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APOLLO EXPERIENCE REPORT - LUNAR MODULE LANDING RADAR AND RENDEZVOUS RADAR

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16. Abstract

A developmental history of the Apollo lunar module landing radar and rendezvous radar subsystems is presented. The Apollo radar subsystems are discussed from initial concept planning to flight configuration testing. The major radar subsystem accomplishments and problems are discussed.

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APOLLO EXPERIENCE REPORT

LUNAR MODULE LANDING RADAR AND RENDEZVOUS RADAR

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SUMMARY

A technical history of the Apollo lunar module landing radar and rendezvous radar subsystems is presented. Radar subsystem accomplishments and problems are presented with discussions of the program plan; subsystem design, development, and testing; subsystem performance, reliability, and quality control; and subsystem problems and changes. Conclusions and recommendations applicable to future space programs are also presented.

INTRODUCTION

In the development of the Apollo lunar module (LM) landing radar and rendezvous radar subsystems, the program was managed chiefly through the prime contractor, who coordinated closely with the various subcontractors to ensure maximum communication. The first prototype units of the radar subsystems evaluated subsystem performance through special tests such as environmental exposure and aircraft flight tests, which simulated actual mission conditions. The deficiencies detected during this series of tests were corrected, and the final-configuration flight units were built. The first flight units were subjected to a full qualification test program and to additional aircraft flight tests to ensure the integrity of the subsystems and the fulfillment of all design goals. The vehicle-interface and subsystem performance tests on the Apollo spacecraft were next in a series of tests to ensure subsystem compatibility. The final subsystem tests were performed during the early Apollo flights. The successful operation of the rendezvous radar and landing radar subsystems during the Apollo missions demonstrates that accurate and highly reliable subsystems have been developed for lunar missions.

PROGRAM PLAN

The program plan called for NASA to monitor and direct the contractor's work, which required extensive analyses, design studies, testing, quality control, et cetera. Monthly technical reviews of the subsystems and periodic design reviews were conducted. The NASA Manned Spacecraft Center (MSC) provided the technical guidance to ensure the technical advance of each subsystem. The resident Apollo spacecraft program office at the prime contractor facilities provided the level of support that was required to resolve some of the technical problems as they occurred.

The contractors also established offices for program management, material review, cost control, and quality analysis and for control of engineering and manufacturing procedures that were used in the design and fabrication of the radar subsystems. Periodic design reviews and technical review meetings were held to provide maximum communication between MSC and the contractors.

The delivered equipment included several subsystems that were flight prototypes. These subsystems provided electrical and electronic parameters from which the final radar configuration was determined. Tests were performed at the contractor's plant and at MSC. The contractor performed the subsystem qualification through a series of tests. During the spring of 1966, radar antenna boresighting was performed at MSC. The flight test program was conducted by MSC with contractor support at the White Sands Missile Range (WSMR), New Mexico. Figure 1 presents a schedule of significant program events.

The radar subsystem for the MSC boresight tests was delivered in April 1966; equipment for the flight test program was delivered in August 1966. The first space flight use of the Apollo radar subsystems was the Apollo 9 (spacecraft LM-3) mission in March 1969. The radar subsystems were first used for lunar landing during the Apollo 11 (spacecraft LM-5) mission in July 1969. The radar subsystems were required during four space flights and two lunar landings to provide data for rendezvous or for both lunar landing and rendezvous. The performance of the radar subsystems was excellent on each occasion.

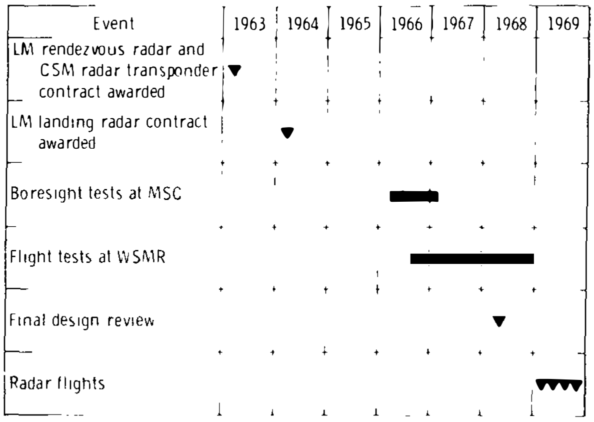

Figure 1. - Schedule of significant program events.

SUBSYSTEM DESCRIPTION

Landing Radar

The landing radar senses the velocity and slant range of the LM relative to the lunar surface by means of a three-beam Doppler velocity sensor and a radar altimeter. The velocity and range information is processed and made available to the LM guidance computer (LGC) in serial binary form and to the LM displays in the form of pulse trains and dc analog voltages. Table I presents significant landing radar parameters. A block functional diagram of the Apollo landing radar is shown in figure 2; the beam configuration is shown in figure 3.

TABLE I. - SIGNIFICANT LANDING RADAR PARAMETERS

Type of system:	
Velocity sensor	cw, 3-beam
Radar altimeter	cw, FM
Weight (nominal), lb	42.0
Size:	
Antenna assembly	
Length, in.	20.0
Width, in.	24.6
Height, in.	6.5
Electronics assembly	
Length, in.	15.75
Width, in.	6.75
Height, in.	7.38
Power consumption:	
Maximum dc consumption, W	132
Antenna pedestal tilt actuator, W	15
Antenna heater (maximum), W	63
Altimeter antenna:	
Type	Planar array, space duplexed
Gain (two-way), dB	50.4
Beam width (two-way)	
E plane, deg	3.9
H plane, deg	7.5
Velocity sensor antenna:	
Type	Planar array, space duplexed
Gain (two-way), dB	49.2
Beam width (two-way)	
E plane, deg	3.7
H plane, deg	7.3
Transmitters:	
Type	Solid state
Frequency	
Velocity sensor, GHz	10.51
Radar altimeter, GHz	9.58
Output power:	
Velocity sensor (minimum per beam), mW	50
Altimeter (minimum per beam), mW	87.5
Altimeter modulation:	
Type	Sawtooth FM
Modulation frequency, Hz	130
Deviations	
Low (altitude > 2500 feet), MHz	±4
High (altitude < 2500 feet), MHz	±20

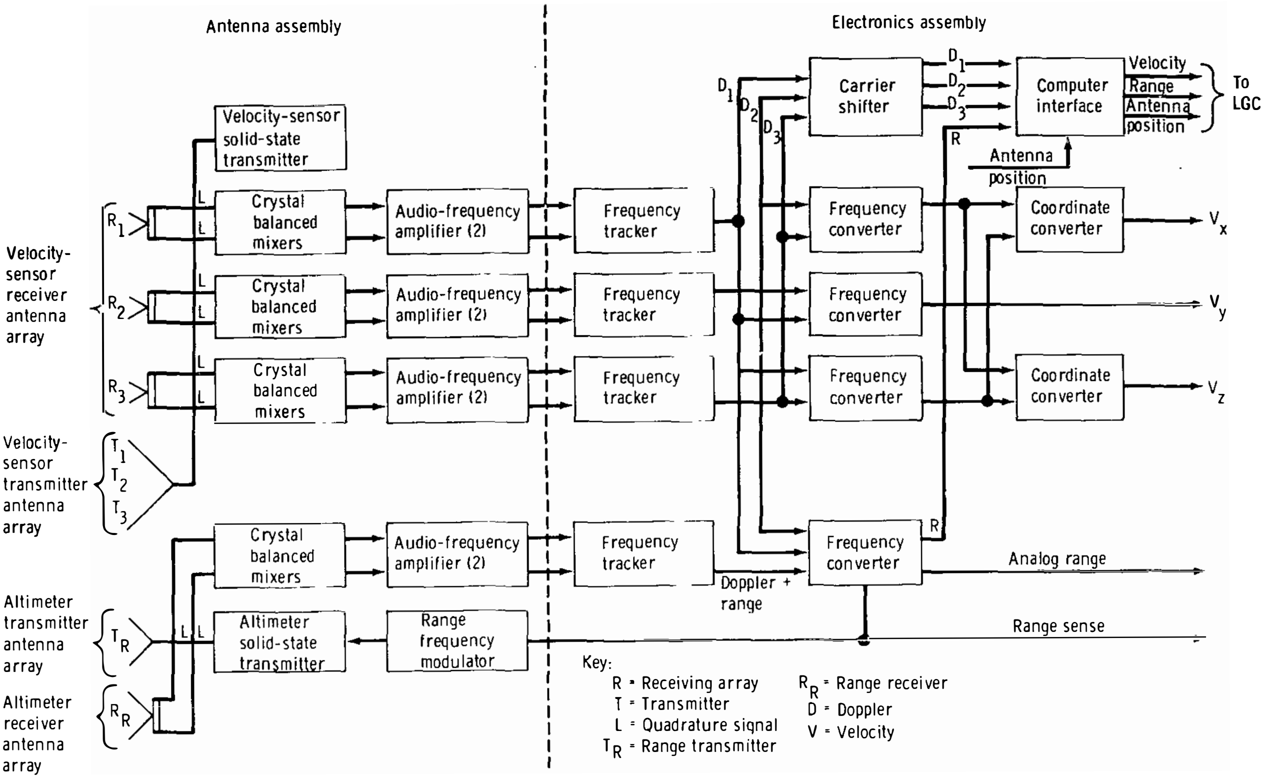

Figure 2. - Apollo landing radar block diagram.

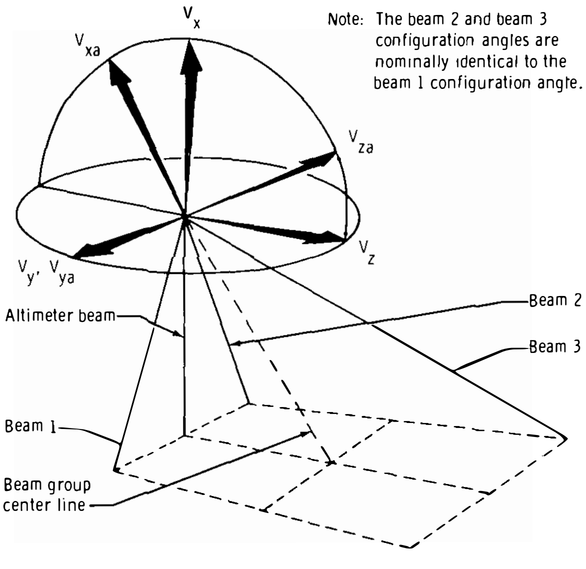

Figure 3. - Landing radar beam configuration. Velocity coordinates are shown with respect to the vehicle and the antenna.

The landing radar, which is located in the LM descent stage, is packaged in two replaceable assemblies. The antenna assembly forms, directs, transmits, and receives four narrow microwave beams. To perform these functions, the antenna assembly is composed of two interlaced phase arrays for transmission and four space-duplexed planar arrays for reception. The transmitting arrays form a platform; four quadrature-pair balanced microwave mixers, four dual audio-frequency preamplifiers, two solid-state microwave transmitters, a frequency modulation (FM) modulator, and an antenna pedestal tilt mechanism are mounted on the platform. The electronics assembly contains the circuitry that is required to track, process, convert, and scale the Doppler and FM/continuous wave (cw) returns, which provide the velocity and slant range information to the LGC and to the display panels.

The transmitting antenna radiates the cw microwave energy from the solid-state velocity-sensor transmitter to the moon. Three separate receiving antennas accept the reflected energy. The received Doppler-shifted energy, which is split into quadrature pairs, is mixed with a portion of the transmitted energy by microwave diodes that function as balanced mixers. The output of the crystal balanced mixers gives the frequency difference between the received signals and the transmitted signals. This frequency difference is the Doppler shift, which is directly proportional to the LM velocity with respect to the lunar surface along the detected microwave beam.

The output of the altimeter transmitter (a sawtooth waveform) is frequency modulated at 130 hertz and is transmitted by a second antenna. The reflected energy received by the receiving antenna is split to form a quadrature pair and, with a sample of the transmitted signal, is coupled to balanced microwave mixers. The frequency difference at the output of the balanced mixers is proportional to the time difference between the transmission and the reception of the modulated energy, plus a Doppler-shift factor. The undesired Doppler-shift factor is compensated for in the range computer.

The quadrature outputs of the three velocity sensors and the altimeter balanced mixers are routed to the four audio-frequency amplifiers. The wideband signals at the audio-frequency amplifier outputs are used as inputs for frequency trackers, which are located in the electronics assembly. The frequency trackers search for the signal over the expected frequency range with a narrowband tracking filter; once the signal is acquired, the frequency trackers follow the signal with a high degree of accuracy. The tracker output is an average frequency, equal to the frequency that corresponds to the center of power of the received Doppler signal spectrum. The Doppler sense is retained. The frequency trackers also provide a dc step voltage to indicate tracker lock.

The tracker outputs are routed to velocity and range data converters, where beam velocity information is resolved into velocity components. The coordinate system is referenced to the body coordinates of the antenna and a line drawn at right angles to the face of the transmitting arrays, which in turn is parallel to the beam group center line.

The velocity data, which are computed with respect to the beam group center line, are given in a pulse train form that is superimposed on a 153. 6-kilohertz reference frequency to facilitate a determination of the sign of the velocity. These velocity pulse trains and the range pulse train are routed to the signal data converter. The signal data converter forms an interface with the LGC by accepting strobe signals from the computer and using these signals to assemble and read out the range and velocity data in serial binary form. The serial binary radar output information is given to the LGC.

Rendezvous Radar

The rendezvous radar is a space-stabilized cw tracking radar for the Apollo lunar missions. This lightweight, highly reliable, and accurate radar subsystem functions in operational environments that are encountered on the earth, in space, and on the moon. The rendezvous radar is a solid-state coherent tracking radar that is used in the LM for performing rendezvous with the command and service module (CSM) in lunar orbit. A block diagram of the rendezvous radar is shown in figure 4, and significant rendezvous radar parameters are presented in table II.

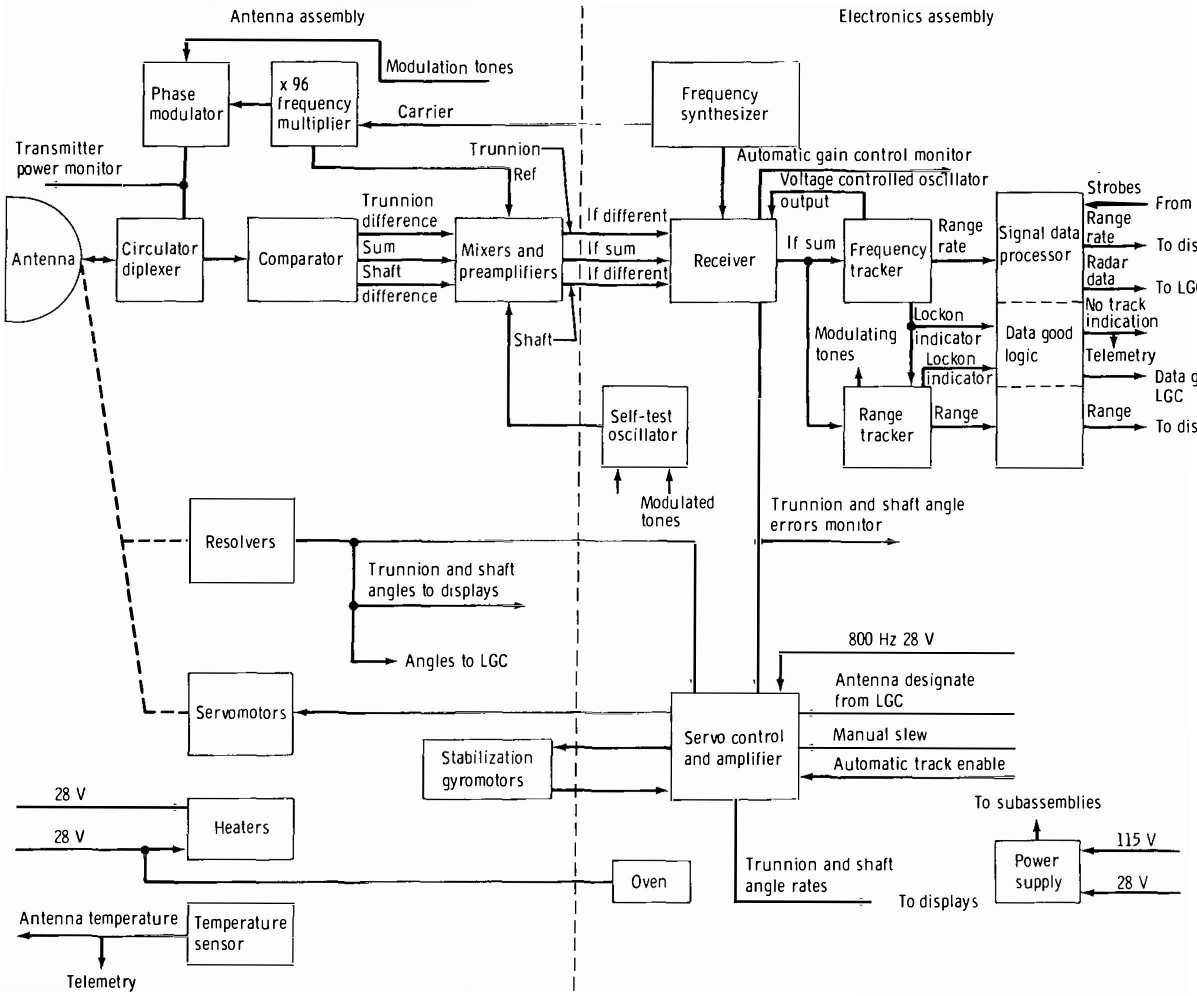

Figure 4. - Apollo rendezvous radar block diagram.

In conjunction with a transponder that is located in the CSM, the rendezvous radar measures line of sight (LOS) range, LOS range rate, LOS angle, and LOS angle rate with respect to the CSM. Both the rendezvous radar and the transponder use solid-state frequency multipliers as transmitters. Transmission and reception are both performed in the cw mode. Gyromotors (located on the rendezvous radar antenna assembly) stabilize the aperture LOS against variations in LM body motion, which permits accurate measurements of angle rate.

Angle tracking is achieved by using an amplitude-comparison monopulse technique to obtain maximum angle sensitivity and boresight accuracy. Range rate is determined

TABLE II. - SIGNIFICANT RENDEZVOUS RADAR PARAMETERS

Radiation frequency, MHz	9832.8
Received frequency, MHz	9792.0 + Doppler
Radiated power (nominal), mW	300
Antenna design	Cassegrain
Angle tracking method	Amplitude monopulse
Antenna reflector:	
Primary (parabolic)	24-inch diameter
Secondary (hyperbolic)	4.65-inch diameter
Antenna gain (at beam center), dB	32
Antenna beam width, deg	3.3 to 4
Antenna sidelobe level (adjacent to main lobe), (minimum), dB	-13
Angular coverage, deg	±70 by 225
Number of gyroscopes	4 (2 pair; 1 pair for redundancy)
Modulation	Phase modulation by 3 tones (200 Hz, 6.4 kHz, 204.8 kHz)
Receiver channels	3 (reference, shaft, and trunnion)
Receiver noise figure, dB	10
Receiver i.f. frequencies, MHz	40.8, 6.8, 1.7
Maximum range (unambiguous), n. mi.	405
Minimum range, ft	80
Minimum discernible signal (for full specification operation), dBm	-122

by measuring the two-way Doppler frequency shift on the signal that is received from the transponder. Range is determined by measuring the time delay between the transmitted-signal modulated waveform and the received signal waveform. A three-tone phase-modulation system is used to obtain high-accuracy range measurements.

The rendezvous radar includes an antenna assembly and an electronics assembly. The antenna assembly converts VHF signals to microwave-modulated signals and transmits them. The return signal is converted into an intermediate frequency (i.f.) signal and is sent to the electronics assembly. The antenna assembly locks on to, and continually tracks the source of, the return signal.

The electronics assembly furnishes crystal-controlled signals that drive the antenna assembly transmitter and provide a reference for receiving and processing the return signal. This assembly also supplies servodrive signals for antenna positioning. The electronics assembly consists of a receiver, a frequency synthesizer, a frequency tracker, a range tracker, servoelectronics, a signal data converter, self-test circuitry, and a power supply.

In addition to the microwave-radiating and the gimbaling elements, the antenna assembly includes internally mounted gyromotors and resolvers, a multiplier chain, a modulator, and mixer-preamplifier components that avoid the necessity of microwave rotary joints and permit the use of flexible coaxial cables between the outboard antenna assembly and the inboard electronics assembly. A flexible cable wrap system is used at each rotary bearing point. The antenna assembly has two axes: the trunnion (azimuth) axis lies parallel to the LM X-Z plane, and the shaft (elevation) axis lies parallel to the LM Y-axis. When the trunnion and shaft angles are 0°, the antenna boresight is parallel to the LM positive Z-axis.

DESIGN AND DEVELOPMENT

The design of the LM radar subsystems was unique because the subsystems were the first solid-state radar subsystems to be operated in the space environment. After the first landing radar and rendezvous radar engineering models had been completed, a thorough design review was held in May 1966. Changes and improvements were made to the radar subsystems after this review, and the design of the production model was finalized. To incorporate all the new features into the production model in an organized manner, another design review was held in April 1968.

During the subsystem design phase, many factors were considered that would affect the operation of the LM radar subsystems (landing radar, rendezvous radar, and transponder). One important factor was the wide range of the thermal environment conditions to which the radar subsystems would be subjected. The electronics assembly for the radar subsystems was required to operate from 0° to 160° F; however, because the antennas are located outside the spacecraft, they had to withstand temperatures of -240° to +240° F. The radar subsystems were also designed to operate under widely varying shock and vibration conditions during the launch and boost phases of the Apollo missions.

One of the most interesting tradeoff studies was of the antenna selection for the landing radar. The tradeoff study considered size, weight, gain, beam width, and ease of fabrication. Two antenna types with a given aperture are compared in table III.

TABLE III. - SUMMARY OF DISH AND ARRAY ANTENNAS

Parameter	Dish system	Array system
Gain, dB	23.8	24.9
Beam width E, deg	4.28	3.00
Beam width H, deg	6.41	5.49
Depth, in.	14.0	3.0

If magnesium is used for the waveguide on both the dish and the array systems and if aluminum honeycomb is used for sandwich structures, the weight difference is approximately 0.91 kilogram, with the dish system being heavier. The boresight technique for the array system is less involved than that for the dish system.

After the array-type antenna was chosen, there was one problem in that the predicted transmitter array beam pointing angles did not agree with the measured results. A series of tests was performed; these tests indicated that the tilted interlaced altimeter array caused a shift in the beam placement. This effect was sensitive to the tuning elements between the velocity sensor and the altimeter radiators. This study resulted in a redesign of the array elements.

Special manufacturing techniques were used because the LM radar subsystems are required to be highly reliable, lightweight, and compact. For example, multilayer boards and cordwood construction were chosen, because they fulfill the reliability and packaging requirements better than other techniques which were considered. Also, to reduce the number of unacceptable solder joints, failure records were kept on each employee in the production line.

SUBSYSTEM TESTS

Landing Radar Boresight Test

The objective of the landing radar boresight test was to acquire sufficient data to provide a basis for analysis of the static effects on landing radar antenna beam geometry and to provide the value of the velocity bias errors to be used in the LGC. This test was conducted at MSC. A detailed description of this test can be found in reference 1.

Rendezvous Radar Boresight Test

The objective of the rendezvous radar boresight test was to obtain sufficient data for the following tasks: (1) to aline the rendezvous radar with the LM vehicle navigation base, (2) to verify the functional operation of the rendezvous radar, (3) to determine the pointing accuracy of the rendezvous radar, and (4) to acquire sufficient data to analyze rendezvous radar target acquisition and angular tracking performance. This test was conducted at MSC. A detailed description of this test can be found in reference 2.

Rendezvous Radar Performance Evaluation Flight Test

The objective of the 1967 rendezvous radar performance evaluation flight test was to verify the capability of the rendezvous radar to perform as required during the Apollo missions. The tests were conducted under flight conditions, which simulated several CSM-to-LM orientations along each of the probable LM rendezvous and lunar-orbit trajectories to demonstrate that the rendezvous radar performed within the required accuracy range at distances representative of the design range. The objective of the simulated rendezvous test was to verify that the tracking, ranging, and velocity loops of the rendezvous radar operated properly during a simulated lunar stay. A T-33 jet aircraft and a helicopter were used for the tests at WSMR. A detailed description of the flight test plan can be found in reference 3.

Landing Radar Performance Evaluation Flight Test

The objective of the 1967 landing radar performance evaluation flight test was to demonstrate the capability of the landing radar to meet performance requirements under dynamic flight conditions and to secure data that were used in evaluating the LGC performance. The tests were conducted, within the capabilities of the test aircraft, under flight conditions that simulated numerous points along each of the probable LM lunar-descent trajectories.

The objectives of this series of tests were (1) to evaluate the performance of the landing radar under dynamic flight conditions, (2) to verify the landing radar mathematical model, (3) to evaluate the performance of the landing radar and the LGC, (4) to verify the adequacy of the landing radar to meet mission requirements, and (5) to define the constraints or necessary design changes. A more detailed description of this flight test can be found in reference 4.

Performance Evaluation of the Apollo Rendezvous and Landing Radar Flight Test

The 1968 performance evaluation of the Apollo rendezvous and landing radar (PEARL) flight test was an extension of the 1967 flight test and was necessary to correct some of the questionable data that resulted from timing errors in the 1967 flight test. In addition to correcting the data, the PEARL program provided data for new profiles, which aided in the evaluation of the landing radar for expected lunar-descent trajectories.

Landing Radar Reflectivity Test

The objective of the 1968 landing radar reflectivity test at WSMR was to improve the estimate of reflectivity as a function of the near-vertical incidence angle, obtained from the 1967 RF scatterometer test. Modifications to the PEARL test aircraft and the landing radar were made to conduct this test. The modifications consisted of changing the antenna mount and the location of radar monitoring points. The electrical properties of the terrain were measured to permit an extrapolation of the reduced data to the lunar environment. Results of this test are incorporated in the present lunar reflectivity model. A more detailed description of this test can be found in reference 5.

Apollo 7 Rendezvous Radar Overflight Test

The objective of the rendezvous radar earth-orbital flight test during the Apollo 7 (spacecraft CSM-101) mission was to determine the performance of the rendezvous radar transponder link under a simulated overpass condition at maximum range. The test conditions were to simulate the lunar-stay phase of a lunar mission by requiring the rendezvous radar to track an orbiting CSM that was within operative range to verify that the tracking, ranging, and velocity loops of the rendezvous radar and the tracking loops of the transponder could function at the extreme limits of their capabilities. The tests were made in the mode II operation configuration (long-range acquisition). A detailed description of this flight test can be found in reference 6.

Radio-Frequency Scatterometer Test

The primary purpose of the 1967 RF scatterometer test was to provide measurements of the backscattering coefficient per unit surface area σ_o for various types of earth terrain. The angular dependence of the backscattering cross section per unit surface area $\sigma_o(\theta)$ and the absolute magnitude are measured by relating the power density of the reflected energy for each Doppler frequency to the respective incidence angle.

Both the accuracy and the altitude capability of the radar subsystems that are used in surface track systems depend upon surface reflectivity characteristics. For a rough surface, a knowledge of the value of σ_o as a function of the variable is usually sufficient to describe surface reflectivity. Therefore, another objective of the reflectivity program was to learn as much as possible about the reflectivity characteristics of various earth surfaces. This information would aid in the design and evaluation of radar for earth, lunar, and planetary missions. The reflectivity program included the following:

1. Reflectivity of various types of surfaces, including sand, desert, and volcanic formations

2. Reflectivity as a function of time for a given surface

3. Reflectivity as a function of altitude

A more detailed description of this test program can be found in reference 7.

Apollo 9 Landing Radar Test

Because the LM landing radar had never been tested in a space environment before the Apollo 9 (spacecraft LM-3) flight, special instrumentation was installed to measure the signals in the velocity and altimeter preamplifier outputs, during the landing radar test. If only crystal noise were present in the channels during the test, the radar was operating properly. However, during the Apollo 9 mission, spurious signals appeared, which were attributed to flaking of the Mylar thermal blanket during the lunar-descent engine burn. This flaking necessitated changing the Mylar thermal blanket to an ablative paint on the lunar-descent stage.

Radio-Frequency View Factor Test

The purpose of the RF view factor test was to determine any false lockon effects caused by Doppler returns from LM structural vibrations during lunar-descent engine firings. Three areas of special interest were the LM legs, the LM engine skirt, and the LM bottom structure.

Results of the test indicated that some degradation of radar performance had occurred. For this reason, three changes were made to correct the problem.

1. The preamplifier rolloff was changed to decrease the landing radar sensitivity to the low-frequency vibrations exhibited by the LM structure.

2. The antenna was rotated 6° to prevent the landing radar beam from impinging on the LM leg structure.

3. A baffle was installed to shield the radar beams from the lunar-descent engine bell reflections.

INTEGRATION AND CHECKOUT TESTS

Test Philosophy

The objective of subsystem testing was to demonstrate the integrity of the equipment after installation on the spacecraft. Subsystem tests were conducted at the LM contractor's plant and at the Kennedy Space Center (KSC). These tests provided a functional verification of the replaceable electronics assemblies to validate the integrated subsystem.

The objective of integrated testing was to determine the physical, functional, and operational compatibility of all subsystems. The functional compatibility of all LM subsystems was demonstrated during simulated flight modes. Integrated tests were performed at the LM contractor's plant and at KSC.

Test Flow

The test flow, which includes testing at the factory and KSC, is shown in table IV.

TABLE IV. - TEST FLOW

(a) Factory testing

LM-3 and LM-4	LM-5 and subsequent	CSM-101, CSM-104, CSM-106, CSM-107, and subsequent
1. Preinstallation test	1. Preinstallation test	1. Rendezvous radar transponder functional verification test
2. Rendezvous radar functional verification test	2. Radar subsystem functional verification test	2. CSM integrated checkout test
3. Landing radar functional verification test	3. FEAT Plugs in Plugs out	
4. FEAT[a] Plugs in Plugs out		

(b) KSC testing

LM-3 and LM-4	LM-5 and subsequent	CSM-101, CSM-104, and CSM-106	CSM-107 and subsequent
1. Rendezvous radar boresight test	1. Rendezvous radar boresight test	1. Combined systems test (O&C building)	1. Combined systems test (O&C building)
2. Combined systems test (O&C[b] building)	2. Combined systems test (O&C building and VAB)	2. LM-to-CSM interface test	2. Combined systems test (VAB)
3. LGC interface test	3. Flight readiness test	3. Flight readiness test	3. Flight readiness test
4. Combined systems test (VAB[c])			
5. LM-to-CSM interface test			
6. Flight readiness test			

[a] Formal evaluation acceptance test.

[b] Operations and control.

[c] Vehicle assembly building.

Rendezvous Radar Test Problems

Gyromotor leakage. - As a result of one gyromotor failure at the manufacturer's plant, a special gyromotor leakage test was incorporated into the LM rendezvous radar test program. The gyromotor failure was caused by a leakage of suspension fluid into the gyromotor float; this leakage resulted in a gravity-sensitive drift. Drift tests were performed on the LM-3 and LM-4 rendezvous radar subsystems at KSC and on the LM-5 rendezvous radar at the manufacturer's plant to determine whether a gravity-sensitive drift term with time dependence was present. The only anomalies that were encountered during this special test were a no-spin-up situation and excessive drift. The special test was deleted after the manufacturer had shown by endurance tests that gyromotors with leakage problems did not have either decreased life or degraded performance.

Gyromotor spin-up failure. - During the special test for gyromotor leakage that was performed on rendezvous radar 18 (spacecraft LM-4) at the boresight range, one gyromotor failed to spin up. The failure was attributed to a nonconcentric rotor bearing, and the faulty gyromotor was replaced.

Gyromotor drift. - The special test for gyromotor leakage performed on the LM-4 rendezvous radar indicated a possible excessive drift in one gyromotor. Although the gyromotor was replaced, later tests showed that the drift of the suspect gyromotor was within acceptable tolerance.

Electromagnetic interference. - During the combined systems test on spacecraft LM-3 at the operations and control (O&C) building, electromagnetic interference (EMI) was encountered and traced to a harmonic of the 1.024-megahertz clock in the pulse code modulation and timing electronics assembly. During the rendezvous radar boresight test on the same electronics assembly on spacecraft LM-3, EMI problems had been traced to a harmonic of the high-frequency tone. To ensure adequate screening of EMI problems, the pilot test was instituted at KSC for spacecraft LM-3 and LM-4, and at the contractors' facilities for spacecraft LM-5 and subsequent spacecraft. The pilot test indicated the susceptibility of the rendezvous radar frequency tracker to spurious signals from the 40.8-megahertz preamplifier. The problems were generally correctable by slight tuning of the 40.8-megahertz preamplifier in the rendezvous radar.

Minimal discernible signal leakage. - During the flight readiness test of spacecraft LM-3 and during the combined systems test on spacecraft LM-4 and LM-5 at the vehicle assembly building (VAB), range tracker lock could not be acquired. The problem was caused by RF leakage in sections of the waveguide that connected the rendezvous radar with the transponder. A flexible waveguide was incorporated in the ground support equipment to correct the leakage for the flight readiness test of spacecraft LM-5 and for subsequent tests.

Voting logic. - Because of a design deficiency, the voting (gyromotor select) circuit did not automatically select the preferred gyromotors. Consequently, a manual switch was installed for gyromotor selection. This problem was first noted during the combined systems test of spacecraft LM-4 gyromotor torquing at the O&C building, during the rendezvous radar boresight tests on spacecraft LM-5, and during the preinstallation test on spacecraft LM-6. The gyromotor manual selection switch was installed on spacecraft LM-5 and subsequent spacecraft.

Cycle slip and moisture absorption. - A cycle slip in transponder 20 occurred during the combined systems test on spacecraft LM-5 and spacecraft CSM-107 at VAB. Initially, the problem was thought to be caused by excessive input signal strength, which would overdrive the microwave phase modulator in the transponder and result in ambiguous ranging because of improperly weighted midtone and hightone inputs to the rendezvous radar up-down counter. However, the cycle slip was later attributed to moisture absorption in the rendezvous radar and transponder ranging tone filters. Since that time, both the rendezvous radar and the transponder were found to have phase-shift problems in the filters for the ranging tones. Extensive testing and bakeout procedures were integrated into the contractor and KSC test cycle to ensure identification and correction of these problems before launch, because design modifications of the rendezvous radar or the transponder to correct this deficiency were too costly. The procedure involved obtaining extensive heater operation prior to launch or any range-tone phase measurement. Adjustment of the phase calibrator circuits of the rendezvous radar or the transponder ensured normal accuracy ranging under nominal mission conditions.

Landing Radar Test Problems

Long-line capacitance. - During the combined systems test on spacecraft LM-5 at VAB, the blanking pulse in the landing radar altimeter low-frequency sweep generator was inhibited by long-line capacitance. The corrective action was to shorten the cable between the deviation inhibit point in the low-frequency sweep generator and the deviation inhibit switch at the bench test console (BTC).

Velocity bias error. - During the landing radar subsystem functional verification test for spacecraft LM-5, a logic race at the input to the landing radar electronics assembly shift register caused a one-count bias error in velocity. Appropriate logic circuit alterations were made to eliminate the logic race condition. In addition, the Gaussian distribution, which had been assumed for the test limits when the Doppler spectrum simulator was used, was corrected to account for the presence of more energy in the tails of the distribution because of the poor approximation of a Gaussian spectrum in a simple three-stage resistance-capacitance low-pass section.

Transponder Test Problems

Self-test. - The original wiring of the test selection switches on CSM panel 101 could impair operation of the rendezvous radar transponder during rendezvous (when other normal functions of this switch, such as reaction control system quad temperature measurements, were performed). This situation resulted from the fact that positions A, B, and C of the right-hand test switch activated the self-test oscillator of the transponder. This problem occurred during the rendezvous radar transponder functional verification test for spacecraft CSM-101. To correct the situation, the test switch was rewired so that the transponder self-test operated from a separate self-test enable switch.

Low supply voltage. - Excessive noise in the phase-lock loop and loss of phase lock were encountered during the CSM integrated checkout test for spacecraft CSM-101 (transponder 13) because of poor transponder inverter power supply regulation. The problem was traced to a low dc input voltage that was caused by excessive line length as well as circuit breaker and isolation diode voltage drops. The dc input voltage was raised to an adequate level by modifying the previous routing of the rendezvous radar transponder dc supply wiring with a direct connection through remotely operated relay controls to the service module power distribution terminals.

Minimum discernible signal. - During the rendezvous radar transponder functional verification tests for spacecraft CSM-103, unreasonably sensitive values of the minimum discernible signal (-142 dBm) were obtained. The unreasonable values were determined to be the result of poor attenuator calibration and poor procedure. The attenuator calibration was degraded because of signal leakage from high-power to low-power paths in the BTC microwave plumbing. The original procedure involved observation of the phase-lock discrete to indicate the lockon point. However, because the spectrum analyzer gave a more accurate indication of the lockon point, the original procedure was deleted in favor of the spectrum analyzer method.

Ground loop of 6.4 kilohertz. - Excessive midfrequency phase error was encountered during the rendezvous radar transponder functional verification tests for spacecraft CSM-104. The problem was caused by a long signal ground path that had not been properly reconnected to the dc ground when the new dc voltage supply connections were made to correct the low supply voltage problem. To correct the problem, the signal ground path was properly connected to the dc ground at the transponder.

Bench test console leakage. - During the CSM integrated checkout test for spacecraft CSM-101, the transponder phase locked on X-band energy that leaked from the BTC. For spacecraft CSM-104 and subsequent spacecraft, the X-band source in the BTC was turned off during periods in which operation of the transponder beacon mode was desired to ensure electromagnetic compatibility, in the most severe condition, between the rendezvous radar transponder and the CSM systems.

SUBSYSTEM PERFORMANCE

The radar subsystems performed very well in flight as shown by the successes of the Apollo 7 (spacecraft CSM-101) mission, the Apollo 9 (spacecraft LM-3) mission, the Apollo 10 (spacecraft LM-4) mission, the Apollo 11 (spacecraft LM-5) mission, and the Apollo 12 (spacecraft LM-6) mission. The results of these flights are summarized in the following paragraphs.

Apollo 7 Mission

The Apollo 7 (spacecraft CSM-101) overflight test of the rendezvous radar at WSMR fulfilled the test objective. All parameters of the rendezvous radar that were tested (shaft, trunnion, range, and range rate) showed the performance to be consistent with observed errors from the rendezvous radar PEARL flight test series at WSMR. Exceptional performance was noted for shaft, trunnion, and range measurements from the rendezvous radar. The rendezvous radar range rate bias appeared to be greater than the master end-item specification.

Apollo 9 Mission

During the Apollo 9 (spacecraft LM-3) earth-orbital flight, the landing radar detected spurious signals that were attributed to flaking of the aluminized Mylar coating during the lunar-descent engine burns. This problem was corrected; therefore, the confidence for reliable operation during an actual lunar landing was increased.

Apollo 10 Mission

Because only limited radar data were available from the Apollo 10 (spacecraft LM-4) flight, an estimate of the lunar reflectivity was made in the vicinity of acquisition only. However, the reflectivity calculation that was based on the Apollo 10 mission data added confidence to the reflectivity model for the LM landing radar performance simulation.

Apollo 11 Mission

The landing radar performed well during the Apollo 11 (spacecraft LM-5) lunar-descent and lunar-landing maneuvers. The data appeared to be well within specification limits, except a few points at low velocities near zero Doppler shift where the landing radar was not expected to track. The two questionable data points were probably caused by poor data processing during the LGC overload alarm. The lunar-surface reflectivity was determined to be in close agreement with the present smooth-surface model at the velocity beam 1 acquisition point.

Apollo 12 Mission

On the Apollo 12 (spacecraft LM-6) flight, the landing radar operated as expected; lockon was obtained early in lunar descent. Calculations based on flight data indicated a higher value of lunar reflectivity than had been expected, which might have been the result of local lunar terrain slopes that gave high angles of beam incidence.

Overall Performance

On all missions up to Apollo 12, the rendezvous radar has performed well, as indicated by the successful rendezvous. On the Apollo 11 (spacecraft LM-5) and Apollo 12 (spacecraft LM-6) flights, the rendezvous radar range data were compared to the VHF ranging system data. In both cases, the range data were in very close agreement. As an example, on the Apollo 12 flight, the mean bias between the rendezvous radar range data and the VHF ranging system data was less than 0.04 percent of the median range at which the comparison was made.

PROBLEMS AND CHANGES

Failure of Multilayer Printed-Circuit Boards

The multilayer printed-circuit boards failed during the rendezvous radar qualification test program. The interlayer columns exhibited open circuits at hot- and cold-temperature extremes. The vendor believed that the boards which had passed thermal cycling were flightworthy, but further tests indicated that the boards would fail after thermal cycling. The corrective action was to identify the manufacturing problem and then to change the process. Therefore, the multilayer boards were replaced with an improved type of board. The improvements resulted from changes in manufacturing techniques.

Landing Radar Detection of Vibrating Structural Members

During vibration testing of the landing radar subsystem that was mounted on an LM mockup, the radar locked on to false targets. Vibrating structural members were generating Doppler interference signals in the reflected signals, and the radar locked on to these Doppler signals. To correct the problem, a metal shield was installed between the radar antenna and the vibrating members to block the view of the members by the radar. In addition, the low-frequency response of preamplifiers was reduced to attenuate the low-frequency false Doppler signals further, and the antenna was rotated to move the beam from the LM structure.

Range Errors in the Rendezvous Radar

During flight tests of the rendezvous radar at WSMR, errors were found in the range readings, the magnitudes of which were in multiples of 2400 feet. The errors were found to be caused by cycle slips in the range tone tracking phase-lock loop. Each cycle slip, or phase shift of 360°, caused a change of 2400 feet in the range reading. The cause of the cycle slips was a low signal-to-noise ratio and a tone phase-shift bias inherent in the design. Therefore, a limiter was added in the transponder tone amplifiers to restrict the peak noise to an amplitude at which the noise would not cause cycle slips.

Arcing in Frequency Multiplier

During thermal vacuum testing, arcing occurred in the transmitter frequency multiplier chains. The problem existed in both the rendezvous radar and the landing radar and was caused by high voltages and inadequate separation of high voltage points. The solution was to rearrange the components to obtain greater separation.

Cracked Solder Joints

On the landing radar, solder joints cracked; this cracking was caused by a buildup of conformal coating in critical locations. The conformal coating had a thermal coefficient of expansion which was different from that of the component leads. As the temperature changed, stress was exerted on the solder joints by the expansion and contraction of the conformal coating. As a result, the solder joints cracked. The problem was solved by changing the manufacturing technique to prevent buildup of large amounts of the conformal coating in spaces where it could exert stress on the solder joints.

Rendezvous Radar False Carrier Lockon

During testing of the Apollo 9 (spacecraft LM-3) radar subsystems, the rendezvous radar locked on to false signals. The rendezvous radar was found to be locking on to a harmonic of the 204.8-kilohertz range tone. The solution was to improve the shielding on the cables between the antenna assembly and the electronics assembly.

Landing Radar Lockon

Data which were obtained from the Apollo 9 (spacecraft LM-3) flight indicated that false Doppler signals were received, which could cause radar lockon. The false Doppler signals were found to be caused by reflections from flaking aluminized Mylar thermal coating, located on the bottom of the lunar-descent stage. When the lunar-descent engine fired, some of the Mylar burned and flaked off. The flakes then caused radar energy reflections that contained Doppler frequencies which were related to the velocity of the flakes. The solution was to replace the aluminized Mylar with a non-flaking thermal paint.

Rendezvous Radar Range Tone Phase-Shift Drift

The phase shift of the rendezvous radar range tone filters was found to vary with time. The problem occurred on the Apollo 9 (spacecraft LM-3) spacecraft and subsequent spacecraft. The phase-shift drift was most serious on the midtone (6.4 kilohertz) filter. The effect of excessive phase shift was to cause range errors that were in multiples of 2400 feet. Turning on the tone filter heaters tended to stabilize the phase-shift drift. The solution was to adjust the filter phase shifts to a small negative value initially, and then to operate the heaters long enough to obtain the phase shift near the desired value of 0°.

CONCLUSIONS AND RECOMMENDATIONS

The success of the Apollo flights and the excellent operation of the radar subsystems have shown that the radar subsystem design, construction, and testing are satisfactory. Nevertheless, a few recommendations may be helpful in planning future space programs.

Careful planning should be provided for all flight tests. In particular, flight tests should not be strictly mission oriented (where the subsystem is tested only under anticipated mission profiles). Instead, tests should also be conducted to evaluate the subsystem capabilities and performance limits. Such data become very important when predictions must be made to indicate subsystem performance under new conditions.

For filtering of range tones, digital filters should be considered to avoid the phase-shift drift problem that was encountered in the rendezvous radar. Digital filters were not practical when the rendezvous radar design was finalized. However, recent advances in the state of the art indicate that digital filters should be seriously considered in future space programs to avoid problems of phase-shift drift.

Consideration should be given in future space programs to compensation in the guidance computer for the Doppler effect in the range channel of the landing radar. Presently, the Doppler effect is removed in the landing radar by subtracting a scaled Doppler shift that is obtained from two of the velocity beams. When the spacecraft velocity is zero, the Doppler shift is zero, and the velocity trackers lose lock. A resulting transient appears in the range channel, which causes a range data transient. If the Doppler effect in the range channel were removed by the guidance computer, a zero Doppler-shift transient would not affect the range data.

Interface control documents should be updated to reflect the flight hardware interface requirements. Several testing problems could have been avoided with updated interface control documents. Provisions for mandatory modification of ground support equipment to meet test requirements should be included in the ground support equipment contract to ensure that the ground support equipment is current. A statement of permissible field adjustments and the required ground support equipment capability to support field adjustments should be included in the interface control documents. All testing groups must maintain close communication. Firm requirements for justification of any deviation in test procedure, equipment configuration, or test stimuli should be negotiated by all testing groups before the test program is begun. In particular, testing of the first two or three vehicles, and the subsystems, should have nearly one-to-one correspondence in test procedure from vendor to launch.

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