LUNAR EXCURSION MODULE RENDEZVOUS RADAR & TRANSPONDER

The Lunar Excursion Module (LEM) carries a rendezvous radar for tracking a transponder located on the lunar surface or on the Apollo Command Module, and for tracking the lunar surface. This radar must make precise measurements of angle, angle rate, range, and range rate along the line of sight. These measurements will provide the data required for successful guidance of the LEM to a rendezvous with the Command Module, which will terminate the lunar excursion part of the Apollo mission. The rendezvous radar and transponder are designed to provide the required accuracies under the widely varying conditions of space flight with high reliability and minimum weight.

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The rendezvous radar is a versatile general-purpose tracking device which furnishes the LEM with accurate relative measurements of position and velocity. Relative measurements may be made to a transponder located on the Command Module to provide the navigation fixes needed to accomplish safe rendezvous. They may also be made to a transponder functioning as an active homing device on the lunar surface, in order to achieve a precise lunar landing. Such relative navigation fixes are used both during the descent and ascent of the LEM vehicle and during the LEM's stay on the lunar surface. The radar also provides continuous relative navigation data throughout the mission. For instance, during the descent to the lunar surface, the radar tracks the Command Module and, by using it as a reference point, assists in the accurate deceleration and landing on the surface.

The radar can also make range and doppler measurements to the lunar surface without the benefit of a transponder. During the terminal landing manuevers, the velocity of the LEM relative to the lunar surface can be determined from the doppler data, and the LEM's altitude can be determined from the range data. In this mode, the rendezvous radar can function as an alternative to or as a monitor of the landing radar.

PERFORMANCE REQUIREMENTS

The performance requirements for the rendezvous radar/transponder are shown in Table I in terms of the required accuracy of output data. Due to the manned space-flight aspect of the LEM mission, the reliability requirements are very high.

TABLE I—Rendezvous Radar/Transponder Accuracy Requirements*

Range	— Less than 1% error
Range Rate	— Less than 1 foot/second error
Angle	— Less than 1/8° error
Angle Rate	— Less than 0.3 milliradian/second error

* Exact figures classified

The rendezvous radar/transponder must operate in the vacuum of space (10^{-10} mm of Hg) and under the vibration conditions associated with the thrust of the main rocket engines of the LEM. The antenna assembly mounted on the LEM body must operate in an external temperature range of −300°F to +250°F, corresponding to the lunar night and lunar day. In certain positions the antenna is exposed to the hot gases expelled by the reaction control jets; these jets operate intermittently during space flight, and the radar must maintain full accuracy during their operation. All the above performance requirements are to be met with a radar and transponder whose total weight is less than 80 pounds.

Table II contains a list of rendezvous radar parameters, and Table III includes the transponder parameters.

TABLE II—Rendezvous Radar Parameters

Radiation Frequency (Classified)	X-band
Radiated Power (Classified)	Less than 1 W

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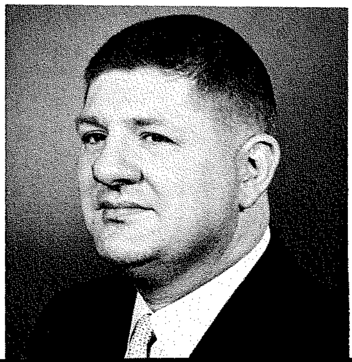

WILLIAM C. CURTIS received his BS degree in Electrical Engineering in 1934 and his MS degree in Electrical Engineering in 1935, both from the University of Illinois. He joined the Industrial Education Department of Tuskegee Institute in 1935 as an instructor of electrical design, and in 1940 became Director of the School of Mechanical Industries. In 1945 he left Tuskegee to attend Harvard University, from which he received an MS degree in Communications Engineering in 1945 and a PhD degree in Engineering Sciences and Applied Physics in 1949. While at Harvard, he was employed at the Raytheon Company where he was in charge of frequency modulation engineering for commercial transmitters. He returned to Tuskegee Institute as Dean of the School of Engineering in 1949. He joined RCA in 1954 and has since been responsible for the direction of theoretical and experimental analysis of new radar techniques. He is Manager, Radar Systems, in Radar Engineering. Dr. Curtis has made patent disclosures on circuits to detect ground intercept of monopulse beams, on techniques for optical pulse compression, and on new film recording techniques for radars. He published one paper on "Time Delay of Variational Current in Glow Discharge Tubes."

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Table II Cont'd

Antenna Design	Cassegrainian
Amplitude monopulse Tracking Method	
Antenna Diameter	24 in
Antenna Gain	32 dB
Antenna Beamwidth	3.25° - 4.0°
Antenna Sidelobe Level	15 dB adjacent to main lobe
Angular Coverage	± 70° x 225°
Number of Gyros	4 (2 redundant)
Modulation (Transponder mode)	PM by 3 tones: 200 Hz, 6.4 kHz, 204.8 kHz
Modulation (Surface mode)	FSK, 50% duty cycle, 6 kHz - 480 kHz
Receiver Channels	3
Receiver Noise Figure	10 dB max
Receiver IF Frequencies	40.8 MHz, 6.8 MHz, 1.7 MHz
Maximum Range (Classified)	Several hundred miles
Minimum Range	50 ft
Maximum Range Rate	± 4900 ft/s
Minimum Range Rate	0 ft/s

TABLE III—Transponder Parameters

Received Frequency	X-band
Radiated Frequency	Received frequency minus 40.8 MHz
Radiated Power	Less than 1 W
Modulation	PM by 3 tones: 200 Hz, 6.4 kHz, 204.8 kHz
Receiver Noise Figure	10 dB max
Receiver IF Frequencies	40.8 MHz, 6.8 MHz

RENDEZVOUS RADAR

The rendezvous radar is basically an X-band, space-stabilized, CW tracking radar designed to track a cooperating transponder. Since the radar and its transponder each utilize solid-state varactor multipliers as transmitters, transmission and reception are on a high-duty-cycle CW basis. Gyros located on the radar antenna stabilize the line of sight against the effects of LEM body motions and permit accurate measurements to be made on the line-of-sight angular rate. Angle tracking uses the technique of amplitude-comparison

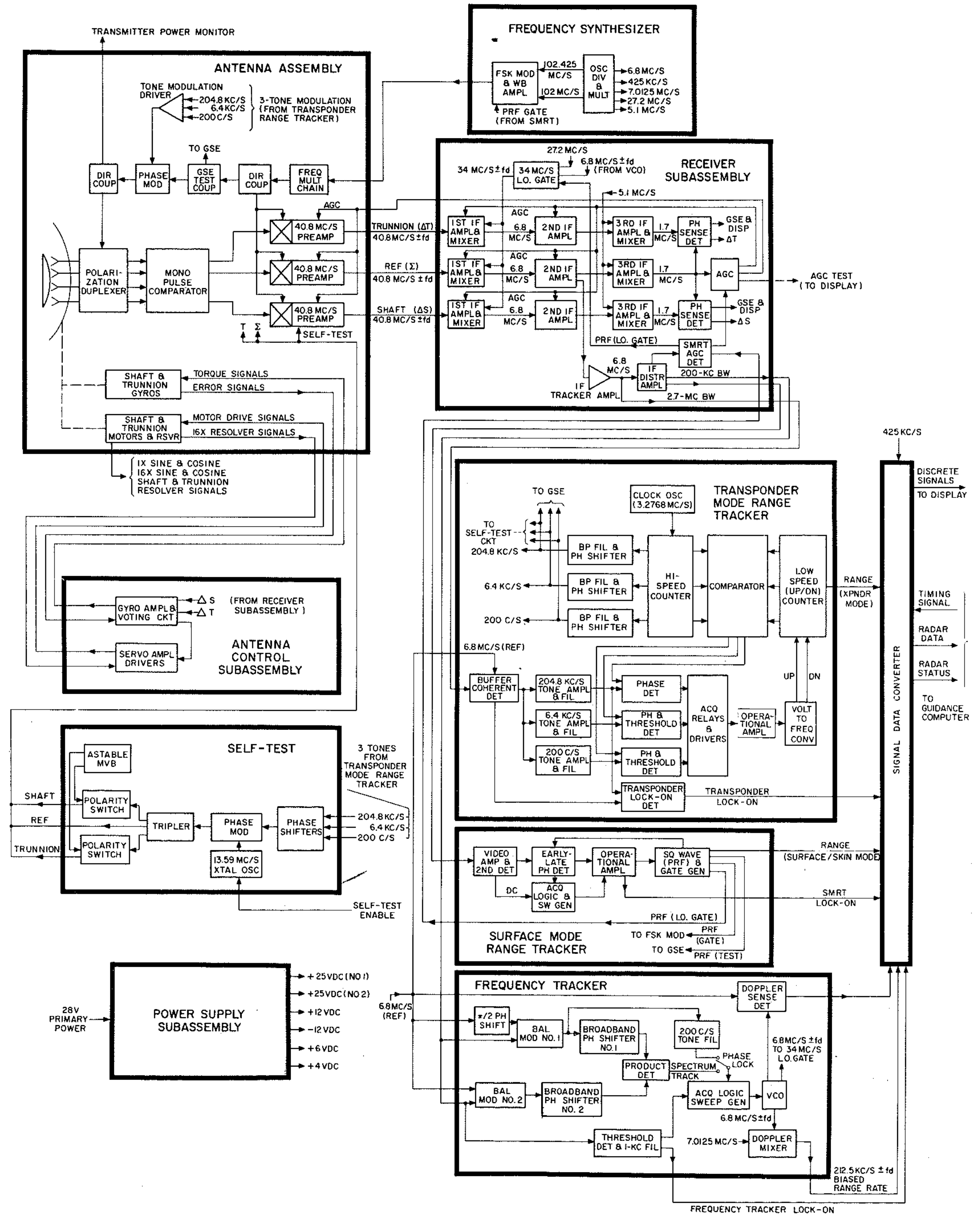


Fig. 1—Detailed block diagram of rendezvous radar.

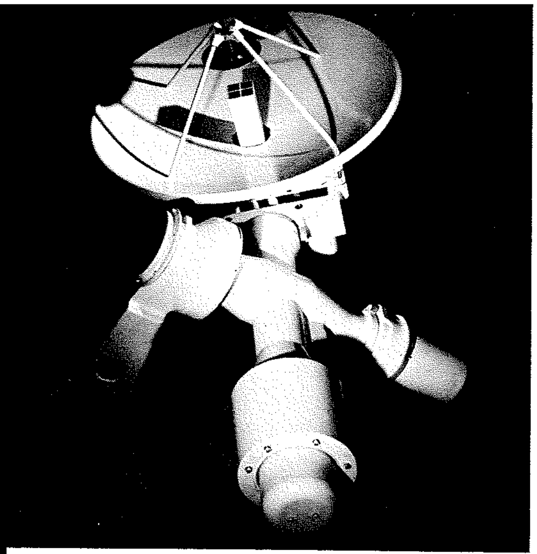


Fig. 2—External view of radar antenna.

monopulse (or simultaneous lobing) to obtain maximum angular sensitivity and boresight accuracy. Range-rate is determined by measuring the two-way doppler frequency shift on the signal received from the transponder. Range is determined by measuring the time delay between the transmitted signal modulation waveform and the received signal waveform. The modulation used during the transponder tracking mode is multitone phase modulation; during the surface mode, the modulation is variable-PRF FSK. The FSK modulation permits the use of a single antenna for both transmission and reception during the surface mode, where the transponder frequency side-step action is not present. A block diagram of the rendezvous radar is shown in Fig. 1.

Antenna Assembly

The radar antenna assembly includes the usual microwave radiating and gimbaling elements and many other internally-mounted electrical components, such as gyros, resolvers, multiplier chain, modulator, and mixer-preamplifiers. The antenna location of the multiplier chain transmitter and the receiver mixer-preamplifiers eliminates the need for a large number of microwave rotary joints and permits the use of flexible low-frequency coaxial cables to connect the outboard antenna components to the inboard electronics assembly. A flexible cable wrap-up system is used at each of the rotary bearing points.

The antenna is a four-horn, amplitude-comparison, monopulse type having a cassegrainian configuration to minimize total depth. The antenna transmits and receives circularly polarized radiation to minimize signal variations resulting from attitude changes of the linearly-polarized transponder antenna. Fig. 2 is an external view of the antenna assembly. Components are distributed inside the antenna to achieve balance around each axis. Each axis is controlled by a brushless servo motor driven by pulse-width modulated drive signals.

Four rate-integrating gyros are used for line-of-sight space stabilization and line-of-sight inertial angle-rate measurement. These gyros in the lower section of the trunnion axis act as a counterweight. Only two of the gyros are used at any one time, and a voting logic system (not located on the antenna) is utilized to transfer control to the other two gyros in the event of a failure in either of the two gyros being used. A two-speed resolver is mounted on each axis for high-accuracy angle-data pickoff for the guidance computer and for display.

The multiplier chain, phase-modulator, and mixer-preamplifiers are mounted internally behind the antenna dish. The multiplier chain supplies X-band power for radiation and local oscillator excitation, which is feasible because the transponder replies with a frequency side-step equal to the radar first IF frequency. The heat dissipated by the multiplier chain is radiated into space by the dish. The phase modulator uses a ferrite rod inside a waveguide and a solenoid for varying the magnetic field inside the rod. The ranging tone signals are applied to the solenoid, varying the electrical length of the rod and providing phase modulation of the X-band carrier. Three balanced mixers and three preamplifiers are included: one for the reference channel, one for the shaft error channel, and one for the trunnion error channel.

Servo Electronics

Included in the antenna servo electronics are amplifiers for driving the antenna shaft and trunnion axis servo motors, amplifiers for driving the gyro torquer coils, and voting logic for selecting the correct gyro pair. The servo electronics, in connection with the antenna components and radar receiver, form an inner and outer closed loop for each axis. The inner, or stabilization, loop keeps the antenna boresight axis fixed in inertial space in the presence of body motions. The outer, or tracking, loop directs the antenna boresight to the target, using tracking error signals from the monopulse receiver.

In the automatic mode the guidance computer will designate the antenna boresight to within one degree of the target and command the tracking loop to close. The antenna will then continuously track the target by maintaining the monopulse receiver angle error signals at null. The antenna may also be manually slewed at fixed inertial rates.

The antenna shaft and trunnion motors are 32-pole, brushless, permanent-magnet rotor types driven by pulse-width modulated drive signals applied to sine and cosine windings of each motor. The direction of rotation is changed by reversing the motor windings which are excited by a pulse-width modulated drive voltage obtained by on/off switching of the 28-VDC power at a 1.8-kHz (kc/s) rate.

A gyro voting system consisting of performance comparison and logical switching circuits automatically detects and removes a malfunctioning gyro. Of the four gyros, two are used to stabilize the antenna and two are used to monitor the performance of the controlling gyros. Each pair can perform either the control or the monitoring function. The voting system determines whether either pair contains a failed gyro and ensures that that pair is not used to stabilize the antenna.

Receiver

The receiver is a three-channel, highly stable, triple-conversion superheterodyne which has intermediate frequencies of 40.8, 6.8, and 1.7 MHz (Mc/s). The bandwidth of the first and second IF amplifiers is approximately 3 MHz, and the bandwidth of the third IF amplifier is approximately 1 kHz. Two channels are provided for amplifying the shaft and trunnion axis error signals and one channel for amplifying the sum or reference signal. The receiver also includes phase-sensitive detectors for generating angle error signals, an AGC circuit for controlling the gain of the three receiver channels, an IF distribution amplifier unit for supplying reference channel signals to range and frequency trackers, and a gated local oscillator mixer for generating the second local oscillator signal. The second local oscillator frequency is obtained by beating the output of the frequency tracker VCO (voltage-controlled oscillator) with a reference frequency to produce a sum frequency exactly 6.8 MHz lower than the incoming 40.8-MHz doppler-shifted frequency. After the second mixer, the doppler frequency shift is removed, and all subsequent signal processing is accomplished at fixed carrier frequencies. The most stringent requirement on the receiver is that the three channels must gain-track within ±2.5 dB and phase-track within 27° over a dynamic range of greater than 110 dB, and over a temperature range of 70°C.

Frequency Synthesizer

The frequency synthesizer generates all of the fixed frequencies required for coherent signal transmission and reception. A single 1.7-MHz stable crystal oscillator and a system of multiplication, division, and mixing produce the required frequencies. During the transponder mode, a CW output signal is generated for excitation of the transmitter multiplier chain. During the surface mode, a variable-PRF FSK-modulated excitation is generated. The synthesizer also generates various receiver local oscillator, clock, and reference frequencies used by the receiver, the signal-data converter, and the trackers.

Frequency Tracker

The frequency tracker tracks either the coherent narrow-line spectrum received from the transponder or the wide spectral distribution received from the lunar surface. During the surface mode the tracker generates a VCO sine wave which tracks the center of power of the received signal spectrum. During the transponder mode, the tracker is switched to phase-lock the VCO with the incoming narrow-line spectrum. Note that the phase detector for the phase-locked loop uses a 6.8-MHz signal from the frequency synthesizer as a reference. The error signal drives the VCO to a frequency that, when mixed with a 27.2-MHz synthesizer signal and used as the local oscillator signal for the second IF mixer, removes the doppler frequency shift from all signals in succeeding IF stages. Thus passage of the 1-kHz-bandwidth signal through the 1.7-MHz filters is assured. The tracker utilizes a frequency sweep circuit for sweeping the VCO frequency across the doppler frequency range (± 100 kHz), searching for the received signal. A threshold circuit senses the presence of the carrier signal within locking range, stops the sweep, and permits the VCO to phase lock.

Transponder Mode Range Tracker

The transponder mode range tracker determines the range to the transponder by measuring the phase angle between the transmitted tones and the received tones. The signal received from the transponder (at 6.8 MHz) is demodulated in a coherent product detector which uses a 6.8-MHz quadrature reference. The individual sine-wave tones are extracted from the receiver noise using bandpass filters tuned to the tone frequencies. Range phase-delay is measured independently on each of the three tones in a closed tracking loop. Three reference square waves are generated locally, each having variable phase with respect to the transmitted tones. This phase delay is adjusted until the reference square waves have matching phase with respect to each of the received tones. The reference square waves are produced digitally by comparison between a running high-speed counter and a low-speed up-down range counter. The low-speed range counter is driven up or down until a phase null is achieved in each of three phase detectors. The range counter is driven up or down by incremental range pulses obtained from a DC-to-PRF converter controlled by weighted integration of the three-phase detector error signals.

Surface Mode Range Tracker

The surface mode range tracker controls the PRF of the frequency-shift-keyed CW transmitted signal. The PRF is automatically adjusted to the value which will cause the returned signal from a transmitted pulse to be centered in time between that transmitted pulse and the next transmitted pulse. Under these conditions the period of the PRF is twice the radar signal transit time.

Signal Data Converter

The signal data converter accepts range and range-rate data from the range and frequency trackers, converts it to 15-bit serial format, and shifts it out to the guidance computer as requested by the computer. The signal data converter also sends various discrete radar status indications to the computer, selects radar modes, and processes display data for activation of the astronaut display panels.

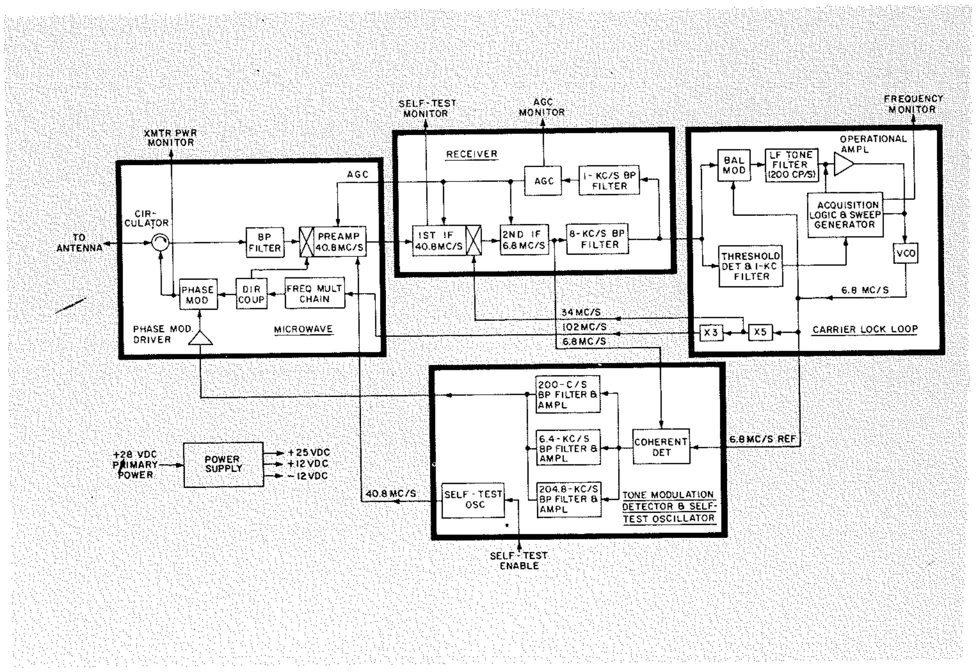
Self-Test

Radar self-test circuits in the frequency tracker subassembly permit testing of the radar without the use of a cooperating transponder. The self-test circuit checks transmitter power, phase-lock at minimum signal level, angle error detection, AGC action, and range and range-rate measurement. Insertion of single values of range and range rate permits quantitative checking by observation of the displays.

Power Supply

The radar power supply is basically a highly efficient DC-DC converter providing six regulated DC output voltages. The unit utilizes the method of switched-tap modulation for input regulation. After chopping, rectification, and filtering, series regulators are used at each output. The use of a 20-kHz chopping frequency makes it possible to minimize the weight of transformer and ripple filter components. Short-circuit protection circuitry senses overload current conditions on any of the output lines and deactivates the 20-kHz chopping oscillator for a preset period of time. If the overload is removed during this period of time, normal operation is resumed; if not, the deactivation cycle continues until the overload is removed.

Fig. 3—Block diagram of transponder.



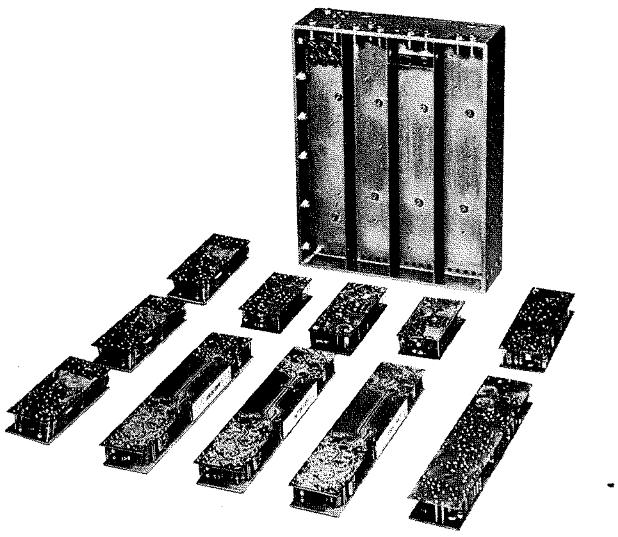


Fig. 4—Cordwood modules of segment No. 1 in radar receiver.

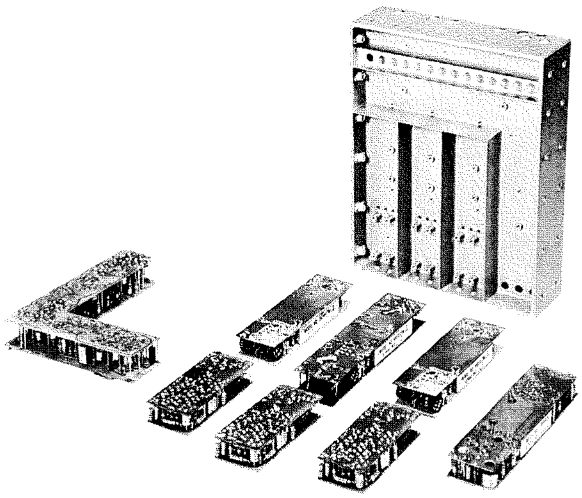


Fig. 5—Cordwood modules of segment No. 2 in radar receiver.

TRANSPONDER

The transponder, in connection with its antenna, receives the transmitted CW radar signal and generates a strong phase-locked reply signal for transmission back to the radar. The ranging modulation on the received signal is also turned around and sent back to the radar. The transponder, like the rendezvous radar, employs a single multiplier chain for both transmitter and local oscillator. This arrangement is made possible by designing the transponder to reply with a carrier frequency that is an exact integer ratio of the received signal carrier frequency; consequently, the transmitted frequency is 40.8 MHz lower than the received frequency. A small portion of the transmitter output is used for local oscillator excitation, and a first IF frequency of 40.8 MHz results. Since the transmitted and received frequencies are separated, the use of a diplexer permits operation with a single antenna. A block diagram of the transponder is shown in Fig. 3. (Refer to Table III for transponder parameters.)

The phase-lock operation of the transponder is as follows. The radar carrier signal is received and converted to the first IF frequency of 40.8 MHz. The signal is amplified and mixed with a 34-MHz second local oscillator frequency to produce a 6.8-MHz second IF frequency. A voltage-controlled oscillator is pulled in frequency in an APC loop to phase-lock the incoming 6.8-MHz IF carrier signal to the VCO signal. Multiplication of the VCO frequency by approximately 1400 produces the transmission (and first local oscillator) frequency. Acquisition is accomplished using a VCO sweep and threshold circuit similar to the one used in the radar.

The ranging tones are extracted from the 6.8-MHz received signal in exactly the same manner as in the radar. After bandpass filtering and amplification, they are applied to the phase modulator for retransmission back to the radar.

Self-test circuits are included to permit testing of the transponder without the use of the rendezvous radar. A test oscillator operating at a single frequency permits the transponder to phase-lock without an external input. The transmitter power and AGC action may also be checked for phase lock at minimum signal level.

ACQUISITION TECHNIQUE

The normal automatic acquisition sequence for the rendezvous radar and the transponder is as follows:

1) The radar antenna, under computer control, is designated in angle so that its transmitted CW radiation can be received at the transponder.
2) The transponder, which was previously sweeping in frequency, stops its sweep and phase locks to the received radar signal.
3) The radar receiver, which was previously sweeping in frequency, stops its sweep and phase locks to the received transponder signal.
4) The radar angle tracking loop is then closed and the angle error is nulled.
5) The radar activates ranging modulation and the range tracking error is nulled.
6) The radar indicates a *data good* condition to the computer.

PACKAGING OF ELECTRONICS

The electronic assembly circuitry is developed in two forms: 1) digital and analog integrated circuits using multilayer boards, and 2) coated (unpotted) cordwood packaging for discrete electronic parts.

Cordwood packaging (Figs. 4 and 5) allows a 2:1 reduction in size over the usual transistor circuit packaging methods. Egg-crate design of packaging cases provides shielding of high-frequency receiver circuits.

Cooling is obtained by bolting case flanges to a *cool* plate varying in temperature from +35°F to +135°F. The design is such that despite this variation, the temperature of an electronic part will not exceed +160°F. Conductive cooling of the electronic parts is achieved by sealing the bottom of a cordwood board to the subassembly web with a high-thermal-conductivity compound. Where required, beryllium oxide ceramic heat sinks are used to conduct excessive heat to the subassembly web.

CONCLUSION

The rendezvous radar/transponder provides the LEM navigation system with the high-accuracy tracking data needed for rendezvous or precise lunar landing. These accuracies are achieved under the widely varying conditions of space flight with high reliability and with minimum weight. The probability of mission success is enhanced through the use of operational modes which can serve as a backup for the primary modes.