JPL PUBLICATION 81-106

Automated Power Systems Management (APSM)

Final Report

A.O. Bridgeforth

November 15, 1981

NASA
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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

ABSTRACT

A breadboard power system incorporating autonomous functions of monitoring, fault detection and recovery, command and control was developed, tested and evaluated to demonstrate technology feasibility.

Autonomous functions including switching of redundant power processing elements, individual load fault removal, and battery charge/discharge control were implemented by means of a distributed microcomputer system within the power subsystem. Three local microcomputers provide the monitoring, control and command function interfaces between the central power subsystem microcomputer and the power sources, power processing and power distribution elements. The central microcomputer is the interface between the local microcomputers and the spacecraft central computer or ground test equipment.

This was the first JPL demonstration of an autonomous, software configurable spacecraft power subsystem. Key autonomous functions were demonstrated including: (a) decreased fault response time from 2 hours (Viking Orbiter (VO75) spacecraft in Mars orbit) to 2 seconds, software selectable time and independent of earth-spacecraft distance or communication link; (b) increased accuracy of power subsystem on-board performance assessment, without increasing telemetry channel allocations, fifteen functions assessed on the breadboard vs. four on the VO75 flight configuration; (c) power processing subassembly fault detection and recovery; (d) individual load monitoring, fault detection and recovery; (e) battery charge control, subassembly performance monitoring, power margin management, and data acquisition, processing and storage.

The automation technology results achieved on this program are useable and will be used on future flight projects. The flexibility afforded by software

configurable load management, redundancy management, and telemetry content provides a new capability for cost effective adaptability to meet planned or unplanned performance requirements during a mission and to minimize hardware design changes to meet new mission requirements.

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SECTION 1

INTRODUCTION

This document is the final report of the Automated Power Systems Management (APSM) program. The APSM program began in 1975 at the Jet Propulsion Laboratory (JPL) and was sponsored by NASA OAST. The program was completed in September 1981. The purpose of the program was to develop and demonstrate the technology required and benefits of autonomous operation of spacecraft power systems to meet the projected requirements of future space missions. This was to be accomplished by: (1) an empirical verification of the benefits to be derived from implementing onboard computational capabilities in a power subsystem, including an accurate assessment of power subsystem performance, detection and correction of equipment faults, and management of user loads; (2) identification of items of advanced technology whose development is necessary to obtain full benefits of onboard computational capability; and (3) to demonstrate an automated breadboard system, based on state-of-the-art power system design.

The APSM concept was developed from studies performed to identify new technologies necessary to provide the performance requirements of future planetary power systems. The results of the studies showed that increased reliability and increased autonomous operation were primary requirements for the long-duration missions to the outer planets which were being considered. Implementation of increased reliability and autonomous operation can have an impact on other power system parameters, i.e.: specific power, cost, etc. Figures 1-1 through 1-9 provide a perspective of these parameters, based on power system state-of-the-art, Viking Orbiter spacecraft (VO75) in 1975.

Figure 1-1 shows how the fault tolerance of power subsystems has improved since the early 1960s. The implementation of functional redundancy, maintenance of maximum performance, and command verification on the Next Generation Power subsystems (as shown in the figure) will be accomplished through increased onboard computational capability, utilizing fault tolerant computers. Power subsystem reliability requirements have been increasing dramatically (as shown in Figure 1-2) as a result of increasing mission durations. The long round-trip light time of outer planet missions emphasizes the need for increasing reliability and fault tolerance because of the decreased capability of responding to problems by ground analysis and command, in a timely manner. The increasing power subsystem flexibility requirements (as measured by the number of loads, telemetry words, and separate commands) are illustrated in Figure 1-3. The major increase has been in the number of commands which reflect the increased number of loads, the increased number of switched functions within the power subsystem, and increased redundancy. Power subsystem automation has increased from none on the early Mariner and Ranger power subsystems to protection of the primary power buses on Voyager and Galileo (as shown in Figure 1-4). All of these automation functions were implemented with hardwire logic. Increased automation capability must be implemented in software in future power subsystems to minimize the penalty of increased mass and complexity associated with hardwire logic. Figure 1-5 shows a relatively modest increase in onboard computational capability prior to the Galileo project. The increased computational capability of the Galileo spacecraft reflect the increased requirements on the attitude control, computer command and sequencer, and flight data subsystems.

Although the requirements imposed on power subsystems have increased greatly since the early Mariner and Ranger spacecraft (as shown in the

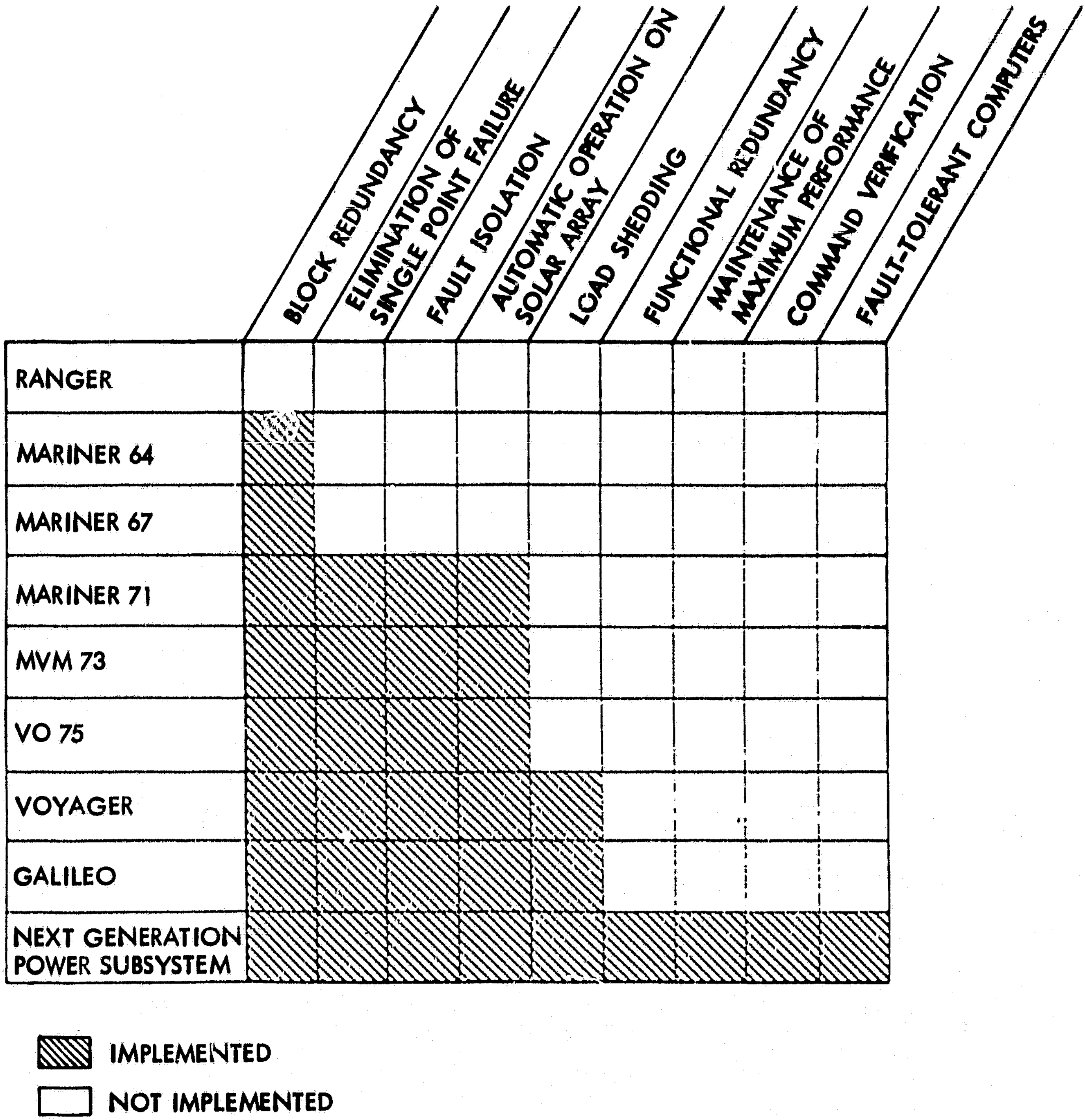

Figure 1-1. Fault Tolerance of Power Subsystems

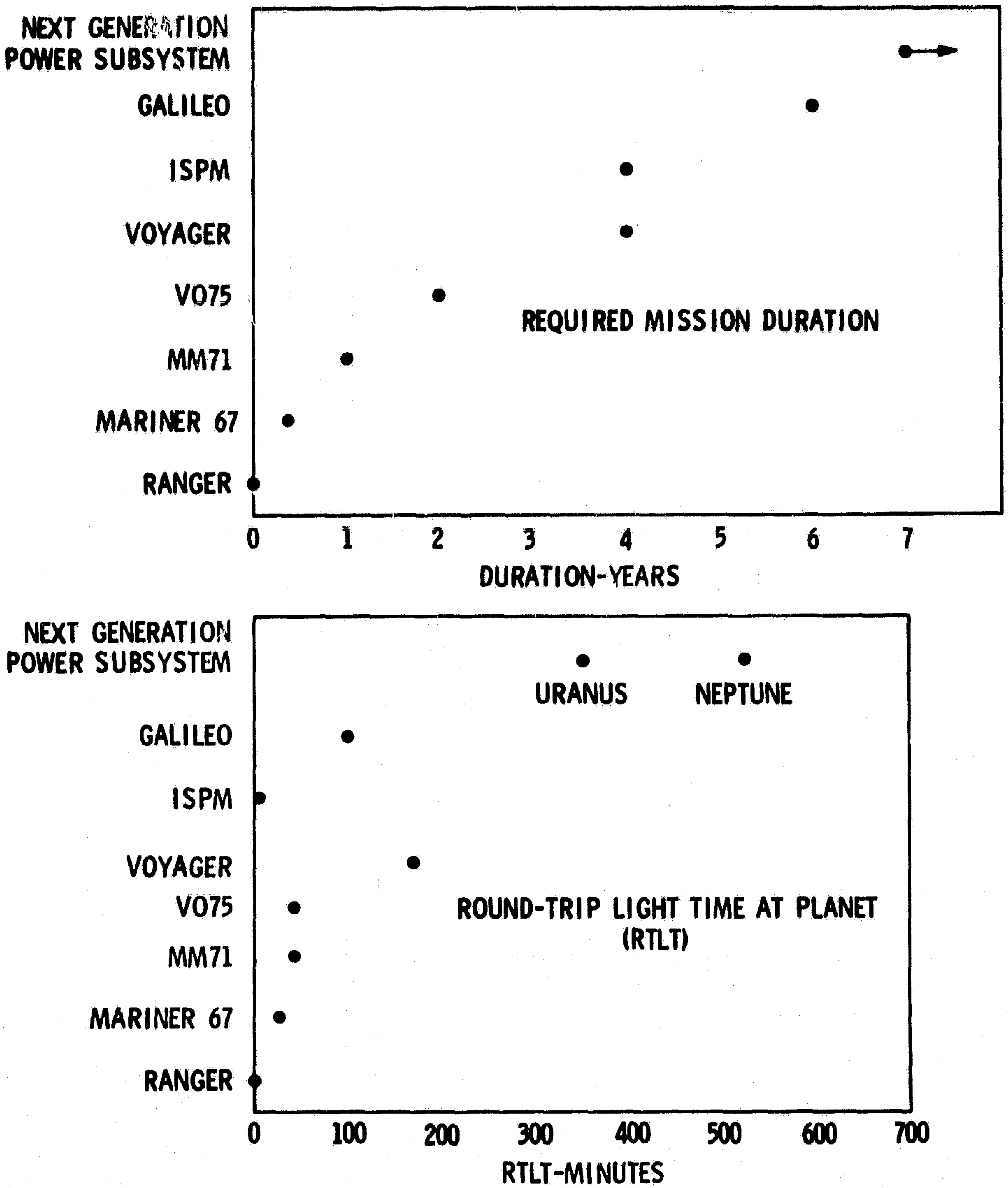

Figure 1-2. Power Subsystem Reliability Requirements

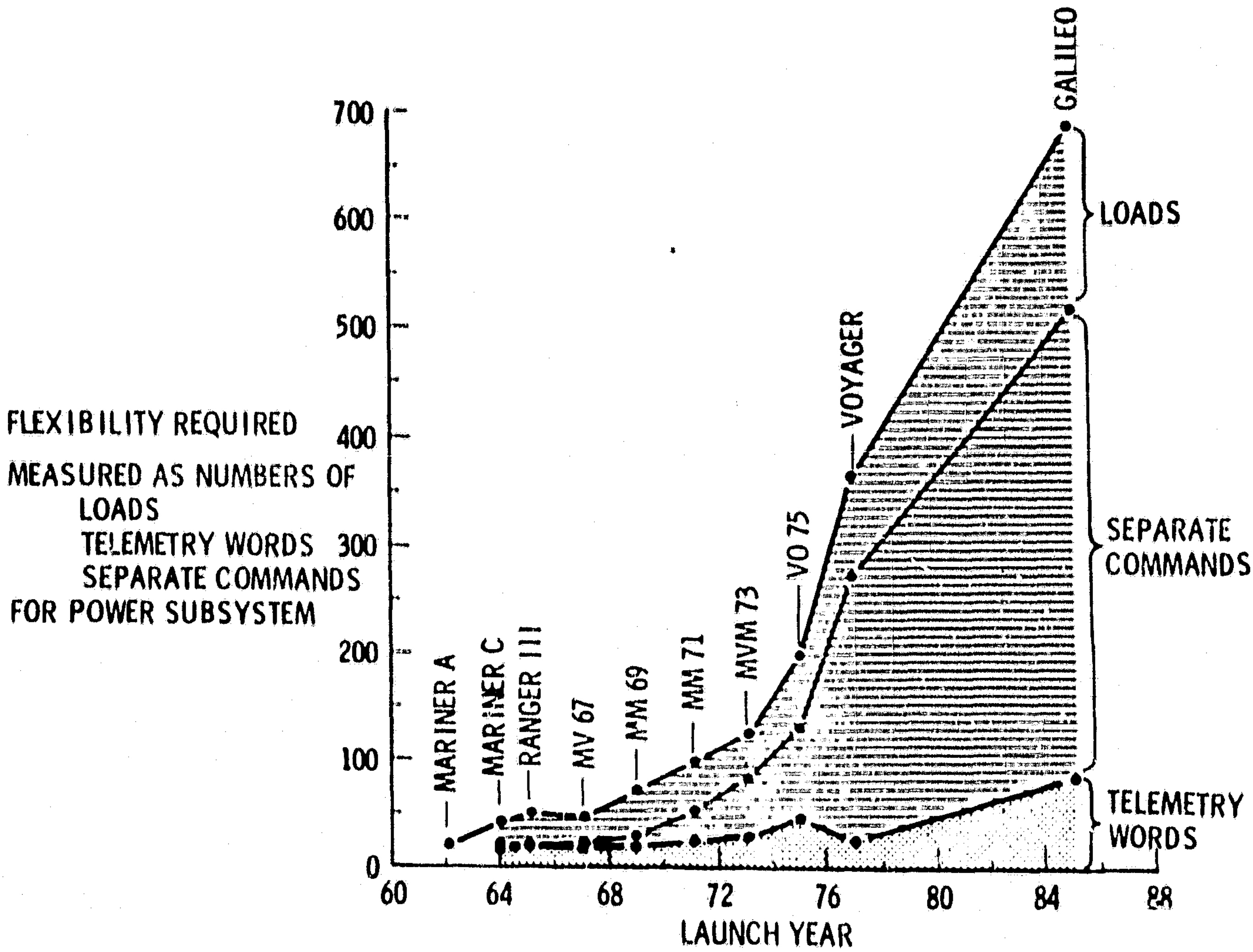

Figure 1-3. Power Subsystem Flexibility Requirements

	1959 - 1962	1963 - 1970	1971 - 1975	1976 - 1980	1981 - 1984
GALILEO					• UNDER VOLTAGE BLOCK LOAD DUMP
VOYAGER				• UNDER VOLTAGE BLOCK LOAD DUMP	• UNDER VOLTAGE AC BUS - MAIN/ STANDBY INVERTER SWITCHOVER
VIKING AND MARINER 71-73			• HIGH RATE/ LOW RATE BATTERY SWITCHOVER	• UNDER VOLTAGE AC BUS - MAIN/ STANDBY INVERTER SWITCHOVER	
MARINER 64-69		• SHARE MODE SENSE AND BOOST CONTROL	• SHARE MODE SENSE AND BOOST CONTROL		
EARLY MARINER AND RANGER	• NO AUTOMATED POWER FUNCTIONS	• MAIN/ STANDBY-BOOSTER REGULATOR AND INVERTER SWITCHOVER	• MAIN/ STANDBY BOOSTER REGULATOR AND INVERTER SWITCHOVER		

Figure 1-4. Power Subsystem Automation

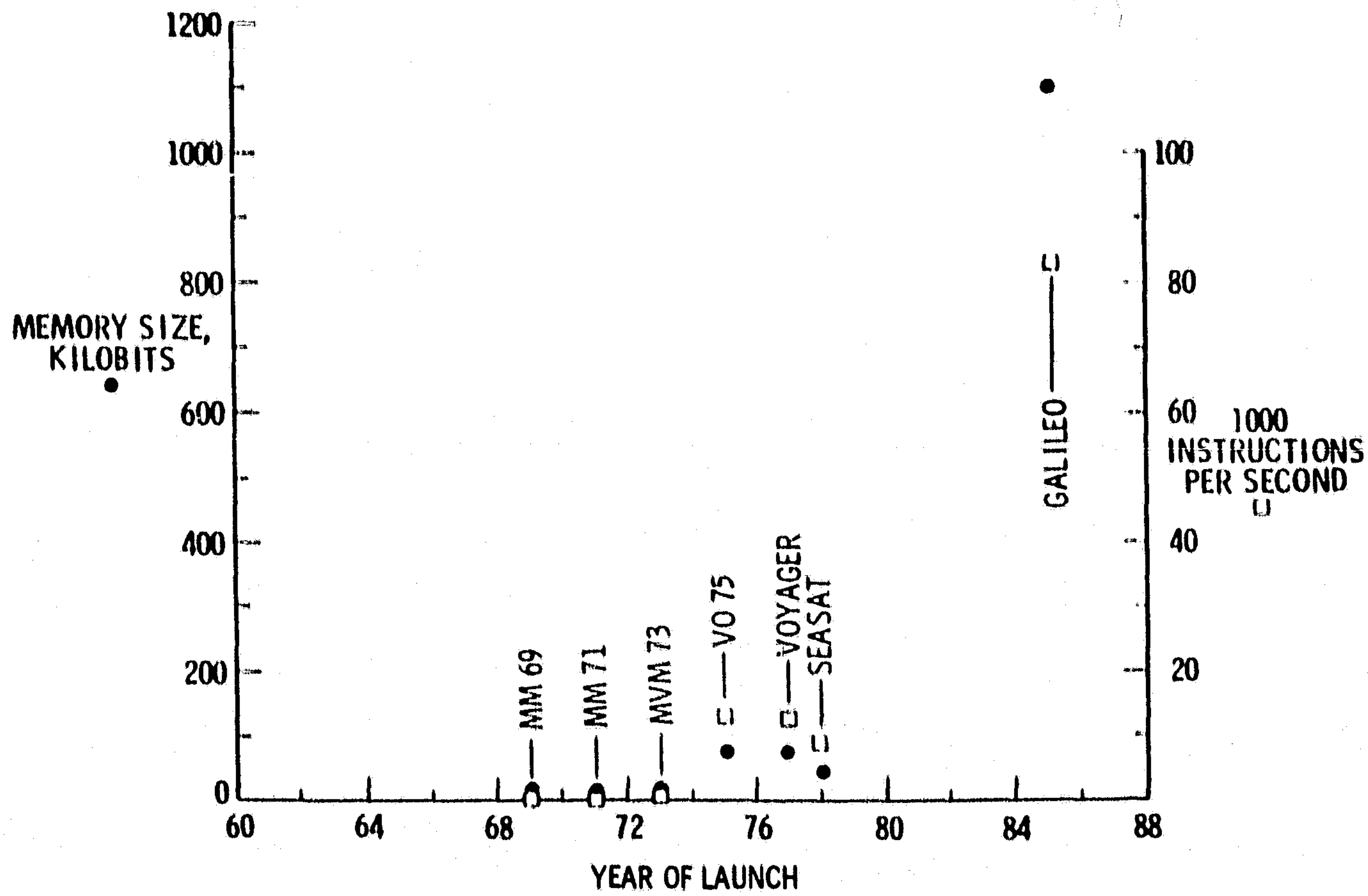

Figure 1-5. Onboard Computational Capability

previous figures) the specific power has remained relatively constant between 3-5 W/kg. The specific power of several spacecraft power subsystems is plotted in Figure 1-6. This data is for the total power subsystem including their respective power sources, solar array/batteries, or RTGs. Figure 1-7 shows the specific power for the power processing electronics, excluding the power sources. The general decrease in specific power since MM69 reflects the increasing functional and redundancy requirements imposed on the power subsystem. Power subsystems for the "Next Generation" spacecraft are projected to have a much higher specific power, if the benefits of automation and other new technologies are implemented.

The data in Figure 1-8 was plotted to show the historical trend of power subsystems cost. Although the cost trend is generally positive, several perturbations are obvious: i.e., MM71, VO75, and Galileo. These perturbations are a result of three principal cost drivers; design/hardware inheritance, electrical design complexity, and quantity of hardware fabricated. The MM71 power subsystem was an 80% design inheritance and 30% hardware inheritance from the MM69 project which resulted in a significantly lower cost. The VO75 power subsystem, however, incorporated less than 10% design inheritance, no hardware inheritance and included 23% more hardware fabrication than MM71. The Voyager power subsystem cost reflects a much less complex design than VO75 and approximately 30% less hardware fabrication. Based on the foregoing data, it appears evident that significant cost reductions for Next Generation power subsystems will require a high degree of design inheritance (flexibility), simple designs, and a stringent control of total hardware fabricated.

The post-launch costs of power subsystems are plotted in Figure 1-9. As anticipated, the costs are closely correlated to the mission durations; i.e.,

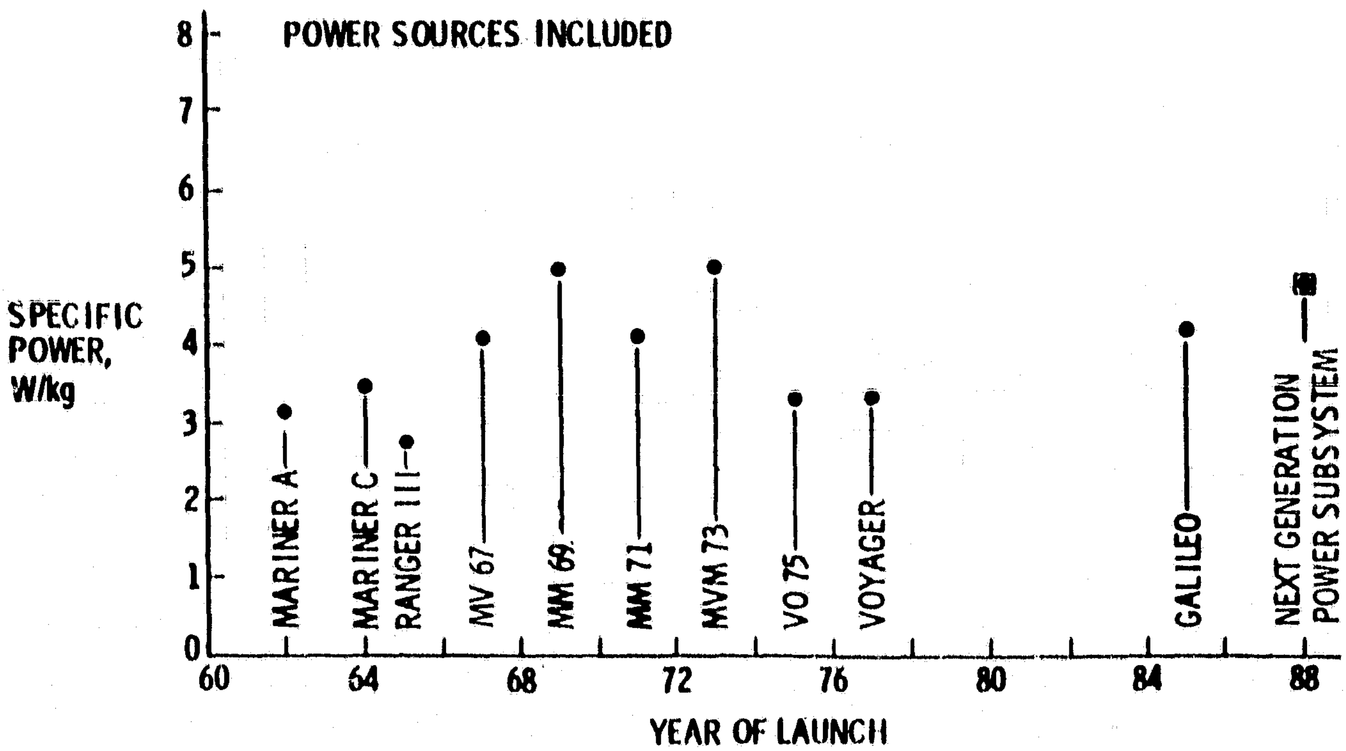

Figure 1-6. Specific Power of Power Subsystems With Power Sources

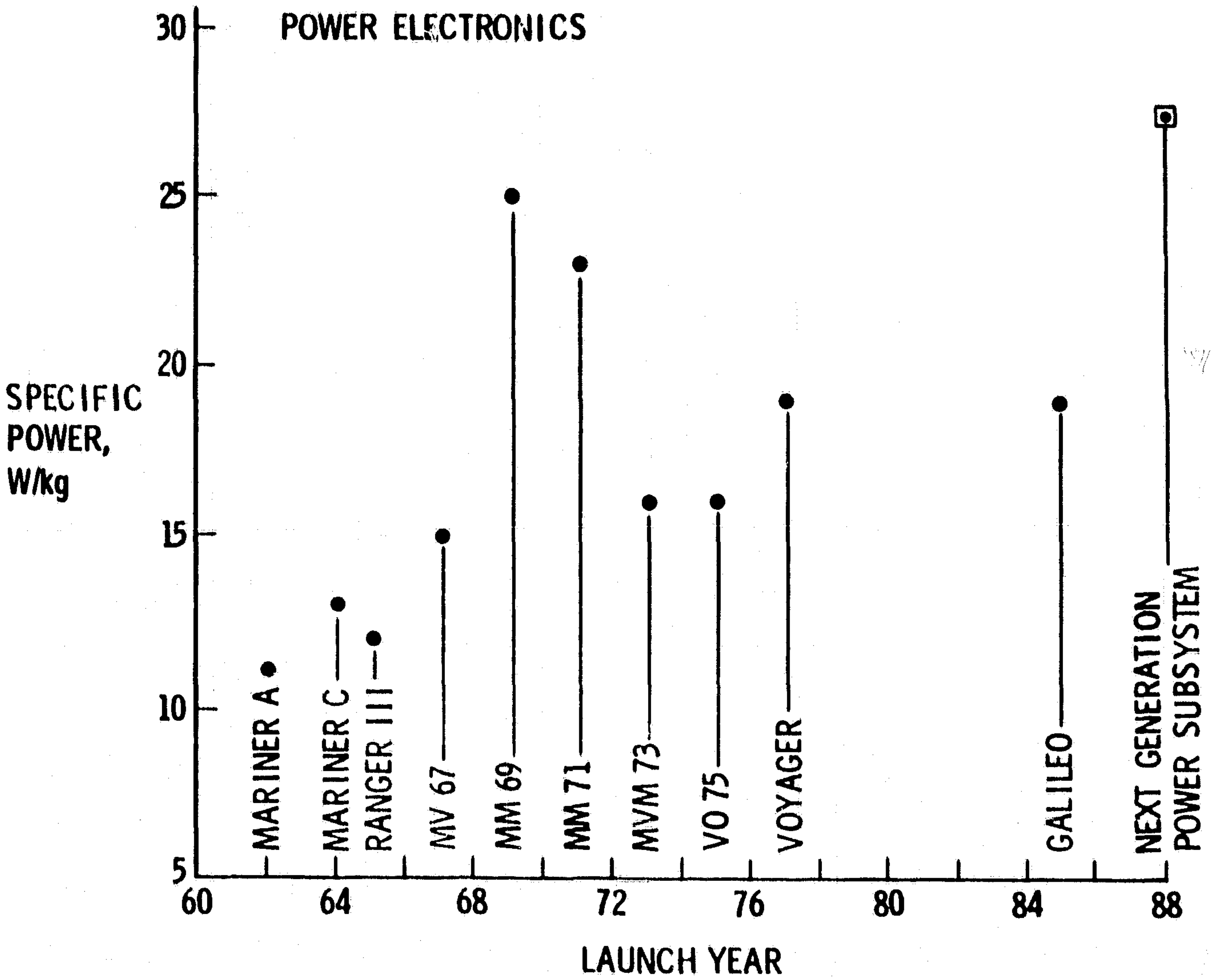

Figure 1-7. Specific Power of Power Subsystems - Power Electronics

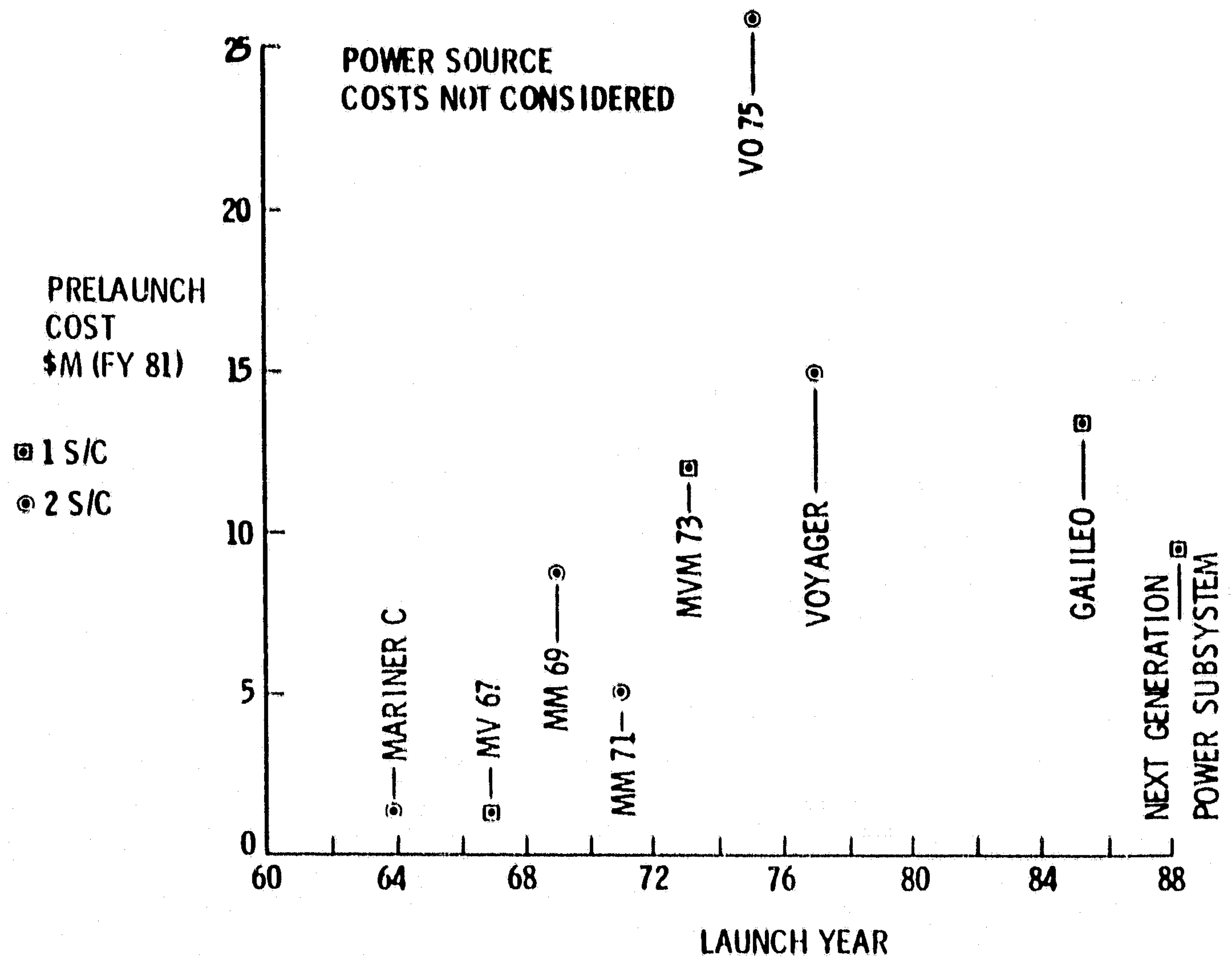

Figure 1-8. Prelaunch Cost of Power Subsystems

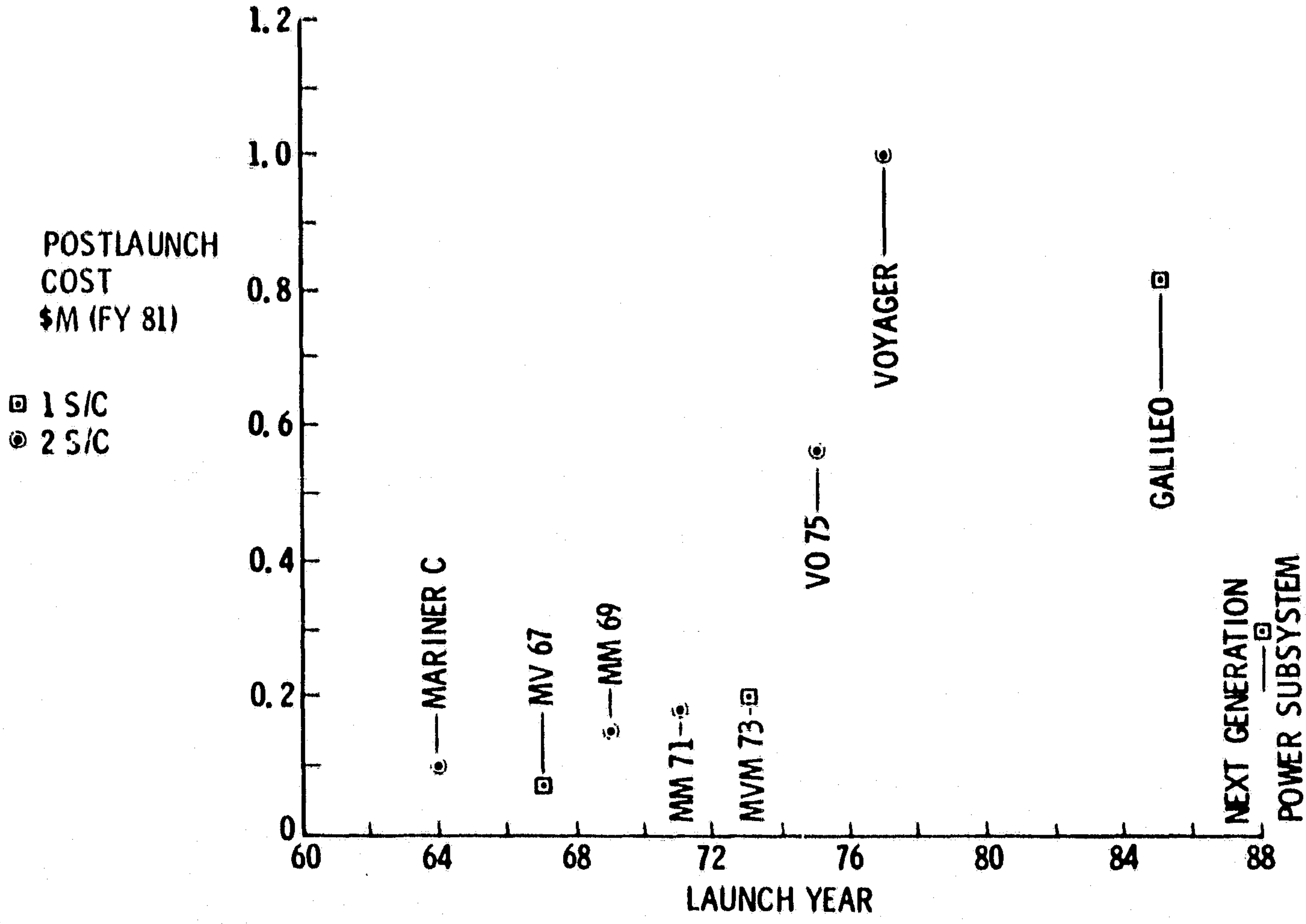

Figure 1-9. Postlaunch Cost of Power Subsystems

MM73 - 0.7 yrs; $190K, VO75 - 2 yrs; $578K, VGR - 4 yrs; $1012K. Reducing the cost of Next Generation power subsystem post-launch mission support will require increased on-board monitoring, and computational and control capability.

In summary, the power subsystem technology at the start of the APSM program can be characterized as shown in Figure 1-10.

- SPECIFIC POWER CONSTANT — 15 TO 20 W/kg
- COSTS HIGH — $10 TO 15M (FY 81) PER MISSION
- REQUIREMENTS INCREASING
  - RELIABILITY
  - FAULT TOLERANCE
  - FLEXIBILITY
- ONBOARD COMPUTATIONAL CAPABILITY BECOMING AVAILABLE

Figure 1-10. Power Subsystem Technology at Start of APSM - Summary

SECTION 2

APSM PROGRAM

2.1 OBJECTIVES

Based on the projected needs of future planetary spacecraft for increased autonomous operation, the following APSM program objectives were established:

a) Develop the techniques and demonstrate the technology required to provide reliable automated power subsystem management with the functional capabilities for:

- Providing accurate assessment of power subsystem performance
- Detecting and correcting equipment faults
- Managing user loads

b) Evaluate the performance of automated power subsystem management as applied to the solar array-battery power subsystem used on the VO75 spacecraft.

2.2 APPROACH

Figure 2-1 illustrates the interaction of a spacecraft power subsystem, without on-board computational cabability, with the other spacecraft subsystems and the ground system. The power source provides unregulated power to the power processing and distribution functions within the power subsystem and from there to the power users. Power subsystem performance data is transmitted to the ground, via spacecraft telemetry, where monitoring and analysis functions are performed. Any performance modifications required, as a result of the analyses, must then be formatted as commands and transmitted to the spacecraft for decoding and implementation. Command response verification must then wait for new performance data to be transmitted to the

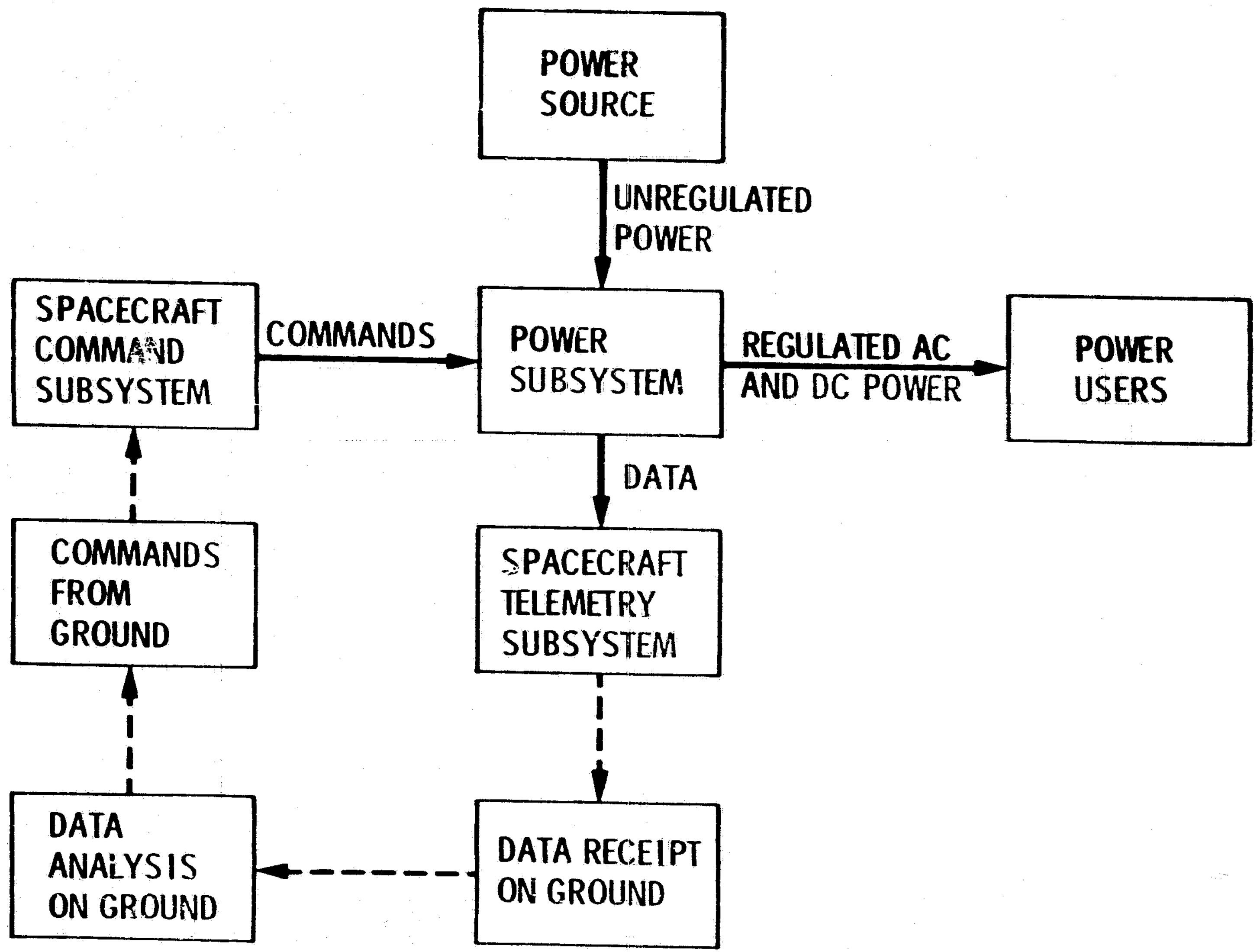

Figure 2-1. Power Subsystem Without Onboard Computation Capability

ground for analysis. In addition to the time required to traverse the loop of data transmittal, analysis, command generation, power subsystem response and response verification, particularly if long round trip communication times are involved, the allocation of telemetry channel space to power subsystem data is limited, resulting in the necessity for a high level of deductive analysis on the ground and consequent increase in loop time.

The APSM approach was to minimize the number of power subsystem functions imposed on the loop and perform the remaining functions on-board by means of a computer, as shown in Figure 2-2. Figure 2-3 shows the steps which were to be taken in implementing the approach.

In developing this approach there were several systems level concepts (Figure 2-4) that were not considered within the scope of this program. Distribution of computational capability is spacecraft specific; i.e., whether the computational capability resides in the power subsystem or in a centralized spacecraft computer depends on the specific spacecraft architecture and the results of applicable tradeoffs. The effect of use of onboard computational capability on other subsystems, such as the command and telemetry subsystems, was not considered because no technological problems were evident. No trade-offs were made between computing on-board and computing on the ground because this decision was also considered mission specific.

Selection of the V075 Power Subsystem as the baseline for the APSM program provided several benefits. The V075 Power Subsystem was a mature design and a state-of-the-art generic planetary power subsystem. The relatively complex design provided the capability for implementing a wide range of autonomous functions. A breadboard of the V075 Power Subsystem was

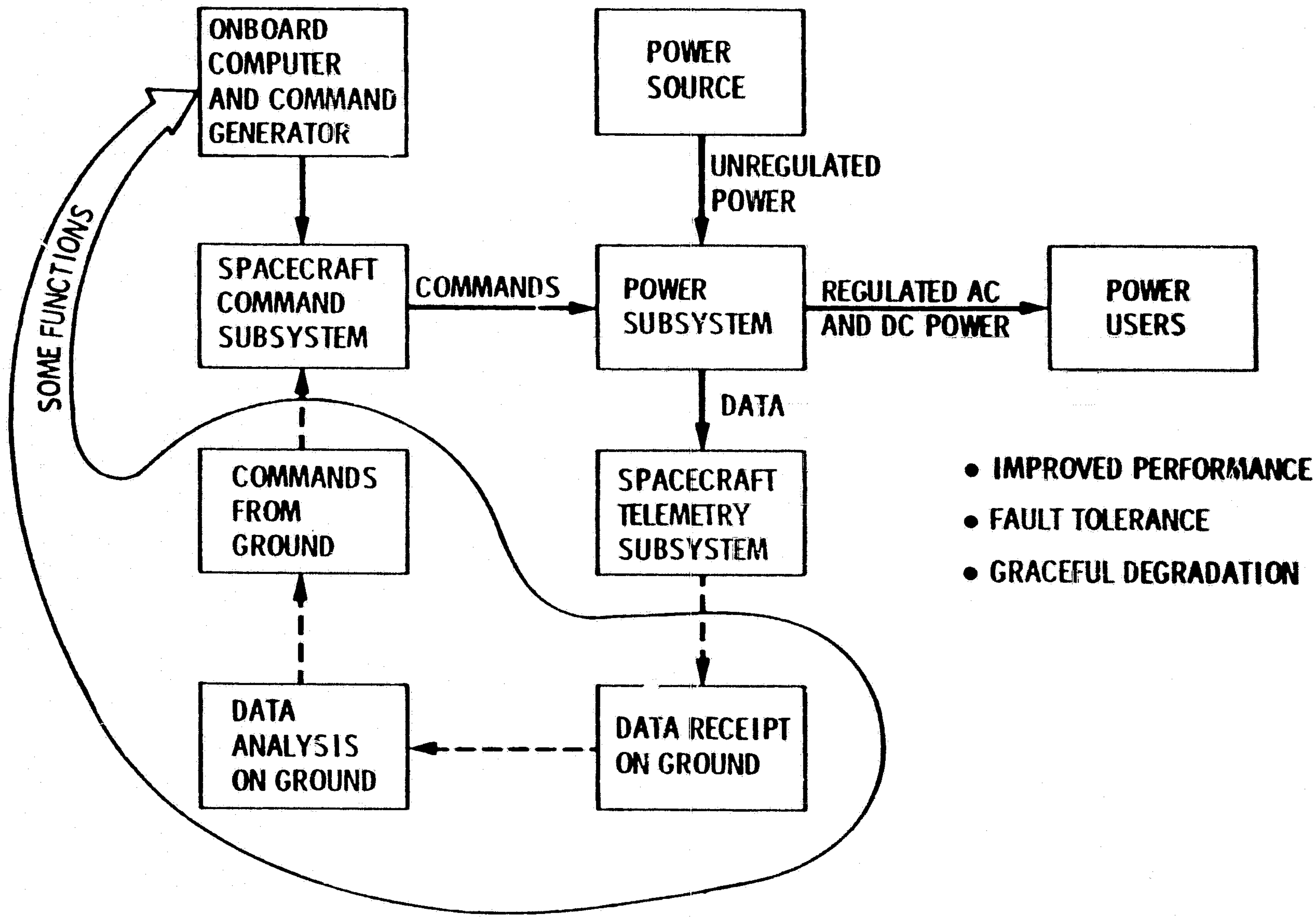

Figure 2-2. Power Subsystem With Onboard Computational Capability

- SELECT BASELINE SUBSYSTEM
- IDENTIFY FUNCTIONS OF THE POWER SUBSYSTEM AS CANDIDATES FOR AUTOMATION
- IDENTIFY ANTICIPATED BENEFITS AND COSTS
- SELECT FUNCTIONS TO BE AUTOMATED
- IMPLEMENT AND EVALUATE AUTOMATION OF SELECTED FUNCTIONS

Figure 2-3. APSM Approach

- DISTRIBUTION OF COMPUTATIONAL CAPABILITY – SPACECRAFT-SPECIFIC
- EFFECT OF USING ONBOARD COMPUTATIONAL CAPABILITY ON OTHER SUBSYSTEMS
- TRADE-OFF BETWEEN COMPUTING ONBOARD AND COMPUTING ON THE GROUND – MISSION-SPECIFIC

Figure 2-4. System Concepts not Considered in APSM Approach available for use. Extensive ground test and in-flight performance data was also available for comparative analysis.

A simplified functional block diagram of the VO75 power subsystem is shown in Figure 2-5. The VO75 Power System utilized a solar array/battery power source which provided unregulated DC power to the power processing functions of redundant regulators, inverters and converters. Regulated AC and DC power was then distributed to individually fused user loads. Battery recharge energy was provided by the solar array through redundant battery chargers. This subsystem also contained a boost converter which forces the solar array-battery sources out of a share-mode condition, whenever the array has the capability of providing the total load power.

The VO75 power system contained a limited number of automated functions, however these functions were incorporated with hardwire logic which could not be modified in-flight and made pre-flight modifications extremely difficult. The four automated functions on the VO75 power subsystem, as shown on Figure 2-6, are: boost mode converter initiation, voltage limit/temperature limit battery charge termination, failed battery charger disconnect, and main-standby boost regulator and inverter power chain switchover. Although individual loads were fused, fuse selection philosophy was based on 200% of normal load, therefore only severe overloads would blow the fuses.

2.3 PROGRAM HISTORY

The APSM program began in FY 1975 with a "Concept Definition Phase" performed under contract by Martin Marietta Corp. (MMC). The program was completed in FY 1981 when all automated functions were tested and verified.

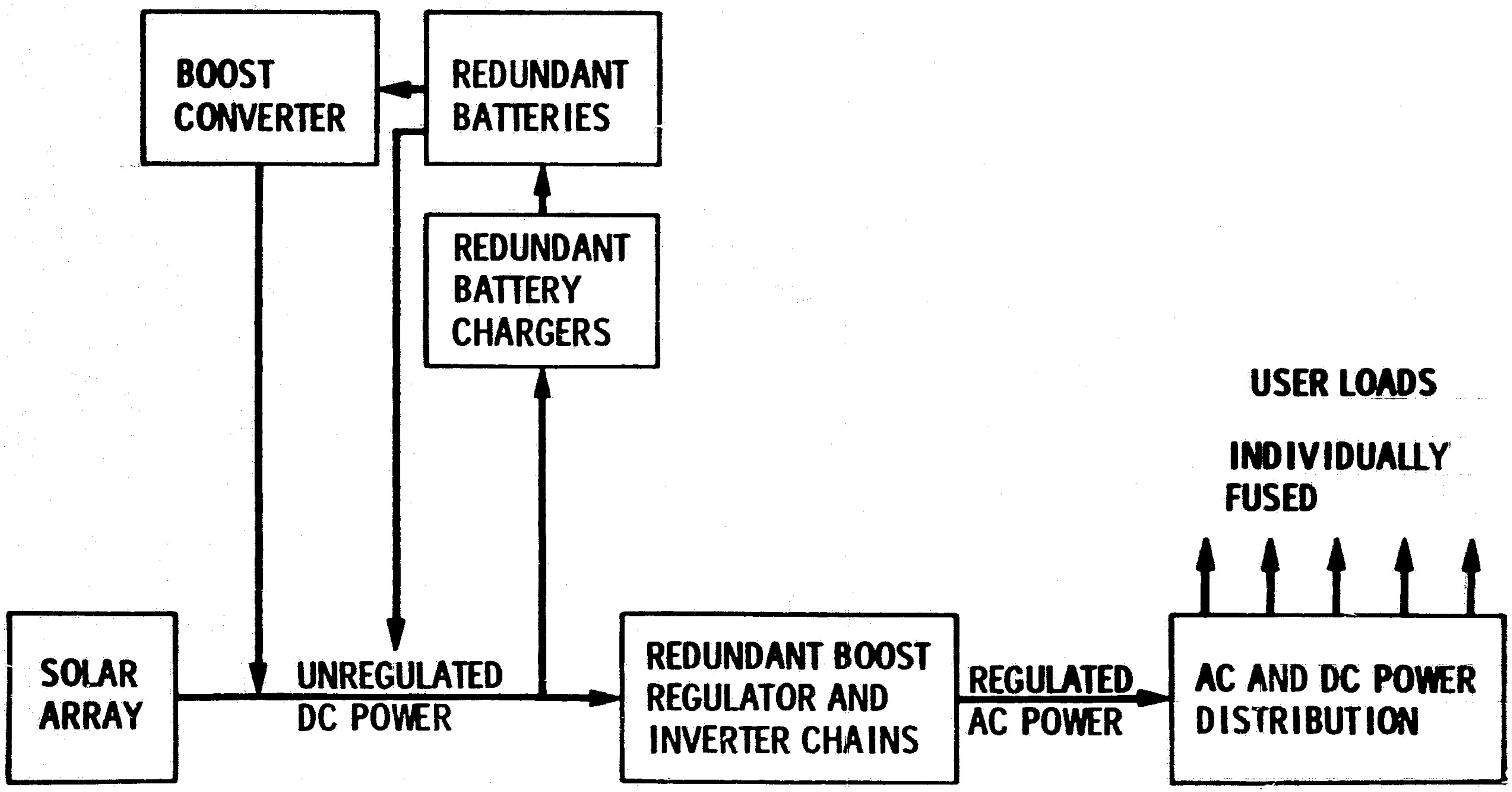

Figure 2-5. V075 Power Subsystem

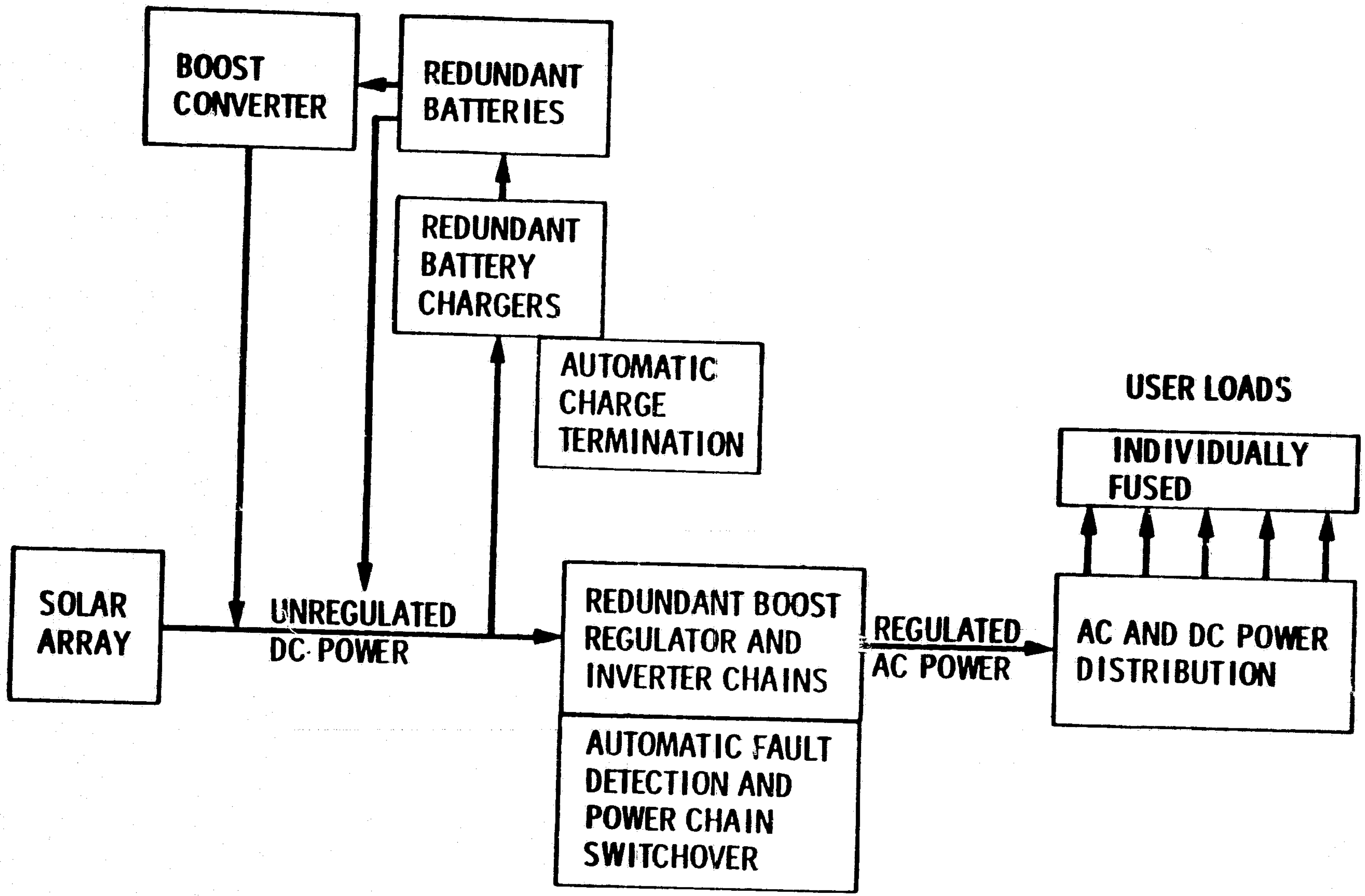

Figure 2-6. V075 Power Subsystem - Automated Functions

2.4 APSM IMPLEMENTATION

Implementation of the APSM system was based on automation of selected key power system functions on a V075 Breadboard Power Subsystem. There were four key subtasks performed to accomplish implementation of the APSM functions. A set of candidate APSM functions was established. These functions were selected to meet a set of objectives established during the conceptual design phase. The objectives were: managing user loads, detecting and correcting equipment faults, and providing an accurate assessment of power system performance during extended planetary exploration missions. The selected candidate functions are described in Figures 2-7 through 2-9. The anticipated benefits to be derived from each of the candidate functions were evaluated and are shown on Figures 2-10 through 2-12. Some of the more significant benefits derived from the candidate functions include: reduced need for ground intervention, improved programmable reaction time to fault conditions, increased flexibility in redundancy selection, individual fault load removal vs block load disconnect of current spacecraft, flexible telemetry content allowing programmable selection of telemetered data to support varied mission activities, and reduction in required solar array margin to reduce cost and mass. Figure 2-13 lists those functions which were selected from the candidate functions to be implemented into the APSM/V075 Power Subsystem. All of the functions above the dashed separation line were implemented and were verified in testing. The three functions below the dashed line were not implemented for the following reasons: the Minimum Solar Array Margin Protection function would require the development of a solar array maximum power point detector, which was not used on V075; the Subsystem Performance Monitoring and Load Profile Determination functions were not implemented

Function	Description
BATTERY CHARGE CONTROL	• AUTONOMOUSLY BEGIN CHARGING WHEN SOC FELL BELOW A PREDETERMINED LIMIT • SWITCH TO LOW RATE WHEN SOC REACHED A PREDETERMINED LIMIT • PREDETERMINED LIMITS VARIED ACCORDING TO TEMPERATURE MODEL
POWER CHAIN FAULT DETECTION AND SWITCHOVER WITH CROSS STRAPPING	• MAIN AND STANDBY BOOSTER REGULATORS CROSS STRAPPED TO MAIN AND STANDBY INVERTERS ALLOWING ANY PERMUTATION OF INVERTERS AND BOOST REGULATORS UPON DETECTION OF A FAULT
SUBASSEMBLY PERFORMANCE MONITORING	• EFFICIENCIES CALCULATED VIA INPUT AND OUT-PUT VOLTAGES AND CURRENTS FOR POWER DEVICES SUCH AS INVERTERS, CHARGERS, ETC. • CELL MONITORING WITHIN BATTERIES
SUBASSEMBLY FAULT DETECTION AND RECOVERY	• DETECTION THROUGH CALCULATION OF REDUCED EFFICIENCY • RECOVERY THROUGH SUBASSEMBLY REPLACEMENT (BLOCK REDUNDANT)

Figure 2-7. Candidate Functions for Automation

Function	Description
POWER MARGIN MANAGEMENT	• SHARE MODE DETECTION AND BOOST CONVERTOR TIME-OUT LEADING TO LOAD SHEDDING
LOAD EQUIPMENT MONITORING AND FAULT DETECTION	• MONITOR LOAD VOLTAGES AND CURRENTS TO DETERMINE IMPEDANCE OF LOAD DEVICES • IF IMPEDANCE FELL BELOW PREDETERMINED LIMIT, DEVICE WAS REMOVED
RELAY STATUS MONITORING	• MONITORED POSITIONS OF ALL RELAY CONTACTS INCLUDING RELAYS FOR CELL BYPASS, CROSS STRAPPING, LOAD DISTRIBUTION, ETC.
DATA ACQUISITION, PROCESSING, AND STORAGE	• SERIAL DATA BIT STREAM - RECONFIGURABLE • DATA STORAGE FOR COMPUTATION
MINIMUM SOLAR ARRAY MARGIN PROTECTION	• PROGRAMMABLE, PRIORITIZED, SEQUENTIAL LOAD SHEDDING IF SOLAR ARRAY MARGIN FELL BELOW A SELECTED VALUE
SUBSYSTEM PERFORMANCE MONITORING	• DETERMINE THE HEALTH (EFFICIENCY) OF THE POWER SUBSYSTEM BY COMPUTING THE INTERNAL POWER LOSSES (TOTAL SOURCE POWER INPUT MINUS THE TOTAL LOAD POWER DELIVERED)

Figure 2-8. Candidate Functions for Automation (cont)

FUNCTION	DESCRIPTION
LOAD PROFILE DETERMINATION	• UTILIZING A PRE-PROGRAMMED OR GROUND GENERATED SEQUENCE OF SPACECRAFT COMMANDS, CALCULATE THE MAXIMUM POWER AND ENERGY STORAGE REQUIREMENT FOR THE SEQUENCE AND COMPARE TO THE SOLAR ARRAY AND BATTERY SOURCES CAPABILITY. SEND AN ALARM FLAG TO THE FLIGHT DATA SYSTEM FOR TRANSMITTAL TO GROUND, IF SOURCE CAPABILITY IS LESS THAN REQUIRED.
LOAD SEQUENCE GENERATION	• UTILIZING THE PRIORITIZED SEQUENTIAL LOAD SHEDDING DATA, GENERATE A NEW LOAD SEQUENCE BASED ON POWER SOURCE CAPABILITY

Figure 2-9. Candidate Functions for Automation (cont)

Function	Benefit
BATTERY CHARGE CONTROL	• REDUCE GROUND INVOLVEMENT a) MANPOWER REDUCTION (75%) b) OPERATIONAL COST REDUCTION ($45K/YR) c) REDUCED MARGIN ($10K/BATTERY)
POWER CHAIN FAULT DETECTION AND SWITCHOVER WITH CROSS STRAPPING	• AUTONOMOUS CONTROL - IMPROVE RELIABILITY a) FAST REACTION TIME b) INTELLIGENCE OPTION DEGRADED UNIT VS FAILED UNIT • CROSS STRAPPING a) PROVIDE FLEXIBILITY b) REDUCE PROBABILITY OF POWER CHAIN FAILURE
SUBASSEMBLY PERFORMANCE MONITORING	• FAILURE ISOLATION ON SYSTEM LEVEL EASILY ACCOMPLISHED
SUBASSEMBLY FAULT DETECTION AND RECOVERY	• ALLOW ONBOARD SYSTEM DIAGNOSTICS AND RECOVERY
POWER MARGIN MANAGEMENT	• AUTOMATIC SHARE MODE RECOVERY

Figure 2-10. Anticipated Benefits from Candidate Functions for Automation - B

Function	Benefit
SUBSYSTEM PERFORMANCE MONITORING	• PROVIDE CONTINUOUS ESTIMATE OF SUBSYSTEM EFFICIENCY
LOAD PROFILE DETERMINATION	• MAXIMIZE NUMBER OF SCIENCE INSTRUMENTS AVAILABLE INCREASE POTENTIAL SCIENCE OUTPUT DATA
LOAD SEQUENCE GENERATION	• REDUCE SPACECRAFT CENTRAL • COMPUTER WORK LOAD • MAXIMIZE NUMBER OF LOAD • COMBINATIONS • REDUCE GROUND INVOLVEMENT

Figure 2-11. Anticipated Benefits from Candidate Functions for Automation (cont)

Function	Benefit
LOAD EQUIPMENT MONITORING AND FAULT DETECTION	• PROVIDE INDIVIDUAL LOAD REMOVAL VS BLOCK REMOVAL • PROVIDE RETRY CAPABILITY
RELAY STATUS MONITORING	• REDUCE GROUND INVOLVEMENT • AUTOMATE COMMAND VERIFICATION
DATA ACQUISITION, PROCESSING, STORAGE	• REDUCE INTERFACE COMPLEXITY • FLEXIBLE TELEMETRY CONTENT
MINIMUM SOLAR ARRAY MARGIN PROTECTION	• ABILITY TO USE MAXIMUM SOLAR ARRAY OUTPUT SMALLER ARRAY LOWER MASS LOWER COST

Figure 2-12. Anticipated Benefits from Candidate Functions for Automation (cont)

BATTERY CHARGE CONTROL	DEMONSTRATE REDUCED MONITORING REQUIREMENTS
POWER CHAIN FAULT DETECTION AND SWITCHOVER WITH CROSS STRAPPING	DEMONSTRATE INCREASED FAULT TOLERANCE AND FLEXIBILITY
SUBASSEMBLY PERFORMANCE MONITORING	DEMONSTRATE INCREASED FAULT TOLERANCE, FLEXIBILITY, AND RECONFIGURABILITY
SUBASSEMBLY FAULT DETECTION AND RECOVERY POWER MARGIN MANAGEMENT	DEMONSTRATE POTENTIAL FOR REDUCED POWER SOURCE MARGIN
LOAD EQUIPMENT MONITORING AND FAULT DETECTION	DEMONSTRATE INCREASED FAULT TOLERANCE FLEXIBILITY, AND RECONFIGURABILITY
DATA ACQUISITION, PROCESSING, AND STORAGE	DEMONSTRATE MORE FLEXIBLE, RECONFIGURABLE TELEMETRY INTERFACE
RELAY STATUS MONITORING	DEMONSTRATE REDUCED TELEMETRY REQUIREMENT
LOAD SEQUENCE GENERATION	PERFORM A TIMED LOAD MANAGEMENT SEQUENCE FROM A SINGLE SPACECRAFT COMPUTER INSTRUCTION

MINIMUM SOLAR ARRAY MARGIN PROTECTION	MAXIMUM POWER POINT DETECTOR REQUIRED
SUBSYSTEM PERFORMANCE MONITORING LOAD PROFILE DETERMINATION	

Figure 2-13. Implementation of Candidate Functions Selected for Automation

because it was determined that all of the data was available to perform these functions but would require more resources to develop the software than could be justified to demonstrate the functions.

Figure 2-14 illustrates the distributed microcomputer configuration selected to implement the APSM functions into the V075 breadboard system. Microcomputer #1 monitored and controlled the power source functions (solar array, batteries, battery chargers, boost converter). Microcomputer #2 monitored and controlled the power processing functions (booster regulators, inverters, converters). Local Microcomputer #3 monitored and controlled the power distribution functions. The Central Microcomputer performed the supervisory functions, performed subsystem level computations, telemetry data storage and formatting, command decoding, and was the data interface between the power subsystem and other spacecraft subsystems.

The total APSM/V075 power subsystem and support equipment are shown in Figure 2-15. The power electronics, batteries, simulated spacecraft loads and APSM hardware were mounted in Racks 1, 2 and 3. Rack 4 included the solar array simulators and an overvoltage raw bus clamp circuit. The support equipment was composed of the Floppy Disc Driver, TI 9900 Computer, TI 810 Printer and TI 913 Video Display Terminal. There is a significant physical difference between the breadboard V075 power subsystem and the flight configuration. Figures 2-16 and 2-17 show the flight configuration of the two V075 power subsystem assemblies. Figures 2-18 through 2-20 show the breadboard configuration of three of the power electronics subassemblies. Figure 2-21 shows the breadboard configuration of the three distributed

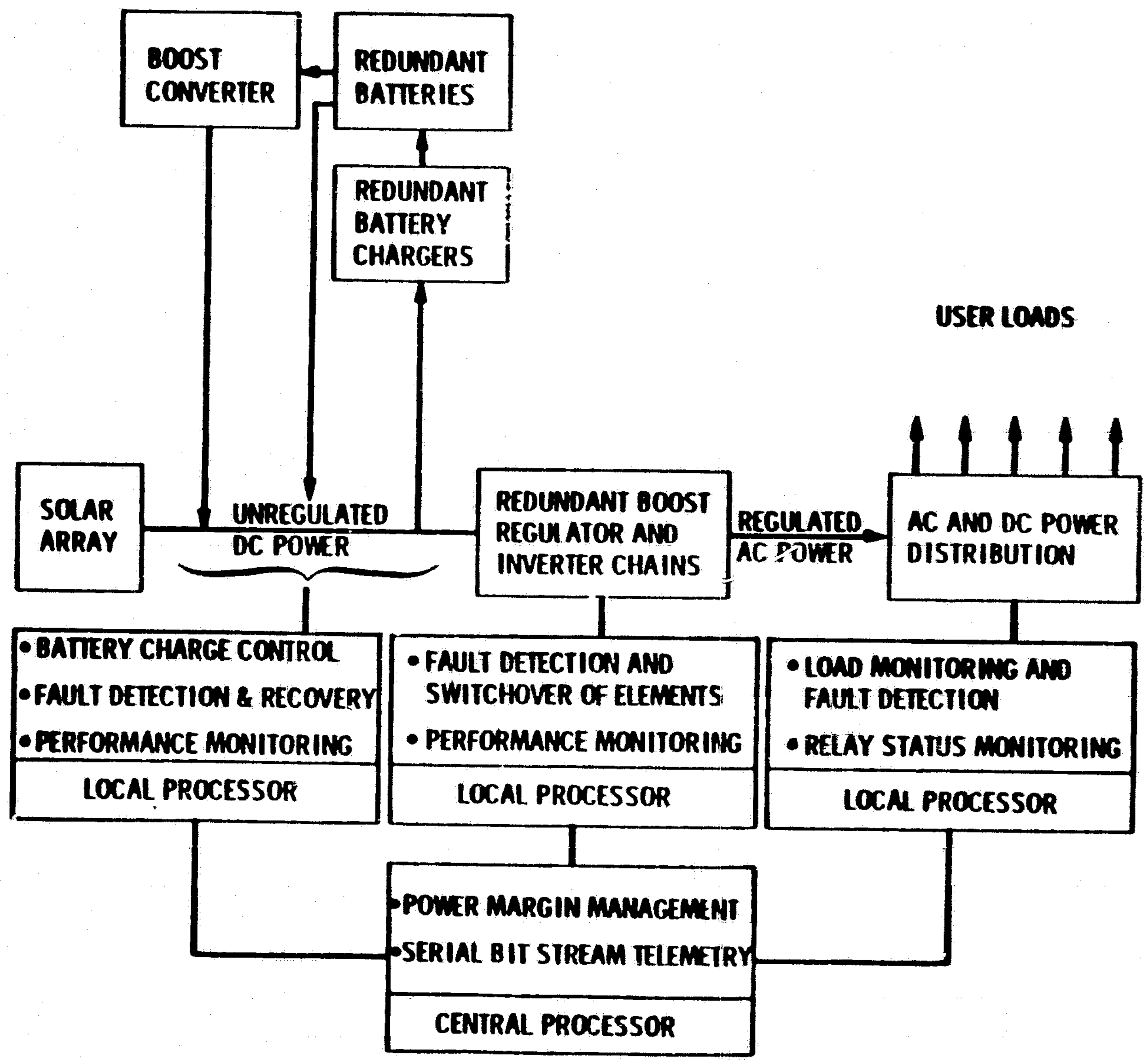

Figure 2-14. V075 Power Subsystem APSM Configuration

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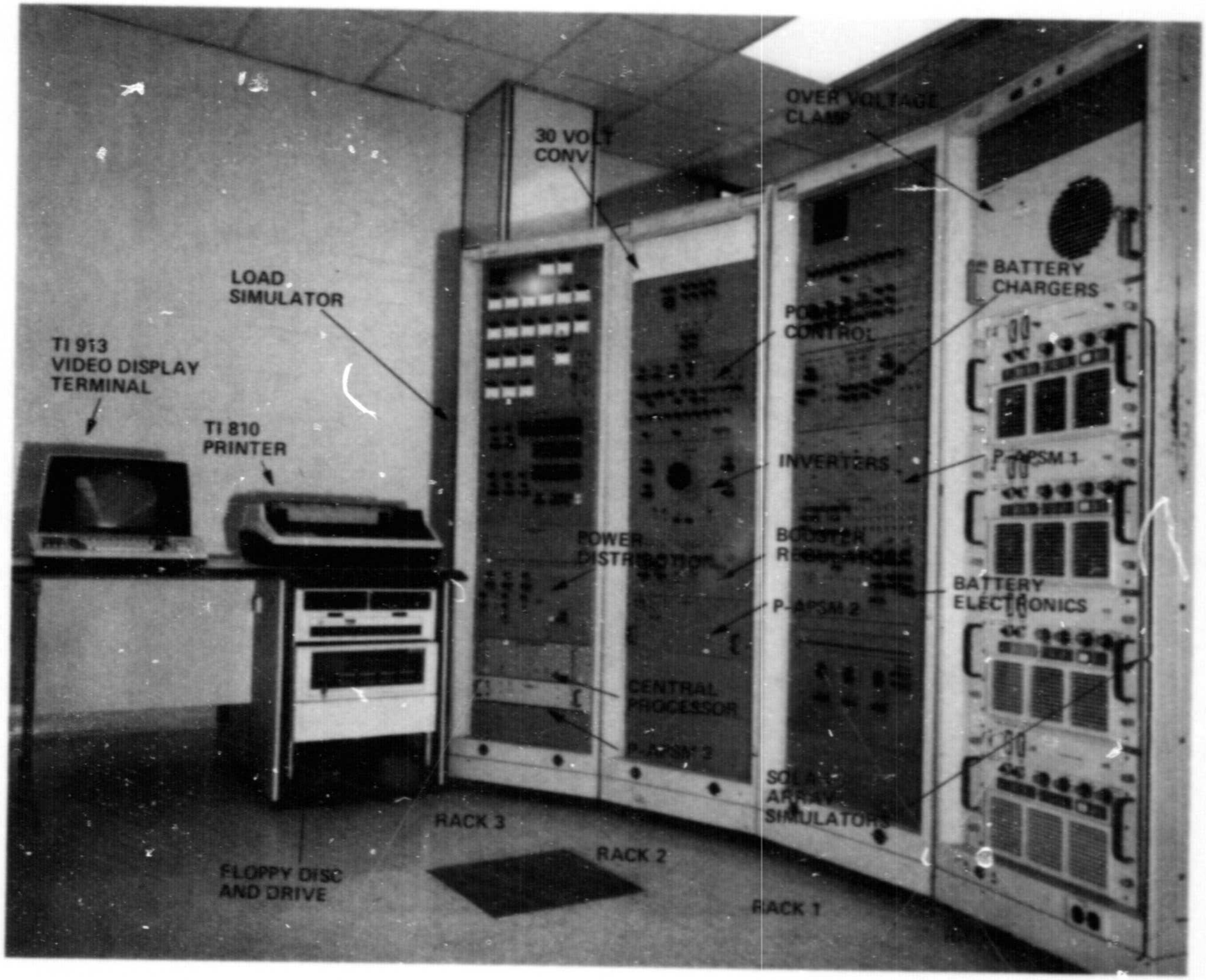

Figure 2-15. APSM/V075 Breadboard Power System

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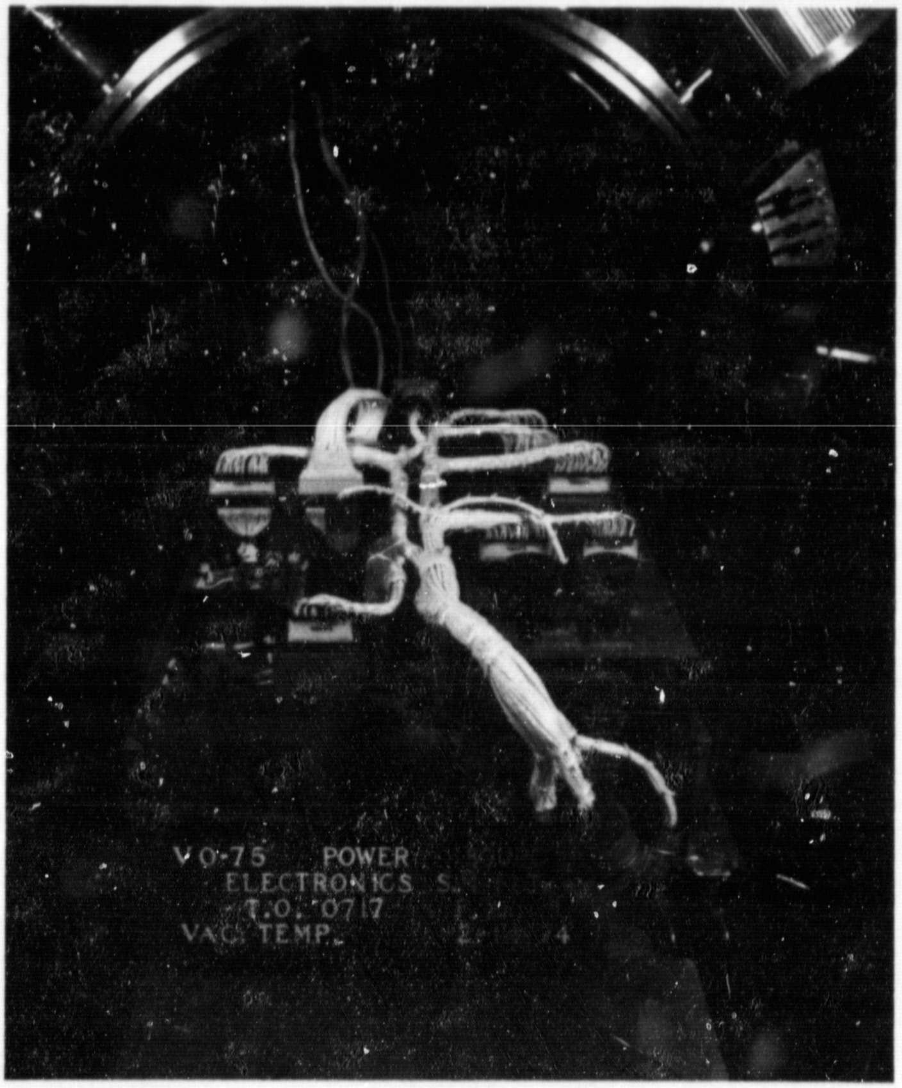

Figure 2-16. V075 Power Electronics Assembly 1 - Flight Configuration

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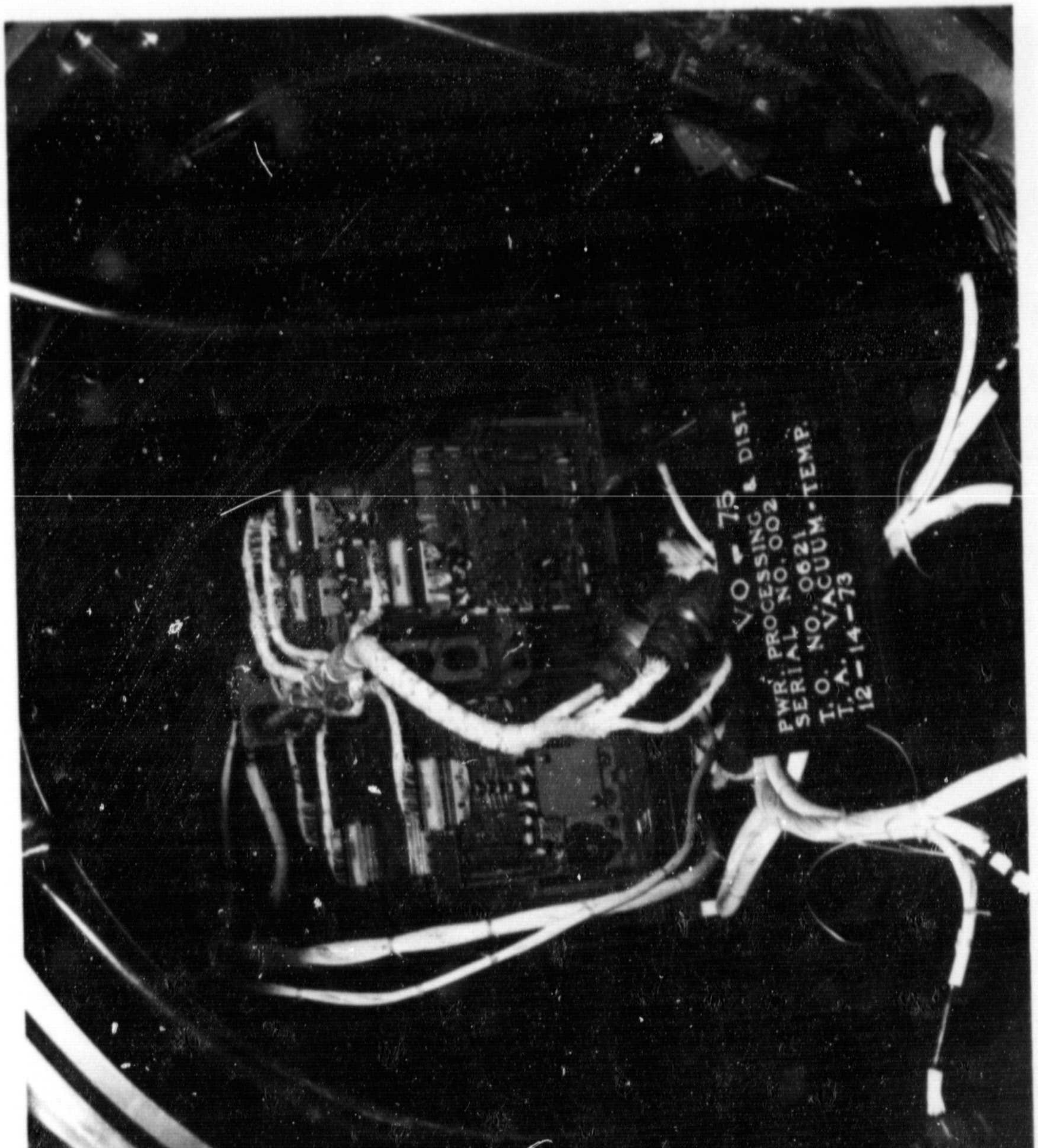

Figure 2-17. VO75 Power Electronics Assembly 2 - Flight Configuration

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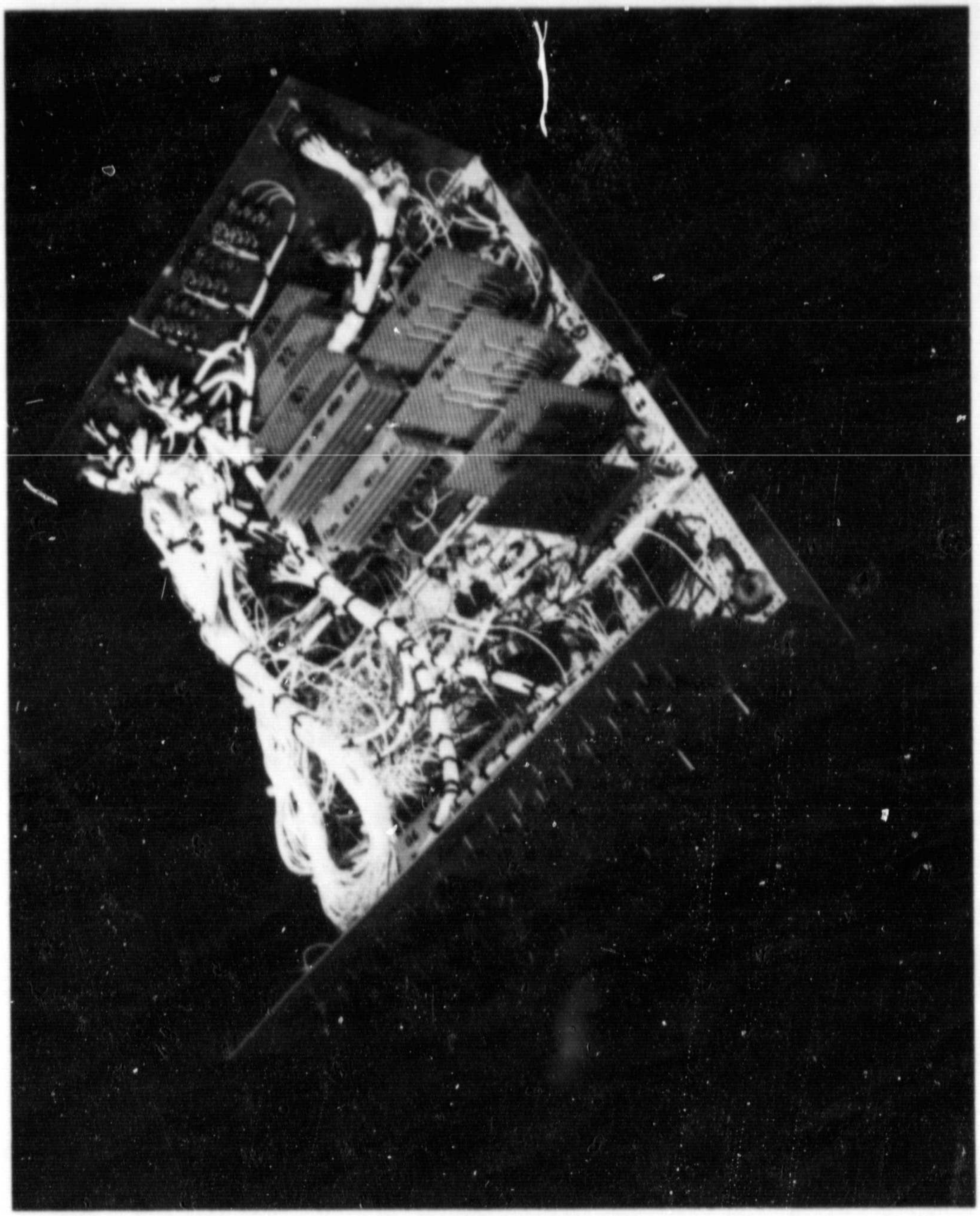

Figure 2-18. Battery Electronics Subassembly Breadboard

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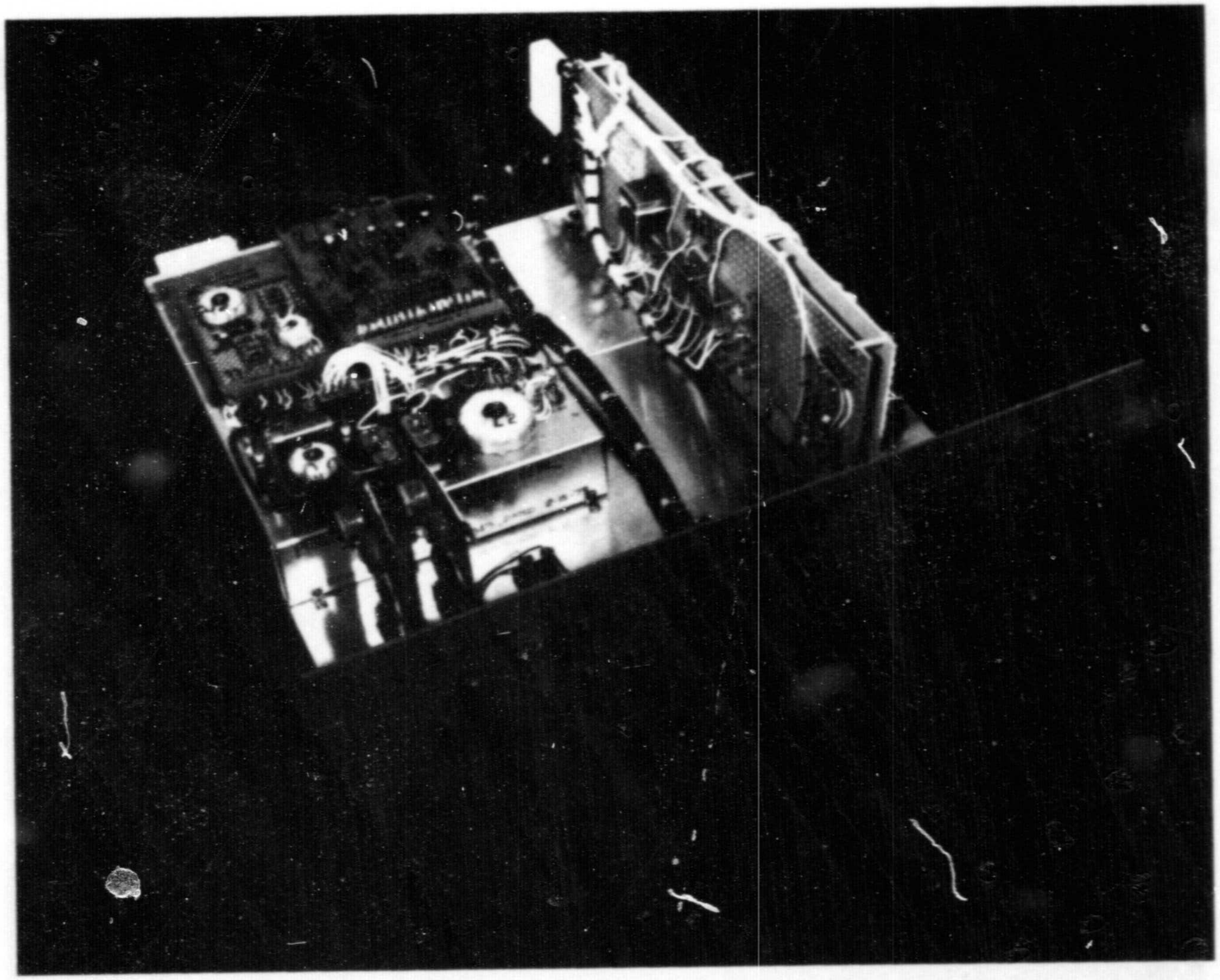

Figure 2-19. Battery Charger Subassembly Breadboard

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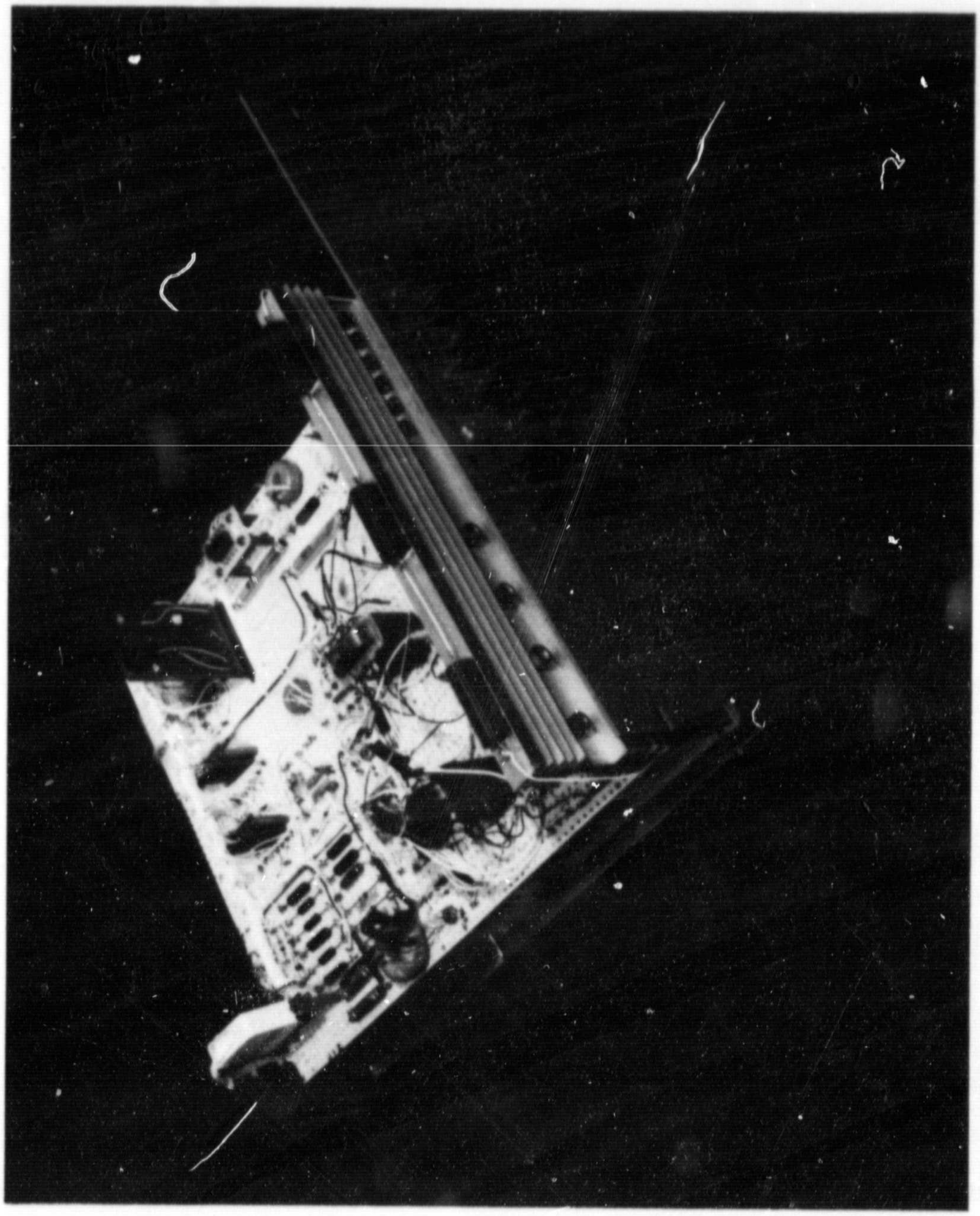

Figure 2-20. 30-VDC Converter Subassembly Breadboard

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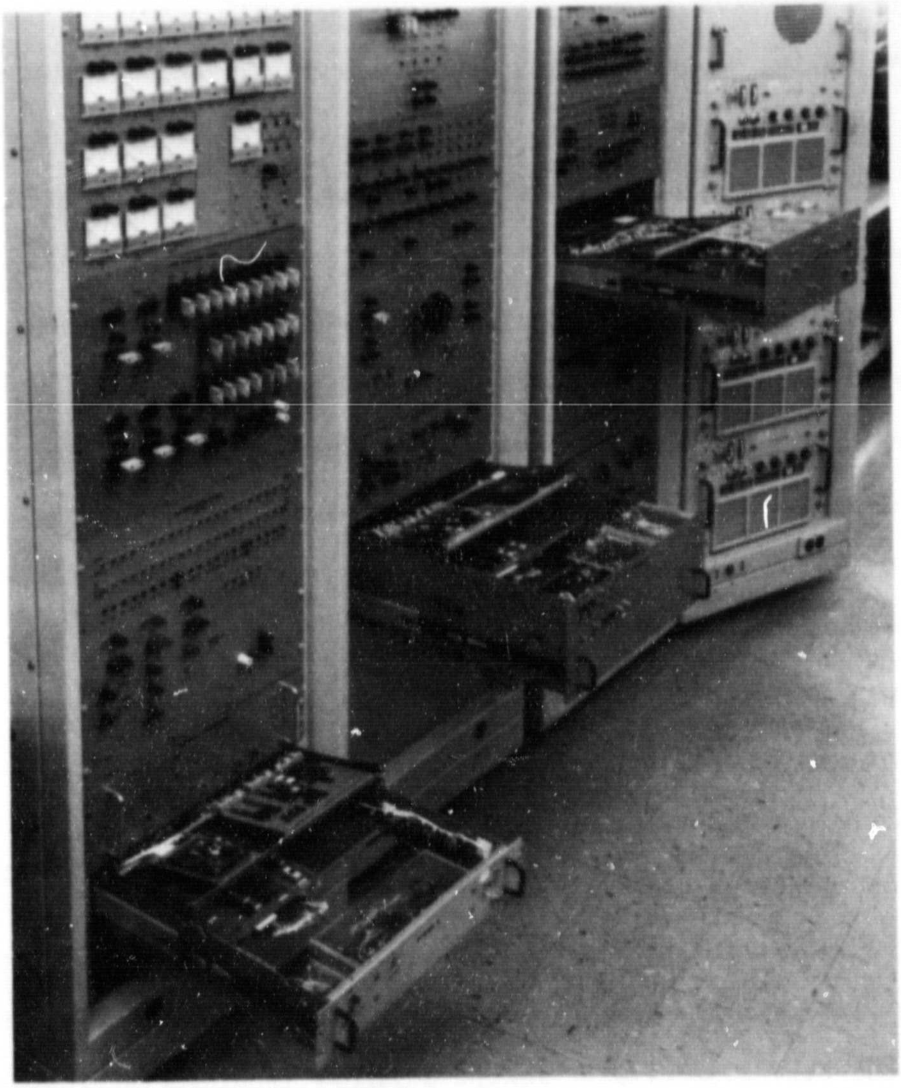

Figure 2-21. Local Microcomputer Subassembly Breadboards - Exposed

microcomputers. Obviously, no attempt was made to simulate a flight configuration because the objectives of this task were to demonstrate the application and performance of the selected APSM functions, and flight type packaging was not one of the objectives.

2.5 EVALUATION RESULTS

The evaluation of the APSM program was performed on three levels: functional performance, subsystem, and programmatic. As shown in Figures 2-22 and 2-23, all of the selected APSM functions were successfully implemented and verified by test. Considering the breadboard configuration of the APSM/V075 subsystem, a major concern during the design and development phase was the probability of unwarranted triggering of power subsystem events or circuits due to transients generated by a valid event, such as an overload simulation or main-to-standby switching of a power processor. Except for some initial decoupling required to isolate the microcomputer timing clock signal, no problems were encountered.

A summary of the significant APSM results is shown on Figure 2-24. Automation of key functions in the power subsystem was demonstrated, including reduced need for ground-based monitoring and analyses; algorithms were developed for functions such as load management and fault detection and recovery; the importance of system considerations in future applications of APSM became increasingly evident, but no new inventions were required to accomplish the task objectives. Recent advances in microelectronics, particularly over the past two years, indicate that the amount of hardware and

Function	Test	Results
BATTERY CHARGE CONTROL	• STATE OF CHARGE ESTIMATOR EVALUATION	• WITHIN ±10% OVER 3 CHARGE/ DISCHARGE CYCLES
	• BATTERY OVER-TEMPERATURE SIMULATION	• CHARGER SWITCHED TO LOW RATE
	• BATTERY STATE OF CHARGE RESPONSE TEST	
	• BATTERY DISCHARGED	• CHARGER SWITCHED TO HIGH RATE
	• BATTERY OVERCHARGED	• CHARGER SWITCHED TO LOW RATE
POWER CHAIN FAULT DETECTION AND SWITCHOVER	• MAIN INVERTER FAILURE SIMULATION	• SWITCHED TO STANDBY INVERTER
	• MAIN BOOSTER REGULATOR FAILURE SIMULATION	• SWITCHED TO STANDBY BOOSTER REGULATOR
SUBASSEMBLY PERFORMANCE MONITORING	• CALCULATE EFFICIENCIES OF SUBASSEMBLIES AND COMPARE TO RESULTS OF HAND CALCULATIONS	• RESULTS WITHIN 5%

Figure 2-22. APSM Functional Performance Results

Function	Test	Results
SUBASSEMBLY FAULT DETECTION AND RECOVERY	• BATTERY CHARGER EFFICIENCY BELOW LIMIT SIMULATION	• CHARGER TURNED OFF
	• BATTERY CELL VOLTAGE BELOW LIMIT SIMULATION	• FAILED CELL BYPASSED AND SPARE CELL CONNECTED
POWER MARGIN MANAGEMENT	• TOTAL LOAD SIMULATED TO BE IN EXCESS OF SOLAR ARRAY CAPABILITY	• SEQUENTIAL LOAD SHEDDING SEQUENCE EXECUTED
LOAD EQUIPMENT MONITORING AND FAULT DETECTION	• SIMULATED VARIOUS LOAD FAULTS	• ACCURATELY DETECTED AND DISCONNECTED FAILED LOAD
	• CALCULATED EACH LOAD IMPEDANCE AND COMPARED TO RESULTS OF HAND CALCULATIONS	• CALCULATIONS WITHIN ±2%
RELAY STATUS MONITORING	• TESTED BY EXECUTION OF SEQUENTIAL RELAY EXCITATION COMMANDS	• ACCURATE MAINTENANCE OF RELAY STATUS DATA
DATA ACQUISITION, PROCESSING AND STORAGE	• COMPARE HARDWIRE MEASUREMENTS WITH APSM DATA	• ACCURACY OF APSM DATA WITHIN MEASUREMENT TOLERANCES

Figure 2-23. APSM Functional Performance Results (cont)

- ACCOMPLISHED OBJECTIVES OF DEMONSTRATING THE AUTOMATION OF KEY FUNCTIONS IN POWER SUBSYSTEM
    - CONTINUOUS MONITORING NOT REQUIRED
    - ALGORITHMS FOR KEY FUNCTIONS SUCH AS LOAD MANAGEMENT, SUBSYSTEM FAULT TOLERANCE
    - HIGHLIGHTED IMPORTANCE OF SYSTEM CONSIDERATIONS SUCH AS INTERFACE MANAGEMENT
    - NEW INVENTIONS NOT NECESSARY TO ACCOMPLISH OBJECTIVES
- APSM ACTIVITY HIGHLIGHTED FUNCTIONS THAT WOULD BENEFIT FROM ADVANCED TECHNOLOGY
    - ACCURATE STATE OF CHARGE INDICATOR
    - SELF-TEST OF STANDBY UNITS
    - MAXIMUM POWER POINT DETECTOR
    - MODULARITY
- AUTOMATION COULD BE SUCCESSFULLY ACCOMPLISHED WELL WITHIN STATE OF THE ART OF ONBOARD COMPUTATIONAL CAPABILITY
- USE OF ONBOARD COMPUTATIONAL CAPABILITY CAN HAVE POSITIVE EFFECT ON POWER SUBSYSTEM CHARACTERISTICS

SPECIFIC POWER	50% INCREASE WHEN COUPLED WITH ADVANCED TECHNOLOGY
PRELAUNCH COST	SLIGHT REDUCTION - SINGLE SPACECRAFT 40% REDUCTION - FIVE SPACECRAFT
OPERATIONS COST	50% REDUCTION
FAULT TOLERANCE	IMPROVED THROUGH PERFORMANCE MONITORING
FLEXIBILITY	INCREASED WITH RECONFIGURABILITY

Figure 2-24. Summary of APSM Results

software required to implement APSM functions could be greatly reduced with these new developments. As examples, math computations are performed, in the APSM system, by each microcomputer executing a software program developed for this function. There are separate math chips, now available, to execute these functions without the need for external programming and consequent additional memory requirement. Gathering of subsystem data measurements in the APSM system required several chips and control software to multiplex the data, perform analog-to-digital conversion and store the results. Here again, devices are available to perform this function without external programming. Several areas of new technology that could benefit autonomous power system performance became obvious as the task progressed. In particular, the capability for verifying the operational status of, or performing diagnostics on, a redundant unit, off line, could be accomplished with the APSM system. The flexibility of the APSM software can provide a cost-effective method for implementing hardware modularity for specific functions; i.e., blocks of power distribution modules with the number of blocks dependent on the particular mission requirements. Software would replace the hardwire logic command decoding currently used on flight power distribution units. Implementation of on-board power subsystem computational capability can provide several potential positive effects on the power subsystem characteristics. It was estimated that through incorporation of APSM features specific power could be increased by 50%, compared to the Voyager power subsystem. The basis for these estimates is shown in Figures 2-25 and 2-26. The cost comparison is based on maintaining equivalent capability. The capability for improved

	MASS	SPECIFIC POWER
VOYAGER POWER SYSTEM	25 KG	19 W/KG
O ADDED AUTOMATION COMPONENTS	+1.5 KG	
O HIGH FREQUENCY POWER PROCESSING	-2.5	
O IMPLEMENT SOLID STATE SWITCHES AND MICROELECTRONICS	-2.5	
O UTILIZE NON-MAG AMP TRANSDUCERS	-0.34	
O IMPROVED PACKAGING	-1.5	
O NEW CIRCUIT CONFIGURATIONS	-1.5	
O REDUCED INTERFACE WIRING	-1.5	
NEXT GENERATION POWER SYSTEM	18 KG	27 W/KG
o ESTIMATED MASS ADVANTAGE	50%	

Figure 2-25. APSM Implementation - Specific Power Impact

TASK	ESTIMATED COSTS	
	WITHOUT APSM, $K	WITH APSM, $K
	SINGLE SPACECRAFT	
DESIGN AND DEVELOPMENT	7,660	7,224
TEST AND OPERATIONS	309	200
PRE-LAUNCH MOS	221	200
TOTAL COSTS	8,190	7,624
ΔCOST SAVINGS = 7%		
	FIVE SPACECRAFT	
DESIGN AND DEVELOPMENT	25,261	16,125
TEST AND OPERATIONS	1,545	500
PRE-LAUNCH MOS	1,105	750
TOTAL COSTS	27,911	17,375
COST PER SPACECRAFT	5,582	3,475
ΔCOST SAVINGS = 38%		

Figure 2-26. Estimated Cost Benefits of Automated Power Systems

fault tolerance is a direct function of having the capability to monitor and perform computations on a greater number of subsystem elements independent of telemetry channel space availability. On-board reconfigurability of both hardware and software provides a high degree of in-flight flexibility to accommodate changing mission requirements.

Programmatically, several significant results were derived from the APSM program. The APSM program was indeed more complex than originally anticipated due to the complexity of the V075 power subsystem and the number of autonomous functions to be implemented. In addition, this was the first JPL effort to automate a spacecraft power subsystem. The importance of having the correct skill mix assigned to a power subsystem automation task became increasingly evident throughout the program. Although the skill mix (power electronics engineers, power subsystems engineers, and software experts) selected for the APSM program was adequate, the broad involvement of a spacecraft systems function on power subsystem automation programs is essential. Both the spacecraft system and power subsystem considerations are required to define and evaluate trade-offs related to spacecraft specific considerations such as distributed versus centralized computational architecture, redundancy management and degree of modularity. The magnitude of the APSM program emphasized the necessity for well disciplined software design management. The technology base established by the APSM program is being utilized at other NASA centers and by industry. Technology transfer has been accomplished by demonstrations, presentations and papers prepared for technical conferences. A list of publications is included in the Bibliography.

Figure 2-27 summarizes a comparison of principal capabilities between the APSM/VO75 breadboard power subsystem and the VO75 flight spacecraft power subsystem. The response time to an occurrence on the VO75 spacecraft in Mars orbit was approximately 2 hours. The response time for the APSM/VO75 breadboard is software selectable and was set at 2 seconds to avoid initiating an unwarranted response to a transient condition. As an example of potential mass savings, the intra-subsystem wiring has been reduced from 96 to 32 twisted pairs. The flexibility of the software-controlled, digital logic of the APSM/VO75 configuration provided the capability for in-flight reconfigurability which was not possible with the VO75 power subsystem. Increasing the number of APSM/-VO75 power subsystem performance measurements provided the data base for assessing 15 functions and the performance of the power subsystem and its subassemblies. The data from 181 measurements was used to provide the decision-based parameters to detect and correct individual equipment faults.

Since the APSM/VO75 was the first power subsystem development to incorporate on-board computational capability, a comparison of its computational characteristics was made with the Attitude Control Subsystem (ACS) computing capability of the JPL Voyager spacecraft. The comparison data is shown on Figure 2-28. Because the autonomous functions performed in a power subsystem are not time critical, high speed logic was not utilized in the APSM/VO75 breadboard to achieve greater computer speed (instructions per second). It was interesting to find that the memory size and lines of code values were nearly equivalent even though no attempt was made to optimize the APSM/VO75 software.

	APSM/VO 75	VO 75
Manage User Loads		
APPROXIMATE RESPONSE TIME	2 SEC	2 HR
CCS INTERFACE (SIGNALS)	32	96
MEASUREMENTS	31	7
MECHANIZATION	IMPEDANCE DIGITAL LOGIC RECONFIGURABLE	GROUND CMD/ FUSED HARDWIRE LOGIC
Accurate Assessment of Power Subsystem Performance		
MEASUREMENTS	37	8
ACCURACY OF EFFICIENCY CALCULATIONS	5%	N/A
FUNCTIONS ASSESSED	15	4
MECHANIZATION	DIGITAL LOGIC RECONFIGURABLE	HARDWIRE LOGIC
Detect and Correct Equipment Faults		
APPROXIMATE RESPONSE TIME	2 SEC	2 HR
MEASUREMENTS	181	46
MECHANIZATION	DIGITAL LOGIC RECONFIGURABLE	HARDWIRE LOGIC

Figure 2-27. Comparison of Principal Capabilities - Summary

	APSM/VO 75	ACS*(VOYAGER)
COMPUTER SPEED INSTRUCTIONS/SEC	4	25
MEMORY SIZE KILOBITS	60	74
SOFTWARE COMPLEXITY LINES OF CODE	4500	5025

*ACS - ATTITUDE CONTROL SUBSYSTEM

Figure 2-28. APSM Onboard Computation Characteristics - Summary

SECTION 3

CONCLUSIONS

The Automated Power Systems Management (APSM) program was completed in FY 1981 with the first JPL demonstration of a software configurable spacecraft power subsystem. Key autonomous functions including: battery charge/discharge control, power subsystem performance monitoring and fault detection and correction were demonstrated. Several critical programmatic elements were identified as necessary to the success of an automation task, but proper skill mix was considered the most important element. System and subsystem requirements must be well defined to minimize the complexity and design time of the autonomy architecture. Management of the software design and developments tasks, particularly change control documentation, was found to be more significant than hardware design management.

The automation technology results achieved on this APSM program are usable and will be used on future flight projects. The flexibility afforded by software configurable load management, redundancy management and telemetry content provides a new capability for cost effective adaptability to meet planned or unplanned performance requirements during a mission and to minimize hardware design changes to meet new mission requirements.

This program was not intended to address or resolve all key automation issues. In fact many new questions evolved during this program. Fault tolerance and redundancy management functions may impose different requirements on the automation capability, for a different type of power

SECTION 4

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