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APOLLO EXPERIENCE REPORT - COMMAND AND SERVICE MODULE COMMUNICATIONS SUBSYSTEM

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16. Abstract

The development of spacecraft communications hardware from design to operation is described. Programs, requirements, specifications, and design approaches for a variety of functions (such as voice, telemetry, television, and antennas) are reviewed. Equipment environmental problems such as vibration, extreme temperature variation, and zero gravity are discussed. A review of the development of managerial techniques used in refining the roles of prime and subcontractors is included. The hardware test program is described in detail as it progressed from breadboard design to manned flight system evaluations. Finally, a series of actions is recommended to managers of similar projects to facilitate administration.

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APOLLO EXPERIENCE REPORT

COMMAND AND SERVICE MODULE COMMUNICATIONS SUBSYSTEM

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SUMMARY

The development of a versatile and highly reliable communication system was required for the Apollo Program. This communications system had to provide two-way voice communications and data transfer between the earth and the spacecraft; transmission of television from the spacecraft to the earth; a capability for precise tracking of the spacecraft; voice and data exchange among the earth, the command module in lunar orbit, the lunar module, and the extravehicular astronauts on the lunar surface; and direction finding and voice communications during recovery operations. Reliability, safety, and simplicity were emphasized in the basic design. Minimum size and weight, minimum power consumption, and extended operation under all mission-environment conditions also were essential design considerations. The primary communications system was to operate in the S-band frequency spectrum, with very-high frequency used for communications between the command and lunar modules and the extravehicular astronauts and for recovery operations. Early in the Apollo Program, a concept of inflight maintenance gave way to one of built-in reliability and redundancy. The redundancy concept proved to be more feasible because of space and weight limitations. Development of the communications system progressed through the logical development cycles: initial basic design through engineering evaluation; design-verification, environment, and mission-life testing; and flight operation. The high-gain antenna was the only major development problem associated with the communication system for the Apollo Program.

INTRODUCTION

The command and service module (CSM) communications system was designed to provide communications between the CSM and the Manned Space Flight Network (MSFN), between the CSM and the lunar module (LM), and between the CSM and the extravehicular (EV) crewmen. In this document, the development of the CSM communications system is reviewed from the initial concepts to the operational system used on the Apollo 11 mission.

The Space Task Group, organized in October 1958, developed the requirement for a communications system that could provide two-way transmission of audio, video, data, control, and tracking information that was essential to the success of the lunar-landing program. The performance functions included in the system were defined more easily than the physical configuration and the circuit parameters of the equipment.

Before meaningful work on the design and development of an effective communications system could begin, it was necessary to define the requirements. Then, it was necessary to delineate the functions that were required; to determine the limitations of size, weight, shape, and power consumption; and to establish the criteria for reliability and environment.

BACKGROUND

Feasibility study contracts for an advanced manned spacecraft were awarded in late 1960. In mid-1961, requests for proposals (RFP) for the spacecraft were given to 12 companies that had shown an interest.

The communications subsystem described in the statement of work submitted with the RFP consisted of the following components.

1. Telemetry equipment
2. A very-high-frequency (vhf) transmitter and receiver
3. An intercommunications system
4. A near-field transceiver
5. Television
6. A C-band transponder
7. An altimeter and rendezvous radar
8. A minitrack beacon
9. A high-frequency (hf)/vhf recovery system
10. A deep-space communications system (S-band)
11. Antennas

The communications subsystem, together with the instrumentation subsystem, was used to perform the following basic functions.

1. Provide information for monitoring spacecraft integrity, operation of spacecraft systems, and the condition of the crewmen during all operational phases

2. Provide precision tracking

3. Provide information essential to a successful spacecraft recovery

4. Provide two-way voice communications among the earth stations, the spacecraft, and the lunar module

PROGRAM PLAN

The prime contractor for the CSM was selected in November 1961. The communications subsystem specifications included the following components.

1. Voice-communications equipment
2. Telemetry equipment
3. Tracking transponders
4. Television
5. Radio recovery aids
6. Antenna subsystems
7. Radio altimeter

In December 1961, the CSM prime contractor selected the communications and data subsystem contractor. The contract statement of work, awarded in January 1962, identified the following five major phases of a development and test plan.

1. Design information and developmental tests
2. Qualification, reliability, and integration tests
3. Major ground tests
4. Major development flight tests
5. Missions

The initial program plan was designed for a telecommunications system that was subdivided into four equipment groups: the radio-frequency (rf) equipment group, the data equipment group, the intercommunications equipment group, and the antenna equipment group. The rf equipment group consisted of the vhf/frequency modulation (FM) transmitter, a research and development vhf/FM transmitter, a vhf/amplitude modulation (AM) transmitter-receiver, a C-band transponder, unified S-band equipment, a vhf recovery beacon, an hf transceiver, and a rendezvous radar transponder. The data equipment group consisted of the up-data link (UDL), pulse-code-modulation (PCM) telemetry, a premodulation processor (PMP), and television equipment. The intercommunications group included an audio center, microphones and earphones, and three audio control panels located adjacent to each of the three couch positions. The antenna equipment group included two vhf/2-gigahertz omnidirectional antennas, two vhf recovery antennas, an hf recovery antenna, a 2-gigahertz high-gain antenna (HGA), four C-band beacon (transponder) antennas, and a rendezvous-radar transponder antenna. In addition, various antenna switches, release and deployment mechanisms, a vhf multiplexer, gimbal drives, servosystems, and sensors were included in the antenna equipment group.

DESIGN

Equipment changes resulted from program philosophy changes, new mission requirements, or normal development. From the outset, simplicity, safety, and reliability were emphasized in the basic design approach. The equipment and the system were to be sufficiently versatile to allow additional capabilities as new requirements were developed.

Approach

Performance and reliability were the first considerations in the selection of parts and materials. Those parts that had already been approved by Specification MIL-E-5400 were investigated first. When a reduction in size and weight or an improvement in performance, reliability, or simplicity of design could be realized, alternative parts were considered. Systems would be solid state unless prohibited by state-of-the-art factors, power, frequency, or similar considerations. The use of toxic, combustible, or foul-smelling materials was prohibited unless the materials were contained within sealed or potted enclosures. The equipment was designed to operate above and below the expected ambient-temperature ranges, with minimum reliance on external cooling.

Requirements

The equipment design excluded as many panel meters, switches, and connectors as possible. The construction was designed for easy maintenance. Each system was as nearly self-contained as possible to facilitate removal from the spacecraft. Connectors were left unpotted, except where necessary to conform to other reliability and design requirements, and provisions were made to ensure that connectors could not be mated improperly.

The communications subsystem was compatible with the primary power system of the spacecraft. Each component was capable of complete recovery within 1 second after a momentary power interruption, was protected against momentary overvoltage or undervoltage and interruptions, and was capable of sustained operation within plus 15-percent or minus 20-percent variation from normal voltage. Power consumption was minimized.

The design requirements also stated that mechanical and electrical interchangeability must exist between like assemblies, subassemblies, and replacement parts whenever practical. The replacement part did not have to be identical physically, but it had to fit without physical or electrical modification of any part of the equipment or assemblies (including cabling, wiring, and mounting).

The equipment was designed for maximum protection against generated interference. Generation of radio interference by the total subsystem or by any component, and the vulnerability of the system to such interference (whether conducted or radiated), were controlled in accordance with program-developed specifications.

To increase the reliability and to minimize the number of plug-in units carried by the crewmen, redundancy was designed into the subsystem wherever feasible. Substitute assemblies and systems were activated by manual switching.

Evaluation Techniques

The equipment and associated documentation were engineered for comprehensive and logical fault tracing, and the subsystem contained sufficient monitor points to allow rapid and complete systems checks. The equipment and the subsystem were designed so that prelaunch tests, before and after mating with the launch vehicle, could be completed readily without significant effect on other onboard systems. The uncoupling of system connections and the introduction of test cabling for these checkouts were kept to a minimum. Functional evaluation of the system was performed by the contractor; however, an early, unpotted, operating prototype system with the drawings, diagrams, and other pertinent documentation was provided to the NASA for review and evaluation.

DEVELOPMENT PROGRAM SUMMARY

The objective of the development program was to provide a communications subsystem design to support the Apollo lunar-landing mission. Early in the program, a basic subsystem design was established to satisfy specific communications functions and data-handling-capability requirements. These requirements were investigated in depth and resulted in detailed equipment specifications.

A major design change point divided the development program into Block I and Block II spacecraft. Although certain functional design changes were made for the Block II communications subsystem, the basic change was in the mechanical configuration. Inflight-replaceable modular-type equipment was replaced with sealed units that had built-in and switchable redundancy.

The Block I and Block II subsystems that evolved consisted of two basic groups of equipment: the electronic packages that had common environmental requirements were located in the command module (CM), and the antennas that had individual environmental requirements were located external to the CSM. This hardware is identified in table I.

The development of the individual equipment parameters was based on the total communications subsystem requirements. The interface parameters, defined in the equipment specifications, were validated and verified in laboratory subsystem tests

TABLE I. - COMMUNICATIONS SUBSYSTEM EQUIPMENT

Equipment	Block I	Block II
Internal		
vhf/FM transmitter	X	
hf transceiver	X	
vhf/AM transmitter-receiver	X	X
vhf recovery beacon	X	X
C-band transponder	X	
Unified S-band equipment	X	X
S-band power amplifier	X	X
Audio center equipment	X	X
PCM telemetry	X	X
Premodulation processor	X	X
vhf multiplexer	X	
vhf triplexer		X
Up-data link	X	X
vhf antenna switch	X	X
S-band antenna switch	X	X
External		
High-gain antenna		X
hf recovery antenna	X	
vhf/uhf scimitar-notch antennas	X	
C-band antennas	X	
S-band omnidirectional antennas	(a)	X
vhf scimitar-notch antenna		X
vhf recovery antennas	X	X

[a]Used only on spacecraft (SC) 017 and 020.

conducted by the major subcontractor as part of the ground test program. Further laboratory tests were performed at the NASA Lyndon B. Johnson Space Center (JSC), formerly the Manned Spacecraft Center (MSC), to establish spacecraft-to-ground-station compatibility. However, the development through qualification testing was on an individual equipment basis.

Initially, equipment development to establish basic electrical design was in the form of breadboards. Then, brassboard units were constructed without the use of formal drawings by engineering personnel. These units established the basic electrical and mechanical design for subsequent equipment-level testing. Formal drawings, resulting from the brassboard program, were used to construct engineering models. Because design changes were expected as a result of testing the brassboard and engineering models, materials and process controls were relaxed. These models were restricted from use on flight spacecraft. The models were used to verify the equipment design in early subsystem laboratory tests and, on the in-house spacecraft to establish the validity of test procedures and equipment for use with flight hardware.

Final-design models were produced under close control and were used for ground and flight spacecraft and for qualification testing. Qualification tests were based on the expected flight environments and were completed before the flight of similar equipment in a spacecraft.

Block II redesign varied with individual equipment. Experience with the Block I models allowed Block II development to proceed immediately with brassboard models that were usable as engineering models. Design progressed from the brassboard models directly to production flight hardware. Preproduction units were fabricated for use in ground tests.

Subsystem tests in ground spacecraft were performed concurrently with qualification testing to verify the compatibility of the equipment with the total spacecraft system. Conducting these tests in the in-house spacecraft allowed the subsystem functions to support tests on other subsystems.

The flight tests were performed after the equipment qualification and ground tests to ensure that the subsystem would meet the requirements of space operations. Unmanned flights qualified the portion of the subsystem that was required for manned earth-orbital flights. The total subsystem was flight qualified before lunar operations were begun.

BLOCK I TO BLOCK II CHANGES

During the Mercury 9 (MA-9) flight, electrical wiring problems were encountered. The cause of these problems was determined to be contaminants (water, urine, sweat, and so forth) migrating to exposed electrical terminals. After an investigation of the Apollo electrical system, the decision was made to seal all electrical wiring and connectors from the internal spacecraft environment. The Block I Apollo hardware was already designed and built in accordance with the inflight maintenance concept, which meant that many module-to-black-box connectors and self-mating black-box-to-spacecraft connectors were used. The subcontractor attempted to "humidity proof" connectors, but this attempt was lengthy and not very effective. The resulting equipment configuration eliminated almost any possibility of inflight maintenance.

In late 1963, the inflight maintenance concept was changed in favor of built-in and switchable redundancy and backup modes to achieve the desired reliability and program requirements. Concurrently (early 1964), the communications subsystem functional requirements were reexamined, resulting in required design changes. It was determined that new packaging techniques would allow for the new required functional changes and that completely sealed units could be built that satisfied the redundancy requirements within the weight and volume allowed. The result was the Block II communications subsystem. The Block I and Block II communications subsystems differed in the following three major aspects.

1. Equipment not considered necessary to the lunar-landing mission was eliminated from the Block II requirements.

2. Deficiencies noted in the Block I design were corrected in the Block II design.

3. New equipment was added because of the requirement for combined LM/CSM operations and the lunar-landing mission.

The eliminated equipment consisted of the vhf/FM transmitter and the C-band transponder, the functions of which were absorbed by the S-band equipment (that is, data transmission and ranging). In addition, the hf transceiver and antenna also were dropped from the program.

The major deficiency was the ineffective humidity protection. Correcting this deficiency involved repackaging the boxes located in the lower equipment bay and replacing self-mating connectors with screw-on-type connectors.

DEVELOPMENTAL TESTING

The objectives of the developmental (D model) testing were to validate the design approach, to develop the final operational design, and to ensure that delivered equipment would meet the design requirements.

Developmental Tests

Developmental tests were performed early in the design phase on equipment, modules, circuits, and components to determine the feasibility of the circuit design, mechanical design, component application, and so forth. All developmental tests (electrical, thermal, and vibrational) were performed by the subcontractor design engineers.

After the electrical design had been established with breadboards and brassboard models, the components were packaged in a manner similar to the expected final configuration. Tests were conducted on these "preproduction" models to obtain information on the effects of component placement on electrical, thermal, and vibrational characteristics. The flight-qualifiable-model design was established by using information obtained in the developmental tests.

The design-verification tests determined that the equipment met operational requirements when subjected to selected environments. These tests included preliminary-design proof tests and parts-application tests. All design-verification tests were conducted by the manufacturer of the equipment. A typical time phasing of the design-verification test program is shown in figure 1. Portions of these tests were repeated, as required, at any design-change point.

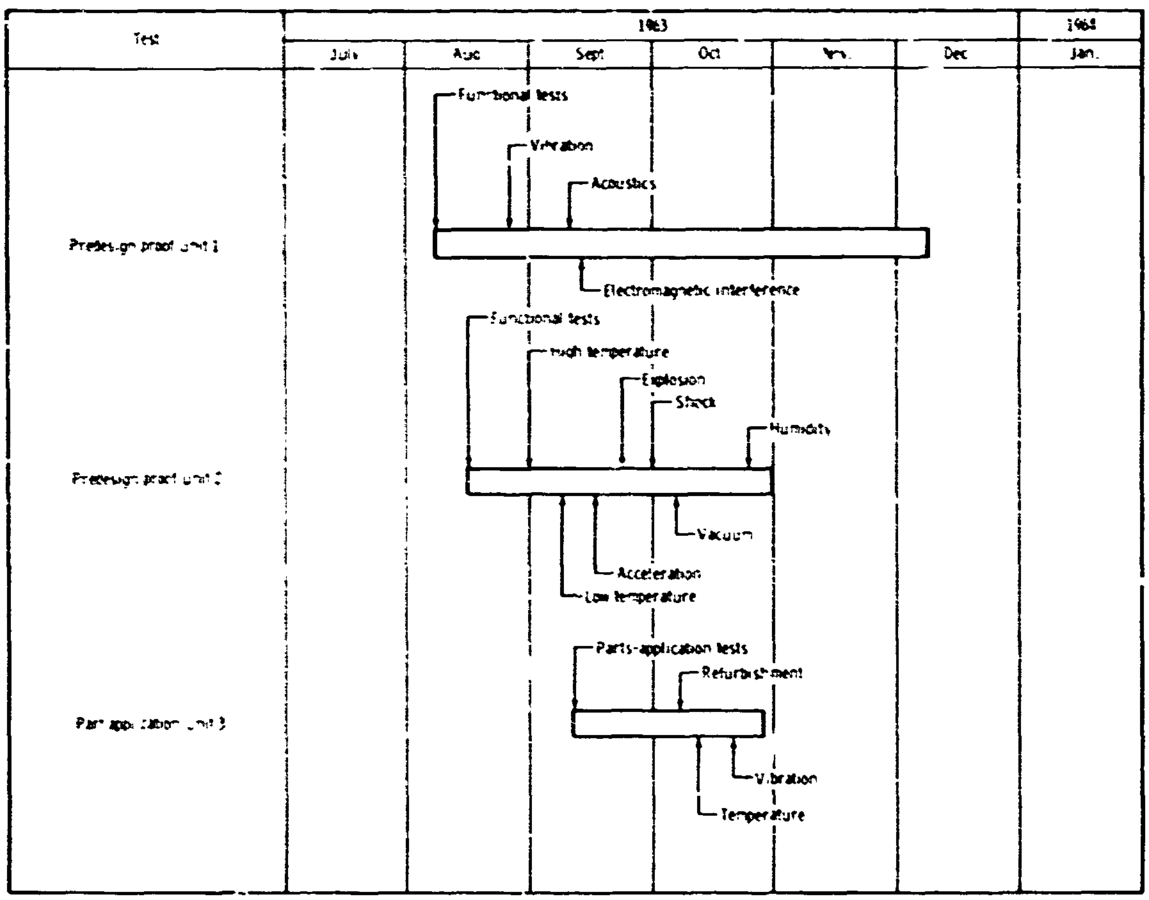

Figure 1. - Typical schedule for design-verification tests.

Preliminary-design proof tests were performed by the subcontractor design engineers on two early engineering (E) models of each major functional assembly. The tests included functional tests under laboratory conditions and normal line voltage, high- and low-line-voltage tests, environmental tests, and electromagnetic interference (EMI) tests. The objectives of the preliminary-design proof tests were to evaluate high- and low-line-voltage functional operation, to demonstrate the capability of the equipment to operate under environmental requirements, and to meet the EMI requirements as cited in each equipment specification.

Electrical, Electronic, and Electromechanical Part-Evaluation Program

The part-evaluation program was conducted to ensure the elimination of all parts not adequate for mission requirements. Parts with limited test or experience data were subjected to an approval test program. The purpose of the part-approval tests was to determine if the part could meet the requirements, either electrical, mechanical, or combinations of both, that were imposed by environmental conditions under which the part would operate. The criterion was an adequate measure of safety.

Qualification Testing

The qualification-test program for the communications equipment was divided into Block I and Block II test programs. The Block I test program was oriented to support the early unmanned and manned flights restricted to near-earth operations. The Block II test program was oriented to support manned lunar missions.

The qualification-test program was accomplished by using two sets of communications subsystem equipment for both the Block I and Block II tests. One set of equipment was subjected to design proof tests. The other set was subjected to mission-life-simulation tests. The Apollo Program ground rules for these tests required that the design proof tests be conducted at the design-limit environmental levels and that the life tests be conducted at normal environmental levels.

Design Proof Tests

In the design proof tests, articles were subjected to sequentially applied environments at maximum expected levels for a typical Apollo mission. The test sequence duplicated (where practical) the environments to which the equipment would be exposed, including the ground-environment, lift-off, orbital, entry, and recovery phases. The environments were applied at the individual black-box level to test for satisfactory performance under any single worst-case condition. Design proof tests consisted of the exposure of one set of equipment to the following environments.

Vibration. - A 5-minute vibration test per axis was conducted for launch-abort conditions. The vibration levels simulated the booster-induced environment for normal and abort conditions. To provide an adequate vibration margin, the exposures lasted six to eight times longer than expected. No vibrations simulating other sources were applied because these vibrations would be well below the booster-vibration level.

Temperature and voltage. - Temperature and voltage tests were divided into operating and nonoperating tests. The nonoperating tests included temperature extremes expected during transportation in an unheated airplane compartment and temperature extremes expected during storage in an uncooled warehouse. In these cases, the equipment was required only to operate properly after exposure. During the operating portion of the test, the temperature extremes expected for flight and entry conditions were simulated. Maximum operating voltage was applied during the high-temperature period, and minimum voltage was applied during the low-temperature period.

Electromagnetic interference. - The first part of the EMI tests consisted of measuring the spurious voltages transmitted by wires (conducted) and the fields emitted (radiated) from each item of equipment. It was required that measured values be less than maximum specified values. The second part of the EMI tests was a demonstration of the capability of the equipment to operate within tolerance in the presence of conducted and radiated interference.

Shock. - Shock tests were conducted to simulate landing shock. All equipment was required to remain intact (that is, not create projectiles that could injure the crewmen). Only that equipment required to operate after splashdown was required to operate within tolerance after exposure to a 78g shock environment.

Explosion. - During the explosion tests, the equipment was required to operate in a 100-percent-oxygen (5 psia) environment without causing an explosion or fire.

Acceleration. - Each piece of equipment was exposed to 20g acceleration to simulate worst-case entry conditions. Operation within specification was required after exposure.

Vacuum. - Vacuum tests consisted of 100 hours of vacuum (1×10^{-5} torr) to simulate the pressure loss that would result from a spacecraft environmental control system failure or a rupture of the spacecraft skin.

Corrosive contaminant oxygen humidity. - The equipment was exposed to 48 hours of a 1-percent salt spray during this test. This spray introduced the maximum contamination expected from human perspiration during an Apollo mission. The salt accumulated during this test was not removed before the remaining tests were conducted. Then, the equipment was exposed to dry oxygen for 50 hours to simulate the first portion of a mission before humidity buildup. Finally, the equipment was subjected to 100-percent humidity for 240 hours and sufficient 100-percent oxygen to bring the total absolute pressure to 5 psi.

Mission-Life-Simulation Tests

The purposes of the mission-life-simulation tests were to demonstrate for a specified period the equipment performance capabilities when the equipment was subjected to environmental stresses that simulated a normal Apollo mission. When possible, the tests were conducted with combined applied environments. Data gathered from the mission-life-simulation tests included component capability, combined-environments capability, life characteristics, and, for Block II, repeatability. The first cycle included exposure to the following conditions.

1. Room ambient conditions (250 hours) with equipment operating, simulated ground checkout of the spacecraft at the contractor facility and at the NASA John F. Kennedy Space Center.

2. Vibration (15 minutes) in each axis simulated nominal expected lift-off vibration.

3. Room ambient conditions (336 hours) simulated the spacecraft environment. During this period, tne equipment was sprayed with a 1-percent salt solution once every 24 hours.

An electrical acceptance test was performed at the conclusion of the previous steps. A second cycle, identical to the first test except for ground checkout, was performed on each test article.

MAJOR GROUND TESTS

The following ground tests were conducted to verify the flight capability of the communications subsystem.

Spacecraft Tests

Spacecraft compatibility. - In-house spacecraft tests were needed to verify the compatibility of spacecraft subsystems and subsystems operation with ground-support equipment and to allow early identification of problems associated with installation and checkout procedures. The in-house spacecraft provided a means of defining and solving problems associated with flight spacecraft without endangering the flight hardware.

The Block I in-house spacecraft was the boilerplate 14 (BP-14) spacecraft. This spacecraft was equipped with engineering-model communications equipment and was constructed for easy access to the installed equipment with test and checkout equipment. Satisfactory completion of the BP-14 tests was required before the unmanned spacecraft flights.

Acoustic and vibration. - The spacecraft was subjected to acoustic and vibration tests. The requirements using Block I hardware were supported by spacecraft (SC) 006. The data obtained verified that the spacecraft communications equipment would not be subjected to vibration levels in flight that would exceed design and qualification levels. Satisfactory completion of these tests was required before the planned manned Block I flights.

Thermal-Vacuum Tests

Block I tests. - Thermal-vacuum tests were performed on SC 008 in a manned configuration, and the tests verified the habitability of the spacecraft. The tests also verified equipment and spacecraft subsystems for Block I manned flights.

Block II tests. - The major change in the configuration of the subsystem installation required that the thermal-vacuum tests conducted on SC 008 (Block I configuration) be repeated on Block II configuration spacecraft by using SC 2TV-1. The thermal-vacuum tests were completed successfully before the Block II manned flights.

Water-Impact and Postlanding Tests

The portions of the communications subsystem that were used as postlanding recovery aids were subjected to water-impact and postlanding tests under controlled conditions during the SC 007 drop tests and the BP-29 flotation tests. Equipment performance was evaluated with respect to design criteria for the recovery aids. The water-impact and postlanding tests were completed successfully before the unmanned Block I flights.

FLIGHT-TEST REQUIREMENTS

Functional and mechanical performance verification (especially during boost conditions) of the scimitar-notch (SCIN) vhf/2-gigahertz antenna (Block I, SC 002) was required before the unmanned Block I missions. Verification was obtained by monitoring the performance of the antenna during the SC 002 tumbling-abort mission at the White Sands Missile Range.

Verification that the communications subsystem would perform within the predicted circuit margins during suborbital and orbital flights was required before manned flight. The Block I subsystem was considered qualified for manned flight after satisfactory comparison of the actual and the predicted performance data taken from the first two unmanned flights (designated SC 009 and SC 011).

Because the Block II vhf and S-band omnidirectional antennas differed from the Block I antennas in configuration and location, it was necessary to flight qualify the Block II equipment. The last two Block I spacecraft, designated SC 017 and SC 020 (unmanned), were flown at entry velocities that simulated lunar-return conditions for total spacecraft qualification, with emphasis on the Block II heat-shield-qualification phase. The Block II vhf and S-band omnidirectional antennas were installed in the two spacecraft. The antennas were considered qualified for manned Block II flights after completion of the SC 017 and SC 020 flights.

The Block II communications equipment was considered qualified for manned earth-orbital flights after completion of the Block I flight qualification, the Block II qualification program, and the ground tests. The Block II communications subsystem was considered flight qualified for the lunar mission after it had been demonstrated that flight performance met the predicted performance on a manned earth-orbital flight. The time phasing and logic of the communications subsystem development are shown in figures 2 and 3.

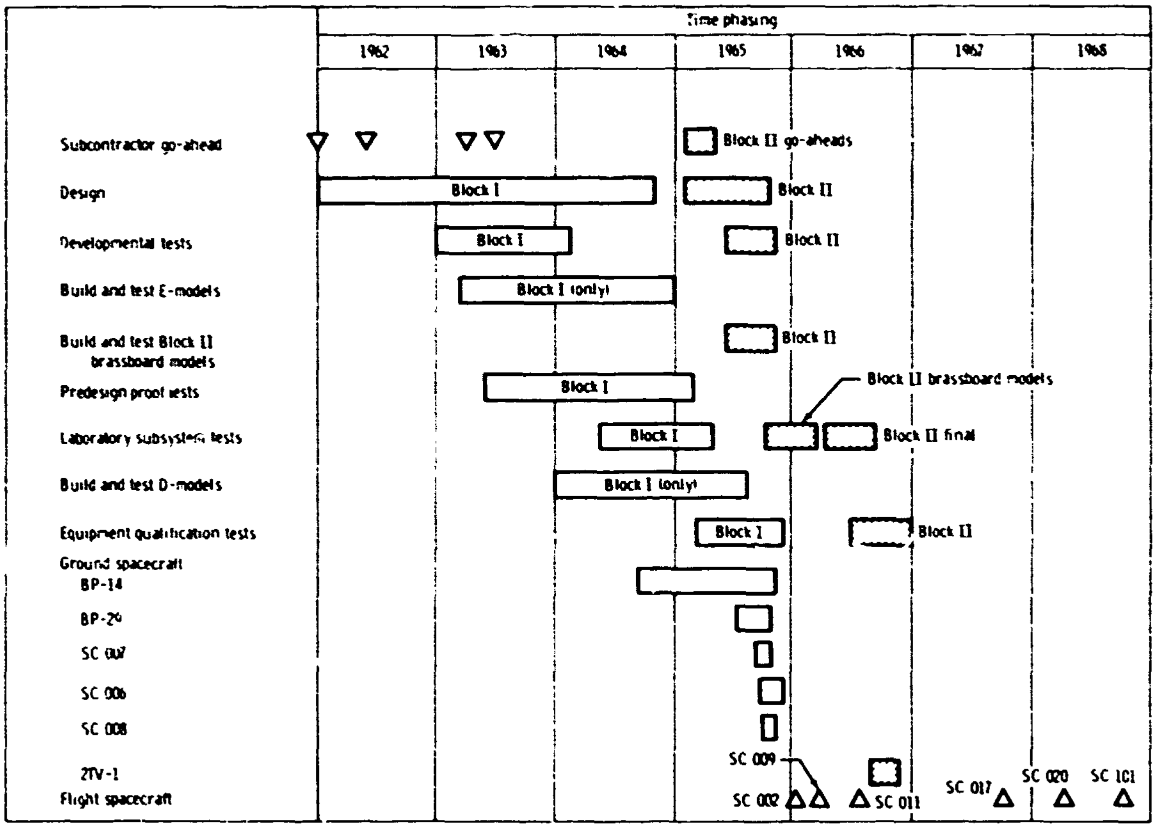

Figure 2.- Time phasing of subsystem test-development logic.

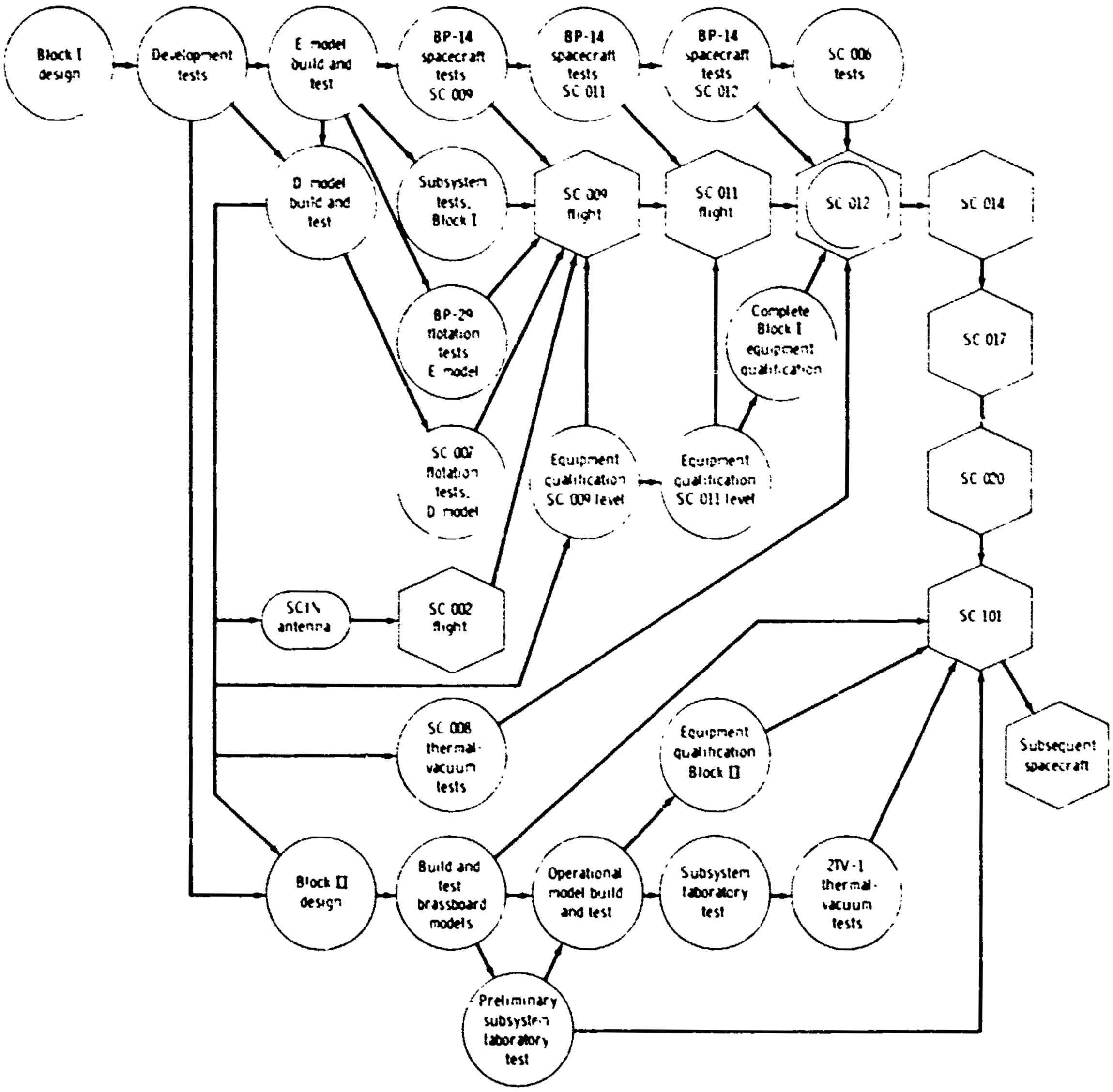

Figure 3. - Subsystem test-development logic, milestone oriented.

MANNED FLIGHT EXPERIENCE AND RESULTS

As a result of the communications subsystem performance on SC 009, 011, 017, and 020 (all unmanned and using Block I black boxes and Block I and Block II omnidirectional antennas) and the performance on the Block II equipment qualification and ground tests, the subsystem was considered qualified to support manned earth-orbital flight. Acceptable performance on this type of mission qualified the subsystem to support lunar-distance missions.

The Apollo 7 mission (SC 101) was a manned, 10.8-day, earth-orbital mission. A complete communications subsystem (without the HGA) was flown on this mission. Virtually all communications modes and functions were exercised, and the performance was evaluated. With minor exceptions, total subsystem performance was nominal. The HGA was not flown on this mission for several reasons: the HGA was not required on an earth-orbital mission and only a minimal checkout of the HGA could be performed in earth orbit.

The Apollo 8 mission (SC 103) was a manned, 6.1-day, lunar-orbital mission. With the exception of the emergency key mode, every communications mode was verified in flight. The HGA was used for the first time on this mission, and it performed normally. Special automatic reacquisition tests were performed to evaluate spacecraft shadowing and reflection characteristics on the HGA operation. During the translunar and transearth coast phases of the mission, the spacecraft was oriented properly with respect to the sun and was rolled to achieve the passive thermal-control mode. Essentially continuous communications were maintained while in this mode by ground-command switching between two diametrically opposed S-band omnidirectional antennas. The success of this method verified the feasibility of this procedure for all subsequent missions.

The Apollo 9 mission (SC 104) was a manned, 10-day, earth-orbital mission and included the first use of a manned LM. Communication subsystem performance was nominal except for a time period when the UDL real-time-command functions were inoperable. No definite cause for the discrepancy was found, although extensive postflight tests and analyses were performed. The Apollo 9 mission provided the first opportunity to use and evaluate the performance of the vhf communications capability between the CSM and the LM. The voice and data link fulfilled the intended function of the communications system on this mission.

The Apollo 10 mission (SC 106) was a manned, 8-day, lunar-orbital mission and was the first lunar-orbital mission using the combined spacecraft (CSM and LM). The HGA was used extensively in various modes on the Apollo 10 mission, and the HGA performance met all the requirements. As was done on the Apollo 8 mission, special reflectivity tests were conducted using the HGA. The results indicated the possibility of automatic-acquisition interference because of service module (SM) reflections for look-angles near the positive X-axis.

The communications subsystem performance on all the manned flights before the lunar-landing mission (Apollo 11) did not indicate the need for any functional or parameter changes. These flights proved that the communications subsystem was compatible with other spacecraft subsystems, with the LM communications subsystem, and with the MSFN. Specifically, the CSM communications subsystem was considered adequate in all respects to support the lunar-landing mission.

INLINE CHANGES

Before any manned Block II flights, various functional changes, especially vehicle testing at the spacecraft contractor facility and on the Block I flights, were needed as a result of ground testing. The changes were added inline; that is, changes were implemented without delaying spacecraft delivery schedules. Equipment changes were made after delivery to the launch facility. The more significant changes made to the originally conceived Block II communications subsystem are summarized as follows.

The S-Band Squelch

If the spacecraft S-band receiver lost phase lock or if the 30-kilohertz up-voice subcarrier modulation was lost for any reason, considerable wide-band noise was experienced in the headsets of the crewmen. The noise was considered objectionable, thus, the addition of a muting circuit (called S-band squelch) was authorized. The change consisted of adding a 30-kilohertz subcarrier level detector driving a muting switch, all located in the PMP. Loss of subcarrier or a low-level subcarrier (also indicative of receiver unlock or loss of up link) activated the muting switch to prevent the resultant noise from reaching the crewmen. This modification was effective on SC 106 and subsequent spacecraft.

Pad Communications

Testing at the launch facility indicated that a change was needed in the spacecraft audio hardware to prevent spacecraft intercommunications interference with the launch-facility communications. The spacecraft intercommunications system also was used as the hardline communications at the launch facility. The spacecraft change that was implemented used the audio-center hf receive-transmit circuitry to provide a complete four-wire capability between the spacecraft and the launch facility. This change was effective on SC 103 and all subsequent spacecraft.

Up-Data Link Interface With the Command Module Computer

The input to the CM computer (CMC), used for updating computer information, was arranged so that the UDL input was paralleled ("OR" circuit configuration) with the hardlines used to update the computer before launch. However, these long hardlines acted as antennas and picked up transients that caused incorrect information to be entered into the CMC. The hardlines were modified by connecting the long lines through UDL relays. Thus, by ground command, the UDL could isolate the computer from the transients. This change was effective on SC 106 and all subsequent spacecraft.

Very-High-Frequency Ranging

The vhf ranging history is recorded elsewhere (ref. 1), but because there was interface with and changes in the communications subsystem as a result of the vhf ranging requirement, it is mentioned here. The changes caused by vhf ranging were minor, but did involve return of vhf/AM transmitter-receiver packages to the vendor for modification and acceptance retesting.

MAJOR DESIGN, DEVELOPMENT, AND PRODUCTION PROBLEMS

In general, the communications subsystem had few major problems in the design, development, and production of the hardware. The S-band HGA was always a pacing item. A detailed history of the HGA with regard to the various aspects of the design, development, and production follows.

In February 1965, a subcontractor was selected to provide the S-band HGA for the CSM. The late start is considered to have compounded problems that developed later. This subcontractor also was working on the LM steerable antenna and seemed to be making satisfactory progress up to that time.

By October 1965, it became obvious that the infrared (IR) system being studied would not provide satisfactory earth tracking. Many problems were associated with the IR tracker, but the two major ones were the inability to acquire and track a "small earth" in a large field of view and the inability to track the earth properly when the earth and the sun were within 5° of each other. The subcontractor was directed to proceed with an rf tracking system similar to that used on the LM steerable antenna.

Early in 1966, other problems of major proportion began to affect the HGA program. The initial unit greatly exceeded the allowable weight, so that a complete redesign was necessary. This redesign required that new parts be ordered, causing considerable schedule slippage. The new requirement for an automatic reacquisition mode increased the slippage. By August 1966, it was determined that the electronics unit, packaged in a box for installation in the SM, would have to be redesigned because the circuit design was environmentally unstable. Testing and replacement of components within the box were impossible without destruction of the unit because of the method of construction of the modules and the method of potting; nevertheless, replacement of parts was often necessary.

By early 1967, three units were available in various degrees of completion. These units were an engineering model (XDV-4) that was to be used on SC 2TV-1, the qualification-test unit, and model XDV-3 that would be assigned to SC 101, the first Block II flight spacecraft.

In March 1967, the formal qualification tests started on XDV-4, but problems were experienced from the beginning. Mechanical failures occurred during every phase of the test. The causes of the failures were attributed to faulty materials, poor workmanship, design errors, rough handling, and ineffective quality control. Failures also occurred in the electronics, both on the antenna and within the SM electronics box. The entire system was extremely sensitive to temperature and humidity changes.

By June 1967, almost every functional part of the system had failed at one time or another. The 2TV-1 antenna was being used as a development model to support the qualification tests. The SC 101 antenna had been removed from the spacecraft and was being used to support the ground test program. The qualification-test unit had so many "fixes" that the validity of the data was questionable.

Although the qualification-test procedure was completed, there were several failures that had not been corrected. This situation necessitated a delta-qualification program, to be run as soon as the antenna and the electronics box could be refurbished.

By December 1967, so many problems were associated with the program that progress appeared to be at a standstill. A special task team was organized to aid the subcontractor in solving his problems and in making more satisfactory progress toward supporting schedules.

A program status review was presented to this task team by the subcontractor in mid-December 1967. The activities to date, the progress, the problems, and the test programs and results (including failures and proposed future actions) were discussed at length. Various causes, such as the following, were determined to have contributed to the schedule slips and hardware deficiencies.

1. Lack of communications between subcontractor departments and personnel

2. Unrealistic work schedules

3. Inadequate procedures for fabrication, assembly, and testing

The subcontractor was optimistic that outstanding problems could be solved and qualified hardware would be available to support SC 103. A follow-on review was scheduled for January 31, 1968.

From mid-December 1967 to the end of January 1968, open failures increased from 19 to 27, and it was obvious the subcontractor has been overly optimistic at the December review. At the January 31, 1968, meeting, the subcontractor was told that it was absolutely necessary for subcontractor management to accept responsibility for meeting quality and schedule requirements. In addition, it was stressed that a qualified set of hardware be made available for SC 103. The subcontractor agreed that the December forecast was optimistic, but accepted the challenge to provide quality hardware in the most expeditious manner possible.

A high-level management committee, composed of representatives of the subcontractor, the major contractor, and the MSC, was appointed and directed to develop a program plan that would achieve the following tasks.

1. Define the tests to be performed

2. Propose equipment allocation

3. Decide on the requirement for new qualification test

4. Propose a work-around-the-program plan to deliver suitable hardware for SC 103

5. Establish manpower requirements

6. Take positive action to close out open failures

The committee was required to review all problems (management, design, material, test, and personnel) and to present plans of action in each area at a top-management status review on February 16, 1968.

Committee progress was reviewed on February 16 and on March 15. After the March 15 review, the decision was made to eliminate the gimbal-motor brakes and to substitute an external mechanical means (snubbers) to restrain the antenna during the boost-vibration phase of the mission. It was decided that antennas under construction would be furnished for use on SC 103 and SC 104. As much testing as possible to support these units would be completed by using hardware already on hand; however, to support SC 106 and subsequent spacecraft, a new antenna and electronics box would be used for another qualification test. Also, it was announced that a full-time program manager from the contractor was being assigned to expedite the subcontractor effort to the maximum extent possible.

The assembly technicians went on strike in April 1968. To partially offset the effects of the strike on the program, the contractor brought in some contractor people and additional people from a subsidiary to assist (primarily in the design-review area). By this time, complete and detailed reviews of status design and documentation were completed or were in progress. It was obvious that a complete repackaging of the electronics box was necessary if reliability and interchangeability were to be achieved. The suitability of the microwave striplines was in doubt also because of the susceptibility of the striplines to temperature variations. Different coefficients of expansion of the copper traces and the polyolefin material (of which the boards were made) resulted in open circuits in the traces after thermal cycling.

In the succeeding months, the following specific actions were taken.

1. It was decided that CSM 103, 104, and (possibly) 106 would be equipped with the electronics box of the original design that used the small module ("mule") type of circuitry.

2. The electronics box was repackaged to eliminate the mules, which were susceptible to failure during thermal stress.

3. The striplines were redesigned.

4. The labyrinth seals on the gimbals were replaced with low-friction dust seals.

5. All of the new equipment was requalified.

The electronics boxes were delivered so that no serious schedule impact resulted. The antenna assemblies for CSM 103 and 104 were delivered and installed after the spacecraft had reached the launch facility. The qualification of these units was waived, and the performance on these two missions was considered satisfactory. The data obtained during these flights were valuable for future flight planning.

The subcontractor also was assigned the task of repackaging the electronics box. Although some problems developed, the new concept proved to be highly satisfactory, and the unit passed qualification testing with little difficulty.

Continuing failures of the striplines led to the decision to replace them with the new version (phase III striplines), which proved to be less vulnerable to thermal cycling. Because of the late go-ahead, this modification was not effective until SC 109. The antennas that were flown with the existing subcontractor striplines performed nominally throughout the missions.

The gimbal-hangup problem was traced to differential temperature [illegible] in the gear train. Heat from the motors was transferred by conduction to the [illegible] the motor shaft, keeping the temperature high while the remaining gears coo[illegible] contracted. This temperature difference caused the gears to bind. The overall dimensions of the drive gears were reduced so that they would not bind.

Despite the HGA development and production problems, the hardware supported the lunar-landing program satisfactorily. The efforts of the various teams and personnel in solving the problems are considered to have been instrumental in the resulting success of the HGA program.

TECHNICAL MANAGEMENT EXPERIENCE

Contractor Responsibilities Compared With Subcontractor Responsibilities

The design, development, and production of the majority of the communications subsystem components were subcontracted by the spacecraft prime contractor to a major subcontractor. The major subcontractor, in turn, built some of the black boxes in-house and subcontracted others. The remaining components of the communications subsystem were subcontracted by the spacecraft prime contractor to individual vendors, to other divisions of the spacecraft contractor, or were built in-house.

It was recognized by the spacecraft contractor that the designation of a "prime" subcontractor allows for a centralized system approach. The subcontractor was selected not only on the basis of technical capability, but also on the basis of ability to combine all of the components into an operable subsystem. This concept proved to be efficient and is recommended for communications subsystems on future programs.

Subsystem Functional Requirements

Initial functional requirements for the communications were determined and established early in the Apollo Program. The subsystem was designed to meet these functional requirements. As the spacecraft systems developed, inputs were made by elements of the MSC and other NASA centers. These unexpected functional requirements resulted in many minor and major redesigns before a design freeze could be accomplished. The redesigns resulted in schedule slips and increased costs. Therefore, it is recommended that the functional requirements of all organizations be brought together as early as possible in the program.

CONCLUDING REMARKS

To determine that communications subsystem design and requirements changes would be desirable, a hypothetical case was examined. Assuming that an Apollo-type program was just beginning, and with the knowledge and experience of the Apollo Program, various changes were considered to be applicable. In other words, what changes to the present communications subsystem would be recommended? The proposals resulting from this investigation are listed as follows.

1. Design in more downvoice channels so that the crewmen would not have to time-share one link.

2. Delete the high-gain antenna medium-beam width transmit capability.

3. Implement a two-axis gimbal system for the high-gain antenna instead of the present three-axis gimbal.

4. Delete the low-power capability in the S-band power amplifier.

5. Install a power amplifier in close proximity to the antenna (or antennas) to reduce line loss of radio-frequency power.

6. Provide a means to select all the spacecraft S-band antennas automatically or by ground command (or both).

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
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