be optimally managed to maximize spacecraft life, but should not limit performance in a high-level-of-conflict situation).

Implementation goals, formulated in response to the policy goals, were constrained by technology and resources. Functional areas addressed were:

- (1) Systems (including thermal control and validation).
- (2) Electrical power and pyrotechnics.
- (3) Attitude, translation, and pointing controls.
- (4) Data processing.
- (5) Payload.
- (6) Telemetry and tracking.
- (7) Command.
- (8) Navigation.
- (9) Propulsion.

As part of this effort, various levels of autonomy were developed and described. These were represented on a scale of 0 (least capable of ground independence and containing no redundant elements) to 10 (most capable of ground independence in the presence of unanticipated changes in the operating environment). The policy and implementation goals presented were intended to correspond to an autonomy of about Level 5. This level would result in a fault-tolerant spacecraft capable of operating in the presence of failures specified a-priori by employing spare system resources. If spares were not available, the system would maximize mission performance, based upon remaining capability and expendables, without ground intervention.

SECTION 7

MISSION DRIVERS

7.1 AUTONOMY REQUIREMENTS

The primary mission drivers toward autonomy for Air Force satellites are:

- (1) The need to minimize ground control of and communications to the spacecraft.
- (2) The need to minimize ground operations cost and complexity.
- (3) The need for long life, reliability, and survivability of the spacecraft.

7.2 SPACECRAFT TECHNOLOGY ADVANCEMENTS NEEDED

The mission drivers for autonomy create a need for the following types of autonomous spacecraft technology:

- (1) Systems technologies for design, programming, and validation of inherently complex autonomous spacecraft.
- (2) High-Speed fault-tolerant computers.
- (3) Sensors and algorithms for autonomous navigation.
- (4) Mass data storage for autonomy programs, data, and audit trails.
- (5) Autonomous control technologies (power control, thermal control, attitude control, etc).
- (6) Long-life reliable components.
- (7) Radiation hardening or protection.
- (8) Autonomy-related technologies with low mass and power requirements because of launch vehicle limitations.

A description of the state-of-the-art and a forecast of technology trends over the next decade is presented in the following section.

SECTION 8

FORECAST OF TECHNOLOGY TRENDS

The following forecasts are a composite of several recent Air Force and NASA technology studies (References 1 through 11).

8.1 DATA PROCESSING

Emphasized in this subsection are forecasts of reliability, computer hardware, and computer software trends.

8.1.1 Reliability

Data processing reliability is expected to improve tenfold in the next decade, mostly due to changes in the use of LSI and VLSI instead of discrete components and small-scale integration. Reliability is also expected to improve because of the growing use of microprocessors which allows architectures, such as distributed computers, that are more suitable to efficient redundancy management. Spacecraft computers have not progressed quite as rapidly as ground-based systems because of conservatism in design and component selection due to higher reliability requirements and a more severe environment, such as radiation, electrostatic discharge (ESD), etc. Reliability and autonomy are related because autonomous techniques can be used to improve reliability and, conversely, more reliable computers will allow the inclusion of autonomous designs.

8.1.2 Computers

Computers in the next decade will be more autonomous and fault tolerant. Computer hardware is expected to increase performance (speed) by a factor of 10 to 50 during the next decade. Data rates from sensors and payloads are expected to go from 1 Mbps to 10 to 100 Mbps in the same period. The physical characteristics, overall size, weight, and power are not expected to change very much because most spacecraft system designers allocate a relatively fixed portion of the total resources to the onboard computer system. Memory capacity of computers is expected to grow by a factor of 16 during the same period. Thus, the overall capability and complexity of onboard computers are expected to grow by at least a factor of 50 to 100 during the next 10- to 15-year period, independent of autonomy drivers.

The main technology change during the next five to ten years will be the development of VLSI design tools, making it easier for the circuit design engineer to implement his circuits using custom VLSI in order to take advantage of the great improvements in gate density per chip. The increased use of LSI and VLSI also will change the technology of both component and subsystem testing since these functions are more difficult to perform when

internal test points are unavailable for direct access. Simple parameter drift screening tests will no longer be valid to assure that VLSI devices are fully tested.

8.1.3 Data Storage

Data storage has autonomy requirements for failure-recovery algorithms, fault traceability, and normal demands for payload data recording. Magnetic-tape recorders have historically had a history of reliability problems and, for storage of less than 10^8 bits, will probably be replaced with solid-state memories toward the latter part of the decade. It is forecast that the present radiation-sensitive MOS semiconductor memory chips of 10^3 to 10^4 bits per hi-rel chip will increase to 10^6 -bit, hi-rel, rad-hard chips using magnetic-bubble technology. There is a need for 10^7 RAM memories and up to 10^9 -bit buffer or experiment memories using these bubble chips.

Bubble memories have the advantages of being nonvolatile, having no moving parts, possessing high information density, and exhibiting reliability comparable to semiconductors. The one limitation is that they use power at a rate proportional to the speed of data transfer. Additional development is needed for input/output circuitry which, at the present time, is fabricated from nonradiation-hard NMOS integrated circuits.

Magnetic-tape recorders have been the standard method of providing large amounts of mass storage (greater than 10^8 bits) in spacecraft which are intended to remain in orbit for extended periods. Several studies have identified spacecraft tape recorders as having one of the highest failure rates of any subsystem. The main problem areas have been bearing lubrication at low speed, tape-head friction and stiction, and mechanical and chemical instability of the magnetic-tape coatings and polymers. There has been little sponsored research and development work in this area in the last decade.

8.1.4 Software

Software is expected to improve more slowly than hardware. Programmer productivity is increasing at a rate of only about 3% per year while hardware is increasing in gate density at a rate of almost 100% per year. In addition to the obvious need to improve software design and management tools, there is a need to develop software operating systems including algorithms for spacecraft autonomous maintenance and for fault detection and correction. Work over the next decade should improve the techniques of automatic program recovery and data protection in case of transient faults, including external interference; self-repair by self-diagnosis and replacement of permanently failed modules; and fail-soft operations (graceful degradation) after all spares are exhausted, gradually extending life but with slightly degraded operation.

Other software mission requirements are also expected to grow as the demand for more autonomy and onboard intelligence increases. There will be a need for algorithms for data compression, feature extraction, and improved coding for autonomous functions, such as redundancy management and onboard navigation. Data compression should improve from the range of 2:1 to 16:1 for image-preserving compression and up to 50:1 to 10^4 :1 for feature extraction for such purposes as navigation.

8.2 NAVIGATION

Onboard navigation accuracy is expected to improve from tens of kilometers to a fraction of a kilometer during the coming decade. Improvement must be made in optical sensors, from 1 arc second accuracy to 0.01 arc second, and in inertial sensors (gyros), from 0.005 degree per hour with 10,000-hour life to 0.001 degree per hour with 100,000-hour life. Another component development needed to permit the improved navigation accuracy is that of increasing the stability of onboard clocks from one part in 10^{13} over 1000 seconds to one part in 10^{16} in 1000 seconds. There is a need to improve the accuracy of horizon sensors which are currently limited to about $\pm 0.015^\circ$.

8.3 ARTIFICIAL INTELLIGENCE

Artificial Intelligence (AI) is not expected to have a significant effect on spacecraft autonomy until the early 1990's. The main areas where AI is expected to play a role are in automated decision-making and planning, activities which a human does well, but AI and machines do relatively poorly. Level 5 autonomy (Reference 8) can be accomplished using standard techniques, but some form of AI will be needed to reach levels at the upper end of the scale. When AI techniques are applied to the management of spacecraft reliability, configuration, and mission direction, they are expected to ease the normal job of the ground controllers and to allow continuation of the normal mission when ground communications are interrupted, even in the presence of unanticipated conditions (Level 6 and above). Artificial intelligence techniques will permit the use of "smart sensors" (the use of microprocessors as a part of instruments and payloads for local distributed processing and decision-making). Some techniques developed for AI, such as video feature extraction and image processing, would permit instrument and payload pointing without ground controller intervention.

8.4 PROPULSION

Long lifetime missions having many orbit trim maneuvers dictate the need for development of autonomous propellant management systems and propulsion systems with higher reliability, long storage times (high-stability materials), and less weight of consumables. For autonomy, sensors are needed to determine propellant center of mass and thruster performance. A 50% to 100% improvement in thruster ISP should become possible during the next decade by changing from pressure-fed monopropellant to pump-fed bipropellant Earth- or space-storables. Further improvement may be possible by using some form of electric or ion propulsion, such as magnetoplasmadynamic (MPD) thrusters.

8.5 POWER SYSTEMS

Power systems will have greater demands made on them by autonomy and long mission lifetimes. One of the main needs is for the development of longer-life secondary (storage) batteries. Launch-vehicle limitations combined with more onboard computing for both autonomy and payload support will probably require the onboard power system to provide greater amounts of power for the same proportion of spacecraft weight and volume, thus demanding an improvement in efficiency or specific mass. The efficiency of solar cells is expected to grow from 14% to 18% in the next seven to ten years, while the specific mass should improve from 9 kg/kW to 2 kg/kW by changing cell material from silicon to gallium arsenide and using lightweight structural supports. Batteries are expected to have higher energy densities and longer life. Secondary batteries should improve by changes to exotic electrochemical systems such as those of the nickel-hydrogen or metal-sulfur battery; but, particular attention must be paid to maintaining long life and high reliability as performance is increased.

8.6 COMMUNICATIONS

There are several areas in communication technology that are expected to change in the next decade. Design of phased array antennas and feeds will improve, permitting more use of electronic antenna beam steering for adaptive nulling and tracking multiple targets. Autonomous operation will require onboard nulling of interfering signals and automatic antenna pointing to desired ground locations. Improvements in "track-while-scan" techniques and generating multiple narrow beams in a wide field of view are also expected. The technology should grow from the present capability of a few narrow beams to a hundred beams by the end of the decade. Also expected is the development of multiple power amplifiers, each having variable phase and amplification under the control of an individual microprocessor. Operating frequencies are expected to increase from super-high-frequency (SHF) to extremely-high-frequency (EHF) bands to provide higher antenna gains, greater bandwidth, and narrower beam width. Technology improvements are expected in the reliability of TWT's, which may be replaced by solid-state amplifiers in the latter part of the decade.

In the field of laser communication, the technology for autonomous control of mirror surfaces is expected to improve in order to compensate for phase distortions in the wave front caused by atmospheric distortion and the bending of lightweight structures.

8.7 STRUCTURES AND CONTROL

The press for greater onboard power and communication gain will place higher demands on the design of large, deployable, lightweight structures. The flexibility of these structures will also necessitate the development of new adaptive control system techniques to provide attitude control and instrument pointing in the presence of a wide range of bending and torsion frequencies. The present state-of-the-art of controlling to a bandwidth of a fraction of the first bending mode will be extended to control as many as 30

bending modes with end-point angular control of the flexible member. In addition, autonomous payload instrument pointing requires development of image motion compensation having the capability of less than 1 arc second stability during slews of up to 10 degrees per second. These improvements in structural control will require increases in the autonomous capability of spacecraft attitude-control systems.

8.8 IMAGING SENSORS FOR NAVIGATION AND ATTITUDE CONTROL

Greater autonomy in these subsystems will call for more reliable, higher performance optical sensors. Major improvements are expected in the development of optical array sensors in most of the wavelength bands, from far UV through the visible range and on to long wavelength IR. The present limit of 800-pixel square arrays in the visible range should improve, although this is still better than can be obtained in the IR bands where more exotic hybrid fabrication techniques and cryogenic cooling are required.

Payload-pointing and stability requirements and autonomous attitude-control and navigation-system requirements are placing new demands on star trackers and horizon sensors. The current designs of many horizon sensors use mechanical scanning, thus limiting their operational lifetime. The next decade should see the replacement of these mechanical scanners with "staring" IR mosaic sensors. Sensor accuracy trends are covered in the navigation subsection of this section.

Another technology change forecast is in improving the stability of IR sensors having a wide variety of spectral sensitivities (perhaps even tunable) and in passive and active microwave sensors for imaging. Many of the semiconductor materials having good IR characteristics have also had technological problems such as poor stability, poor mechanical properties, difficult fabrication processes, etc. Another related IR-sensor improvement will be the development of a low-temperature cryogenic refrigerator for focal-plane cooling which has a reasonable mechanical and electrical efficiency. In the area of microwave sensors, there will be improvements in large-area antenna arrays and onboard synthetic-aperture radar correlators to reduce the bandwidth of the signals sent to the ground stations.

8.9 GROUND STATIONS

Another technology expected to improve in the next decade to permit spacecraft autonomy and uplink independence from fixed ground stations is the development of mobile ground/airborne control stations which can command the spacecraft in the event of loss of fixed installations. Although not strictly autonomous in themselves, these mobile stations will provide an alternate method of backup commands for both maintenance and mission control. The spacecraft autonomy must be compatible with the normal command modes, as well as those from a station having much more restricted capability.

SECTION 9

CRITICAL TECHNOLOGY PRIORITIZATION

The technologies discussed in this section were ranked in a two-stage prioritizing process. First, a set of technologies was proposed and ranked by the participants in the ASP Project. Second, the technologies were grouped together into the categories listed in Section 7 of this report and then given a final ranking by the ASP Project staff and the author (Appendix C). The listing in this present section is the final priority order.

9.1 SYSTEM DESIGN, PROGRAMMING, AND VALIDATION TECHNOLOGY

The highest priority is for a system-design methodology for the architecture of autonomous systems. There are no generally recognized and tested physical laws pertaining to autonomous systems such as those for mechanics, thermodynamics, etc. Most of the time, the designer of an autonomous system has not even readily applicable design rules at hand. The design is carried out by using intuitive, unreliable approaches. Thus, there is a great need for the development of a design methodology which establishes the architecture, the interaction between subsystems (including partitioning and isolation), the degree of on-chip versus block versus functional redundancy, and the architecture used in the operating system of the redundancy-management computer.

Development is needed in programming and software for autonomous systems. New operating systems or executives are required to detect faults, store critical data for recovery, switch in redundant spares, and roll back the operational software to a breakpoint where the last correct data existed.

There is a need for the development of validation techniques for autonomous systems since, by their very nature, they tend to mask faults and continue operation even if some of the redundant units have failed. There is a need to develop a method of periodic and autonomous test and evaluation of redundant functional elements to establish the status of nonoperational spares as well as units which are degraded or assumed failed.

9.2 HIGH-SPEED FAULT-TOLERANT COMPUTERS

Future Air Force autonomous spacecraft require a network of self-checking fault-tolerant computers to provide necessary processing, control, and redundancy management. There is also a need for developing a testing methodology for VLSI to ensure integrity of the autonomous functions. Practical computer building-block modules that may be used with commercially available microprocessor and memory chips to form a high-speed fault-tolerant computer need to be developed. Although small-scale or medium-scale integrated circuits could be used in the implementation, the size, weight, and power increases to existing spacecraft designs would be excessive. Thus,

there is a need for developing the building-block modules in LSI or VLSI. However, several recent development programs have had major schedule and cost overruns because of the difficulty in implementing LSI or VLSI components even after the circuits have been breadboarded and tested in SSI or MSI. One of the key technology developments needed before circuit designers can implement new subsystems in VLSI is improved high-level VLSI chip-layout software. Although there is approximately \$100 million being spent in the DOD VHSIC program, it is not expected to simplify the development of custom VLSI for a new component design. It may also be necessary to develop new special microprocessor chips to permit the use of the new standard DOD software language, Ada, although it may be possible that microprocessors which implement the Ada language will soon be available on the market in hi-rel rad-hard form. One possible implementation of a fault-tolerant redundancy-management computer is described in Reference 4.

9.3 AUTONOMOUS NAVIGATION SENSORS AND ALGORITHMS

No flight-proven capability currently exists for autonomous navigation and stationkeeping. Addition of this function will require both new sensors (optical and possibly inertial), as well as a sizeable onboard computer (described in Subsection 9.2 above).

Optical sensors for star trackers are typically implemented with image dissectors or photomultiplier tubes and have had a history of high failure rates because they require the use of high voltages (typically 1200 volts). In addition, to obtain the required accuracy and sensitivity for navigation, the star trackers need large optical elements. Star trackers should be developed using solid-state charge-coupled devices (CCD's) which are superior in terms of stability and damage resistance and have no known wearout mechanisms. Sun sensors having the requisite accuracy and wide field of view for navigation purposes also need to be developed. High-accuracy horizon sensors using IR mosaic arrays need to be developed to replace their mechanical scanning counterparts.

If this autonomous navigation capability is on the spacecraft, it will automatically provide most of the capability for propulsion resource management and some of the elements of autonomous attitude control. In addition to the hardware elements of the autonomous navigation system, there is a need for the development of new computing algorithms capable of reliable operation without human intervention. This implies development of autonomous data-editing algorithms, techniques for positive convergence, and algorithms for detecting and correcting abnormal conditions.

9.4 MASS DATA STORAGE

Autonomous maintenance of spacecraft redundancy places additional requirements on the data-storage subsystem. Large amounts of mass storage are needed to retain program memory for fault recovery after power transients as well as to preserve a record of the fault-corrective actions taken, perhaps

while out of contact with the ground stations. An audit trail of the events occurring just prior to the fault and the ensuing redundancy management steps taken must be preserved for ground analysis. This places a requirement on the telemetry or redundancy-management system to record the detection of the fault, the reconfiguration process itself, and the identities of the units switched in and out. This audit trail must be kept until the ground controllers can take whatever additional action is required. Retention must occur, even during power interruptions or the occurrence of additional faults. This means that the audit-trail memory must be especially fault-tolerant and nonvolatile.

One of the best devices to satisfy this requirement is the bubble memory. Devices and systems are currently available from several manufacturers, but the related input/output circuits are nonrad-hard NMOS integrated circuits packaged in plastic dual-inline form. Bubble devices and their electronic circuits must be hardened, packaged, and hermetically sealed in order to meet military space environmental requirements.

If the amount of mass storage exceeds 10^8 bits (as example, for payload data recording during long periods of blackout), there is a need to improve the reliability of magnetic-tape recorders. This will be covered in Subsection 9.6.

9.5 AUTONOMOUS FUNCTION CONTROL

Each of the subsystems must be capable of accomplishing many of its own functions autonomously. The following sub-subsections describe the needed technology improvements in two high-priority areas.

9.5.1 Attitude Control and Stabilization

The spacecraft must be able to activate sophisticated control strategies, manage its onboard resources using self-maintenance of its functions, and make appropriate decisions about the best way to carry out its assigned tasks. Adaptive control strategies employing optimal filtering techniques will be needed to stabilize spacecraft with large flexible antennas and solar panels. Improved basic reliability and lifetime of attitude-control electromechanical sensors and actuators (such as gyros and star trackers) will be required (see Subsection 9.6). Development of autonomous momentum- and propellant-management systems and methods to autonomously calibrate and verify the capability of spare subsystems without disturbing the function of the active elements will also be necessary.

9.5.2 Battery Charge State

A substantial portion of the ground maintenance effort is spent in tracking the state-of-charge and reconditioning of spacecraft secondary (storage) batteries. Development of either an adaptive model of a battery

(using voltage, current, temperature, pressure, and charge history) or an ampere-hour integration system to provide the same information is needed to determine the current state of battery charge and the optimal autonomous recharge strategy.

9.6 RELIABILITY, PERFORMANCE, COST, AND ENVIRONMENT

In addition to the specific system and subsystem technologies mentioned above, there is a need to improve the intrinsic reliability and resistance to environmental effects (including radiation, ESD, temperature, etc.), to reduce mass, power, and cost, and to improve performance. Most of these developments fall outside the scope of this assessment, but one item bears emphasis. The intrinsic reliability of most spacecraft, even with redundant spares, is less than the desired lifetime of many Air Force missions. There is a need for research and development on reliability enhancement at the component and subsystem level, particularly for electromechanical devices (such as tape recorders), optical sensors, and traveling-wave tubes. Some of these components may be replaced by solid-state devices having no moving parts. This should improve reliability.

There is a need for the development of radiation-hard LSI and VLSI components and optical sensors. As the density of semiconductor logic and memory devices increases, there is a greater sensitivity to damage from ionizing radiation and electrostatic discharge. There is a need for the development of a series of rad-hard components which can become building blocks of future autonomous spacecraft designs. Some of these needs will be satisfied by the DOD VHSIC program but, as mentioned in Subsection 9.2 on high-speed fault-tolerant computers, it will be necessary to develop the capability to rapidly design and fabricate custom rad-hard VLSI.

APPENDIX A

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APPENDIX B

GLOSSARY

Ada	New Department of Defense standard software language
AI	artificial intelligence
APC	attitude and pointing control
ASKS	autonomous stationkeeping system
ASM	autonomous spacecraft maintenance
ASP	autonomous spacecraft project
CCD	charge-coupled devices
DOD	Department of Defense
DSCS	Defense Satellite Communications System
EHF	extremely high frequency
ESD	electrostatic discharge
FORS	fiber-optics rotation sensor
hi-rel	high reliability
IC	integrated circuit
IR	infrared
ISP	specific impulse
IUS	Inertial Upper Stage
kW	kilowatts
LSI	large-scale integrated (circuits)
MOS	metal oxide semiconductor
MPD	magnetoplasmadynamic (thruster)
MSI	medium-scale integrated (circuits)
NMOS	N (type) metal oxide semiconductor
Pixel	picture element
rad-hard	radiation hardened
RAM	random-access memory
ROM	read-only memory
S/C	spacecraft
SD	Space Division (U. S. Air Force)
SHF	super high frequency
SSI	small scale integrated (circuits)
S/W	software
TBD	to be determined
TT&C	Telemetry, Tracking and Command
TWT	traveling-wave tube
VHSIC	very-high-speed integrated circuits
VLSI	very-large-scale integrated (circuits)
WH	watt hours

APPENDIX C

SUMMARY OF CRITICAL TECHNOLOGY INPUTS

This appendix contains an index and a compilation of the technology needs input sheets for the Air Force Autonomous Spacecraft Project. Each input sheet describes the mission requirement, the technology need, and a schedule estimate for the technology. No attempt has been made to edit this material for consistency of style, format, and degree of detail. The major headings are in the same priority order as in Section 9 and, within each major heading, the technologies are in priority order; however, relative comparison between technologies in different major headings cannot be made.

INDEX

- C.1 System Design, Programming, and Validation Technology
 - C.1.1 Autonomy Methodology
 - C.1.2 Autonomous Verification of Redundancy
 - C.1.3 Autonomous System Testing Methodology
 - C.1.4 VLSI Partitioning
 - C.1.5 Interaction Methodology
 - C.1.6 S/W Failure Detection & Correction
 - C.1.7 Resource Management
- C.2 High-Speed Fault-Tolerant Computers
 - C.2.1 VLSI Fault-Tolerant Computers
 - C.2.2 Optimal Computing Configuration
 - C.2.3 Microcomputer Redundancy Management
 - C.2.4 Spacecraft Operating System
- C.3 Autonomous Navigation Sensors and Algorithms
 - C.3.1 Navigation Onboard Algorithms
 - C.3.2 Orbit Control Onboard Algorithms
 - C.3.3 Solid-State Precision Star Tracker
 - C.3.4 Wide-Angle High-Accuracy Sun Sensor
 - C.3.5 Navigation System Level Simulation
- C.4. Mass Data Storage
 - C.4.1 Rad-Hard Bubble Memory - LSI
 - C.4.2 Transient Signature Storage
- C.5. Autonomous Function Control
 - C.5.1 Battery Monitor Model
 - C.5.2 Autonomous Attitude Determination
 - C.5.3 Intelligent Attitude Control
 - C.5.4 Autonomous Propulsion Mass Sensing
- C.6. Reliability, Performance, Cost, Environment
 - C.6.1 Precision Payload Pointing System
 - C.6.2 Fiber Optics Rotation Sensor
 - C.6.3 Active Spacecraft Charge Control
 - C.6.4 Rad-Hard VLSI

C.1. SYSTEM DESIGN, PROGRAMMING, AND VALIDATION TECHNOLOGY

C.1.1. AUTONOMY METHODOLOGY

C.1.2. AUTONOMOUS VERIFICATION OF REDUNDANCY

C.1.3. AUTONOMOUS SYSTEM TESTING METHODOLOGY

C.1.4. VLSI PARTITIONING

C.1.5. INTERACTION METHODOLOGY

C.1.6. S/W FAILURE DETECTION & CORRECTION

C.1.7. RESOURCE MANAGEMENT

ASP TECHNOLOGY REQUIREMENTS
C.1.1. AUTONOMY METHODOLOGY

REQUIREMENT:

Future spacecraft that are capable of autonomous internal reorganization and dynamic task deduction based on unspecified and/or unanticipated changes in the external environment need to be developed.

DESCRIPTION OF NEW TECHNOLOGY:

The use of on-board decision making to localize and correct anomalies can be accomplished by first determining a set of measurable parameters that can indicate the occurrence of expected failures. A decision tree analysis algorithm can be determined such that a path through the tree will either lead to the cause of the problem or to indecision. Should the algorithm fail to determine the cause of failure, if necessary it can communicate with the ground such that human intervention can occur. The time for determination of corrective action on the ground will be reduced by first pass on-board analysis.

ESTIMATE OF DEVELOPMENT SCHEDULE:

Assuming developments of 1) general purpose autonomous system design methodologies, 2) VLSI fault-tolerant computers, and 3) VLSI software processing algorithms have been completed, a study to define and preliminary needs and methodology for using on-board decision making to achieve very high levels of autonomy is estimated to require two years.

ASP TECHNOLOGY REQUIREMENTS

C.1.2. AUTONOMOUS VERIFICATION OF REDUNDANCY

REQUIREMENT:

To develop a method of periodic and autonomous test and evaluation of redundant functional elements to establish the status of non-operational spares as well as degraded/assumed failed operational units.

DESCRIPTION OF NEW TECHNOLOGY: A way of periodically and autonomously testing and evaluating redundant elements while they are not operational is needed. The information obtained by such testing eliminates the risk of accidentally replacing a degraded primary unit with a failed redundant unit. A method of off line autonomous verification and evaluation of units within a subsystem that have been automatically replaced is required. The resulting information verifies the autonomous decision and the status of the failed unit. The result of an Advanced Development effort will provide a working model and methodology that would aid the designers of many subsystems.

ESTIMATE OF DEVELOPMENT SCHEDULE:

1. The development of a general working model/methodology is estimated to require 12 to 18 months.
2. The application to specific power related units is estimated at 4 manyears.

ASP TECHNOLOGY REQUIREMENTS
C.1.3. AUTONOMOUS SYSTEM TESTING METHODOLOGY

REQUIREMENT:

Analysis capability to assess reliability of a given autonomous design - accounts for reconfigurability of the system - points out "tallpole" elements of sensitivity to projected failures.

DESCRIPTION OF NEW TECHNOLOGY:

Software tool augmented by engineering methodology plus criteria for testing autonomous systems. Incorporates conventional fault trace analysis with dynamic reconfiguration, accounts for intermittent faults - models system logic and performance degradation. Both system hardware and software features.

ESTIMATE OF DEVELOPMENT SCHEDULE:

Model Scope - 2 Years

Model Development - 3 Years

Model Validation - 2-5 years

ASP TECHNOLOGY REQUIREMENTS

C.1.4. VLSI PARTITIONING

REQUIREMENT:

It is expected that future autonomous spacecraft will require the use of fault-tolerant VLSI components. It is not yet known what the best strategy might be in terms of partitioning system function into chips such that the system as a whole is more reliable.

DESCRIPTION OF NEW TECHNOLOGY:

By adding more on-chip redundancy to improve chip reliability, more area is added to the chip. This added area first of all reduces the chip yield and if not managed properly might also reduce overall chip reliability. It is necessary to determine a cost/performance measure such that it is possible to evaluate system behavior for various partitions of the overall function into chips and for various approaches to fault tolerance.

ESTIMATE OF DEVELOPMENT SCHEDULE:

This is a fairly long term project of about 4 years and will probably require the use of fairly sophisticated simulation tools which do not exist. The development of these tools will require on the order of 20 manyears with system analysis taking another 10 manyears.

A S P T E C H N O L O G Y R E Q U I R E M E N T S
C.1.5 I N T E R A C T I O N M E T H O D O L O G Y

REQUIREMENT: Future military spacecraft will, in order to gain increased autonomy, contain larger software components. In order for software to be reliable and fault tolerant it must be modular in nature with low connectivity between modules.

DESCRIPTION OF NEW TECHNOLOGY: Design techniques need to be developed that can best ensure that a modification of an element of one module will not affect any other module. There are already techniques for developing probabilities after the fact, but no methodology yet exists for predicting connectivity based on design or implementation language.

ESTIMATE OF DEVELOPMENT SCHEDULE: The estimated time to develop the methodology is approximately two (2) calendar years.

A S P T E C H N O L O G Y R E Q U I R E M E N T S
C.1.6. S/W FAILURE DETECTION & CORRECTION

REQUIREMENT: Future military satellites have been mandated to include autonomous features beginning in 1986. It is clear that the inclusion of these features will require the addition of large amounts of onboard software which, in turn, can introduce a new class of failure modes. Surveys of existing failure detection and correction techniques indicates that the vast majority of the work has been directed toward hardware failures with relatively little attention given to software failures. Since a software failure can have the same impact on a mission as a hardware failure, an upgrade of the software failure detection and correction technology is required.

DESCRIPTION OF NEW TECHNOLOGY: The development of S/W failure detection and correction techniques requires both the identification of the various failure modes and the development of generalized techniques for detection and correction. Currently, techniques are available for detecting hardware induced errors (bit errors, etc.), however, relatively little technology appears to be available for the detection of errors within the S/W itself.

The technology for the development and testing of S/W which is capable of monitoring and correcting for interval S/W errors is required. The technology should be general, in order to allow for application to a wide range of S/W developments.

ESTIMATE OF DEVELOPMENT SCHEDULE:

TBD

ASP TECHNOLOGY REQUIREMENTS

C.1.7. RESOURCE MANAGEMENT

REQUIREMENT:

Develop a rationale, techniques, and supporting guidelines for the on-board management of resources on an autonomous spacecraft.

DESCRIPTION OF NEW TECHNOLOGY:

Many of the large scale ground computing systems utilize rules to autonomously allocate scarce system resources. This technology should be expanded, particularized, and applied for autonomous spacecraft.

ESTIMATE OF DEVELOPMENT SCHEDULE:

TBD

C.2. HIGH SPEED FAULT-TOLERANT COMPUTERS

C.2.1. VLSI FAULT-TOLERANT COMPUTERS

C.2.2. OPTIMAL COMPUTING CONFIGURATION

C.2.3. MICROCOMPUTER REDUNDANCY MANAGEMENT

C.2.4. SPACECRAFT OPERATING SYSTEM

ASP TECHNOLOGY REQUIREMENTS

C.2.1. VLSI FAULT-TOLERANT COMPUTERS

REQUIREMENT:

Future spacecraft design architectures for achieving very high levels of autonomy will require a network of distributed self-checking fault-tolerant computers to provide the necessary processing, control, and reliability. Computers with long life coupled with low cost, weight, and power must be developed if a practical implementation of these architectures is to be realized.

DESCRIPTION OF NEW TECHNOLOGY:

Practical computer building-block modules that may be used with commercially available microprocessor and memory chips to form a self-checking, fault-tolerant computer need to be developed. The need for low weight and power characteristics dictates the use of VLSI technology.

ESTIMATE OF DEVELOPMENT SCHEDULE: The development of self-checking, fault-tolerant computer building-block module designs that are VLSI implementation compatible is currently being pursued at JPL using conventional IC technology. A follow-on development would incorporate radiation-hardened custom VLSI technology and be carried through flight qualification. As part of this effort, the development of a methodology for testing VLSI circuitry to insure integrity for autonomous functions poses significant problems. Assuming availability of custom radiation-hardened VLSI components, this follow-on development is estimated to require five years.

ASP TECHNOLOGY REQUIREMENTS
C.2.2. OPTIMAL COMPUTING CONFIGURATION

REQUIREMENT:

Determine the optimal subsystem and subsystem/system configuration of computing capability for an autonomous computing subsystem.

DESCRIPTION OF NEW TECHNOLOGY:

A study is needed to provide the methodology to designers that will enable them to determine the degree of distribution or centralization of the microprocessors and their tasks. For example, centralized systems may be inadequate for large amounts of data gathering and processing. Distributed systems may require a higher level of complexity in interfaces, redundancy and programming. There are some configurations which are both centralized and distributed and therefore have different characteristics.

ESTIMATE OF DEVELOPMENT SCHEDULE:

The estimated development time for this task is 20 to 30 months.

ASP TECHNOLOGY REQUIREMENTS

C.2.3. MICROCOMPUTER REDUNDANCY MANAGEMENT

REQUIREMENT:

Systems require redundancy techniques and fault tolerant capabilities for the subsystem level computing functions in autonomous satellite applications.

DESCRIPTION OF NEW TECHNOLOGY:

A study is needed to determine when, where, and how redundancy and fault tolerance should be implemented in spacecraft microcomputers. The study will also include identification of the many advantages, disadvantages, and engineering tradeoffs associated with the various levels of fault tolerance in the autonomous portion of the system. A development program to test and demonstrate the implementation of a redundant autonomous microcomputer system is also needed.

ESTIMATE OF DEVELOPMENT SCHEDULE:

1. It is estimated that the study program would require from 24 to 36 months.
2. It is estimated that a demonstration program would require from 15 to 30 months.

ASP TECHNOLOGY REQUIREMENTS

C.2.4. SPACECRAFT OPERATING SYSTEM

REQUIREMENT:

With the application of on board computer capabilities to autonomous system control at the spacecraft system level, the need for a well-designed operating system, tailored to autonomous system tasks, has substantially increased.

DESCRIPTION OF NEW TECHNOLOGY:

A logical design for such a system should be developed that incorporates recent advances in operating-system technology. This design should enable changes to be made to the spacecraft software in a controlled way after the spacecraft has been launched.

ESTIMATE OF DEVELOPMENT SCHEDULE:

TBD

C.3. AUTONOMOUS NAVIGATION SENSORS AND ALGORITHMS

C.3.1. NAVIGATION ON-BOARD ALGORITHMS

C.3.2. ORBIT CONTROL ON-BOARD ALGORITHMS

C.3.3. SOLID STATE PRECISION STAR TRACKER

C.3.4. WIDE ANGLE, HIGH ACCURACY SUN SENSOR

C.3.5. NAVIGATION SYSTEM LEVEL SIMULATION

ASP TECHNOLOGY REQUIREMENTS

C.3.1. NAVIGATION ON-BOARD ALGORITHMS

REQUIREMENT:

As a part of project overall onboard navigation system requirements, military spacecraft will be required to accurately determine their orbital locations. Current orbit determination systems are implemented in large mainframe computers and require a team of experienced operations and analysts for their execution. These characteristics are not compatible with the characteristics of an onboard orbit determination technique. In addition, onboard orbit determination systems are expected to utilize measurement data types not currently used by existing ground based systems.

DESCRIPTION OF NEW TECHNOLOGY:

The existing orbit determination technology needs to be upgraded to allow its application in an onboard computer environment. This requires the development and testing of algorithms which are compatible with both the new measurement data types and the characteristics of flight computers. In addition, the algorithms must be capable of reliable operation without human intervention for extended periods of time. The latter requirement implies development of both reliable data editing techniques and techniques for positive convergence.

ESTIMATE OF DEVELOPMENT SCHEDULE:

In support of the overall navigation need date of 1986, the detailed orbit determination technology is required by 1984. A minimum of 24 months of concentrated effort is required to develop the required level of technology.

ASP TECHNOLOGY REQUIREMENTS

C.3.2. ORBIT CONTROL ON-BOARD ALGORITHMS

REQUIREMENT:

The overall development of an onboard navigation capability requires the development of onboard orbit control techniques, in order to meet projected mission requirements. Currently, identified needs vary from holding a specified station in geosync. orbit to performing evasive maneuvers.

The existing system relies on a team of analysts using large mainframe ground computers to perform this function.

DESCRIPTION OF NEW TECHNOLOGY:

The existing orbit control technology must be upgraded to allow its application in an onboard computer environment. This will require both the modification of existing techniques and the development of new algorithms, in order to provide for fully automated operations. In addition to the development of techniques for automatically computing nominal in-orbit maneuver commands, the technology for automatically detecting and correcting for abnormal conditions must be developed.

ESTIMATE OF DEVELOPMENT SCHEDULE:

In support of the overall navigation need date of 1986, the detailed orbit control technology is required by 1984. A minimum of 24 months of concentrated effort is required to develop the required level of technology.

ASP TECHNOLOGY REQUIREMENTS

C.3.3. Solid-State Precision Star Tracker

REQUIREMENT: Autonomous spacecraft will place new demands on the star trackers used for attitude reference in terms of long operating lifetime, stability and the ability to reliably perform guide star discrimination. Available star trackers, such as the NASA standard tracker, are image-dissector instruments which are susceptible to damage from illumination overloads, are unsuitable for long term usage because of failure-prone high voltage circuits (typically 1200 volts), and are intrinsically not suited to star field tracking for pattern recognition purposes. Operator-aided reference star acquisition is currently required for all but the brightest guide stars.

DESCRIPTION OF NEW TECHNOLOGY:

A star tracker based on the silicon charge coupled device (CCD) technology could meet all of the requirements of autonomous spacecraft. These devices are greatly superior to image dissectors in terms of damage resistance, long term stability and angular measurement precision and accuracy. CCDs have no known wear-out mechanism, operate at low voltage (typically 15 volts) and can track a number of stars simultaneously, facilitating pattern recognition.

ESTIMATE OF DEVELOPMENT SCHEDULE:

	<u>FY</u>
Prototype Design	83
Fabrication	84
Environmental Test	85
Flight Ready	86

ASP TECHNOLOGY REQUIREMENTS

C.3.4. WIDE-ANGLE, HIGH-ACCURACY SUN SENSOR

REQUIREMENT:

A wide-angle sun sensor with accuracy higher than currently available ones is required for autonomous navigation. Current wide sensors have accuracies of approximately one arc minute. Accuracies of the order of one tenth of this amount are required if sun sensing is to be comparable in accuracy to star sensing.

DESCRIPTION OF NEW TECHNOLOGY:

Linear CCD arrays are now available which allow accurate, redundant, sun sensors to be constructed.

ESTIMATE OF DEVELOPMENT SCHEDULE:

	<u>FY</u>
Breadboard design	82
Breadboard test	83
Prototype design complete	84
Fabrication	85
Environmental Test	86
Flight ready	87

ASP TECHNOLOGY REQUIREMENTS
C.3.5. NAVIGATION SYSTEM LEVEL SIMULATION

REQUIREMENT:

Future military spacecraft require the capability to determine and control their orbits without active ground support, while numerous requirements studies have been conducted; only rudimentary navigation systems have been developed and flight tested.

DESCRIPTION OF NEW TECHNOLOGY: Given the overall problem, a number of new technology developments are required. This sheet considers the system level technology requirements. Supporting sheets consider various complementary technology developments.

At the system level a number of diverse hardware and software elements must be integrated to provide a navigation capability which meets the mission requirements. For example, geosync. satellites typically require stationkeeping control within 0.1° of a specified station. To achieve the objectives requires the reallocation of this error budget among the component navigation subsystems. To achieve the proper reallocation requires system level integration and simulation in a realistic environment. The system simulation should have the capability to investigate the performance requirements on specified navigation subsystems and to investigate the interaction of different subsystem components.

ESTIMATE OF DEVELOPMENT SCHEDULE: The earliest need date is 1985 for a synchronous communications satellite with implementation into more complex missions proceeding into the 1990's. Development of the initial computer simulation capability is estimated to require 30 months with an additional 12 months required to adapt the system to follow-on missions.

Development of system level simulations utilizing actual hardware, including the spacecraft computer is estimated to require 24 months given the prior partial development of the computer simulation.

C.4. MASS DATA STORAGE

C.4.1. RAD-HARD BUBBLE MEMORY - LSI

C.4.2. TRANSIENT SIGNATURE STORAGE

A S P T E C H N O L O G Y R E Q U I R E M E N T S
C.4.1. R A D - H A R D B U B B L E M E M O R Y - L S I

REQUIREMENT:

Future autonomous spacecrafts require non-volatile solid state memories in the capacity range between 10^6 and 10^7 bits for storage of diagnostic data collected over long periods of time. Bubble memories are capable of performing the required functions, but flight-qualifiable devices and subsystems have not yet been developed.

DESCRIPTION OF NEW TECHNOLOGY:

Bubble memory subsystems in the desired capacity range are currently available from several manufacturers. These subsystems use bubble devices and custom integrated circuits packaged in plastic dual-in-line form. Some integrated circuits are built in NMOS technology and could not be radiation hardened. Bubble devices and electronic circuits must be hermetically sealed in a flight acceptable manner and custom NMOS LSI devices must be duplicated in CMOS technology.

ESTIMATE OF DEVELOPMENT SCHEDULE:

The development of a radiation-hardened, flight-qualified bubble memory can be accomplished with low risk in a period of two years.

ASP TECHNOLOGY REQUIREMENTS

C 4.2. TRANSIENT SIGNATURE STORAGE

REQUIREMENT:

To provide detailed telemetry information prior to, during and immediately after a subassembly failure/redundant element switch over.

DESCRIPTION OF NEW TECHNOLOGY:

A method will be developed to autonomously gather and store detailed telemetry data pertaining to a failing or rapidly degrading element for later transmission to Earth. Ground analysis of such data could lead to a better understanding of the failure and therefore an optimal method of repair/recovery.

ESTIMATE OF DEVELOPMENT SCHEDULE:

The estimated development time would be 18 to 24 months.

C.5. AUTONOMOUS FUNCTION CONTROL

C.5.1. BATTERY MONITOR MODEL

C.5.2. AUTONOMOUS ATTITUDE DETERMINATION

C.5.3. INTELLIGENT ATTITUDE CONTROL

C.5.4. AUTONOMOUS PROPULSION MASS SENSING

ASP TECHNOLOGY REQUIREMENTS

C.5.1. BATTERY MONITOR MODEL

REQUIREMENT: Future military spacecraft require a capability to determine battery state-of-charge within 5% over a series of 50 solar eclipses without assistance from ground observation. Present power systems require either a very conservative design or ground intervention to avoid inadvertent battery discharge.

DESCRIPTION OF NEW TECHNOLOGY: At least two approaches are possible: 1) a precision battery model using voltage, current, temperature, state-of-charge and charge history as parameters, and 2) an ampere-hour integration system that also requires battery modeling for ampere-hour efficiency. Other approaches may also be feasible. A study of alternatives should be performed to determine the best approach, followed by development of the selected approach.

ESTIMATE OF DEVELOPMENT SCHEDULE: It is estimated that at least 1-2 manyears would be required to review available battery data and charge models and to select an approach. Development of the approach would require 2-3 manyears. It is estimated that this development program would extend over a period of 18 to 30 months.

ASP TECHNOLOGY REQUIREMENTS

C.5.2 AUTONOMOUS ATTITUDE DETERMINATION

REQUIREMENT: Traditional spacecraft design and operation requires ground support to provide or enhance its attitude determination capability and accuracy. Functions such as compensation of known systematic errors in the sensor measurements, inflight calibration for structural and instrument misalignments, attitude prediction and estimation during solar occultation periods, and sun and earth acquisitions are typically performed based on ground support. The development of an autonomous attitude determination capability will eliminate the need for much of this ground intervention and will thereby enhance overall spacecraft autonomy.

DESCRIPTION OF NEW TECHNOLOGY:

Sensor hardware (such as a star tracker) to satisfy autonomous attitude determination requirements.

Concepts for attitude determination algorithms to incorporate in flight software.

Spacecraft dynamical modeling for use in attitude estimator design; the size of model should not exceed limitations of on-board computational capabilities. Attitude estimator analytical design to establish preliminary assessments of achievable attitude determination system performance.

Comparative evaluation between sequential and batch processing of sensor data for attitude determination computations.

Attitude determination system performance by means of computer simulation based on complete nonlinear spacecraft models including sensor noise, quantization, spacecraft three-axis kinematics, etc.

Computation and storage requirements for on-board implementation system.

ESTIMATE OF DEVELOPMENT SCHEDULE:

4 years to flight readiness.

ASP TECHNOLOGY REQUIREMENTS

C.5.3. INTELLIGENT ATTITUDE CONTROL

REQUIREMENT: The remote manual control of sophisticated military spacecraft (systems) is increasingly intractable economically and technically because of communication delays and the complexity of ground functions. The approach remaining to reduce total mission cost is to increase the local autonomy of the spacecraft (system), communicating with it at a high level. Since a spacecraft (system) must, at all possible costs, accomplish its mission, the control organization must be extremely robust, accounting for both system maintenance and degradation as well as operation fault identification and accomodation.

DESCRIPTION OF NEW TECHNOLOGY: Develop technology and design architecture for an autonomous modular, hierarchical spacecraft control system with the following features:

- a) accepts and executes high level goal-oriented commands.
- b) adheres to system operational and mission constraints.
- c) provides extensive error checking and fault tolerance in a high level sense, e.g. systems faults and operational faults.
- d) provides for automatic self-test error/fault identification and recovery.
- e) provides expectation/verification performance self-assessment and health maintenance.

ESTIMATE OF DEVELOPMENT SCHEDULE

7 years to flight readiness

A S P T E C H N O L O G Y R E Q U I R E M E N T S
C.5.4. AUTONOMOUS PROPULSION MASS SENSING

REQUIREMENT:

Autonomous propulsion systems will require increased sensing of thruster performance/health and of propellant mass and center-of-mass. Current sensors are typically heavy and provide limited accuracy. Extensive ground analysis and reconstruction is currently substituted for the on-board sensing required by autonomous spacecraft.

DESCRIPTION OF NEW TECHNOLOGY:

Sensor developments required include: light-weight pressure or thrust transducers with pulse measurement capability; light-weight propellant mass-gauging systems with accuracies better than 1%; mass flow sensors. Potential may exist to adapt some techniques developed for manned programs, however, the much smaller systems required for unmanned spacecraft indicate that new approaches are required.

ESTIMATE OF DEVELOPMENT SCHEDULE:

About 2-1/2 years is required to develop and qualify each sensor type. Development should be preceded by a 1 year study to define sensor types and requirements.

C.6. RELIABILITY, PERFORMANCE, COST, ENVIRONMENT

C.6.1. PRECISION PAYLOAD POINTING SYSTEM

C.6.2. FIBER OPTICS ROTATION SENSOR

C.6.3 ACTIVE SPACECRAFT CHARGE CONTROL

C.6.4. RAD-HARD VLSI

ASP TECHNOLOGY REQUIREMENTS
C.6.1. PRECISION PAYLOAD POINTING SYSTEM

REQUIREMENT: To achieve precision pointing performance, payloads typically must satisfy more stringent control requirements than the overall structures on which they are mounted. Pointing systems are required in order to decouple and isolate these payloads from the overall vehicle dynamics and less precise orientation control

DESCRIPTION OF NEW TECHNOLOGY:

Develop functional and mechanization approach and select pointing systems for analysis and development based on criticality and mission requirements.

Design estimation and control laws for attitude and pointing control.

Develop coupled dynamical models for combined attitude/pointing control and iterate estimation and control designs.

Apply emerging technologies such as nongyroscopic inertial sensors, magnetic suspension, etc. with application to precision instrument pointing.

Apply antenna pointing concepts which utilize monopulse sensing and electronic beam steering techniques.

Define and analyze control system architecture utilizing selected emerging technologies.

ESTIMATE OF DEVELOPMENT SCHEDULE:

4 to 5 years for flight readiness

ASP TECHNOLOGY REQUIREMENTS

C.6.2. FIBER-OPTICS ROTATION SENSOR (FORS)

REQUIREMENT:

Presently available spun mass and laser gyros have limited lifetimes which do not allow full time use for S/C control on long flight time missions. Gyros are typically used for acquisition or reacquisition maneuvers. At other times celestial and earth sensors are used. Unplanned events involving the celestial references may result in a loss of S/C orientation. The FORS inertial reference is expected to have an operating lifetime of 15 years, and so is expected to be suitable for full time use on long-life missions.

DESCRIPTION OF NEW TECHNOLOGY:

The availability of low-loss, single-mode, optical, fiber waveguides has made possible a new class of inertial references devices operating on the principle of a closed-loop interferometer. Light circulating through the loop in both directions experiences a relative phase delay, proportional to the rotation rate about the loop axis. Potential performance is a rotation-rate sensitivity of a few milli-arc seconds per second.

ESTIMATE OF DEVELOPMENT SCHEDULE:

FY

Intermediate level integrated optics chip delivered	81
Laboratory Model FORS assembled and tested	82
Complete integrated optics chip development	83
Engineering Model sensing head completed	84
Flight hardware fabrication	85
Flight ready	86

ASP TECHNOLOGY REQUIREMENTS
C.6.3. ACTIVE SPACECRAFT CHARGE CONTROL

REQUIREMENT: A.F. spacecraft must survive in the natural environments in space for a 10-year period with long periods in which there are no ground control and/or correction. These spacecraft will encounter charged particle environments that will severely curtail their life span if not provided with proper protection. An autonomous spacecraft must be able to protect itself from soft errors, and anomalous commands produced by its interaction with a charged particle environment.

DESCRIPTION OF NEW TECHNOLOGY: Active spacecraft charge control techniques lend themselves to autonomous applications and have had considerable development activities to date (AFGL-Herb Cohen and others). Activities to be undertaken involves the development of sensor systems needed for a practical system. The types of sensors to be considered are: 1) Measure local electric field strengths or plasma energy/density parameters as a predictor of an electrostatic discharge which will be used to "safe" the spacecraft systems against damage from an electrical storm or, 2) to monitor for ESD sparks to be used in conjunction with spacecraft logic to prevent ESD caused command anomalies. Another area of activity is the development of a plasma generator to be used in conjunction with spacecraft potential monitors to prevent spacecraft differential charging to ESD sparking levels.

ESTIMATE OF DEVELOPMENT SCHEDULE: Flight experience with plasma sources on SCATHA and other spacecraft can be considered in developing a sensor/control system. Plasma sources will be flying in the 84 to 88 time frame and sensors and interfaces could be developed for these flights.

ASP TECHNOLOGY REQUIREMENTS

C.6.4. RAD-HARD VLSI

REQUIREMENT:

One of the assumed requirements for ASP is the availability of RAD hard LSI/VLSI components. To date, the availability of suitable components needs to be shown.

DESCRIPTION OF NEW TECHNOLOGY:

It will be necessary to discover the fundamental features, processing steps, design rules, etc. that lead to RAD hard components capable of meeting ASP requirements. This research should be conducted purely at the device physics level without regard to specific circuits.

ESTIMATE OF DEVELOPMENT SCHEDULE:

I would guess that it might take on the order of 2-4 years to develop and validate methods leading to RAD hard ASP components.