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LEVEL II

Autonomous Spacecraft Project

Assessment of Autonomous Options for the DSCS III Satellite System

Volume I: Overview and Findings

Approved for Public Release; Distribution Unlimited

6 August 1981

Interim Report for Period
1 November 1980 through 6 August 1981

Prepared for

U.S. Air Force Systems Command
Headquarters, Space Division

Through an agreement with

National Aeronautics and Space Administration

by

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

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This volume presents an overview of an assessment of the ability of the next generation Defense Systems Communications Satellite (DSCS III) to be made autonomous, i.e., to operate successfully without ground intervention for up to six months. The assessment concludes that while the current DSCS III design incorporates some autonomy, extensive revisions, particularly in the health and welfare maintenance areas and in stationkeeping, would be required to achieve autonomous operations for six months. Options for providing a six-

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month autonomous operations capability are outlined. These require primarily the addition of some on-based computing capability and autonomous stationkeeping sensors. Mass and power impacts of the additions would be relatively modest, but on-board computing and control complexity would increase substantially.

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ASSESSMENT OF AUTONOMOUS OPTIONS FOR THE DSCS III SATELLITE SYSTEM

VOLUME I: Overview and Findings

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PREFACE

This document is the first of three volumes which make up the assessment of autonomy for the DSCS III satellite system. Volume I is an overview and summary of the assessment. Volume II is a functional description of the existing DSCS III satellite system and an assessment of its current autonomy. Volume III presents options, at the functional level, for increasing the autonomy of DSCS III.

The DSCS III assessment was a team effort. Authorship of specific sections of the report by individual JPL contributors is acknowledged in Volumes II and III.

The results reported herein are based almost exclusively on a JPL review of DSCS III documentation provided by USAF Space Division. This documentation was judged generally adequate for the assessment. However, some difficulty was experienced in obtaining the needed material in a timely manner, and in some cases it was necessary to make assumptions and/or extrapolations since needed data were not available. Access to the DSCS III library at Space Division was provided for team members near the end of the assessment activity. This source of information will be valuable during the autonomous DSCS III design phase.

Because the critical nature of the first DSCS III vehicle requires intense activity by General Electric Company project personnel, JPL was requested to avoid contacting these personnel for information or assistance during the assessment activity. Several contacts were made with Aerospace Corporation personnel, who provided assistance to the JPL team.

DSCS III functions were classified in various ways as part of the assessment. Since these classifications are specified throughout the volumes, a ready reference is provided in Appendix B which defines the classification schemes.

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Figures

Tables

SECTION 1

PURPOSE OF THE DSCS III ASSESSMENT

The DSCS III Assessment was performed to:

(1) Assess the current autonomy level of DSCS III against recently developed autonomy goals (Reference 1),

(2) Assess the extent to which DSCS III is amenable to autonomy upgrading,

(3) Suggest autonomy addition options for possible consideration during subsequent DSCS III block changes, and scope the complexity and mass/power implications of such options, and

(4) Prepare for the autonomous DSCS III design task.

SECTION 2

BACKGROUND

2.1 PROGRAMMATIC BACKGROUND

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 (listed in order of priority from Reference 1):

(1) Enhancing spacecraft survivability against on-board 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 (FY'87), with spacecraft launched after this date capable of performing missions for unattended periods on the order of six months.

During the fall of 1980, the Jet Propulsion Laboratory (JPL) initiated a project for Space Division with the purpose of applying planetary spacecraft autonomy technologies and procedures to military satellites. This report is an output of Phase I (Project Definition Phase) of the JPL Autonomous Spacecraft Project (ASP).

The Task Plan for all of Phase I is contained in Reference 2. Relative to the work reported herein, the Task Plan states:

> For DSCS III, critique the existing design capability for meeting autonomous operation goals, and identify how additional autonomous operation features could be included within the existing system design
>
> (1) Without additional hardware, and
>
> (2) With modest hardware addition or changes.

This effort is referred to as the "DSCS III Assessment" task.

Future Phase I efforts will include a DSCS III redesign for autonomy (at the system and subsystem preliminary requirements level). Subsequent phases of the project are expected to proceed through autonomous subsystem designs and demonstrations and a system-level demonstration.

2.2 THE DSCS III SATELLITE

This satellite is a principal element of the Defense Space Communications System (DSCS) and consists of continuously operating, superhigh frequency (SHF) communications satellites in synchronous, equatorial orbits, in four widely separate geographic regions.

The mission provides satellite communication support in the 1980s to the Department of Defense and other U.S. Government and Allied users under unstressed conditions, and provides protected support to selected users who have been assigned missions of extreme importance in the defense of the U.S.A. under conditions of stress. DSCS III must maintain critical defense communications in a nuclear and electronic jamming environment.

The first DSCS III satellite will be launched in 1981 from the Eastern Test Range (ETR) on a Titan IIIC, as dual launch with a DSCS II.

Dry mass at launch $\leq$ 860 kg

Wet mass at launch $\leq$ 1137 kg

Other DSCS satellites will be launched throughout the 1980s. A program of continuous upgrading of functional capability by block procurement is planned. Autonomous fault protection and navigation capabilities are scheduled to be introduced in the late 1980s. The study described in this report assessed the design of the first satellite, which is assumed to be representative of the first block of satellites. No attempt was made to evaluate planned changes for future blocks.

SECTION 3

SUMMARY OF CONCLUSIONS AND OBSERVATIONS

The conclusions and observations are summarized here and are related to the purposes of the assessment. Information supporting these conclusions and observations is summarized in Section 7. Volumes II and III contain the detailed supporting material.

3.1 AUTONOMY LEVELS VS. GOALS

Levels of autonomy were defined by the Goals task documented in Reference 1, and are reproduced here in Appendix A. Levels range from 0 to 10. Conclusions/observations relative to the current autonomy of DSCS III vs. the goals defined in Reference 1 include the following:

(1) The existing DSCS III functions are at levels of autonomy ranging from 0 to 5. The average level appears to be about 2 or 3. This means that there is a high level of dependence on ground operations for analysis, planning, and decision making. The power and thermal control functions have many hard-wired, autonomous functions, and attitude control has considerable autonomy implemented in both software and hardware. However, spacecraft resource management and health/welfare maintenance are almost entirely ground directed. Stationkeeping is completely directed by the ground.

(2) A primary goal expressed in Reference 1 is for the spacecraft to operate for 60 days with nominal performance and for 6 months with acceptable performance, without ground intervention. A spacecraft autonomy level of about 5 is required to meet this goal. A Level 5 spacecraft (see Appendix A) is capable of executing a prespecified program of events and is also autonomously fault tolerant.

(3) The goal of 60 days nominal performance and 6 months acceptably degraded performance levies basically the same requirements on autonomy. This means that the sensing and computing additions required to make the spacecraft fully autonomous for 60 days should also enable 6 months operation without ground intervention.

(4) The autonomous DSCS III assessment philosophy assumes that the requirement for 6-month performance without ground intervention arises from a high-level-of-conflict situation. It has been assumed that under other conditions the ground will be able to periodically update the initial orbital state from which the spacecraft will have to operate independently. If this assumption is not valid, the spacecraft autonomy level may have to be increased beyond 5 (see Appendix A) to somehow provide its own initial state.

(5) On-board redundancy management is required for a high probability of meeting the 60-day/6-month requirement, particularly if hostile threats to the spacecraft are considered.

(6) Autonomous stationkeeping is also required, even for 60 days performance, since east-west stationkeeping maneuvers are required more frequently to meet the ±0.1° stationkeeping requirements. The maneuvers could occasionally occur as frequently as every few days (depending upon station location and sun-moon perturbation phasing).

3.2 AUTONOMOUS CAPABILITIES OF EXISTING DESIGN

Volume II provides a functional description of the existing DSCS III system. Some observations can be made about the current autonomy and its capacity for being increased by on-board software changes only.

(1) The DSCS III system currently has a good deal of autonomy in its power, thermal control, attitude control, and telecommunications service functions.

(2) The DSCS III system has generally adequate data, sensing, redundancy, and cross-strapping for integrity maintenance (health and welfare), but almost all analyses and direction of redundancy management are done by the ground.

(3) No present DSCS III capability exists for autonomous stationkeeping, or ephemeris maintenance.

(4) One computer system (primarily performing attitude control functions) is presently on board. In-flight or preflight reprogramming to increase autonomy is feasible, but its possibilities appear very limited. Some changes could be readily introduced to provide flexibility of response to situations which now result in survival modes. Other changes could improve operability of the spacecraft by the ground and/or provide some additional measures of fault

protection. The overall capability of the DSCS III spacecraft to be made autonomous, in its current configuration, appears to be considerably less than that of the Voyager or Viking planetary exploration spacecraft.

(5) In its current configuration the DSCS III spacecraft cannot be made free of ground intervention for even 60 days.

3.3 OPTIONS FOR INCREASING AUTONOMY

A range of options was developed during the assessment. The options are documented in Volume III. They range from modest computer and sensor additions (less than 5% total mass/power impacts) to additions which could be equivalent to a redesign of the spacecraft. The options could be implemented in a phased program, examples of which are presented later in Volume I. Some observations concerning the options include:

(1) The DSCS III spacecraft can be made fully autonomous for 6 months by adding features to create an autonomy level of 5. This will require additions or redesign which do not meet the assessment's definition of "modest" changes.

(2) A number of options are available for creating partial or phased autonomy with modest changes to hardware and software. These are described in Section 7, and, in more detail, in Volume III.

(3) For functions which require large numbers of sequential ground commands, on-board sequencing can be a substantial contributor to 6 months operation without ground intervention. Sequencing is suitable for events which can be predicted and for which no on-board decisions are required (e.g., some routine service and health maintenance functions). For the remaining functions on-board sensing, analysis, decision making, direction, control, and action are required.

(4) The existing ACS computer has some capability for add-on to make additional functions autonomous [up to 18k of 16-bit words random-access memory (RAM) or read-only memory (ROM) and 49% of central processing unit (CPU) time]. Fully exploiting this capacity will have costs in terms of mass, power, and design and operation inefficiencies. If this option were pursued, further study would be required to determine the exact impacts.

(5) Autonomous redundancy management for integrity maintenance will require a sizeable addition to on-board computing capacity (from 8k to 32k 8-bit words). Additional sensors to acquire direct health measurements may also be required.

(6) Addition of autonomous stationkeeping will require new location sensors as well as added on-board computer capability (between 16k 16-bit and 32k 32-bit words of memory). Addition of this function will at the same time provide most of the capability for on-board propulsion resource management and autonomous attitude control. Addition of the improved sensors will improve spacecraft operability, even if the autonomous navigation computing function is added later.

(7) Two modest-to-extensive additions (plus their executive control) are required: an on-board redundancy management function such as described in Section 4 of Volume III, and an autonomous stationkeeping function as described in Section 2 of Volume III. The added combination of these functions, plus the expansion of the ACS computer capacity and the addition of executive control functions, is equivalent in scope to a system redesign.

(8) Nonvolatile, long-term data storage will be required for fault protection audit trail storage, program storage, and storage of parameters for autonomous stationkeeping. Up to 10^9 bits of mass storage could be required.

(9) Very preliminary estimates of mass and power impacts on the spacecraft have been made. These are not based on a system-level design. (The design task is to follow the assessment.) The estimate does not include possible requirements for structural changes, additional health/welfare state sensors, additional propulsion capability, or contingencies. For a fully autonomous, Level 5 spacecraft, estimates of mass increases range from 55 to 131 kg. Estimates of the required power increases range from 47 to 127 W. ["Modest" mass increases are defined to be about 43 kg (5%) of spacecraft dry mass. "Modest" power increases are defined to be about 45 W (5%) of spacecraft power.] Telecommunication autonomy may be necessary, and could add as much as 5% additional mass and power.

(10) Very preliminary estimates of autonomous spacecraft complexity in terms of active on-board memory have been made. These are not based on a system-level design. A Level 5 spacecraft may have as many as 10 active computer processors on-board, containing between 784k and 2032k bits of information. Nonvolatile, bulk memory and standby processors are not included. By this measure of complexity, a Level 5 spacecraft may be equivalent to JPL's Galileo spacecraft in terms of systems design and validation difficulty.

(11) Ground system impacts of spacecraft autonomy will depend on the philosophy with which the autonomy is introduced and used. Spacecraft autonomy creates increased requirements

for validation and testing to create confidence in the autonomous features. Spacecraft control ground operations could conceivably be reduced to zero either by creating and fully validating a Level 5 spacecraft, or by shifting some spacecraft control functions to payload control. The latter option may cause unacceptable impacts on payload control operations.

(12) A phased program of autonomy increments can mitigate mass/power and operations impacts by introducing autonomy changes in conjunction with other planned changes to the DSCS III payload and spacecraft. For an on-going program, such as DSCS III, this is probably the preferred approach. If the autonomy additions are compared with planned changes to DSCS III in future block procurements, the impacts of autonomy additions are relatively modest.

3.4 CONSIDERATIONS FOR DESIGN TASK

The task of providing a conceptual design for an autonomous DSCS III will be conducted, building on the results of this assessment. Several issues relevant to the design task were identified during the assessment. These include the following:

(1) A top-down design approach is necessary, even if autonomous capability is added incrementally, to make trade-offs and ensure compatibility of time-phased additions.

(2) The biggest challenge in implementing DSCS III full autonomy is likely to be in the system and software design and validation areas, rather than in hardware development and implementation.

(3) Five major system trade-offs must be addressed during the autonomous DSCS III design phase:

  (a) Phasing of additions vs. redesign.

  (b) Distributed vs. central computing.

  (c) Additional direct health sensors vs. increased health inference logic.

  (d) Level of ground dependence vs. spacecraft autonomy level.

  (e) Fault detection and correction strategy.

(4) Ground costs vs. spacecraft costs must be considered in selecting functions to be made autonomous and in selecting levels of autonomy for each function.

(5) The impact on the ground operations of adding autonomy to the DSCS III satellite will depend on trade-offs between:

(a) The level of preflight validation, on-orbit checkout, and in-flight self-validation of the autonomy features vs. the level of ground monitoring of the autonomous functions in-flight.

(b) The degree to which Category II (lifetime extending/operability improving) functions are made autonomous.

(c) The degree to which the payload control function can assume monitoring of spacecraft functions during high levels of conflict.

SECTION 4

CONSTRAINTS

4.1 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 EXTERNAL THREAT CONSIDERATIONS

Space Division and JPL agreed that 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.

4.3 CONSIDERATION OF DESIGN FEATURES NOT RELATED TO AUTONOMY

The assessment evaluated the ability of the current DSCS III design to be made more autonomous, and several options addressed specifically to DSCS III autonomy have been developed. The assessment was not to consider performance improvement options such as reductions in mass, improvements in pointing accuracy, or extensions of design lifetime. However, autonomy additions could be expected to improve reliability and extend lifetime.

SECTION 5

ASSUMPTIONS

5.1 USE OF GOALS DOCUMENT

The generic goals presented in the Goals Document (Reference 1) were assumed to be applicable to an autonomous DSCS III. In fact, the assessment will be used to test the utility of these goals as part of the forthcoming Design Methodology task (see Reference 2). In addition, the existing DSCS III and the options for its increased autonomy were evaluated against the levels of autonomy given in the Goals Document.

5.2 ASSESSMENT PRIORITIES

All the DSCS III functions were addressed in the assessment. However, when time and/or staffing constraints limited the scope or depth of the assessment, the following priorities were used:

(1) On-station functions over initialization (postlaunch) functions.

(2) Normal modes of operation over abnormal modes. For example, options for maintaining performance when all spares were depleted were not investigated as deeply as simple redundancy management.

SECTION 6

APPROACH

6.1 STRUCTURE OF ASSESSMENT

6.1.1 Assessment Process*

Figure 6-1 is a flow diagram of the assessment process. First, a structure, identified as (1) in the figure, was developed for categorizing the functions of DSCS III. Both requirements (2) and capabilities (3) of the existing DSCS III were identified and were documented in this structure. The generic autonomy goals (4) from an early version of the Goals Document (Reference 1) were overlaid on the existing DSCS III requirements to produce requirements (5) for an autonomous DSCS III. The capabilities of the existing DSCS III were evaluated and concepts were formulated for increasing its autonomy. These concepts are the autonomous options (6). The options (6) were compared with the requirements (5) and were classified (7) by level of autonomy and difficulty of implementation. Recommendations (8) were made for revisions to both goals and level-of-autonomy definitions in the final Goals Document. The results of this process are documented in this report (9).

6.1.2 Functional Structure*

Information on DSCS III was available on a subsystem basis. The existing DSCS III subsystems are shown with relation to each other in Figure 6-2. However, in order to assess DSCS III's capabilities for autonomy, it was necessary to describe its capabilities in a functional manner. The structure selected to express this functional description is used both for the primary functions required for the spacecraft to operate satisfactorily and for the primary functions required for it to operate autonomously. Spacecraft functions are grouped into three categories:

(1) Provide services to payload.

(2) Manage spacecraft resources.

(3) Maintain integrity of spacecraft.

Services are those functions which the spacecraft provides to make it possible for the payload to operate satisfactorily, viz, a stable platform, power, thermal control, and alternate S-band or X-band telemetry and command channels.

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*The assessment structure and process are based on concepts developed by R. V. Morris of JPL.

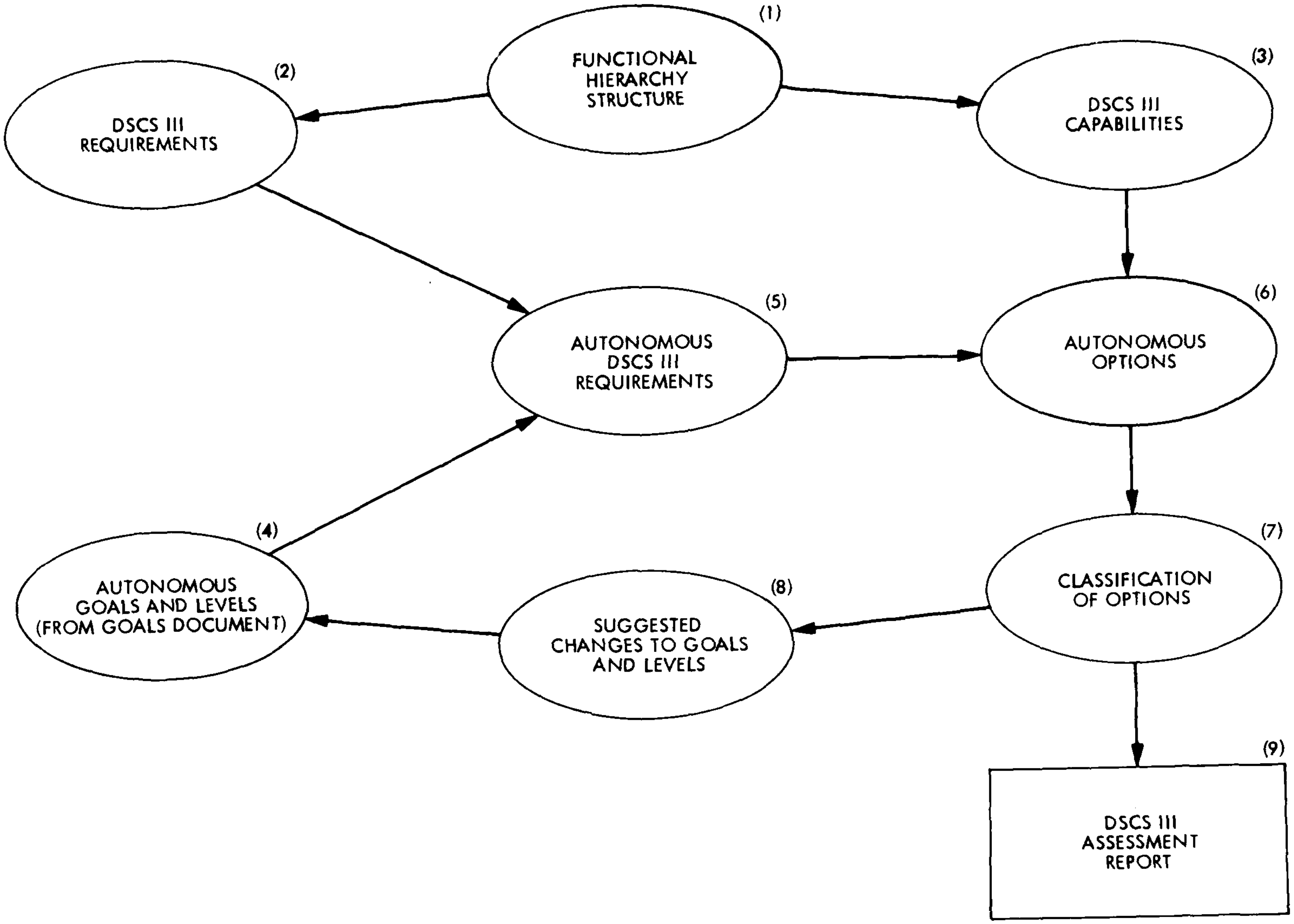

Figure 6-1. Autonomy Assessment Work Plan

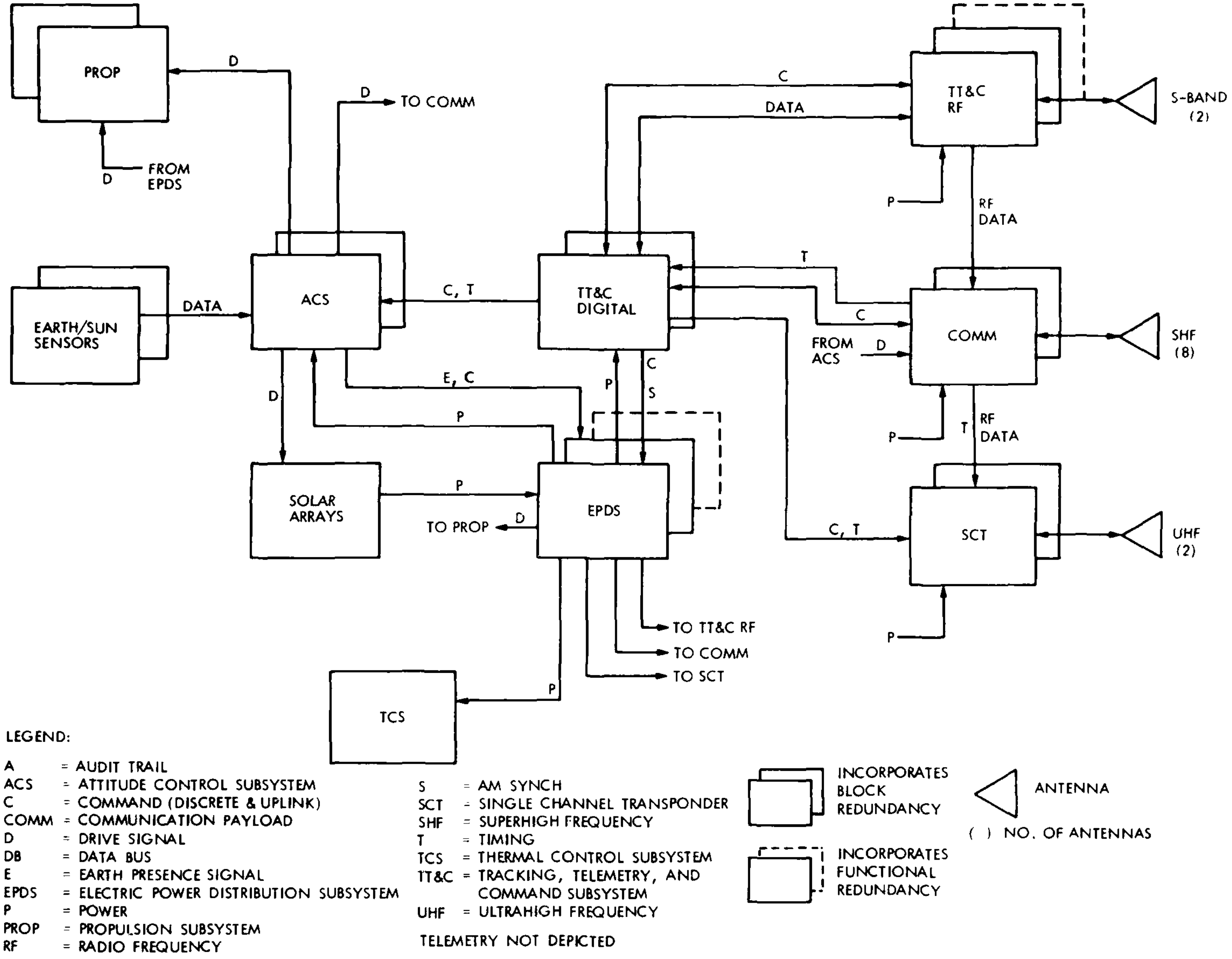

Figure 6-2. Current DSCS III Satellite System Block Diagram

Resources are those limited expendables which must be managed for the spacecraft to survive and perform as required, viz, power and propulsion resources.

Integrity refers both to health and welfare and to protection of the spacecraft from failures.

In order to analyze an autonomous operation, it is convenient to subdivide it into the functional classes of activity:

(1) Sense (or perceive a need).

(2) Direct (and control an action plan).

(3) Act (execute the plan).

These functions are, of course, required for the spacecraft to operate whether they are done autonomously or with ground intervention. However, an autonomous activity must involve all three of these functions.

Both categories (spacecraft and autonomy) were used to classify each DSCS III function. Together, they form a functional structure illustrated as a matrix in Table 6-1.

Table 6-1. Autonomous System Functional Structure

FUNCTIONS	SENSE	DIRECT/CONTROL	ACT
PROVIDE SERVICES TO PAYLOAD			
MANAGE SPACECRAFT RESOURCES			
MAINTAIN INTEGRITY OF SPACECRAFT SYSTEM			

Each of the horizontal autonomy functions (sense, direct/control, act) must be performed to carry out the vertical spacecraft functions. Here, sense means the act of obtaining the information needed to carry out the vertical functions. For example, the spacecraft must sense its orientation in space to provide accurate pointing for the payload. It must sense the hydrazine mass remaining in the propellant tanks to manage the rate of expenditure of the hydrazine resource resulting from thruster firings. It must sense faults or failures of the spacecraft hardware and software to maintain the integrity (health and welfare) of the system. The sensing function also includes the analysis required to interpret the data obtained by the sensors. This may include analysis of data from a combination of sensors, or recognizing patterns of measurements which indicate (for example) a failure.

The sensed information is then used to formulate a plan of action (direct) and to issue the instructions control which will cause the plan to be carried out (act). Thus, a maneuver sequence is developed in response to a sensed degradation in the orbit position of the spacecraft. This sequence directs the electronics controlling the thruster firings (among other things). The actual firing of the thruster is the action taken.

For the DSCS III Assessment this matrix structure was reformatted as a functional hierarchy, as illustrated in Figure 6-3. This structure forms the basis for this report and is discussed in the next section. The functional hierarchy was used to structure both the existing DSCS III and the autonomy options. It therefore served to:

(1) Match requirements and functions at the appropriate levels.

(2) Identify areas of overlap between functions.

(3) Identify gaps in the existing DSCS III's capability to sense, direct, control, or act to carry out its functions autonomously.

(4) Provide a common reference for work done by the various elements of the study team.

(5) Provide a basis for an autonomous DSCS III design.

6.1.3 Assessment Functional Classification

The DSCS III functions were classified in three ways: by level of autonomy, by importance, and by difficulty of implementation.

6.1.3.1 Levels of Autonomy. The levels specified in the Goals Document (Reference 1) were applied to both the existing DSCS III and the autonomy options. These levels (from 0 to 10) are reproduced in Appendix A.

6.1.3.2 Importance. The primary requirement which drives the DSCS III autonomy is for the spacecraft to operate with reduced ground intervention. As stated in the Goals Document:

> The autonomous spacecraft shall be capable of successfully performing the mission function for an extended period of time without ground support at a specified level of conflict. Specifically:
>
> (1) Autonomous spacecraft shall operate without performance degradation for up to 60 days from the last initialization update.

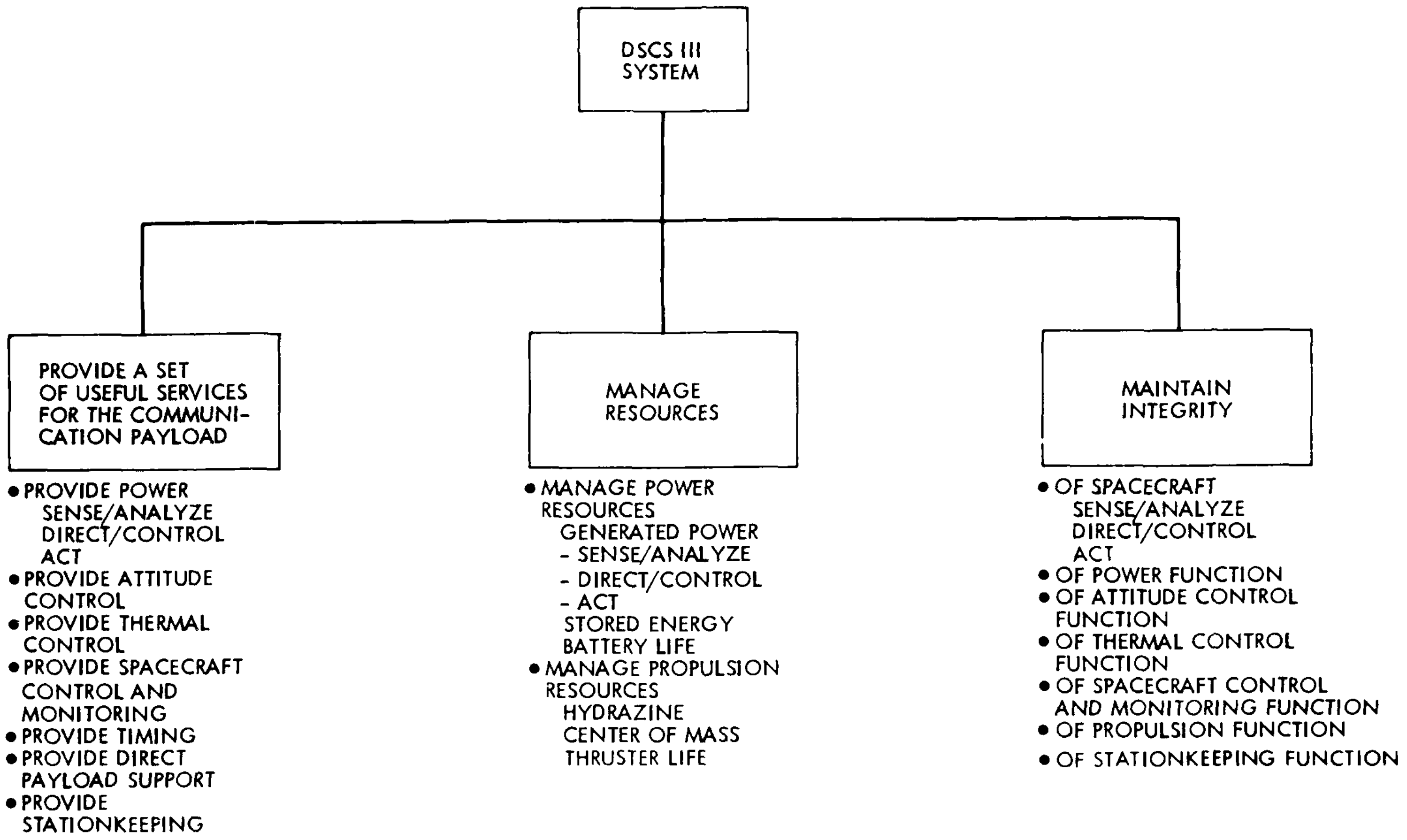

Figure 6-3. DSCS III Functional Hierarchy

]

(2) Autonomous spacecraft shall operate for up to 6 months from the last initialization update. They shall do so within acceptable performance degradation limits for mission-prioritized functions as defined by each mission.

These requirements were used as the basis for prioritization of autonomous operation as follows:

(1) Category I: Functions which must be performed autonomously for the spacecraft to meet the 60-day/6-month requirement.

(2) Category II: Functions which must be performed autonomously for lifetime protection (battery conditioning, etc.) or which, if performed autonomously, would increase the operability or operational flexibility of the spacecraft.

(3) Category III: Functions not requiring autonomy.

6.1.3.3 Difficulty of Implementation. There are three modes by which the DSCS III satellite system can be made more autonomous: Software, Add-on, and Redesign. The first is to utilize the existing hardware capabilities of the system and make software changes to increase autonomy. The attitude control subsystem includes a computer which is capable of being reprogrammed to increase the spacecraft autonomy (see Section 2.2 and 4.2 of Volume III). This mode will be referred to as the Software mode. It will produce the least expensive modification to DSCS III but is very restricted in its ability to add autonomous capability to the system. The Add-on mode adds hardware as well as software to the spacecraft but avoids making major design changes. The third mode, Redesign, allows consideration of redesigning the DSCS III system to increase its capabilities for autonomy. The Add-on and Redesign modes have gradations of difficulty. This assessment classified hardware modifications as "modest" or "extensive."

For the purposes of the DSCS III Assessment task, "modest hardware" modifications may consist of the following:

(1) New hardware introduced into the spacecraft system to perform autonomy functions, and/or

(2) Modifications of hardware already existing in the spacecraft system.

In order to be classified as "modest," arbitrary constraints were defined:

(1) The effects of added hardware would not allow the mass or power of the spacecraft to grow more than 5%, or the mass or power of an individual subsystem to grow more than 20%.

(2) No more than 15% of the spacecraft system's electrical interfaces would be impacted.

(3) If hardware is modified, the major function of that hardware would not be changed.

(4) No more than 20% addition of piece parts would be allowed, and no more than 20% new electrical interfaces would be allowed.

Any changes with scope larger than a "modest" modification are referred to as "extensive." Throughout the document the following designations are used to classify functions by their difficulty of implementation:

Class A = Software changes only
Class B = Modest additions
Class C = Extensive additions
Class D = Redesign

6.2 STRUCTURE AND USE OF THE DOCUMENT

6.2.1 Structure

Volumes II and III of this assessment report are structured in accordance with the functional hierarchy, Figure 6-3. Volume II contains the detailed description of the existing DSCS III functions, and Volume III contains the corresponding details of the options for increasing autonomy. Detailed functional block diagrams are included in Volume II. Each element in these block diagrams corresponds to a paragraph in Volumes II and III. Furthermore, each paragraph in Volume II has a corresponding paragraph in Volume III which is identified by the same decimal number. For example, Paragraph 2.2.1.4 in Volume II describes the Reacquire References function as it now is performed. It is partially autonomous. Paragraph 2.2.1.4 in Volume III describes how the Reacquire References function could be made fully autonomous. Requirements on each function are included in Volume II at the beginning of that function's description. Volume II includes an overview of the DSCS III mission and system, and its requirements.

6.2.2 Use

The structure of the document lends itself to use by people interested in particular functional aspects of the DSCS III system. The function of interest can be identified either from the table of contents or from the functional hierarchy diagrams. DSCS III specialists, for example, can evaluate the accuracy of a DSCS III functional description in Volume II, and then can identify the specific autonomy option suggested for that function in Volume III. Volume I was prepared for readers interested in a broader perspective of the assessment, and also contains necessary background and definitions for users of Volume II and III.

SECTION 7

ASSESSMENT SUMMARY

This section contains:

(1) A summary characterization of the current DSCS III's autonomy status,

(2) A summary discussion of options for increasing the autonomy of DSCS III, and

(3) Some preliminary estimates of the direct mass, power, and complexity impacts on DSCS III which would accrue if one of the possible autonomy-incrementing strategies were implemented.

7.1 SUMMARY OF AUTONOMY LEVELS OF THE EXISTING DSCS III SPACECRAFT FUNCTIONS

Figure 7-1 summarizes the autonomy levels of the existing DSCS III functions. As before, the functions are classified as Services, Resources, and Integrity, and by Category (I, II, III). The length of each bar in the figure represents the number of functions at that level of autonomy. (Refer to Appendix A for autonomy level definitions.) Category I, II, and III functions are designated separately.

Figure 7-1 illustrates that the Services functions tend to cluster around Level 3, the Resources functions around Level 1 or 2, and the Integrity functions around Level 2. Services functions, except for stationkeeping, are at higher levels because:

(1) The power and thermal control functions have a good deal of hard-wired, autonomous functions, and

(2) The attitude control function has considerable autonomy implemented in both software and hardware, whereas

(3) Resources and Integrity functions are almost entirely ground directed, and

(4) Stationkeeping is entirely ground directed.

Figure 7-1 also illustrates that the majority of functions are Category I, that is, they must be autonomous for the spacecraft to operate for 6 months without ground intervention. In order to meet the requirements, the majority of Category I functions will need to be raised to about Level 5.

Table 7-1 lists the functions which were used to make up Figure 7-1, by autonomy level and category. The paragraph numbers in Table 7-1 refer to Volumes II and III. Volume II contains a detailed description of the current functions. Volume III gives details on options for increasing the autonomy of each function.

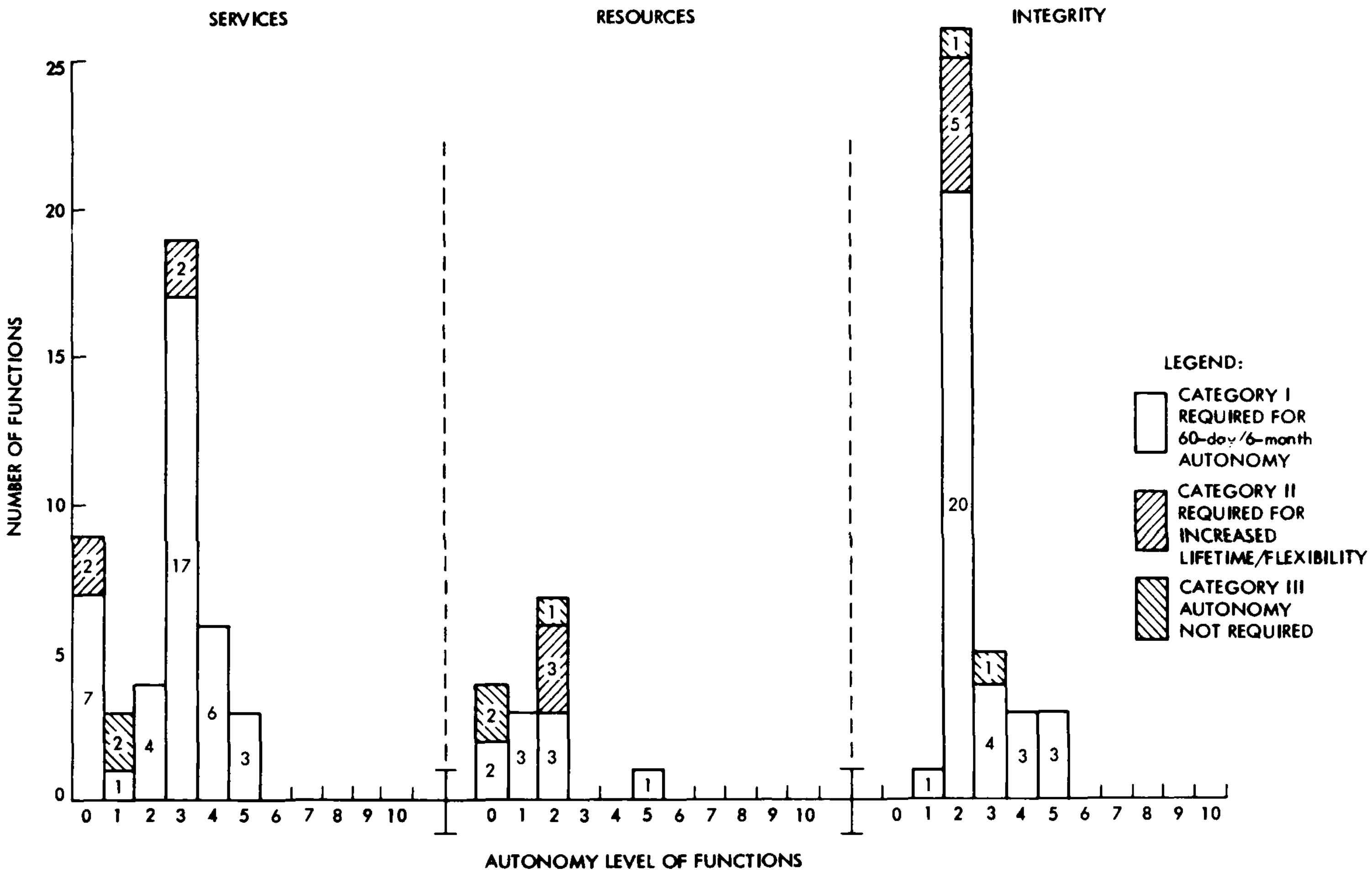

Figure 7-1. Summary of DSCS III Functions' Autonomy Levels and Need for Autonomy

Table 7-1. List of Current DSCS III Functions by Autonomy Level and Category: (a) Services, (b) Resources, (c) Integrity

(a) SERVICES

LEVEL	CATEGORY					
	I		II		III	
0	2.7.2.1	PROCESS LOCATION MEASUREMENTS (NAV)	2.7.1.2	SPACE SEGMENT TRACKING (NAV)		
	2.7.2.2	DETERMINE S/C LOCATION (NAV)	2.7.2.6	VERIFY NAVIGATION PERFORMANCE (NAV)		
	2.7.2.3	PROPAGATE EPHEMERIS (NAV)				
	2.7.2.4	PLAN MANEUVERS (NAV)				
	2.7.2.5	GENERATE MANEUVER COMMANDS (NAV)				
	2.7.4.1.1	SELECT TANKS (NAV)				
	2.7.4.1.2	SELECT THRUSTERS (NAV)				
1	2.3.4.2	CONTROL CATALYST BED HEATERS (TCS)			2.6.1.1	REORIENT GDA (ACS)
					2.6.1.2	RECONFIGURE MBA (ACS)
2	2.1.3.1	SENSE DISTRIBUTION RELAY STATUS (EPDS)				
	2.1.3.2	DIRECT/CONTROL POWER DISTRIBUTION (EPDS)				
	2.1.3.3	OPEN/CLOSE RELAYS (EPDS)				
	2.7.4.1.4	DIRECT/CONTROL MANEUVERS(ACS)				
3	2.2.1.2	ACQUIRE EARTH (ACS)	2.4.1.3	SEND TELEMETRY (TT & C)		
	2.2.1.3	CONFIGURE S/C (ACS)	2.4.2.4	RECEIVE COMMANDS (TT & C)		
	2.2.1.4	REACQUIRE REFERENCES (ACS)				
	2.2.2.1	DETERMINE ATTITUDE (ACS)				
	2.3.2.1	ENABLE SURVIVAL HEATERS (TCS)				
	2.3.2.2	ENABLE CONTROL HEATERS (TCS)				
	2.3.3.1	ENABLE SURVIVAL THERMOSTATS (TCS)				
	2.3.3.2	ENABLE OTHER HEATERS (TCS)				
	2.3.4.1	CONTROL ELECTRIC COMP. HEATERS (TCS)				
	2.3.4.3	CONTROL SURVIVAL HEATERS (TCS)				
	2.4.1.1	ACQUIRE INFORMATION (TT & C)				
	2.4.1.2	GENERATE TELEMETRY (TT & C)				
	2.4.2.5	PROCESS COMMANDS (TT & C)				
	2.4.2.6	DISTRIBUTE INSTRUCTIONS (TT & C)				
	2.7.4.1.3	WARM UP CATALYST BED (ACS)				
	2.7.4.1.5	FIRE THRUSTERS (ACS)				
	2.7.4.2	MAINTAIN ATTITUDE IN MANEUVERS (ACS)				

Table 7-1 (continued)

LEVEL	CATEGORY		
	I	II	III
4	2.1.1.1 ORIENT SOLAR ARRAY (ACS)		
	2.1.1.2 MAINTAIN SA ORIENTATION (ACS)		
	2.2.1.1 ACQUIRE SUN (ACS)		
	2.2.2.2 DIRECT/CONTROL ATTITUDE (ACS)		
	2.2.2.3 CONTROL ATTITUDE (ACS)		
	2.5.1 PROVIDE TIMING (ACS)		
5	2.1.2.1 REGULATE MAIN BUS VOLTAGE (EPDS)		
	2.1.2.2 PROVIDE AUXILIARY VOLTAGES (EPDS)		
	2.1.2.3 FIRE ELECTRO-EXPLOSIVE DEVICES (EPDS)		
	(b) RESOURCES		
0	3.1.2.2 ASSESS POWER STATE (EPDS)		3.1.1.2 SOLAR ARRAY OPERATING POINT (EPDS)
	3.1.3.2 ASSESS BATTERY DEPLETION (EPDS)		3.2.1.3 REDUCE N/S STATIONKEEPING (NAV)
1	3.1.2.1 SENSE ON-BOARD PARAMETERS (EPDS)		
	3.1.3.1 SENSE BATTERY PARAMETERS (EPDS)		
	3.2.2.1 DETERMINE C OF M LOCATION (PROP)		
2	3.1.2.3 EXECUTE RELAY COMMANDS (EPDS)	3.2.1.1 COMPUTE HYDRAZINE MASS (PROP)	3.2.3.2 MANAGE THRUSTER STEADY-STATE LIFE (PROP)
	3.1.3.3 EXECUTE RELAY COMMANDS (EPDS)	3.2.1.2 DIRECT HYDRAZINE MNGMT. (PROP)	
	3.2.2.2 SELECT TANKS (ACS/PROP)	3.2.3.1 MANAGE THRUSTER PULSE LIFE (PROP)	
3			
4			
5	3.1.1.1 MANAGE SOLAR ARRAY ATTITUDE (ACS)		

Table 7-1 (continued)

(c) INTEGRITY

LEVEL	CATEGORY					
	I		II		III	
0						
1	4.2.1.2	PROTECT POWER BUS (EDPS)				
2	4.2.2.1	BATTERY CHAIN FAILURE (EPDS)	4.2.3.1	BASELINE ENERGY STORAGE (EPDS)	4.3.4.1	RAM PATCH (ACS)
	4.2.2.3	SECONDARY CONVERTER FAILURE (EPDS)	4.3.4.4	ALL AXES SUN CONTROL (ACS)		
	4.2.2.5	SINGLE LOAD SWITCH FAILURES (EPDS)	4.5.1.3	MAINTAIN TELEMETRY TRANSMISSION (TT & C)		
	4.2.4.1	FAILED BATTERY CHAIN (EPDS/ACS)	4.5.2.3	MAINTAIN S/C COMMAND RECEPTION (TT & C)		
	4.2.4.2	SAD POT FAILURE (ACS)	4.7.1	MAINTAIN TRACKING FUNCTION (TT & C)		
	4.3.1.2	SENSE DEVICE STATE (ACS)				
	4.3.2.1	ATTITUDE DURING ECLIPSE (ACS)				
	4.3.2.5	YAW RATE REDUCTION (ACS)				
	4.3.3.1	REACTION WHEEL FAILURE (ACS)				
	4.3.3.2	ACE FAILURE (ACS)				
	4.3.3.3	EARTH SENSOR FAILURE (ACS)				
	4.3.3.4	SUN SENSOR FAILURE				
	4.3.4.3	TELEMETRY CONTINGENCY MODES (ACS)				
	4.4	MAINTAIN THERMAL CONTROL (TCS)				
	4.5.1.1	MAINTAIN INFO ACQUISTION (TT & C)				
	4.5.1.2	MAINTAIN TELEMETRY GENERATION (TT & C)				
	4.5.2.4	MAINTAIN COMMAND PROCESSING (TT & C)				
	4.5.2.5	MAINTAIN COMMAND DISTRIBUTION (TT & C)				
	4.6.1	MAINTAIN THRUSTER HEALTH (PROP)				
	4.6.2	MAINTAIN PROPELLANT SYSTEM (PROP)				
3	4.2.1.1	ISOLATE LOAD FAULTS (EPDS)			4.3.4.2	GROUND OVERRIDE (ACS)
	4.2.2.2	SA OR SHUNT DISSIPATOR FAILURE (EPDS)				
	4.2.3.2	BATTERY OPERATIONS INTEGRITY (EPDS)				
	4.3.2.2	LOSS OF EARTH PRESENCE (ACS)				
4	4.3.1.1	DATA TRANSFER HANDSHAKES (ACS)				
	4.3.1.3	PROTECT FROM FALSE COMMANDS (ACS)				
	4.3.1.4	CHECK PARAMETER STATES (ACS)				

Table 7-1 (continued)

LEVEL	CATEGORY		
	I	II	III
5	4.2.2.4 REG ELECTRONICS/QUAD RELAY FAILURE (EPDS) 4.3.2.3 NUCLEAR EVENT (ACS) 4.3.2.4 PROTECT EARTH SENSOR (ACS)		

LEGEND:
ACS = ATTITUDE CONTROL SUBSYSTEM
EED = ELECTRO-EXPLOSIVE DEVICE
EPDS = ELECTRIC POWER DISTRIBUTION SUBSYSTEM
GDA = GIMBAL DISH ANTENNA
MBA = MULTIBEAM ANTENNA
NAV = NAVIGATION
POT = POTENTIOMETER
PROP = PROPULSION SUBSYSTEM
RAM = RANDOM ACCESS MEMORY
SAD = SOLAR ARRAY DEVICE
TCS = THERMAL CONTROL SUBSYSTEM
TLM = TELEMETRY
TT & C = TRACKING, TELEMETRY, AND COMMAND SUBSYSTEM

7.2 EXAMPLE OF A PHASED PROGRAM FOR CREATING A LEVEL 5 AUTONOMOUS DSCS III SPACECRAFT

Table 7-2 summarizes the options for adding autonomy to DSCS III. All of the Category I functions through Class C* must be added to make the DSCS III spacecraft system performance acceptable while independent of the ground for 6 months. The arrows in Table 7-2 indicate that the function may be partially performed at the lower class (where the arrow starts), but will probably require the higher class of modification (where the arrow ends) to be completely autonomous. Table 7-2 illustrates that extensive add-ons or redesign will be necessary to create a fully autonomous spacecraft. Functions which must be made more autonomous are of all three types: provide services, manage resources, and maintain integrity.

Table 7-2. Classification of Options for Increasing DSCS III Autonomy

CLASS / CATEGORY	A SOFTWARE MODE	B MODEST ADD-ON	C EXTENSIVE ADD-ON	D REDESIGN
I REQUIRED FOR 60-day/6-month AUTONOMY	• SOME ATTITUDE CONTROL FUNCTIONS, e.g.: → - VALIDATE EARTH LOSS - REACQUIRE EARTH - REACTION WHEEL FAILURE DETECTION/ SHUTDOWN - NONSTANDARD MOMENTUM DUMPING	• BATTERY RESOURCE MANAGEMENT • FULL AUTONOMY OF ATTITUDE CONTROL SERVICE FUNCTIONS → • SPACECRAFT REDUNDANCY MANAGEMENT →	• POWER LOAD ANOMALIES AND CONVERTER SELECTION → • AUTONOMOUS STATIONKEEPING → • AUTONOMOUS ATTITUDE CONTROL FOR MANEUVERS	[a]
II LIFETIME PROTECTION OF INCREASED OPERABILITY	• SELECT BATTERY CHARGING PARAMETERS	• PROPULSION RESOURCE MANAGEMENT • TELECOMMUNICATIONS INTEGRITY MAINTENANCE →	• EVENT PREDICTIONS • NAVIGATION PERFORMANCE ASSESSMENT	
III AUTONOMY NOT REQUIRED	• ALTERNATE PAYLOAD COMMAND GENERATION • PAYLOAD ANTENNA POINTING	• BATTERY RECONDITIONING	• ANTENNA POINTING PREDICTS	

[a] ARROWS INDICATE THAT THE FUNCTION MAY BE PARTIALLY PERFORMED AT THE LOWER CLASS BUT WILL PROBABLY REQUIRE THE HIGHER CLASS OF MODIFICATION TO BE COMPLETELY AUTONOMOUS.

Figure 7-2 is a flow diagram showing three examples of incremental paths for addition of these autonomy options to the DSCS III spacecraft. Each path in Figure 7-2 could potentially lead to achieving

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*Category I functions are those which must be autonomous. Class C functions require extensive additions to the existing DSCS III spacecraft.

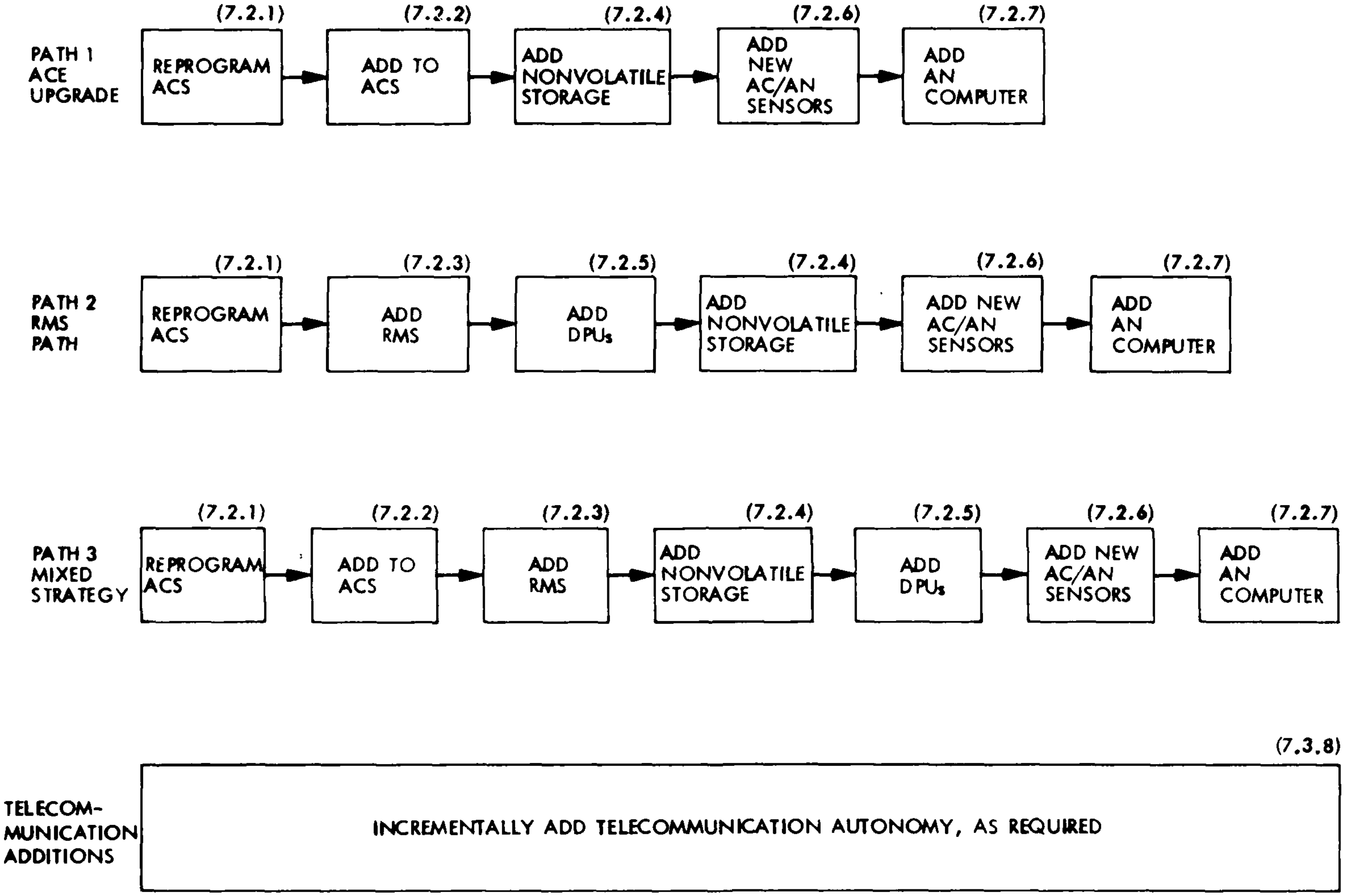


Figure 7-2. Some Examples of Paths to a Level 5 DSCS III

Level 5 autonomy, but the steps would be different from path to path. Since no system-level design work has been performed, the paths to full autonomy shown in Figure 7-2 are only a subset of those possible. In fact, some of the steps along the paths may be unfeasible or undesirable. However, the example paths are discussed to illuminate issues which design and implementation of an autonomous DSCS III will have to face. The design implications of the path selection will be significant even if the steps are more-or-less functionally constant. It is emphasized that the design examples developed for the assessment are only conceptual and are in no way exhaustive of the design possibilities.

In order to provide some feeling for the scope of potential impacts on DSCS III of increasing autonomy, some bounds on mass and power impacts have been estimated. It must be emphasized that many secondary mass/power impacts cannot be identified without a system design effort, although they may be as large as the primary impacts. "Secondary" impacts are those changes to the spacecraft which would result from incorporation of the autonomous features. For example, the existing spacecraft volume or available attachment area may be inadequate for the computer additions, or the fields of view may be inadequate for the autonomous navigation sensors, requiring structural modification. Table 7-3 summarizes the range of estimates. In Table 7-3 examples of the function to be made autonomous by each step are listed, roughly in order of increasing difficulty, corresponding to the minimum-to-maximum capability progression possible in each step.

Table 7-3. Summary of Range of Estimates

STEP	EXAMPLES OF FUNCTIONS	IMPACTS			
		MASS		AVERAGE POWER	
		MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
REPROGRAM ACS	• MACRO COMMAND BLOCKS • OPTIMIZED PARAMETERS AND CONTROL LAWS FROM FLIGHT EXPERIENCE • INVALID EARTH LOSS SIGNAL FILTER	NONE		0	9.5 W
ADD TO ACS	• REDUNDANCY MANAGEMENT OF ACS • FULL AUTONOMY OF ACS EXCEPT FOR MANEUVERS	TBD (512 WORDS)	TBD (18k WORDS)	> 2.6 W (512 WORDS)	< 65 W (18k WORDS)
ADD RMS	• REDUNDANCY MANAGEMENT OF TT&C PLUS SELECTED SPACECRAFT FUNCTIONS • REDUNDANCY MANAGEMENT OF ALL S/C • REDUNDANCY MANAGEMENT PLUS SERVICE AND RESOURCE MANAGEMENT FUNCTIONS	(8k WORDS) 6 kg (INC NV STORAGE)	(32k WORDS) 12 kg (INC NV STORAGE)	(8k WORDS) 8 W (INC NV STORAGE)	(32k WORDS) 12 W (INC NV STORAGE)
ADD NONVOLATILE STORAGE	• AUDIT TRAIL • PROGRAM STORAGE • AUTONOMOUS STATIONKEEPING DATA STORAGE	(10^6 bits) 1.5 kg (BUBBLE)	(10^9 bits) 18 kg (TAPE)	(10^6 bits) 2 W (BUBBLE)	(10^9 bits) 3 W (TAPE)
ADD DPUs	• SUBSYSTEM FAULT DETECTION AND CORRECTION	15 kg (5 REDUNDANT DPUs AT 3 kg EACH)		10 W (5 REDUNDANT DPUs AT 2 W EACH	
ADD AUTO. NAV. SENSORS	• ATTITUDE CONTROL FUNCTIONS • INCREASED FLEXIBILITY IN GROUND - DIRECTED MANEUVERS • AUTONOMOUS NAVIGATION ENABLED	20 kg	55 kg	24 W	90 W
ADD AUTO. NAV. COMPUTER	• AUTONOMOUS NAVIGATION • *INCREASED AUTO. NAV. ACCURACY*	16k, 16 bits *6 kg*	32k, 32 bits 10 kg	16k, 16 bits 3 W	32k, 32 bits 5 W
ADD TELECOMMUNI-CATION AUTONOMY	SEE TABLE 7-4	0	30 kg	0	[illegible] W

NOTE: UNLESS OTHERWISE SPECIFIED, WORDS ARE 8 bits IN LENGTH

Estimates for the attitude control subsystem (ACS) microcomputer additions are based on available literature on the LSI11 computer. This was inadequate to evaluate potential mass impacts. Estimates for the autonomous navigation sensors are also based on available literature.

Mass/power estimates for all other computer additions are based on the design assumptions for the redundancy management subsystem (RMS) (see Section 4.1.1.2 of Volume III). This design utilizes Galileo technology and techniques. Estimates for other mass/power impacts are based on JPL design experience and rules of thumb.

The following paragraphs describe the steps, the implications of their implementation, and the preliminary estimates of their mass and power requirements.

7.2.1 Reprogram ACS Computer (Software Changes Only)

As discussed in Section 2.2.4 of Volume III, the existing ACS microcomputer may be capable of being reprogrammed to deal with a limited number of functions autonomously. Two modes for reprogramming are possible: in flight and prelaunch. The existing ACS microcomputer has redundant RAMs with 1000 16-bit words each, which can be reprogrammed in flight by the RAM patch mode, or before launch. Additional autonomous features would compete with other functions currently in the RAM, which has a total capacity to approximately contain the Voyager ACS fault routines (1000 words) described in Section 1.3 of Volume III. As long as the RAMs remain redundant, therefore, the ACS will have less fault protection capability than Voyager's ACS. If the standby RAM were allowed to be used for fault protection routines, the ACS could possibly be brought to about the same level of autonomy as the Voyager ACS. However, it should be noted that the Voyager computer command subsystem (CCS) provided executive control and fault protection for the ACS computer on Voyager. No CCS equivalent is available in the existing DSCS III.

The ACS computer has redundant 8k ROMs. All available ROM space is now used, but only about half of this is for the attitude control programs. The remainder is used by the executive routines and the payload beam forming network (BFN) program. The basic ACS programs also utilize only about half of the CPU computational cycle time, with the BFN program taking the remainder (when the BFN program runs). It appears that the CPU can handle about twice the ACS load if strategies and priorities for handling BFN and autonomy improvements are established. For example, flexible interleaving of health checks and fault detection and analysis for redundancy switching could be accomplished at multiples of basic computational frame time. BFN execution should also be adaptable within a few frames, since it is not a dynamic, real-time issue.

The ACS currently has no control access to manage redundant ACS blocks for fault recovery.

7.2.1.1 In-Flight Reprogramming. Options for reprogramming the ACS computer after launch appear to be very limited. JPL's experience is that after in-flight experience with a system is gained, the on-board computers can often be reprogrammed to remove excessive conservatism caused by lack of familiarity with how the spacecraft would really operate in flight. An example is the opening of attitude control autopilot tolerances in the fault protection algorithms on Voyager, and the use of both CCSs on Viking and Voyager to serve the sequence function, rather than holding one in standby reserve.

Some options for reprogramming may become feasible in DSCS III with more in-flight experience, but will most likely be limited to the type of changes already anticipated to be introduced by the existing RAM patch mode. These include changes to existing routines to change program code, work around degraded ROM, and allow simple enable/disable of autonomous functions. More information on the existing computer is needed to evaluate the possibilities for in-flight reprogramming, but they are likely to be very limited because of the computer's characteristics. RAM patching could provide a 13% increase in available memory, and uses the redundant RAM while the prime RAM is active.

7.2.1.2 Prelaunch Reprogramming. After the first one or two DSCS IIIs are flown, the experience gained may allow changes in the ACS computer software to increase the spacecraft autonomy. Such a situation occurred when experience gained during the Viking prime mission allowed the extended prime mission to be conducted more autonomously. Even if this is the case, the present ACS computer appears fairly full with its current autonomous attitude control software. It is likely that only a few, simple autonomous functions could be added, unless the standby RAM could be programmed independently.

Candidate functions for increasing autonomy would be those which currently send the spacecraft into a survival mode, greatly reducing its operational capabilities while a situation is analyzed. Two examples of this are the loss of earth presence signal (Section 4.3.2.2 of Volume II) and the battery discharge 80-minute timer (Section 4.2.3.2.2 of Volume II). In both cases the spacecraft turns off nonessential loads (including the payload functions), turns on the S-band telemetry alert to ground, and remains in this survival mode until instructed to change by the ground. In both cases modes of triggering the survival mode can be envisioned for which the survival response is excessive. Certainly, if autonomy is to be introduced, an early requirement would be to eliminate loss of the payload function unless the circumstances are severe enough to warrant it.

Some relatively simple tests for the cause and/or severity of the situation could be introduced so that the survival mode would only be entered when necessary. For example, battery discharge rate could be measured instead of battery charge time, and loads shed only when necessary. This would require a replacement of the 80-minute timer with a battery discharge indication and adding hardware interfaces and software to the ACS to determine an acceptable discharge level.

Another example is to cross-check the earth presence signal loss with the earth sensor readings and attitude states just prior to the "loss" signal. This would identify whether the earth presence signal indicators were at fault rather than the spacecraft being turned away from the earth. The incorporation of logic to enable earth reacquisition if the spacecraft were turned away might also be feasible. The primary driver on the computer requirement for automating this is the extent to which fault isolation and correction (what caused the turn?) and reacquisition verification are felt to be needed.

The above examples have not been designed in this assessment phase and are used only for specifying the type of functions which might be candidates for prelaunch reprogramming. It is unlikely that very extensive additional autonomy can be added without some level of hardware change (e.g., replacing the 80-minute timer).

If the CPU capacity of the existing ACS computer were fully utilized, the computer would require about twice as much power on the average as its current consumption. As stated in Section 4.3.5 of Volume III, average power use could increase by 9.5 W. In-flight reprogramming via the RAM patch will require power, but this is already designed into the system.

7.2.2 Add to ACS Computer (Hardware/Software)

7.2.2.1 Addition of RAM or ROM Modules to ACS. As mentioned in Section 2.2.4 of Volume III, the minimum addition to the ACS RAM or ROM would be 512 words. Possibly one or two such additions would provide enough capability to provide autonomy for the functions which currently result in a spacecraft survival mode, as discussed in the preceding section. Additional ROM could be used for providing more flexibility in the ACS service functions. For example, blocks of commands now sent from the ground could be stored in the ACS, requiring only a single ENABLE command from the ground for the spacecraft to implement the entire block. This would save ground time and uplink time, and reduce the probability of command and decoding error.

Some ACS redundancy management functions could be introduced, but these would require hardware modification for new inputs and outputs to provide access to the ACS direct current (DC) relay matrix, electric power distribution subsystem (EPDS) DC relays, or the TT&C command decoder as described in Section 4.3.5 of Volume III.

7.2.2.2 Maximum Addition to ACS. Section 4.3.5 of Volume III gives an upper limit of 18k words (nonredundant) additional RAM or ROM space for the ACS microcomputer. In comparison with the approximately 1000 words used for attitude control fault protection on Voyager plus another 1000 words for CCS autonomy, this would appear ample for ACS services and integrity maintenance, as well as additional spacecraft functions. An initial assessment of the DSCS III attitude control ground software has identified at least seven points of comparison with the Voyager attitude control flight software. These points of comparison are for fault detection and recovery functions and are described in Section 4.3 of Volume III. The assessment shows that the Voyager and DSCS III attitude control function fault protection algorithms have some similarity. This implies that the DSCS III ground algorithms will be useful in designing Voyager-type fault protection for the ACS, and that the ACS upgrade path will allow on-board ACS integrity maintenance to be performed. One example of a thruster firing fault protection algorithm was developed for DSCS III during the assessment. The routine would comprise about 75 words and be executed within 1 to 1.5 ms with the current CPU on DSCS III. With the addition of sufficient input/output (I/O), memory, and interface lines, the ACS could manage its own redundancy. A capability for the ACS computer to conduct self-test and redundancy swaps could be added by providing ports to monitor the CPU heartbeat. A RAM refresh monitor of the CPU could be implemented by a read/write comparison between accumulator and memory location.

If the maximum ACS addition were made, redundancy would be required; therefore, the total impact could be as much as 32k words of memory. Information on commercial equivalents of the LSI11 gives power requirements for 4k of 16-bit ROM as 14 W average/20.5 W maximum. Of this total the first 512-word ROM module added would require 2.63 W, with remaining ROM modules requiring 1.63 W, each.

No mass information on the LSI11 RAM or ROM addition was available. Estimates of the mass impact of increasing the ACS capacity are therefore not included. It should be noted that the remaining computer mass/power estimates for the RMS and autonomous navigation computers assume modern, low mass/power, complementary metal oxide semiconductor (CMOS) computer technology. Therefore, the ACS additions are expected to be considerably higher in terms of mass and power than the RMS and autonomous navigation computers discussed below. One issue in adding large amounts of additional RAM or ROM to the ACS computer is the age of the computer. This technology has been superseded since 1975 in terms of low mass and power, and parts may be difficult to procure.

7.2.2.3 Other ACS Modifications for Enhanced Autonomy. The capability for an "all-axes inertial" mode of operation can benefit the autonomy of the attitude control function. This would require adding pitch and roll rate gyros, as a minimum. For maximum benefit (to provide autonomous recovery from 3-axis dynamic problems), precision, rate-integrating gyros should be added to all three axes. Gyros would also provide an independent path to verify attitude state estimation based on optical sensors. In addition, they would allow the performance of mutual calibration/drift correction and fault diagnosis with the optical sensors, without the spacecraft survival mode being necessary.

7.2.2.4 ACS Upgrade vs. RMS. Adding to the ACS computer may be the least expensive way to add autonomy for additional ACS service functions and some spacecraft system functions, such as the survival modes. In order for the ACS to handle spacecraft-level redundancy management in addition to its own ACS redundancy control, duplication of I/O devices between the ACS and the TT&C would probably be necessary. To provide new inputs will require adding ports which function in a similar fashion as the existing sensor port. This port(s) would process both analog and bi-level digital signals. Output access could be provided to both the ACS and EPDS by adding a new port to drive the ACS resident DC relay matrix as the TT&C command decoder now does, but in a shared mode with the TT&C. This could also be used to issue EPDS DC commands.

At some point the cost of adding many I/O devices will exceed the cost of adding a new computer to connect with the existing TT&C I/Os. Therefore, trade-offs must be made to determine this point. This trade will determine whether the mixed strategy path should be followed, or whether either the ACS upgrade or RMS path is preferable.

In upgrading the ACS computer, trades will be necessary between adding ROM or RAM. RAM is programmable in flight, but is vulnerable to radiation effects and a power off/on. ROM can only be programmed before launch but is not susceptible to radiation and power on/off. The JPL experience is that the flexibility for reprogramming to revise or add autonomous capabilities in flight is very important. This can allow for (1) increasing autonomy as more confidence is gained in the system, (2) correcting autonomy algorithms for flaws which can only be discovered in flight, or (3) compensating for degradations in the satellite system (such as spares depletion).

Since it appears that expansion to include full spacecraft redundancy management and autonomous navigation is beyond the expansion capability of the ACS, at least one other spacecraft computer will be needed.

7.2.3 Add Redundancy Management Subsystem

The most straightforward way of making the DSCS III satellite system maintain its own integrity is to provide an on-board system for managing the spacecraft's redundancy. The addition of a redundancy management subsystem for integrity maintenance of the TT&C subsystem is described in Section 4.5 of Volume III. Such a subsystem would have access to telemetry data from the whole spacecraft and could therefore be used for management of redundancy throughout the spacecraft. The RMS includes nonvolatile storage.

7.2.3.1 Minimum Option. The preliminary design work done during the assessment sized the minimum RMS at 6 kg and 8 W of power. This could undoubtedly handle redundancy management for the TT&C subsystem. Some spacecraft redundancy management could also be performed. The easiest type of fault correction (that is, where the solution to a fault is to switch units) could be implemented first, but faults would probably not be isolated. Some crucial or time-critical switching decisions for the spacecraft could also be made. Since the RMS has access to the command stream, it is in a position to function as an executive computer, much as the CCS on Voyager and Viking. With 8k words of read/write memory devoted to fault protection functions (compared with 1000 to 2000 words on Viking and Voyager), substantial fault protection should be possible. The extent to which the minimum redundancy management function could handle fault correction would depend on the capability required to analyze and isolate faults. The RMS could also handle autonomous responses to the survival mode situations discussed in the ACS upgrade options.

7.2.3.2 Maximum Option. The RMS could increase in size and capability as described in Section 4.1.1 of Volume III. The maximum practical memory size for an RMS alone (no distributed processing units) appears to be about 32k words. Verification of this limit requires a much more comprehensive design effort. Interactions with the ACS computer must also be addressed. The maximum RMS is estimated to weigh 12 kg and require 12 W of power.

As a test of whether the ground algorithms for integrity maintenance of the current DSCS III would be applicable to on-board redundancy management, a battery high-temperature-recovery algorithm was programmed for the RMS. The RMS design appears to lend itself to having this typical algorithm on-board, at a cost of 361 8-bit words. The algorithm is described in Volume III, Section 4.1.3.

7.2.4 Add Long-Term Storage

Section 4.1.1.3.2 of Volume III estimates that 10^6 bits of storage would be required for the RMS to store fault protection diagnostic data and audit trails for 60 days. This estimate was not, of course, based on a system design effort. Nonvolatile storage will also be required for storing routine maintenance and service function audit trails. For functions such as hydrazine resource management, much longer-term data storage than 60 days may be required to do trend analysis for slowly varying conditions. Storage of extensive software programs that can be accessed by the RMS for reloading volatile memories throughout the spacecraft will be required. If the ACS upgrade path is taken, nonvolatile storage will have to be introduced. If the RMS path is taken nonvolatile mass storage will still need to be added.

When the autonomous navigation function is added, even more long-term storage will be required for such things as star maps, ephemerides of the sun and moon, and environmental model constants.

Long-term, nonvolatile storage required for full autonomy may therefore require capacities up to 10^9 bits. Design decisions will be necessary to determine the best way of adding such storage. For example, up to 10^7 bits, bubble memory is probably the best technology to use. For 10^7 to 10^9 bits, magnetic tape is superior. It may be more efficient to add a tape storage capability in excess of immediate need to allow for future expansion. The storage must be radiation hardened.

The RMS mass and power estimates include nonvolatile storage. To add nonvolatile, bubble memory storage to the ACS upgrade path would require between 10^6 and 10^7 bits for a modest number of functions. Estimates made using Galileo technology are 1.5 kg and 2 to 8 W of power for 10^6 bits of bubble memory and a 100k-bit/second data rate. The 2 W number assumes standby operation, and the 8 W estimate is for active operation. Increasing the capability to 10^7 bits will increase the power requirements to 3 W and 16 W, respectively. The mass requirement for a 10^7-bit memory is estimated to be 3 kg.

For mass storage (10^7 to 10^9 bits) a magnetic tape recorder system has been sized. The sizing is based on the Galileo tape recorder subsystem, and assumes redundant recorders with 9 x 10^8 bits of storage capacity each (one active, one in standby). The technology is radiation hardened. Mass for this design is estimated to be 18 kg. An average power of 3 W is required. During certain brief periods, peak power of 20 W may be required, but the impact of this peak load on the power subsystem is estimated to be negligible.

7.2.5 Add Distributed Processing

Expanded redundancy management capability can be realized by adding distributed processing units (DPUs) as described in Section 4.1.2 of Volume III. Strategies for incorporating the DPUs depend on whether previous steps expanded the ACS computer functions to include redundancy management.

Use of a maximum option RMS design in conjunction with DPUs should provide the capacity for redundancy management of the ACS and autonomous navigation functions as well as those of other spacecraft functions.

In the final Level 5 spacecraft there are likely to be as many as five major functions requiring DPUs. Before the addition of autonomous navigation, these could be Power, Attitude Control, Thermal Control, Telecommunication, and Propulsion. The payload is also likely to have its own autonomy. The RMS could manage payload redundancy with the addition of a DPU and control links. But, because this study did not assess payload autonomy, the potential payload DPU is not considered further.

When autonomous navigation is added, the propulsion DPU could be shifted to the autonomous navigation function because this will handle most autonomous propulsion functions, as described in Section 4.6 of Volume III.

As described in Section 4.1 of Volume III, redundant DPUs are estimated to weigh 3 kg and require 2 W of power, each. Thus, five redundant DPUs are estimated to weigh 15 kg and require about 10 W of power.

7.2.6 Add New Sensors for Attitude Control and Autonomous Navigation

Sensors which could allow orbital position determination could be added to the spacecraft and used for attitude control before the full autonomous navigation capability is installed. This would require significant changes in the ACS interface ports and logic. A side benefit of installation of sophisticated sensors would be that the restrictions would be eliminated which forbid maneuvers near noon and midnight because of the current sun sensor system. This would add operational flexibility to the ground maneuver system. Some very approximate estimates of mass and power requirements have been made for three examples of possible navigation sensors: space sextant, multimission attitude determination and autonomous navigation (MADAN), and a British autonomous stationkeeping system (ASKS).

Such sensors could be added at a number of points in the flow of autonomy additions. The time frame will be determined largely by the availability of technology. Revision of the ACS interfaces and logic to utilize these sensors is linked to their addition. With the new attitude control/autonomous navigation sensors added, the existing sun and earth sensors can be deleted, saving approximately 3.2 kg and 3.5 W. Structural implications, particularly with respect to fields of view, have not been addressed.

The system components, description of assumptions, and appropriate values are given for each example in the following paragraphs.

7.2.6.1 Space Sextant. Preliminary space sextant estimates for an operational system were obtained from two briefing chart sets (Reference 3). The minimum mass case is for a single space sextant aboard the spacecraft at minimum mass. The maximum mass is for a two-space-sextant, redundant set at maximum mass. Power figures assume only one unit operational with any other powered down. (It is not clear whether these are peak or average power figures.)

$20\ \text{kg} < \text{mass} < 55\ \text{kg}$

$45\ \text{W} < \text{power} < 60\ \text{W}$

7.2.6.2 MADAN Sensor Package. A potential MADAN (Reference 4) configuration is one of three star sensors and one earth sensor, with one star sensor inactive. Mass power figures for this configuration are a maximum of the baseline MADAN sensor, and a minimum for a lower-performance, strategic satellite (STRATSAT) version. These give:

$20\ \text{kg} < \text{mass} < 31\ \text{kg}$

$70\ \text{W} < \text{power} < 90\ \text{W}$

7.2.6.3 Autonomous Stationkeeping (ASKS). The configuration was developed for the European Space Research Organization (ESRO) and is documented in a British report (Reference 5). The sensor setup basically consists of a Polaris sensor, sun sensors, and an earth sensor. The configuration here consists of the on-board DSCS III earth sensors, and 6 ADCOLE sun sensors, two active at a time. The figures represent minimum weight, as no mounting, sun shade, or interface connection weights are included, with specific values obtained from Reference 6.

$22\ \text{kg} \approx \text{mass}$

$24\ \text{W} \approx \text{power}$

7.2.7 Add Autonomous Navigation Computer

Computer sizing for the autonomous navigation function will be performed as part of the autonomous DSCS III design phase. Some very rough estimates of computer characteristics have been extrapolated from the British ASKS configuration, including sufficient margin for fault detection/protection and growth. In terms of word length and memory requirements these are:

16 bits $<$ word length $<$ 32 bits
16k words $\lesssim$ memory size $\lesssim$ 32k words

Floating-point arithmetic capability is required for maximum efficiency of the design, coding, maintenance, and operation of navigation algorithms.

In any event, introduction of this large navigation computer to the system containing an expanded ACS computer or a large RMS computer, or both, will require executive-level decisions. Trade-offs will have to be made between having functions carried out at the lowest possible level for simplicity and reliability, and having a higher-level executive in control. An example is hydrazine tank selection. The RMS function affects tank selection in failure cases. The ACS places requirements on tank selection for center-of-mass control. The Navigation function influences tank selection through maneuver size and frequency requirements. A careful design trade-off is necessary to provide executive control of tank selection in a manner that satisfies the requirements of all these subsystems while minimizing the chances of conflict in control authority.

Since the RMS has access to the spacecraft command system, it may be in the best position to provide the executive function. The option also exists to combine the RMS, ACS, and Navigation functions in a single computer facility. At least one internally fault-tolerant computer is needed to maintain the integrity of the other computers. The RMS design includes internal fault tolerance.

A very rough estimate was made, using the RMS technology mass/power ranges, for the computer requirements given above. The RMS uses an 8-bit word. It was assumed that 16- and 32-bit words could be created by adding 8-bit word processors. Therefore, a 16k 16-bit machine was assumed equal to a 32k 8-bit machine. This would require one Galileo subchassis which would weigh about 3 kg, and would consume about 3 W of power. Additional memory could be added for about 2 kg/2 W to bring the processor to 128k 8 bits, or the equivalent of a 32k 32 bit processor. Therefore, the upper limit of the range for an autonomous navigation computer should be about 5 kg and 5 W total. Redundant autonomous navigation computers will be necessary plus executive control by a fault-tolerant computer. Therefore, the total impact will be 10 kg and 5 W for the larger two computers, or 6 kg/3 W for the smaller computers, with one computer powered at a time.

7.2.8 Autonomous Options for Telecommunication Functions

Volume III describes options for adding autonomy to the Telecommunications functions. Sections 4.1.3 and 4.5.3 of Volume III describe autonomous options for the Telemetry function. Section 4.5.4 of Volume III discusses autonomy options for the Command functions. Section 4.7.1 of Volume III presents options for increasing the autonomy of the Tracking function.

Table 7-4 summarizes the mass and power estimates for these telecommunication autonomy options. Some of the autonomy options rely on an RMS, others are independent. In any event, selection of telecommunication autonomy options is independent of other autonomy options which might be chosen. Telecommunication is only required for the 60-day/6-month requirement for unattended spacecraft operation to be met because of a requirement for an X-band TT&C downlink for payload user tracking, timing, and telemetry. These functions could be retained by providing telecommunication autonomy, or by providing a direct, X-band downlink to payload control for payload functions. The latter option will impact payload control ground operations. However, meeting other autonomy goals in Reference 2 would require telecommunication capability, viz, both telemetry for audit trails, and command for ground executive control of autonomous functions.

Table 7-4. Telecommunication Function Autonomy Options -- Rough Mass and Power Estimates

OPTION	MASS, kg	POWER, W	COMMENT	VOL. III REFERENCE
I. MAINTAIN TELEMETRY				
A. ON/OFF SEQUENCER	0.5	0.5		4.1.3
B. RF POWER MONITOR	0.3	0.5	NO CHANGE WITH RMS	4.5.3.1
C. TELEMETRY FAILURE SENSING	---	---	PART OF RMS	4.5.3.2
D. DIRECT FAILURE SENSING	6 TO 12	10 TO 20		4.5.3.3
II. MAINTAIN COMMAND				
A. USE AS IS	0	0		4.5.4.1
B. S-BAND COMMON FREQUENCIES	0.3	0.3		4.5.4.2
C. X-BAND DUAL CARRIER	0.5	20	BOTH COMMUNICATION SUBSYSTEM FREQUENCY STANDARDS ON AND BOTH DECRYPTERS ON	4.5.4.3
D. TELEMETRY FAILURE SENSING	---	---	PART OF RMS	4.5.4.4
E. DIRECT FAILURE SENSING	5 TO 10	8 TO 16		4.5.4.5
F. CYCLIC COMMAND "NOT TO SWITCH"	1.0	1.0		4.5.4.6
III. MAINTAIN TRACKING				
A. XMT RCV FUNCTIONS			SAME AS I AND II ABOVE	4.1.3,4.5.3, 4.5.4
B. LEAVE RANGING ON	0.0	0.0	NORMAL OPERATIONAL MODE	4.7.1.1
C. RANGING ON CYCLIC	0.5	0.5		4.7.1.2
D. S-BAND STABLE OSCILLATOR	6.0	12.0		4.7.1.5
E. S-BAND STABLE OSCILLATOR USE SHF OSCILLATOR	0.5	0.5	SYNTHESIZE FROM COMMUNICATION SUBSYSTEM REFERENCE	4.7.1.6

NOTE: ALL ESTIMATES ARE ROUGH AND INTENDED ONLY TO GIVE AN APPROXIMATE MASS AND POWER RANGE.

The options listed in Table 7-4 are roughly in order of increasing difficulty, and increasing mass/power impact. Specific paragraphs in Volume III which refer to each option are referenced. Note that the on-off sequencer is a precursor addition for many of the other autonomous functions, but that the other additions are relatively independent.

7.2.9 Relation of Autonomy Options to Current DSCS III Design

Figure 6-2 (see Section 6.1.2) is a subsystem level, block diagram of the existing DSCS III design. Existing block and functional redundancies are shown, as are links between subsystems. Figures 7-3(a) and 7-3(b) illustrate an example of how one option to create a Level 5 autonomous spacecraft could be added to the existing design. Figures 7-3(a) and (b) correspond to Path 3 of Figure 7-2 (the mixed strategy). Paths 1 and 2 of Figure 7-2 can be similarly related to the existing DSCS III block diagram.

Other options are possible, of course, including those where subsystem boundaries are redefined or whole subsystems are replaced. For example, in Path 2 the RMS might be designed to completely replace the ACS and autonomous navigation computers, resulting in a combined central computing subsystem. The diagrams shown in Figures 7-3(a) and (b) are merely to put the autonomous options in a DSCS III subsystem perspective. Actual implementation of autonomy will be addressed in the forthcoming design task.

In Figure 7-3(a) the first five steps of Figure 7-2 are shown as they might be added to the existing DSCS attitude control and TT&C subsystems. Up to 18k words of redundant ROM or RAM could be added to the ACS computer. (Other possible additions such as gyros are possible, but are not illustrated here.) The RMS could be added to interface only with the TT&C, and the DPUs and nonvolatile storage would interface with the existing TT&C system through the RMS.

Figure 7-3(b) illustrates how the further addition of the autonomous navigation function could be accomplished. New attitude control/autonomous navigation sensors replace the existing attitude control sensors and interface both with the (possibly upgraded) ACS and with the new autonomous navigation computer. An interface between the propulsion system and the autonomous navigation computer is also added. The RMS is revised to function in an additional capacity as an executive for the autonomous navigation computer. Additional control and data lines could be added to let the RMS function as an executive for the ACS computer, as well.

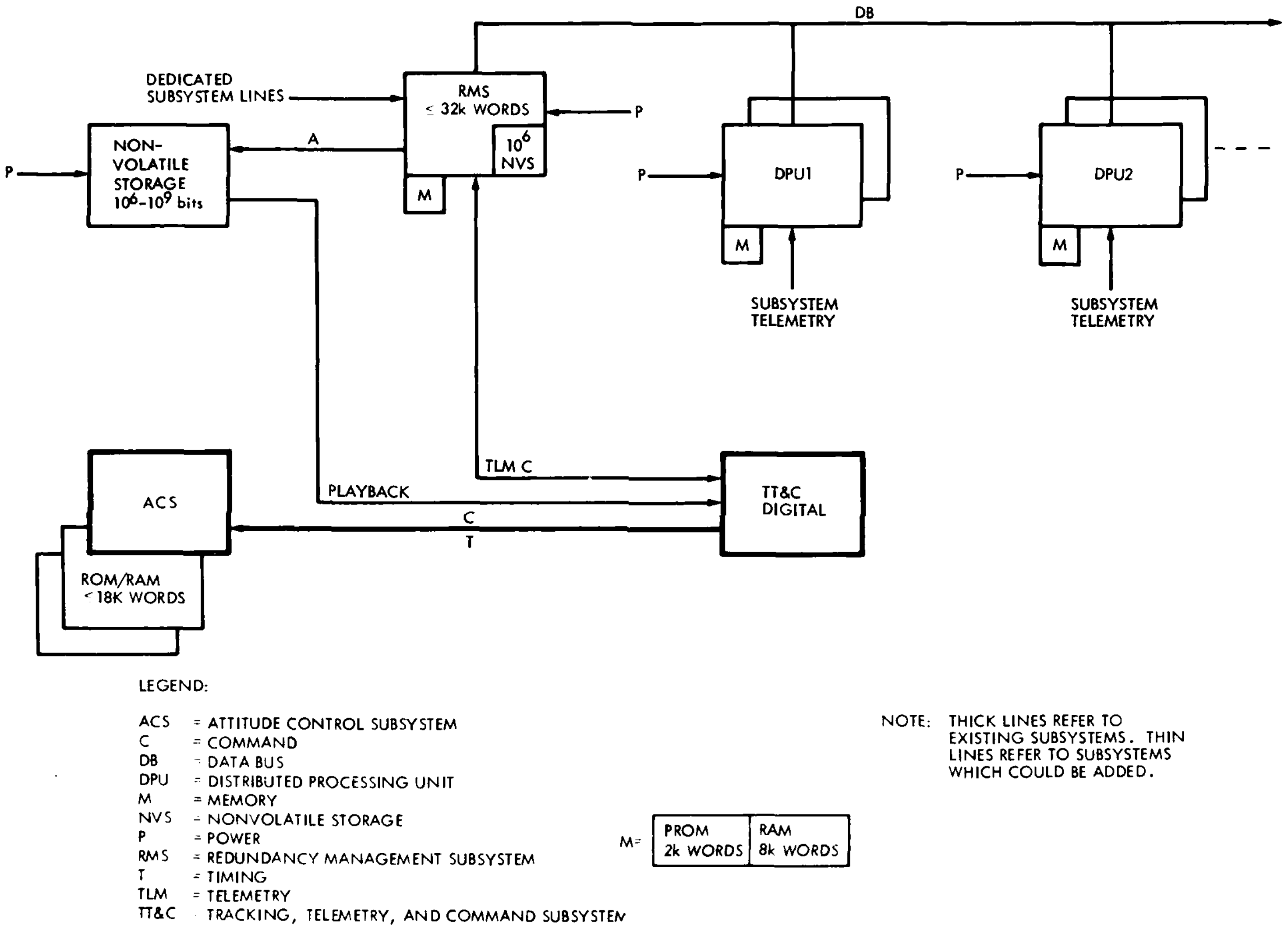
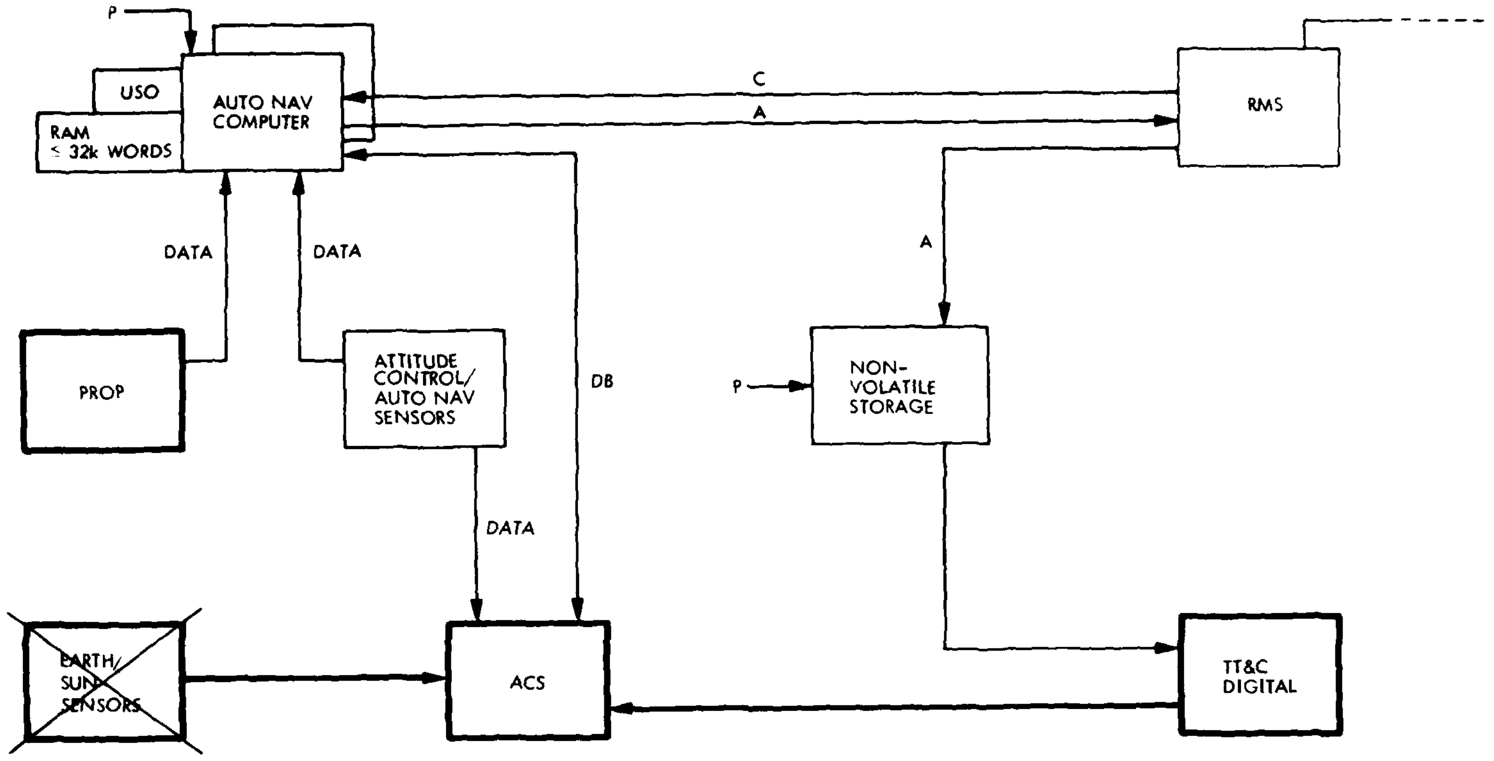


Figure 7-3a. Example of Mixed Strategy Path Additions to the Existing DSCS III System: First Five Steps



LEGEND:

A = AUDIT TRAIL
ACS = ATTITUDE CONTROL SUBSYSTEM
C = COMMAND
DB = DATA BUS
P = POWER
PROP = PROPULSION SUBSYSTEM
RMS = REDUNDANCY MANAGEMENT SUBSYSTEM
TT&C = TRACKING, TELEMETRY AND COMMAND SUBSYSTEM
USO = ULTRA STABLE OSCILLATOR

X = THESE SENSORS CAN BE DELETED IF THE ATTITUDE CONTROL/AUTO NAV SENSORS ARE ADDED

NOTE: THICK LINES REFER TO EXISTING SUBSYSTEMS. THIN LINES REFER TO SUBSYSTEMS WHICH COULD BE ADDED.

Figure 7-3b. Example of Mixed Strategy Path Additions to the Existing DSCS III System: Last Two Steps

7.3 SUMMARY OF MASS/POWER/COMPLEXITY IMPACT PRELIMINARY ESTIMATES

In addition to the obvious impacts of autonomy on spacecraft mass and power, there are impacts on the design in terms of complexity. The Level 5 autonomous spacecraft may have up to 10 active computer processors on board containing up to 2×10^6 bits of information. In addition, nonvolatile data storage of up to 10^9 bits may be required. The hardware design of these computing elements appears relatively straightforward, and potential hardware solutions are described in Volume III. However, JPL experience (and the general experience of computer users) has shown that the design, validation, and operation of systems which include large amounts of computing capability is a challenging problem.

Section 7.3.1 discusses estimates of the mass/power impacts of autonomy. Section 7.3.2 discusses estimates of the complexity impacts of autonomy.

7.3.1 Spacecraft Autonomy Mass/Power Impacts

In order to provide a range of possible impacts of implementing Level 5 autonomy, the mass and power estimates of implementing the RMS path (Path 2 of Figure 7-2) have been summarized in Figures 7-4 and 7-5. These figures illustrate the range of impacts attendant on adding the RMS to the long-term storage, the DPUs, the autonomous navigation sensors, and the autonomous navigation computer, in steps. The top line represents the maximum total mass/power added by each step, the bottom line represents the minimum. The figures show that redundancy management may be accomplished with "modest impact," but autonomous stationkeeping is likely to require "extensive" modification. The figures show a range of 55 to 131 kg and 47 to 127 W, for the fully autonomous spacecraft additions, excluding health and welfare state sensors, propulsion impacts, and spacecraft structural changes which might be necessary to implement the autonomy features.

The lower end of the mass and power impact range would be a more-or-less "modest" impact to the DSCS III satellite, while the upper end of the range would mean "extensive" impacts (up to 15% of mass). However, mass additions of as much as 50% are planned in future DSCS III block procurements, where the spacecraft dry mass is planned to be as much as 1200 kg for a satellite incorporating autonomous fault protection and stationkeeping.

Since mass/power estimates on the ACS microcomputer are unavailable, a summary of the "ACS upgrade" path cannot be provided. The impacts will likely be higher than the RMS path because:

(1) The computer technology is older and more mass and power intensive, and

(2) Additional I/O devices and connectors are required to duplicate existing TT&C control links.

Impacts of any desired telecommunication autonomy would be over and above those summarized in Figures 7-4 and 7-5. The mass estimates in Figure 7-4 were derived by adding some (power and cabling) of the secondary mass impacts, described in the following paragraphs, to the mass estimates from Table 7-3.

The additional power requirements of the autonomous functions will require increased power from the DSCS III power subsystem. Some rough rules of thumb have been used to estimate the mass impact of these power increases. No attempt was made to deal with power profiles in making these estimates. The total additional mass required is about 0.13 to 0.15 kg/W of additional power required. Power requirements were taken from Table 7-3. The mass range is based on current and near-future technology for solar panels, and on nickel-cadmium batteries.

Additional connectors and cabling will be required to implement the autonomous functions. These could add considerable mass to the spacecraft. However, this is dependent on:

(1) The number of connections.

(2) The routing strategies.

(3) The connector/cable materials.

Rule-of-thumb estimates of the mass impacts of cabling and connectors result in an increase in the mass of autonomy options of 5 to 10%.

Significant increases in spacecraft mass will increase the propellant requirements for attitude control and maneuvers. This will either result in a shorter on-orbit life, or will require a larger propulsion system with, in turn, increased overall spacecraft mass. Propulsion impacts have not been estimated.

The estimates of mass and power do not include potential added spacecraft state sensors which may be required to implement the autonomous features. Therefore, the estimates assume that the existing telemetry data are adequate for on-board autonomy computations. Future design efforts may reveal the need for additional state sensors, which would add an unknown, but probably small amount of mass and power requirements.

Adding the autonomous components to the spacecraft will require that they be attached to the spacecraft structure. The impact of structural fasteners, brackets, or changes to the structure itself has not been included.

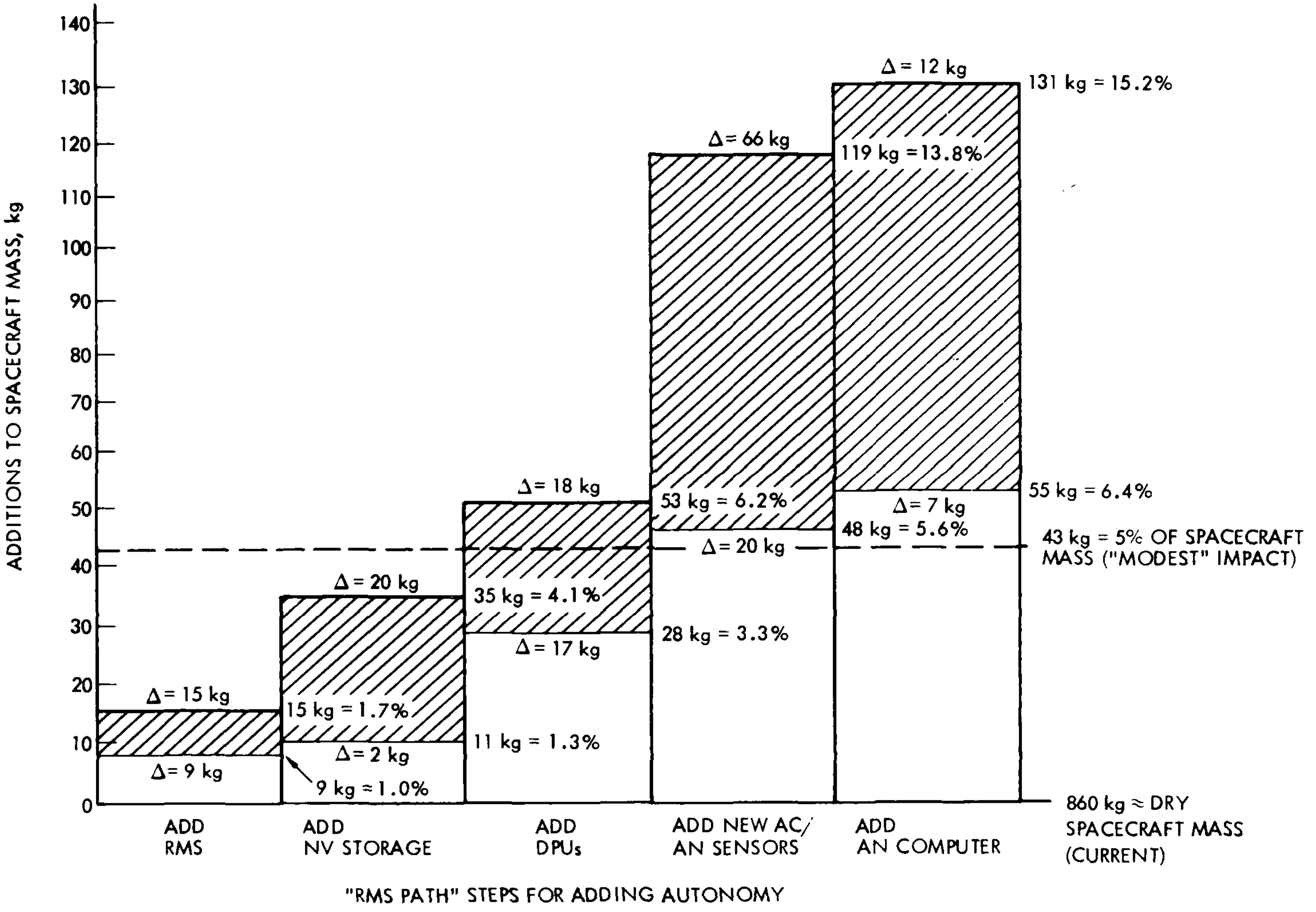


Figure 7-4. Preliminary, Estimated Mass Impacts of Autonomous Additions, Excluding Structure, Propulsion, and State Sensors

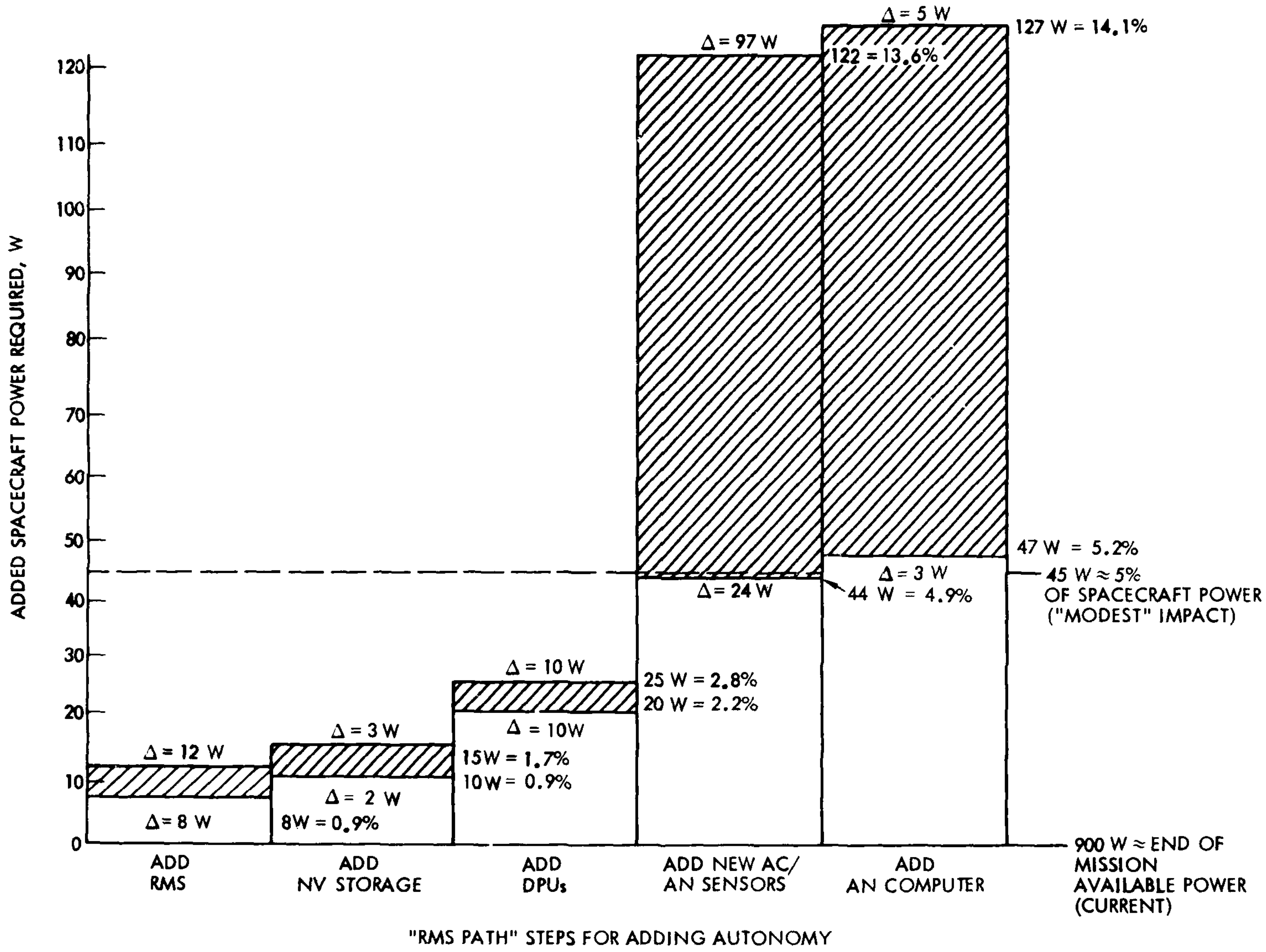


Figure 7-5. Preliminary, Estimated Power Impacts of Autonomous Additions, Excluding State Sensors

Addition of features for the autonomy of the Telecommunications functions will depend on how the TT&C functions of Command, Telemetry,and Tracking are utilized when the spacecraft is made autonomous. Some of the telecommunication autonomy options in each category (telemetry, command, tracking) shown in Table 7-4 can be added together. For example, the on/off sequencer and radio frequency (RF) power monitors in the telemetry options could be added separately or in combination. However, options designated as d, e, or f are probably best implemented singly. Thus, telecommunication autonomy impacts can be added, as desired, to the mass and power estimates in Figure 7-4 and 7-5.

Telecommunication autonomy can be implemented at a cost of 0.3 to 35 kg in mass, and 0.3 to 52 W of power, excluding structure and propulsion impacts.

7.3.2 Spacecraft Autonomy Complexity Impacts

Complexity is difficult to express in simple terms. Figure 7-6 presents two measurements: (1) the number of active computer processors and (2) bits of information contained on board in the active processors. Figure 7-6 differs from Figure 7-4 and 7-5 in that the mixed strategy (Path 3 in Figure 7-2) is displayed in Figure 7-6. This shows the cumulative effect if the ACS were upgraded and the RMS, DPUs, and the autonomous navigation computers were added to create a Level 5 spacecraft. This path could result in as many as 10 active processors being on board. These processors could contain between 704k and 2032k bits of information in active memory. An additional 10^6 to 10^9 bits could be required for nonvolatile storage.

JPL's Viking, Voyager, and Galileo experience and the USAF Defense Meteorological Satellite Program (DMSP) experience are included in Figure 7-6 for reference. This illustrates that, in terms of total active processing complexity, the Level 5 autonomous spacecraft would be somewhere betweeen Voyager (349k bits in 4 active processors) and Galileo (1984k bits in 18 active processors). About 20% of this capacity is devoted to fault protection on the JPL spacecraft. The remainder of the capacity is for sequences to provide services to the payload of science instruments. JPL is currently developing the Galileo spacecraft and support system, and has discovered that the task of designing and validating a computer system of this complexity is formidable. It is expected that systems design and validation of a Level 5 autonomous spacecraft may be equivalent. For USAF projects, a major advantage will be realized when the investment associated with this process can be amortized over a class of similar defense satellites.

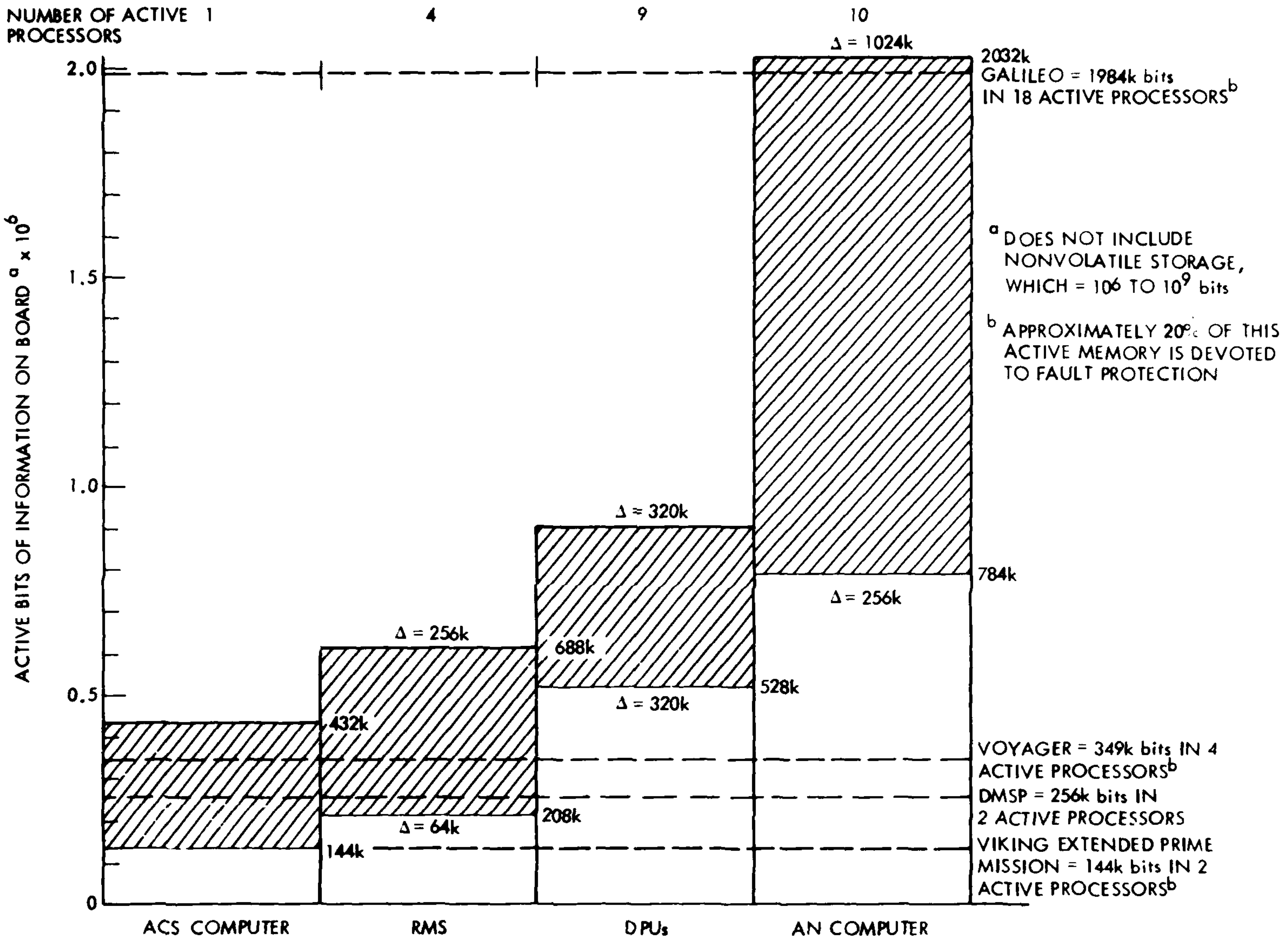


Figure 7-6. Preliminary, Estimated Impacts of Complexity Expressed in Number of Active Computer Processors and Bits of Information

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GLOSSARY

ACRONYMS, SYMBOLS, AND TERMS

A	audit trail
AC	attitude control
AN	autonomous navigation
ASKS	autonomous stationkeeping system
ASP	Autonomous Spacecraft Project
BFN	beam forming network
C	command
Category I	required for 60-day/6-month autonomy
Category II	required for increased lifetime/flexibility
Category III	autonomy not required
CCS	computer command subsystem
Class A	software changes only
Class B	modest additions
Class C	extensive additions
Class D	redesign
CMOS	complementary metal oxide semiconductor
COMM	communication
CPU	central processing unit
D	drive signal
DB	data bus
DC	direct current
DMSP	Defense Meteorological Satellite Program
DPU	distributed processing unit
DSCS	Defense Space Communications System
E	earth presence signal
EED	electroexplosive device
EPDS	electric power distribution subsystem
ESRO	European Space Research Organization
ETS	Eastern Test Range
G	ground
GDA	gimbal dish antenna
I/O	input/output
JPL	Jet Propulsion Laboratory
M	memory
MADAN	multimission attitude determination and autonomous navigation
MBA	multibeam antenna
NV	nonvolatile
NVS	nonvolatile storage

P	power
POT	potentiometer
PROP	propulsion subsystem
RAM	random-access memory
RCV	receive
RF	radio frequency
RMS	redundancy management subsystem
ROM	read-only memory
S	AM synch
SAD	solar array drive
S/C	spacecraft
SCT	single channel transponder
SHF	superhigh frequency
STRATSAT	strategic satellite
T	timing
TBD	to be determined
TCS	thermal control subsystem
TLM	telemetry
TT&C	tracking, telemetry, and command subsystem
UHF	ultrahigh frequency
U.S.A.	United States of America
USAF	United States Air Force
USO	ultra stable oscillator
XMT	transmit

APPENDIX A

LEVELS OF AUTONOMY

(Reproduced directly from Reference 1)

In performance of a space mission, four major policy goal categories have been identified. These are:

(1) Ground interaction reduction.

(2) Spacecraft integrity maintenance.

(3) Autonomous features transparency.

(4) On-board resource management.

The extent to which these goals have been accomplished to date has been through a mix of functions resident in either the space segment or the ground segment. Furthermore, the ground segment, as an integral part of the total system, has been responsible for accomplishing maintenance, navigation mission control, and payload data processing. Thus, only minimal spacecraft autonomy has been needed.

The levels of autonomy described in this appendix are used to define a step-wise increase in spacecraft autonomous capability. By proceeding through the levels, autonomous capability is increased in the space segment and dependency on the ground segment is reduced.

The levels of autonomy are described as follows:

Level 0. A design without redundant elements which meets all mission needs by operating without the on-board control of state parameters (such as rates and position). May respond to a prespecified vocabulary of external commands, but cannot store command sequences for future time-or event-dependent execution or validate external commands. (An open-loop, on-board system controlled from the ground.)

Level 1. Includes Level 0 but uses on-board devices to sense and control state parameters (such as rates and positions) in order to meet performance needs. Is capable of storing and executing a prespecified command sequence based on mission-critical time tags. Will respond to prespecified external commands, but cannot validate external commands. Functionally redundant modes may be available for a degraded-performance mission.

Level 2. Include Level 1 plus the use of block redundancy. Ground-controlled switching of spare resources is required. Uses cross-strapping techniques to minimize effect of critical command link (uplink) failure modes. Significant ground-operator interaction is required to restore operations after most faults if spare spacecraft resources are available.

Requires operator interaction for fault recovery. Is capable of storing and executing mission-critical events which are sensed on-board and may be independent of time.

Level 3. Includes Level 2 and is capable of sensing prespecified mission-critical fault conditions and performing predefined self-preserving (entering a safe-hold state) switching actions. Is capable of storing contingency or redundant software programs and being restored to normal performance (maintaining the command link with a single link fault) in the event of a failure. Timers may be used to protect resources. Requires ground operator interaction for fault recovery. In general, the failure to sense and/or execute the mission-critical event(s) will cause mission failure or loss of a major mission objective.

Level 4. Includes Level 3 but is also capable of executing prespecified and stored command sequences based on timing and/or sensing of mission events. Ground-initiated changes to command sequences may be checked on-board for syntactical errors (parity, sign, logic, time). Uses coding or other self-checking techniques to minimize the effects of internally generated data contamination for prespecified data transfers. Requires ground-operator interaction for fault recovery. In general, failure to sense and/or execute the mission event(s) or state-changes (excluding failure-induced state-changes) will cause mission failure or loss of a major mission objective.

Level 5. Includes Level 4 and is also autonomously fault-tolerant. Is capable of operating in the presence of faults specified a-priori by employing spare system resources, if available, or will maximize mission performance based upon available capability and/or available expendables (i.e., self-loading of contingency programs) without ground intervention.

Level 6. Includes Level 5 and is capable of functional commanding with on-board command-sequence generation and validation prior to execution. Functional commanding may include a high-level, pseudo-English language, spacecraft-system/operator communication and control capability.

Level 7. Includes Level 6 and is capable of autonomously responding to a changing external environment, defined a-priori, so as to preserve mission capability. The capability to change orbit in order to compensate for degradation or to protect the satellite from an external threat is included.

Level 8. Includes Level 7 and is capable of operating successfully within the presence of latent design errors which could cause loss of major mission objectives.

Level 9. Includes Level 8 and is capable of task deduction and internal reorganization based upon anticipated changes in.the external environment. This situation is exemplified by multiple satellites operating in a cooperative mode. In the event of a satellite failure, remaining satellites would detect autonomously the condition (task deduction) and may generate and execute orbit-and spacecraft-reconfiguration commands.

Level 10. Includes Level 9 and is capable of internal reorganization and dynamic task deduction based on unspecified and unknown/unanticipated changes in external environment. The system will strive to maximize system utility. Thus, mission objectives should be adaptive and automatically reprogrammable. System resources should be maximized to preserve task adaptiveness.

APPENDIX B

CLASSIFICATION DEFINITIONS

Levels of Autonomy: An arbitrarily defined scale, ranging from "0" to "10", is used to define a stepwise increase in spacecraft autonomous capability. These levels are defined in Appendix A.

Function Categories: Three categories are defined for spacecraft functions:

(1) Provide services to payload.

(2) Manage spacecraft resources.

(3) Maintain integrity of spacecraft.

See Section 6.1.2 for a more complete discussion of functional categories.

Functional Classes of Activities: Within each functional category, defined above, three classes of activity are necessary:

(1) Sense (or perceive a need).

(2) Direct (and control an action plan).

(3) Act (execute the plan).

Table 6-1, Section 6.1.2, relates the function categories to the class of activities, and the related discussion on Page 20 and 21 expands upon these definitions.

Prioritization Categories: Not all spacecraft functions need be made autonomous in order for the spacecraft to meet its predefined goals. Functions were therefore prioritized into three categories of importance:

(1) Category I: Functions which must be performed autonomously for the spacecraft to meet the 60-day/6-month requirement.

(2) Category II: Functions which must be performed autonomously for lifetime protection (battery conditioning, etc.) or which, if performed autonomously, would increase the operability or operational flexibility of the spacecraft.

(3) Category III: Functions not requiring autonomy.

Section 6.1.3.2 discusses the basis for the categories.

Implementation Difficulty: It is recognized that it will be more difficult to implement some autonomous functions than others. Classes of difficulty are defined as follows:

Class A = Software changes only
Class B = Modest additions
Class C = Extensive additions
Class D = Redesign

Section 6.1.3.3 amplifies these definitions.