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APOLLO EXPERIENCE REPORT - VERY-HIGH-FREQUENCY RANGING SYSTEM

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16. Abstract

The history of the Apollo very-high-frequency ranging system development program is presented from the program-planning stage through the final-test and flight-evaluation stages. Block diagrams of the equipment are presented, and a description of the theory of operation is outlined. A sample of the distribution of errors measured in the aircraft-flight test program is included. The report is concluded with guidelines or recommendations for the management of development programs having the same general constraints.

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APOLLO EXPERIENCE REPORT

VERY-HIGH-FREQUENCY RANGING SYSTEM

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SUMMARY

This report documents the history of the development of the Apollo very-high-frequency ranging system from the inception of the program through flight evaluation. The implementation of the program plan is outlined, and the formation of a task team to effect contractor/Manned Spacecraft Center interface is described. The design and operation of the system are detailed, and a description of the system itself is included. Design evaluation is outlined, and the development and testing are described. The performance of the system in flight is outlined briefly, and major changes are described. Finally, recommendations are made for developmental programs having the same general constraints.

INTRODUCTION

In the early developmental stages of the Apollo spacecraft, the requirement was established to provide the command-service module (CSM) with the capability to perform an active (rescue) rendezvous with a disabled lunar module (LM) in flight. A rendezvous radar for this purpose was designed into the CSM to permit successful completion of such a rescue mission. However, during the summer and fall of 1964, personnel at the Manned Spacecraft Center (MSC) conducted an extensive weight-reduction study of the CSM. One facet of this study was the consideration of the feasibility of eliminating the rendezvous radar from the CSM. Various substitute systems to obtain the data necessary to perform an active CSM rendezvous were considered, including modification of the very-high-frequency (VHF) communications system to permit measurement of line-of-sight range and use of the optical sextant to measure the relative angles. Analytical studies indicated that sufficient information could be obtained by measuring only the angles. Although measurement of range with the VHF transceivers was shown to be feasible, insufficient justification existed to provide this capability. As a result of this study, the contractor was directed to eliminate the rendezvous radar from the CSM system and to provide the computer software necessary to use the angle data from the sextant.

As the Apollo Program progressed into the summer of 1967, the results of numerous crew simulations indicated that insufficient time would be available during a mission to obtain the necessary optical "marks" to complete an active CSM rendezvous successfully and that insufficient fuel would be available from the reaction control system fuel budget. Without range information, no effective way existed to use the service propulsion system to complete the rendezvous. At that time, the use of ground-track data was suspect because of unexplained anomalies in the Lunar Orbiter tracking data. These anomalies were later discovered to have been caused by mascons, which caused the lunar-gravity-potential model to be inaccurate. As a result of this new information, and to provide tracking data on the lunar far side, it was decided to provide the capability for measuring the range from the CSM to the LM. Several systems were considered, including self-contained ranging systems and radars. It was concluded that, from considerations of weight and volume, the preferred solution would be to modify the existing communications system and to use the existing entry monitor system (EMS) to display the range. The VHF communications system provided the necessary duplex link, so the problem was reduced to (1) providing the range modulation and tracker equipment and (2) processing the data for display on the EMS.

In September 1967, the major contractors were directed to implement the VHF ranging system. The target date for delivery of the first flight hardware was established as December 1968.

PROGRAM PLAN

Implementation of the VHF ranging system was complicated because of the combination of tight schedules and the complexity of interfaces with the various subsystems and contractors. The interfaces of the various organizations involved are shown in figure 1. The short developmental schedule and the complex organizational interfaces necessitated bypassing the normal program-management philosophy. Consequently, a task team was formed with representatives from all the pertinent contractors and organizational elements within MSC. The team leader from the CSM Project Engineering Division of the Apollo Spacecraft Program Office (ASPO) was supported by representatives from the Program Control Division of ASPO, the Systems Engineering Division of ASPO, and the Telemetry and Communications Systems Division of the Engineering and Development Directorate. The CSM part of the system was managed by the CSM contractor and included the EMS display, the CSM VHF transceivers, the digital ranging generator (DRG), and the CSM ground-support equipment (GSE). The command module computer (CMC) interface and software development were managed by the CMC contractor. The LM portion of the system was managed by the LM contractor and included the VHF transceivers, the range tone transfer assembly (RTTA), and the LM GSE.

The team was to conduct biweekly reviews with the responsible contractors and subcontractors for a period of 3 to 4 months and monthly thereafter. The initial 6 weeks were to be used primarily to develop the detailed functional, performance, and interface specifications for the CM and LM VHF ranging equipment. The next 2 weeks were to be concentrated on defining checkout requirements and the certification test, and the subsequent weeks were to involve close monitoring of hardware development and production. The objectives of the task team were fulfilled or exceeded in all instances. For example, the CMC Interface Control Document was completed within 6 weeks from the program starting date.

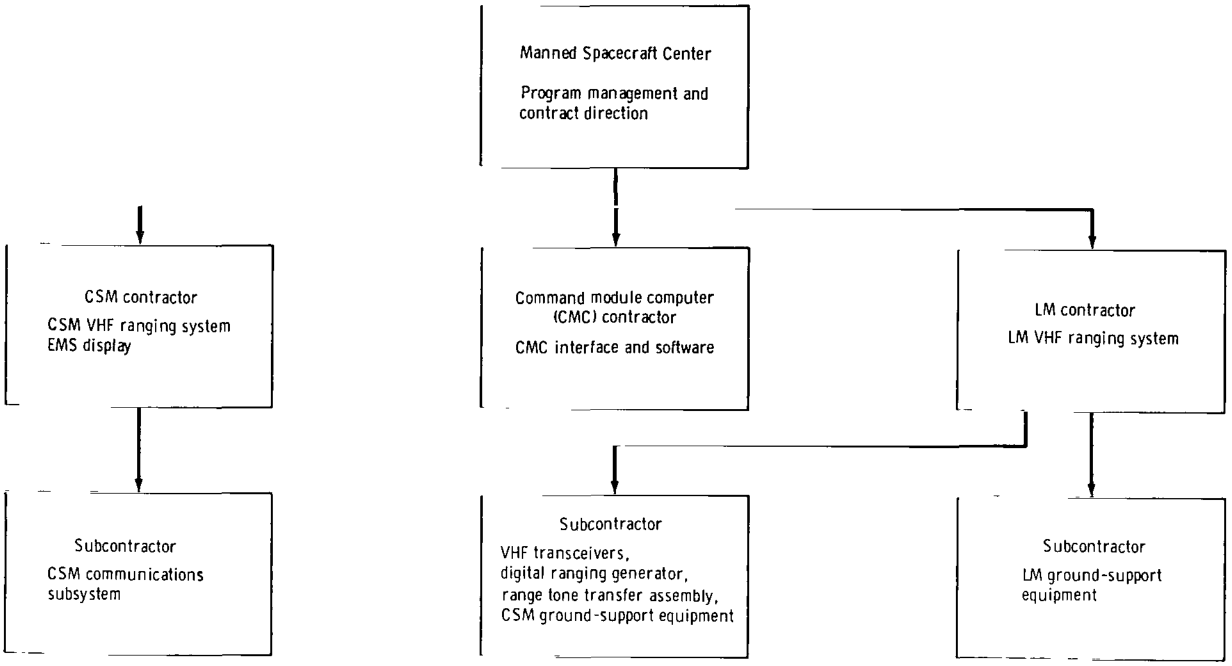

Figure 1. - Manned Spacecraft Center/contractor relationship for VHF ranging program.

It was expected that by December 15, 1967, the team could be disbanded. However, because of the tightness of the schedule (13 months for delivery of flight hardware), the team functioned until early 1969.

DESIGN

The VHF ranging system was implemented to provide a range-measuring capability from the CSM to the LM in the event of a rendezvous for which the CSM would be required to perform all maneuvers (CSM-active rendezvous). The system was to use the existing VHF communications transceivers as the radio-frequency (rf) link between the two spacecraft; the emphasis was on minimal modifications of existing equipment.

As the system evolved, hardware changes were required to only three existing electronic equipment items; namely, the CSM VHF transceiver, the LM VHF transceiver, and the CSM EMS display. The CSM and LM transceivers were modified to accept the ranging modulation, and the EMS display was modified to display the range measurement. No interface changes were required for the CMC because the interface for the deleted CSM rendezvous radar still existed. However, computer-software changes were required to process the data.

Constraints

The ranging system was configured around the existing CSM and LM VHF transceivers, and several stringent constraints had to be observed. These constraints were as follows.

1. Changes to the VHF transceivers were to be as minimal as possible.

2. The voice and data operation of the VHF transceivers could not be degraded in a nonranging mode.

3. Audio quality could not be adversely affected during ranging.

4. Removal of the ranging equipment or power removal from the ranging equipment could not adversely affect the VHF transceiver performance.

5. Failures in the ranging equipment could not adversely affect the transceiver performance.

6. Ground and direct-current returns of the equipment had to remain isolated.

Requirements

The performance requirements for the VHF ranging system were loosely defined at the beginning of the program. Initial requirements placed on the contractor were a minimum range of 200 nautical miles, a design-goal accuracy of ±250 feet, and simultaneous voice/ranging to at least 200 nautical miles.

As the program progressed, the requirements changed many times before the performance specifications finally were established as follows.

Range (with simultaneous voice)	200 n. mi. to 500 ft
Accuracy, ft	±450 (random, ±180; bias, ±270)
Maximum tracking velocity, ft/sec	±600

Approach

The system concept was designed to make maximum use of the existing VHF communications transceivers, as explained in the system description to be presented. The CSM, as the vehicle needing the range information, became the active range-measuring vehicle, and the LM became the transponder vehicle. Thus, the CSM equipment initiated the ranging tones and supplied the range information to the onboard computer and to a visual display.

A block diagram of the equipment configuration is shown in figure 2. The existing Apollo hardware used and the new equipment required to provide the ranging capability are shown in this diagram. The DRG is shown in figure 3, and the RTTA is shown in figure 4.

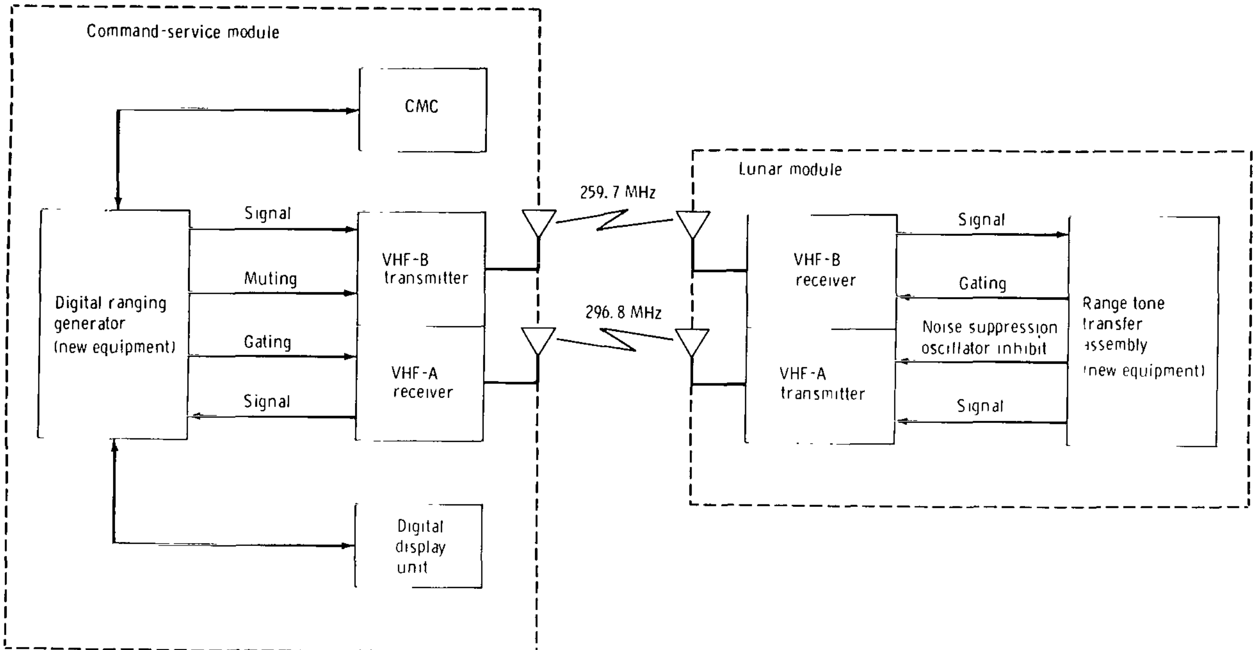

Figure 2. - Equipment configuration of the VHF ranging system.

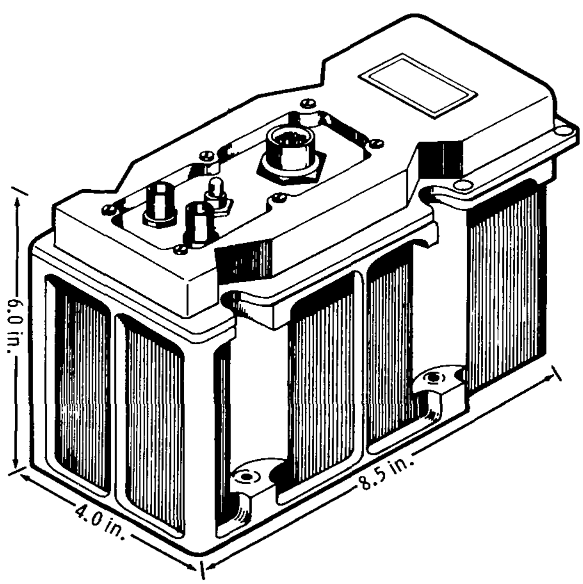

Figure 3. - Digital ranging generator.

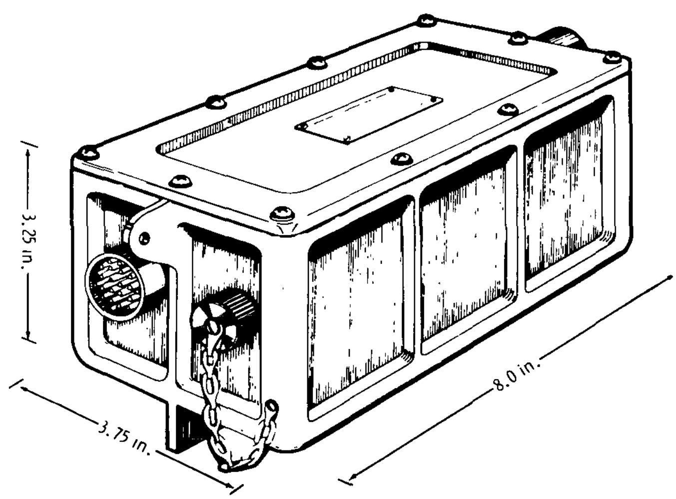

Figure 4. - Range tone transfer assembly.

To display the range reading, the existing EMS was modified to accept, display, and count a train of pulses derived from the range tracker, with each pulse representing 0.01 nautical mile. The range was then displayed and "up" or "down" counted as the range increased or decreased. The CMC interface was the existing interface originally provided for use with the CSM rendezvous radar, which had be deleted earlier.

To satisfy the simultaneous voice/ranging operational requirement, it was necessary to accept a slight amount of range "jitter" because the VHF transmitters use on-off modulation; that is, the audio is amplified and clipped, and the transmitter carrier is turned on during one-half of the audio cycle and off during the other half. During the on portion, the audio signal is chopped by the range tone; however, during the off portion, no range tone can be transmitted. Therefore, 50 percent of the range pulses are eliminated, resulting in a slight random error in the range measurement.

After the system block diagram was completed and the tracking-loop characteristics determined, design of the actual circuitry was started. In addition, testing was begun on the transceivers to determine the propagation delay variations. These delay variations were the major source of error in the system; thus, these measurements were the beginning of a complete system-error model.

System Description

The Apollo VHF ranging system is a three-tone system. The ranging signal consists of three square-wave components at 31.6 kilohertz, 3.95 kilohertz, and 247 hertz. The 31.6-kilohertz signal provides the range-measurement accuracy, while the 3.95-kilohertz and 247-hertz signals provide unambiguous range measurements for the required 200-nautical-mile operating range. A clock drives a tone generator that produces these frequencies. The 3.95-kilohertz signal is transmitted first; a modulo-2 combination of 3.95 kilohertz and 247 hertz is then transmitted. Finally, the 31.6-kilohertz signal is transmitted to achieve maximum range accuracy as these signals are selected in the CSM to track the signal returned by the LM. In the LM, the 31.6-kilohertz signal is tracked with a voltage-controlled oscillator (VCO) to reconstitute the returned signal during the transponding mode only. By means of an automatic sensor, the mode being used in the LM is selected and the VCO tracker is switched in and out accordingly.

A description of the operation of each unit is as follows. The DRG in the CSM, in conjunction with the CSM VHF communications transceiver (fig. 5), acts as a signal tracker during ranging. System power is initially turned on within both the LM and CSM. Power turn-on inhibits the DRG range trackers, resets the range display to zero in the CSM, and withdraws the CSM "data good" signal (which indicates to the CMC when data are available). The system remains in this initial condition until the CSM astronaut operates the VHF ranging reset switch. This action resets the program and initiates ranging acquisition. Initially, a 3.95-kilohertz tone is transmitted from the CSM; this signal is transponded by the LM and received and locked by the midloop tracker in the CSM. A 3.95-kilohertz tone combined with a 247-hertz tone is then transmitted from the CSM. This tone is again transponded by the LM, received by the CSM, and locked by the coarse-loop tracker. This loop locks the 247-hertz signal and provides for a theoretical unambiguous range read-out for as far as 327 nautical miles. This signal is then locked by both the midloop tracker and the coarse-loop tracker.

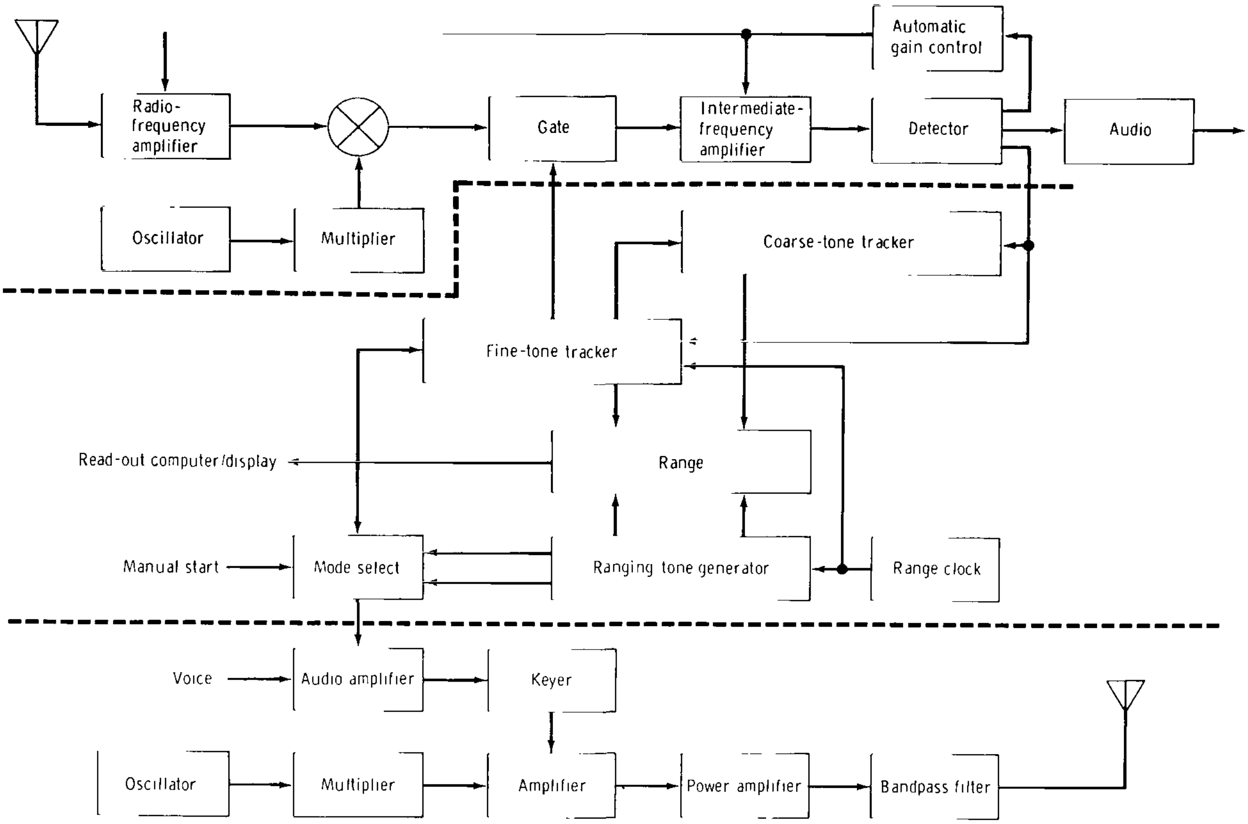

Figure 5. - Command-service module ranging function.

This step in the ranging acquisition program provides an increased tracking resolution of both the 247-hertz and 3.95-kilohertz tones. At this point in the acquisition, a DRG tracking logic test is conducted to determine if the signal is being tracked properly. If undesirable tracker operation is detected, a reset occurs and the program returns to the initial inhibit condition. If, however, the test shows acceptable tracker operation, a 31.6-kilohertz tone is transmitted and, simultaneously, a 31.6-kilohertz gating signal is applied to the CSM receiver.

The LM has a signal sensor that determines when the 3.95-kilohertz tone is being received; during this period, the LM acts as a simple transponder. However, when the 31.6-kilohertz signal is received and the 3.95-kilohertz tone disappears, the LM attempts to lock the 31.6-kilohertz signal and gates the LM receiver accordingly. The LM tracks the received 31.6-kilohertz signal and retransmits the tracked signal to the CSM. The CSM then tracks the LM-generated 31.6-kilohertz signal using the fine-loop tracker.

The condition is finally reached in which the CSM is tracking the 31.6-kilohertz signal that it originated and that is now delayed by the two-way distance between vehicles. At this point, the following sequence is initiated (fig. 6). The DRG range counter and DRG range register are cleared. The range count is transferred to the DRG range

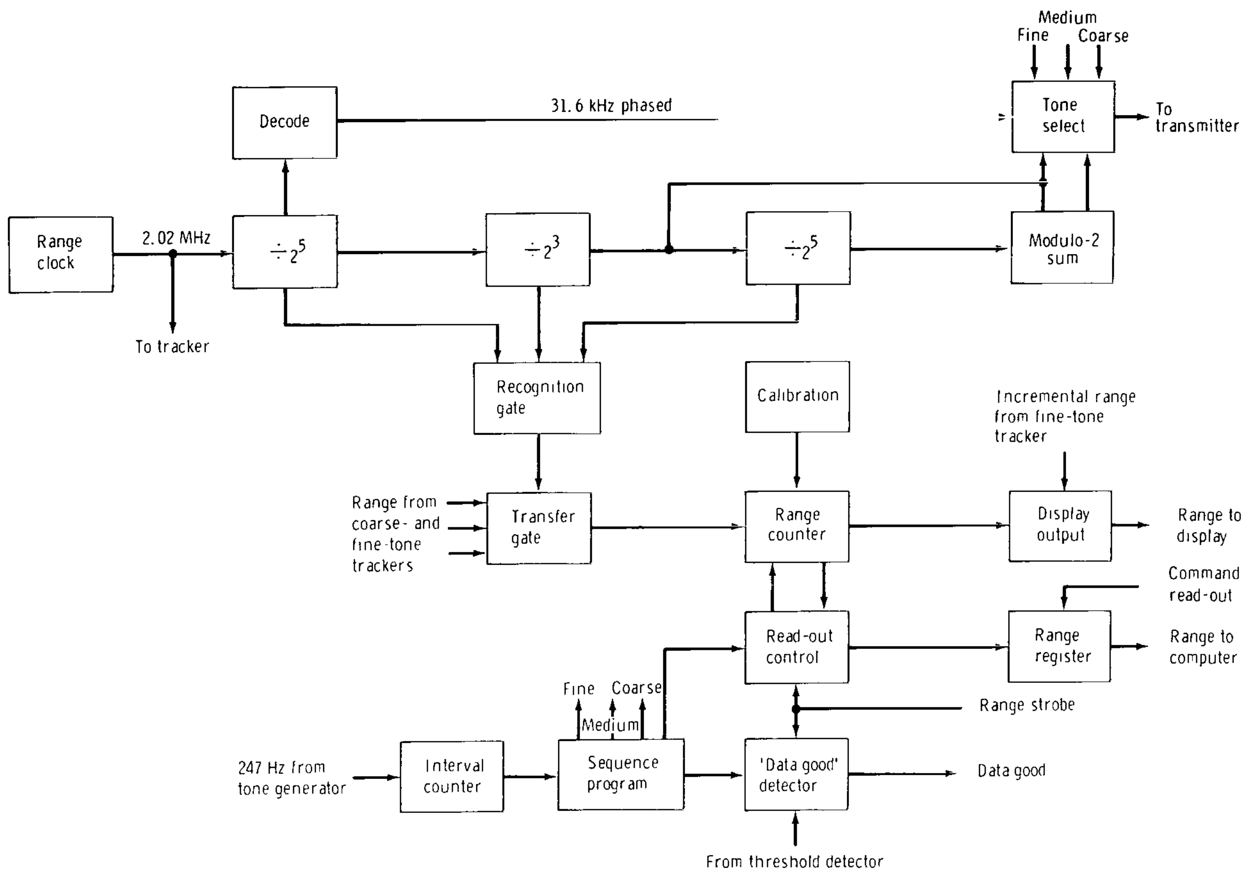

Figure 6. - Ranging tone generator and data output.

counter. This range count is then down-counted to remove predetermined equipment delay and then represents actual CSM-to-LM range. A good-track test is performed again to determine correct tracker operation at this time. If good tracking exists, the range information in the counter is sent to the EMS for display by down-counting the DRG internal range counter to zero at a rate of 31.6 kilohertz.

These count pulses are supplied to the EMS display as a serial pulse train. This display reads actual CSM-to-LM range and continues to be updated by the range-update pulses generated by the tracker as it tracks the 31.6-kilohertz tone. Simultaneously with the initiation of the EMS display, a data-good signal is provided to the CMC by the DRG to indicate that the computer can request a range data read-out at any time. When the computer sends a series of read-out strobes to the DRG, the following sequence is initiated upon receipt of the first strobe. The internal DRG computer output register is cleared, the range data are transferred from the DRG range counter to the output register, and a good-track test is performed to determine correct tracker operation. (If the test fails, the display is reset, "data good" is withdrawn, and the program is returned to "tracking inhibit.") If the test indicates correct tracker operation, the range in the DRG output register is clocked out by the computer-command read-out pulses.

The RTTA in the LM, in conjunction with the LM VHF communications transceiver (fig. 7), acts as a signal transponder during ranging. The operation of this equipment is as follows. Initially, the CSM-transmitted 3.95-kilohertz midtone is received at the LM. The LM RTTA signal sensor detects the presence of this tone and opens the path for direct retransmission. (The received signal is amplified, clipped, and retransmitted.) The next acquisition tone received is the combined 3.95-kilohertz and 247-hertz tone. This tone combination has 247-hertz spectral sidebands centered about 3.95 kilohertz and is accepted by the signal-sensor filter. The signal sensor remains activated, and direct retransmission continues. Finally, the 31.6-kilohertz tone is received by the LM, and the signal sensor drops out. Dropout of the signal sensor activates the VCO servoloop, and the 31.6-kilohertz tone is then tracked. The RTTA tracker generates a 31.6-kilohertz tone, phase locked to the received signal, and this generated tone is transmitted to the CSM.

The tracking technique used in both the CSM and LM was an early/late 31.6-kilohertz gating signal. Track is good when the early and late signals gate equal energy of the incoming 31.6-kilohertz pulses. The early and late signals are altered at a 5.3-kilohertz rate (three early, three late). These signals gate the rf signal (rather than the audio signal) to avoid the large range inaccuracy that would be introduced by intermediate-frequency delay variations if the audio signal were tracked.

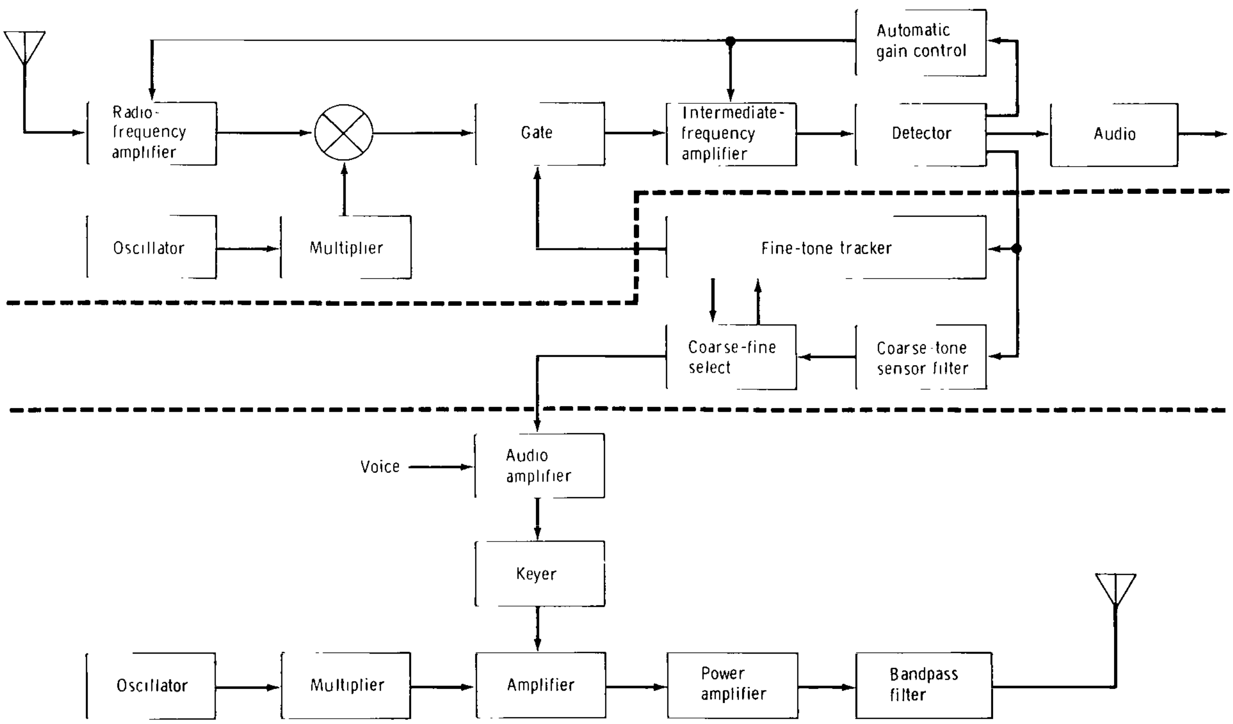

Figure 7. - Lunar module transponder.

Evaluation of Design

Two major design reviews, the Preliminary Design Review and the Critical Design Review, were conducted to monitor and evaluate the system design as it evolved. In addition, monthly technical reviews also were established.

During the early stages of the program, an extensive system analysis and some breadboard circuit analyses were performed at the MSC. To demonstrate the design, a breadboard was built by the vendor and a demonstration was conducted for MSC personnel to evaluate fully the effect of ranging operation on audio operation. In addition, low-signal-level acquisition was demonstrated. The demonstration was a total success, and production was initiated on the prototype hardware.

DEVELOPMENT

Prototype Hardware

Including the breadboard and a first production unit (called an engineering model), six CSM prototypes and seven LM prototypes were constructed. Of these, two of the digital range generators were shipped to the CSM contractor to undergo vehicle tests, and three of the range tone transfer assemblies were shipped to the LM contractor to undergo vehicle tests. The remaining units were entered into design-verification testing at the vendor's facility to undergo operational tests and to complete the system-error model. Later, one set of equipment was shipped to the White Sands Missile Range (WSMR) temporarily for a flight test.

Qualification Hardware

Two digital range generators and two range tone transfer assemblies were constructed for qualification testing, and all four units passed the testing with no problems. The qualification units were constructed in parallel with the flight hardware because of the tight schedule and long lead time for obtaining high-reliability parts. This situation led to the delivery of flight hardware before completion of qualification tests. However, all black-box qualification tests were completed by mid-March 1969, 2 months before the first flight of the equipment.

Flight Hardware

Flight-hardware development began immediately after the engineering models successfully completed enough confidence tests to ensure that no major design changes would be needed. The major problem in producing the flight hardware was obtaining high-reliability parts. Some part-qualification tests were not completed when the equipment was flown, even though the black-box qualification had been completed. The first LM flight unit was shipped on November 30, 1968, and the CSM unit on December 3, 1968, only 12 days and 8 days later, respectively, than the original dates set in September 1967.

TESTING

Black-Box Testing

Each unit produced was subjected to an acceptance test to determine if all parameters were acceptable before delivery of the equipment. In addition, two CSM and two LM units were subjected to qualification testing at a black-box level.

Subsystem Testing

A systems test area was constructed at a subcontractor facility early in the program to evaluate system errors and low-rf-level acquisitions. The engineering models and preproduction models were used extensively in the systems test area to complete the system-error model and to gain confidence in the design before qualification and flight-model production were started. When problems or questions arose, the area proved extremely effective as a means of finding solutions.

Ground Vehicle Testing

Tests were performed on each vehicle by the prime contractors before shipment to John F. Kennedy Space Center (KSC), where additional tests were performed. In addition to the separate vehicle tests, an integrated CSM/LM test was performed at KSC. This test was performed because no equipment-matching requirements had been placed on the vehicles. The sets of equipment, therefore, had not been previously operated and tested together. The test proved that the particular black boxes would operate together and also gave an indication of the bias error for the operation of this particular equipment set.

Flight Testing

A flight test program was conducted at WSMR in the fall of 1968. The tests were performed with the CSM equipment located at a ground base and the LM equipment installed in a T-33 jet aircraft, as shown in figure 8. Various flights were flown to simulate CSM-active rendezvous trajectories and to achieve the maximum range and range rates specified for the system. The VHF range data were recorded at the ground base and were then evaluated with aircraft-tracking data from the WSMR FPS-16 radars. A summary of data accumulated during one of the flights is shown in figure 9, wherein the percentage of data points accumulated at 1-second intervals is plotted as a function of the error in feet.

The flight test verified that the system could operate successfully over the required range and range rates within the error limits allowed. The system operated successfully from ranges of 1000 feet to 200 nautical miles, with range rates up to 600 ft/sec. Documentation of the results of the tests was performed by the prime contractor.

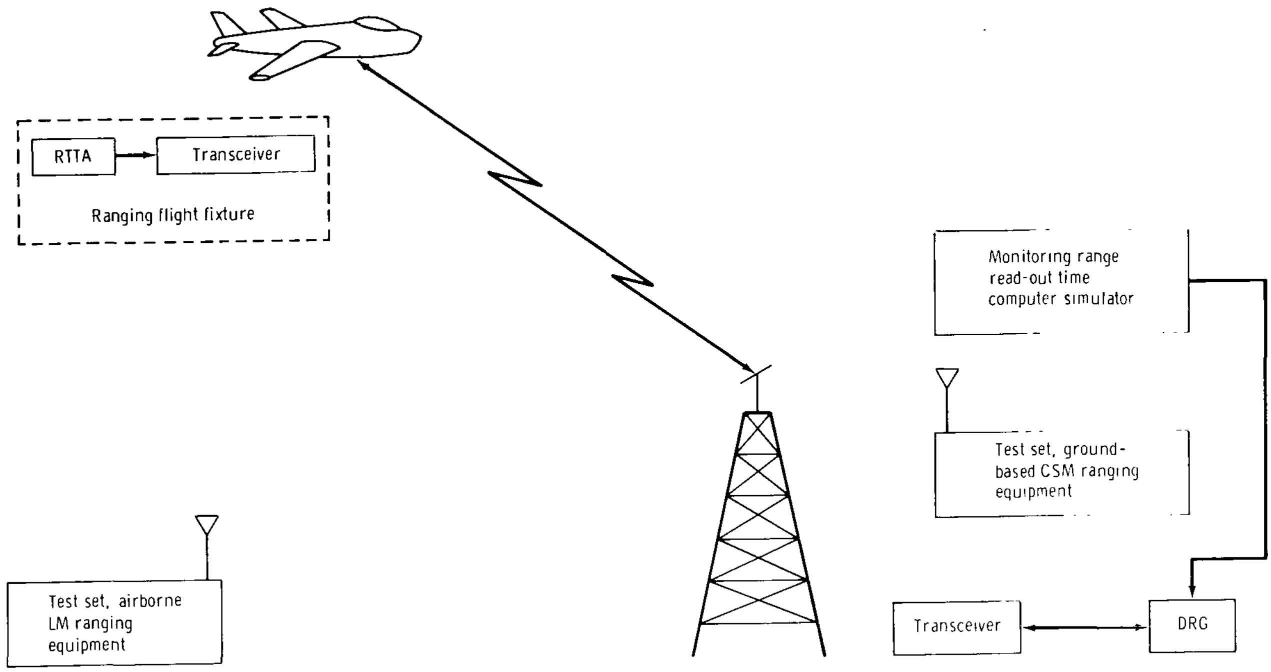

Figure 8. - Field test configuration.

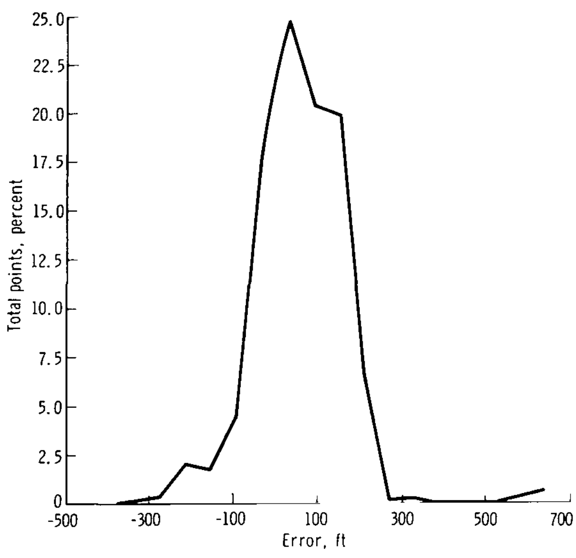

Figure 9. - Summary of flight 3 of VHF ranging flight tests at WSMR.

PERFORMANCE

The VHF ranging system was flown initially on the Apollo 10 mission. The system operation proved to be exceptional; the range was 320 nautical miles, and the accuracy compared to within a few feet of that of the rendezvous radar range-measuring system.

After the Apollo 10 flight, the system use was expanded by using more range measurements for the CMC rendezvous program to update the onboard state vector and to calculate closing range rate between the CSM and LM at orbital insertion. Although some problems did occur while using the VHF ranging system in later flights, the problems proved to be caused by inadequate rf-power margins. These problems were caused by using the wrong antenna or by vehicle maneuvers that caused low VHF antenna-gain products. During all flights, this system has equaled or exceeded specified performance requirements.

MAJOR CHANGES

Although the original system concept was carried to completion, some minor changes were made during the breadboard phase of design. These consisted of tone-frequency changes, acquisition-procedure changes, and changes of the gating point in the receiver.

Once production had been started on the flight hardware, only one delay was encountered. This delay occurred in manufacturing the multilayer circuit boards used in the DRG and RTTA. The material being used to fabricate the boards was susceptible to moisture penetration. The moisture then caused delamination spots during the drying cycle of the fabrication. The problem was resolved by changing the resin content of the material.

Some difficulties were encountered in the LM GSE development, mainly because of the restricted schedule that required the GSE and the flight hardware to be developed in parallel. The problems arose when one division of a subcontractor was selected to develop the LM GSE, while the flight hardware and the CSM GSE were being developed by another division of the same subcontractor. While both organizations were divisions of the same corporation, they were subcontractors to different companies, and the LM GSE contractor organization (not considering themselves a member of the task team) initially chose to be the interface between the two divisions. After a considerable schedule slip (made up by using engineering test equipment for spacecraft testing), the two subcontractor divisions interchanged cognizant engineers and developed an acceptable GSE design. Although the equipment was delivered late, no program slips were encountered.

CONCLUDING REMARKS

Although the very-high-frequency ranging system development began late in the Apollo Program and, therefore, had to follow an extremely accelerated schedule, the program was highly successful. The system proved to be very helpful to the command module pilot in computing rendezvous parameters during the Apollo 10 mission. This result supported the use of the system for command-service module rendezvous computations for Apollo 11 and subsequent missions and established a high degree of confidence in the system.

Because of the short schedule for development of the very-high-frequency ranging system, the Manned Spacecraft Center task team was very important. The team function made possible almost immediate direction to the contractors. Without this immediate direction, the schedule could not have been maintained.

Task teams are most useful in initially defining system and hardware requirements and in solving hardware, software, and personnel problems associated with initiating a program. The very-high-frequency ranging system task team was most effective in starting the program initially. Later, the team provided support to an ongoing program. In this respect, the team was very effective, as demonstrated by performance. It is strongly recommended that this approach be used for future developments where requirement definition is incomplete, time is short, and multiple contractor interfaces are involved. However, the task team was effective because it had direct support from top management and considerable latitude of action. The team could not have been as effective had this top-level support not been provided. Technically, the very-high-frequency ranging system has demonstrated that a unified communications/range-measuring system without subcarriers is feasible. Therefore, it is recommended that this type of system be given serious consideration in future spacecraft applications and in aircraft applications.

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