THE APOLLO VHF RANGING SYSTEM

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Summary. - Redundancy of functions on manned space flights has been an important concept for crew safety. However, a redundant system generally implies doubled weight - a luxury that can not easily be afforded on a spacecraft. The Apollo Command Module-Lunar Module rendezvous mission was performed with the rendezvous radar system. RCA developed a VHF Ranging System, which permitted the voice/telemetry radios to be adapted as a backup for the radar's ranging function at relatively low additional weight. The proven accuracy and reliability of the VHF Ranging System resulted in its selection as the sole rendezvous sensor for subsequent earth orbital manned missions. The constraints imposed by existing radios are discussed, the ranging options and selected implementation are described, and the system accuracy is reviewed.

Introduction. - As the Apollo program proceeded, NASA became increasingly concerned for the safety of its crews on manned space flights. Redundancy became a requirement for all crew safety functions. One critical period of the Apollo missions was the rendezvous of the Command Module and the Lunar Module. The RCA-developed rendezvous radar provided the critical range, range rate, and angle measurements necessary to complete the rendezvous. Use of a redundant radar for backup was out of the question because of its 80-lb weight. Angle measurements could be obtained from the navigation sextant; range rate could be obtained by differentiation of range data in the spacecraft computer. However, redundant range data was not available.

After investigating the requirements and possible solutions to the problem, RCA proposed to Frank Borman, the commander of the first Apollo flight to the moon, that the voice radios be adapted to perform the ranging function. Slight modifications of the RCA-built VHF voice radios and the addition of a ranging interrogator and transponder at a weight of less than 10 lbs total would provide an accuracy of 100-ft rms at several hundred miles.

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The Apollo VHF ranging system development was authorized in the Fall of 1967. Slightly more than a year later, the system was successfully flight-tested at the White Sands Proving Grounds, and the first space-qualified flight hardware was delivered. Since it has performed flawlessly on every Apollo Lunar rendezvous mission, it became the sole rendezvous ranging sensor on the Skylab mission and on the Apollo-Soyuz earth orbital mission. The Lunar Module VHF radio and ranging transponder were the first and only American made equipment installed in a Russian spacecraft.

VHF duplex system. - The basic VHF ranging system, as illustrated in Figure 1, uses a fall duplex communications systems. The Command Module (CM) VHF transmitter is modulated by a voice signal or by a ranging signal, or both functions can be carried out simultaneously. The signal is transmitted via a diplexer and antenna for reception by the Lunar Module (LM) VHF receiver. The voice information signal is obtained by conventional envelope detection; the ranging signal is demodulated and applied to the transmitter. In some modes it is fed directly from the envelope detector to the transmitter without synchronization. The LM transmitter and antenna radiate a voice and/or ranging signal which is picked up by the CM receiver. The voice and ranging modulation are fed to separate circuits. The range information is demodulated and causes a range tracker to follow the transmission path delay Comparison of the time position of the received ranging waveform with respect to the transmitted ranging waveform at the CM, yields the range readout.

Transmitter configuration. - The VHF transmitters in the CM and LM use speech clipping for the conversion of the analog voice signal to a bi-level waveform. The bi-level voice signal amplitude modulates the RF carrier in a binary fashion (on-off) by means of a keyer. The modulated carrier is further amplified and filtered before transmission. In the receiver, the bi-level waveform is filtered and a very intelligible voice signal is recovered.

The CM and LM VHF transmitter configuration is shown in Figure 2. The RF carrier is derived from a crystal-controlled oscillator, which drives a multiplier and an amplifier chain. The voice signal is processed by successive clipping and appears as a bi-level waveform at the input of the keyer. In some units, a data input also drives the keyer. For minimum impact on the communications system, the most suitable ranging waveforms are square waves or a combination of square waves. Thus the ranging signal, the bi-level voice signal, or the combination signal drives the keyer and causes on-off modulation of the RF carrier to take place in the amplifier chain. The transmitter is capable of handling signals with a bandwidth of several MHz so that it does not severly limit the range measurement accuracy capability.

Receiver configuration. - The VHF receivers in the CM and the LM, shown in Figure 3, are fixed-tuned receivers designed to operate over a wide dynamic range of signal levels.

A received signal at 259.7 MHz or 296.8 MHz is applied to a broadband gain-controlled RF amplifier and then translated to a 30-MHz IF signal. A crystal-controlled oscillator, frequency multiplier, and mixer perform the heterodyning function. The IF channel consists of relatively broadband IF amplifiers and a narrowband crystal filter. The filter's transmission bandwidth of approximately 60 kHz determines the receiver's selectivity. The IF amplifier preceding the envelope detector is also gain-controlled to maintain a relatively uniform output level. The filter characteristics are shown in Figure 4.

Although the IF filter bandwidth is about 60 kHz, the frequency stability of the transmitter and receiver oscillators may result in nearly ± 15 kHz of drift of the carrier frequency. Due to the steep skirt selectivity of the crystal filter near its band edge, it is not recommended to pass signals with frequency components in excess of 15 kHz through the receiver. Ranging signals much below 15 kHz may be passed through the IF amplifier. However, certain factors must be considered, such as the delay through the receiver and the variation of this delay with temperature, signal level, and from one unit to the next. The fixed delay for a typical receiver through the detector output is approximately 21 µs.

Most of this delay is attributable to the crystal filter and the IF amplifier. The delay varies about ±0.6 µs due to temperature changes and about ±0.9 µs due to signal level variation. The variation between different sets can be as much as ±3 µs, in addition. Frequency offsets between the transmitter and the receiver local oscillators will also add several microseconds to the total delay uncertainty.

Ranging considerations. - The variable delay determines the limit of measurement accuracy achievable with a given system regardless of the ranging waveform or signal-to-noise ratio. The variable delay is usually some fraction of the fixed delay and can therefore be minimized by also reducing the fixed delay. This requires the use of the widest bandwidth circuits available relative to the frequency spectrum of the ranging waveform. Better performance can thus be expected from a ranging signal which does not have to pass through the band-limited IF amplifiers and filters. It must therefore be correlated before the filter, so that only an error signal is passed. Since the error signal is usually heavily filtered, a narrowband IF channel is adequate to pass it. The ranging signal may have frequency components of the order of 100 kHz or more, because the transmitter and the RF amplifier in the receiver can handle several megahertz.

A combination ranging approach lends itself to the reception of two or more ranging tones, where only the highest fundamental frequency can not be passed by the receiver IF. The highest frequency tone is demodulated to preserve system accuracy; the lower frequency tones needed for ambiguity elimination are not demodulated in the transponder. This is acceptable, even from an accuracy point of view, because the range measurement accuracy is not influenced by tolerable errors in the ambiguity resolving waveforms.

Ranging implementation. - To obtain measurements by means of the VHF radio equipment, a 3-tone ranging technique is used. To be compatible with the on-off modulation of the available transmitters, on-off modulation is used for ranging purposes. To avoid reducing the transmitter duty cycle, and thereby reducing transmitted power, a time sequential transmission of tones is used. Fine range is measured with a 31.6 kHz square-wave tone. Range ambiguity is resolved with a mid-frequency of 3.95 kHz and a low frequency tone, which is a modulo 2 combination of a 3.95 kHz and a 247-Hz square wave. This combination has the advantage of a maximum unambiguous range of about 327 nm while the signal is narrowband and centered about 3.95 kHz. Since normal tracking provides range measurements, the mid-and coarse-tone signals are only transmitted when range tracking is initiated, when an interruption of tracking has occurred, or when the range data is to be checked. A manually initiated operation provides for automatic acquisition and tracking of the mid-and coarse-range signals for an 8-second period. Thereafter, automatic switching to the fine-ranging signal occurs. At the CM, both the transmitter and receiver tracker are sequenced through the appropriate mode. At the LM transponder, the presence of narrowband modulations, either mid-or coarse-range tones, is sensed and the mode of operation is automatically changed, The ranging tones are shown in Figure 5.

Transponder operation. - The primary goal of the ranging system development was to minimize changes to existing equipment. The VHF set and its interfaces with the ranging transponder unit are shown in Figure 6. In the coarse-ranging mode, the VHF receiver operates in its normal fashion. A composite ranging tone centered about 3.95 kHz is received, clipped to produce a bi-level signal, and then applied to the transmitter to key the modulator as is otherwise done with voice signals. A coarse-tone signal sensor inhibits the fine-tone tracker from degrading the signal and selects the appropriate signal for application to the transmitter input.

In the fine-ranging mode, the received signal is on-off gated by interrupting the signal path preceding the crystal filter at a 31.6 kHz rate. The phase of the incoming square wave is correlated with the signal generated by the fine-tone tracker. By accurately tracking the received signal with a locally generated waveform, the latter may be used to key the transmitter with a noiseless signal. Smoothing in the tracking loop reduces the phase jitter to a relatively small value.

In the fine-ranging mode the received signal is the 31.6 kHz square wave, which is gated before it reaches the narrowband IF filter. The gating waveform is derived by counting down from 2.022 MHz which is generated by a voltage-controlled crystal oscillator (VCXO). The countdown chain also produces a square wave at 5.27 kHz which is used to shift the phase of the 31.6 kHz signal by ±2 μs. By shifting the phase of the reference signal, suitable early and late versions of the waveform are produced to provide a tracking-error signal. The early/late switching of the reference signal is essential to the tracking operation, and it is performed at a rate slow enough to be passed by the IF amplifier.

After correlation of the received signal with the reference signal, IF filtering, and detection, the remaining fine tone is attenuated and only the carrier components remain. If a tracking error exists, a switching-frequency component at 5.27 kHz will also be present. This is faltered, and then an “early minus late” signal subtraction is accomplished by means of a synchronous detector. The latter lets the detected and correlated ranging signal pass directly into a low-pass filter during the early portion of the switching cycle; during the late portion of the switching cycle, the ranging signal is inverted. The filter thus performs the subtraction and yields the average value of the early minus late ranging signal. The presence of an error voltage causes the VCXO to change its frequency in an attempt to reduce the error. The VCXO drives the waveform generator and therefore controls the phase of the ranging waveform. For good performance, the loop filter and the VCXO form a second-order phase-lock loop of less than 30 Hz bandwidth. This assures an adequate signal-to-noise ratio and tracking accuracy with negligible dynamic error.

In the LM transponder, the late response waveform for receiver gating is also applied to the transmitter. Since it is used directly to key the transmitter, the total transponder delay consists of the 2 µs late delay, the transmitter delay, and the delay encountered up to the receiver’s mixer. Since the ranging code has been demodulated before the IF, the IF delay does not influence the time position or static range accuracy.

For further details of how range tracking occurs through use of receiver gating in the Apollo VHF ranging system, refer to Appendix A.

Range tracker operation. - The CM VHF radio equipment implemented for the ranging function is illustrated in Figure 7. The appropriate ranging waveform, which is generated by means of the range clock and the ranging tone generator, is selected to provide either coarse or fine ranging. It is then applied to the transmitter where the keyer on-off modulates the RF carrier. The RF signal modulated with either the 31.6 kHz or the 3.95 kHz ranging tone, is then transmitted to the LM receiver.

The LM VHF equipment acts as a transponder and replies with the same signal it has received. The reply signal is received by the CM receiver, which is also modified to allow gating ahead of the IF filter to generate a tracking error signal when the fine-tone ranging mode is used. The range tracker may be shown functionally as a coarse-tone tracker and a fine-tone tracker. The range clock drives the fine-tone tracker, which in turn drives the coarse-tone tracker. Both trackers generate a waveform which is correlated with the received signal, before the IF filter for the fine tone, and after the detector for the coarse tone. The selection of the coarse- or fine-tone tracker is made concurrently with the selection of the transmitted ranging waveform. In the coarse ranging mode the receiver gate will pass the signal without interruption so that the maximum available signal-to-noise ratio will be realized.

A subtraction of the nominal system delays is also performed before the data is transferred in serial form to the 5-decimal digit display and the spacecraft computer. The output data is available and displayed with a resolution of 0.01 nm up to a maximum range of 327.67 nm.

Voice/ranging transmission. - The Apollo VHF radio transmitter can be operated in either of two modes. In the non-ranging mode, the input audio signal is amplified, added to the 30 kHz sawtooth waveform from a noise suppression oscillator (NSO) and clipped, to produce a pulse-width-modulated signal. Strong audio signals will override the sawtooth waveform and will result in a clipped audio signal. In the absence of an audio signal, a 30 kHz square wave is transmitted, so that the amplitude modulated transmitter is always operating at a 50% duty cycle.

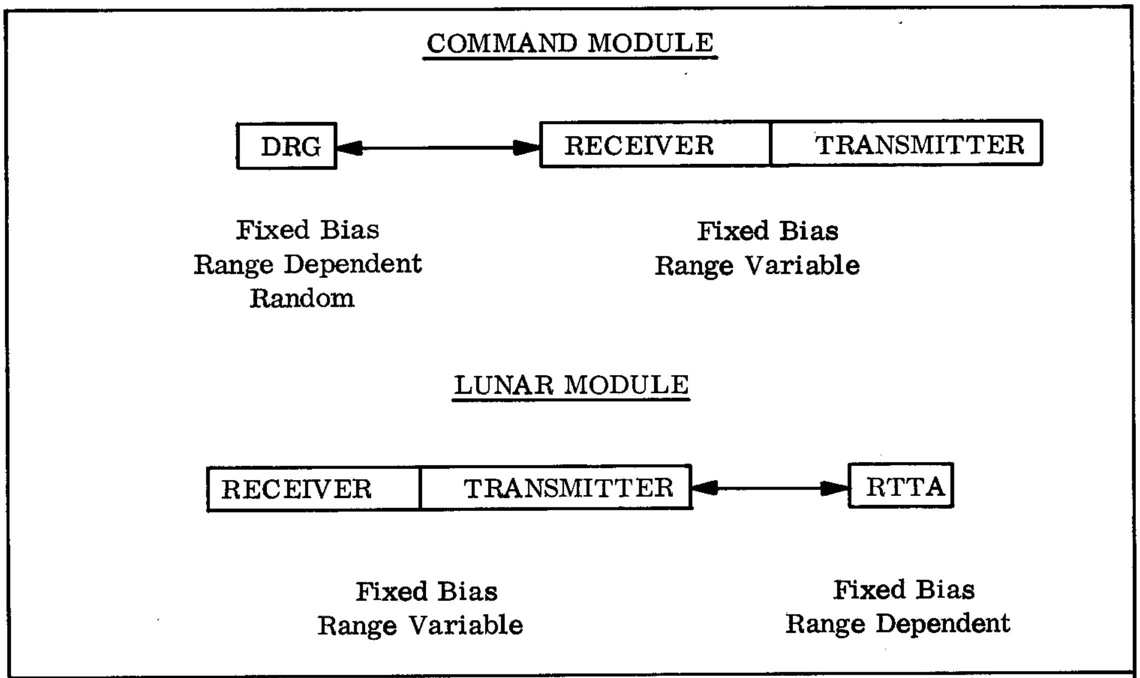
In the ranging mode, the NSO is disabled, and the 31.6 kHz ranging square wave is substituted. During acquisition by the ranging system, the lower frequency tones will, of course, be transmitted.

Without the presence of voice or other audio signals, the transmission duty cycle is still 50% Audio signals applied to the transmitter follow the identical path, but due to the absence of the NSO sawtooth waveform they are always clipped. In the ranging mode, voice signals therefore appear as clipped speech. This is combined in a logic AND function with the 31.6 kHz ranging square wave, so that the duty cycle of the transmitted signal can drop to as little as 25%. The RF envelope derived in Figure 8 consists of the clipped audio waveform, which is further amplitude modulated (in on-off fashion) by the ranging square wave.

In the receiver, the high-frequency components due to either the NSO or the ranging square wave are filtered out by the audio amplifier. The audio signal is thus recovered.

Apollo VHF ranging accuracy. - The range errors fall into a number of categories as shown in Table 1; the major types are bias errors and random errors. The total range error includes the bias errors in the radio receiver and transmitter due to delay variations. In the Apollo system, the CM transceivers had 424 ns peak range error, while the LM transceivers had 395 ns peak range error. The ranging tone transfer assembly (RTTA) and the digital ranging generator (DRG) bias errors are due to offsets in product detectors, filter amplifiers, fixed and voltage controlled oscillators, and delay variations in interface circuits.

TABLE 1 RANGE ERROR TYPES



Fixed	-	Fixed for each set of equipments-transmitter & receiver combined
Range Variable	-	Varies with signal level in an unpredictable fashion although known for each transceiver
Range Dependent	-	Varies with signal level; smaller errors at higher signal level
Noise	-	Very small in VHF ranging
Granularity	-	Due to digital tracker and display
Voice	-	Noise level increases and loop bandwidth changes

The combination of all range errors amounted to a three sigma value of about 600 ns or 330 ft as shown in Table 2. These are three sigma errors allowing for all units under any of the specified spacecraft environmental conditions and for ranging or ranging/voice modes. The rms range error is therefore about 100 ft at maximum range. Actual measurements on four Apollo systems are shown in Table 3, which indicate good agreement between predicted and actual range errors. It must be pointed out that these accuracies were achieved without individual system calibration. This permitted flight line replacement of units, without the need to recalibrate the system.

TABLE 2. ACCURACY MODEL (3 sigma) IN NANOSECONDS

	200nm Ranging	200nm R/Voice	10nm Ranging	10nm R/Voice
Range Variable Bias Errors	283	283	283	283
Range Dependent Bias Errors	196	330	30	30
Fixed Bias Errors	562	562	562	562
Total Bias Errors	659	710	631	631
Random Errors	68	151	61	209
Total Error	663	726	634	665

TABLE 3. ACTUAL APOLLO RANGE ERRORS (-86dBm)

System	Apollo 10	Apollo 11	Apollo 12	Apollo 13
Delay, µs	3.008	2.706	3.047	2.675
Calibration, µs	2.835	2.835	2.835	2.835
Error, µs	0.173	-0.129	0.212	-0.160
Error, feet	86	-64	106	-80

Apollo ranging system characteristics. - The Apollo ranging system characteristics are summarized in Table 4. Photographs of the Command Module VHF radios, the Lunar Module VHF radios, the Digital Ranging Generator and the Ranging Tone Transfer Assembly are shown in Figures 9, 10, 11 and 12, respectively.

Conclusions. - The Apollo VHF Ranging System demonstrated that it is feasible to achieve highly accurate range measurements with conventional voice radios. Despite the narrowband ranging modulation, accuracies on the order of 100 feet rms have been obtained. Furthermore, this range information is available while voice communication is in progress. Operation from zero range to over 300 nm has been demonstrated with 5 watt average power voice radios.

Application of this type of ranging technique to aircraft, vehicular and hand-held voice radios should provide a low cost relative navigation capability to military and commercial users.

TABLE 4. APOLLO VHF RANGING SYSTEM CHARACTERISTICS

	Digital Ranging Generator (DRG)	Ranging Tone Transfer Assembly (RTTA)
• Weight • Size • Power	6.2 lbs 8-1/2 X 4 X 6 inches 19.7 watts	2.9 lbs 8 X 4 X 3-3/4 inches 4.3 watts

- Use of existing VHF equipments (259.7 MHz and 296.8 MHz) with applique boxes (DEG & RTTA)
- Three fall duplex system operating modes
  - a) Ranging or
  - b) Voice or
  - c) Voice/Ranging combined
- Three tone system for accuracy and unambiguous range (247 Hz, 3.95 kHz and 31.6 kHz)
- Square wave tones - compatible with Apollo transmitter modulation
- Fully qualified for spacecraft environment
- Unambiguous range readout to 327.68 nm
- Range accuracy (3) ±350 feet to 200 nm
- Display readout resolution - 0.01 nm
- Computer data resolution - 0.01 nm
- Acquisition time 12 - 14 seconds (Three Tones)
- Minor changes in spacecraft wiring
- Flight hardware delivered in 14 months

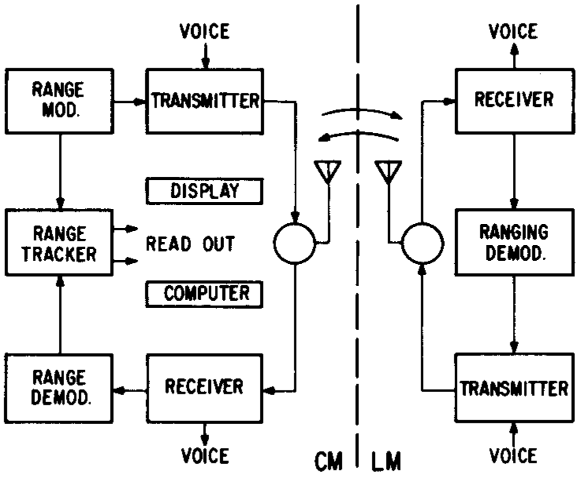


Figure 1. VHF ranging system

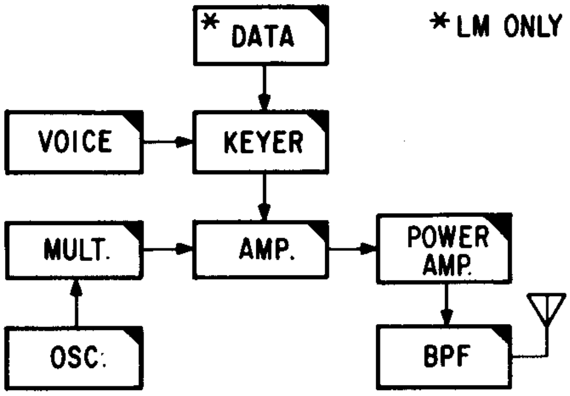


Figure 2. VHF transmitter

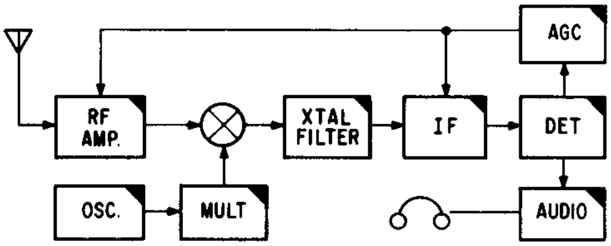


Figure 3. VHF receiver

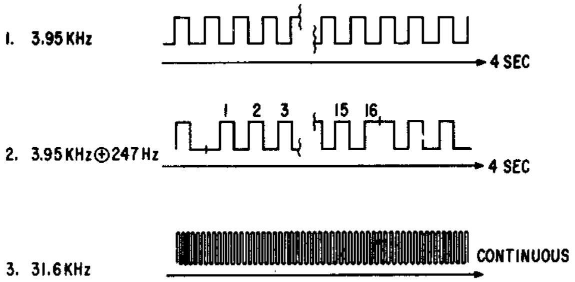


Figure 5. Ranging tones generated

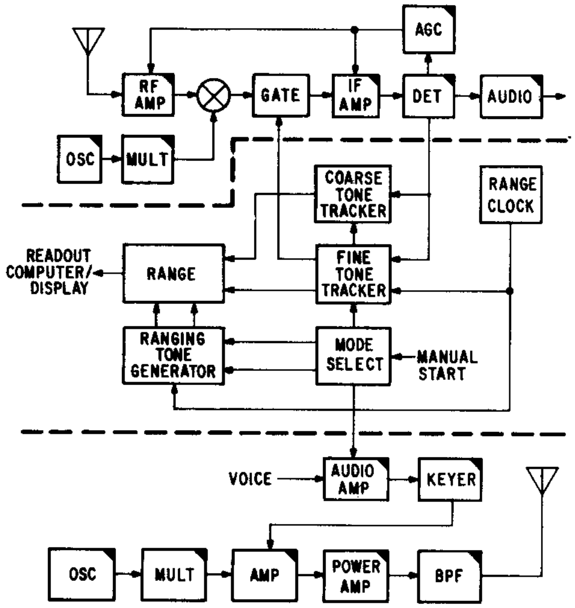


Figure 8. Ranging and (ranging function)

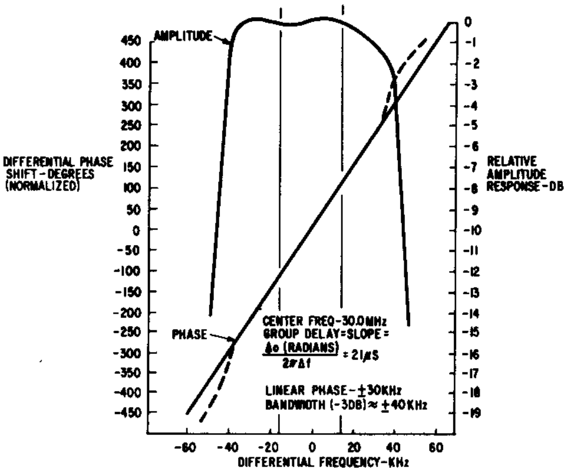


Figure 4. VHF receiver crystal filter characteristics

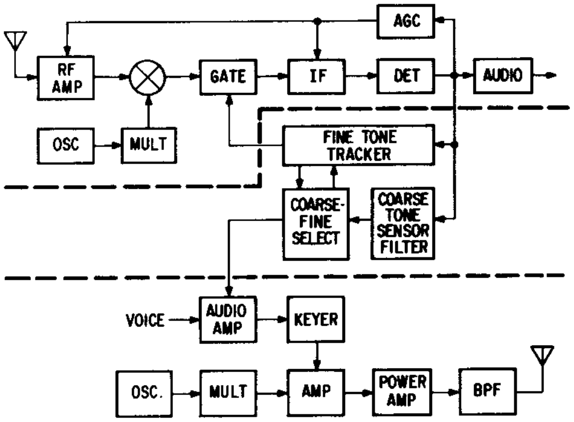


Figure 6. LM transponder (ranging function)

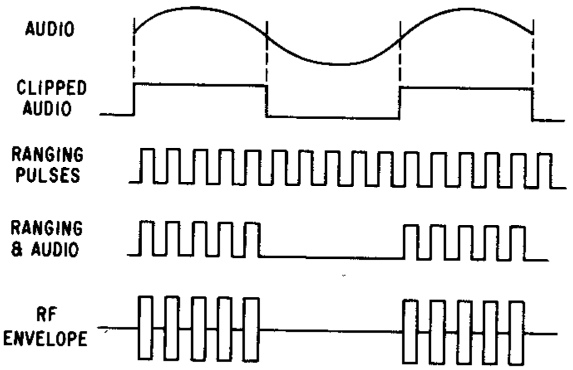


Figure 7. CM VHF radio audio waveforms

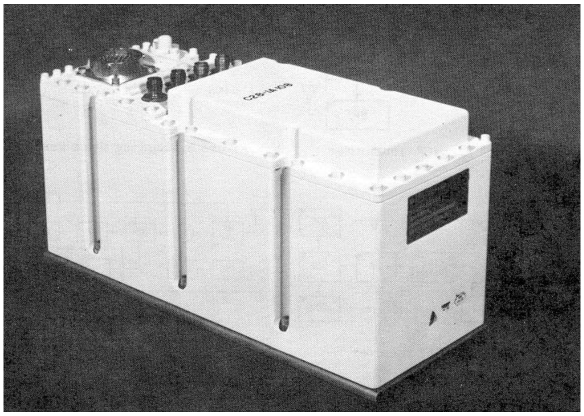


Figure 9. Command module VHF transceiver

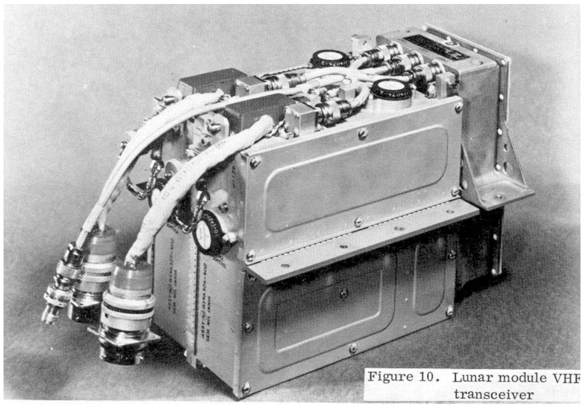


Figure 10. Lunar module VHF transceiver

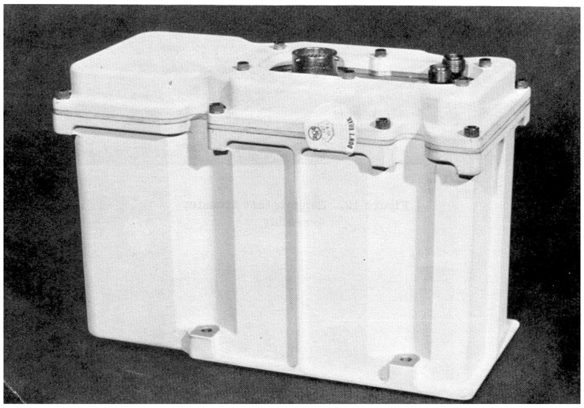


Figure 11. Digital ranging generator

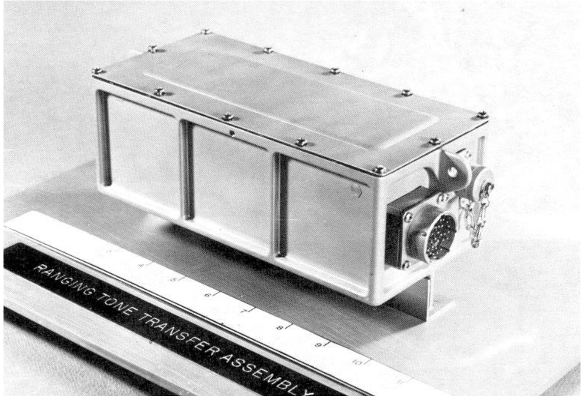


Figure 12. Ranging tone transfer assembly

APPENDIX A

Range Tracking Through Receiver Gating. - In the Apollo VHF Ranging System, the range measurement is accomplished by accurately tracking a 31.6 kHz square wave. Because this square wave is not passed by the receiver IF filter and because of the large delay variation in the IF filter-amplifter, a scheme of receiver gating is used. Since this gating or correlation takes place before the bandwidth limiting components, the system measurement accuracy is greatly enhanced. The principle of the gating operation is explained below.

Consider a dual IF tracking receiver as shown in Figure A-1. It has a broadband RF section and mixer which do not impair the high-frequency components of the ranging signal. After the mixer, the receiver is split into an “early” channel and a “late” channel, where each consists of an RF gate, an IF filter-amplifier, and a detector. The gate allows the incoming signal to pass only for half the time under control of a reference square wave. The exact time interval is a function of the “early” and “late” reference signal phasing, which for illustration purposes will be taken as 1/8 cycle advanced for the “early” signal and 1/8 cycle retarded for the “late” signal. These reference square waves are derived by digital countdown logic which is driven by a voltage-controlled oscillator (VCO).

Figure A-2 shows the input signal which will be assumed to agree in phase with the local reference in the tracking system. The relative time positions of the “early” and the “late” reference signals into the respective RF gates are also shown. The gate outputs shown at the bottom indicate that equal amounts of signal energy will reach the IF filter-amplifiers and detectors. Subtraction of the late output signal from the early output signal and filtering therefore produces no error signal to drive the VCO from its current phase position.
In figure A-3, the input RF signal is assumed to be delayed by 1/8 cycle with respect to the tracking system. The “early” gate disagrees in time position by a 1/4 cycle so that the

gated output signal is only half the width of the incoming signal. However, the “late” gate agrees in time position so that the entire RF signal is passed by the gate. There is now an obvious difference between the detector outputs of the early and late channels, which will cause the VCO to change phase in an effort to minimize the error signal.

The error discriminator curve can be derived simply as shown in Figure A-4. The baseband waveform is the square wave shown at the top. When it is multiplied by a replica of itself at all phase delays, the triangular autocorrelation function results. It reaches a maximum when the square wave and the reference are aligned; it is zero when they are out of phase. Autocorrelation functions for an “early” and “late” signal can also be drawn. They are also triangular but displaced in phase. A point on these correlation functions will exist for the “early” and “late” receiver channels for a particular phase of the incoming square-wave-envelope RF signal. The subtraction of receiver outputs may be represented by subtraction of the respective autocorrelation functions. This produces the time discriminator curve shown at the bottom of Figure A-4 One of the zero crossings is the null around which the VCO tracks the signal phase.

The use of a dual IF channel receiver has several disadvantages. First, it requires a certain amount of equipment duplication which is seldom available in existing voice or data radio transceivers. Second, it is difficult and expensive to build two channels of identical bandwidth and gain. For these practical reasons, it is therefore advisable to time share a single IF filter-amplifier channel as shown in Figure A-5. The identical reference signals are produced, but they are applied to the gate in sequence. The input to the differential amplifiers, which performs the “early/late” subtraction, is switched in synchronism. After filtering, the appropriate time error signal is obtained to drive the VCO and synchronize it with the incoming waveform. The VCO output and its subharmonic frequencies may then be used for retransmission or for comparison with a transmitted signal to extract range measurements.

In the Apollo VHF Ranging System the “early/late” switching rate is 5.27 kHz so that three “early” gating pulses are followed by three “late” gating pulses. This frequency passes through the IF filter-amplifier without difficulty. The actual early and late displacements are 1/16 cycle to maximize the voice signal which is also obtained at the output of the envelope detector. The actual waveforms are illustrated in Figure A-6.

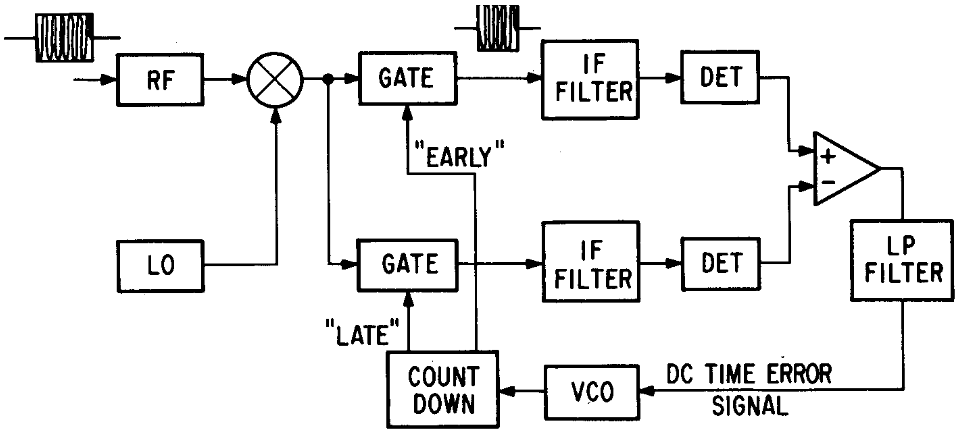


Figure A1. Dual IF tracking receiver

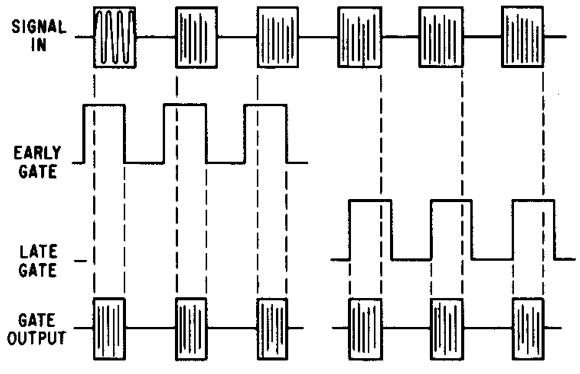


Figure A2. Tracking waveforms, input signal locked

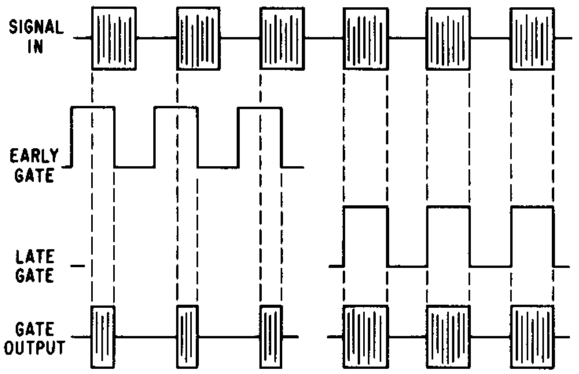


Figure A3. Tracking waveforms, input signal delayed 1/8 cycle

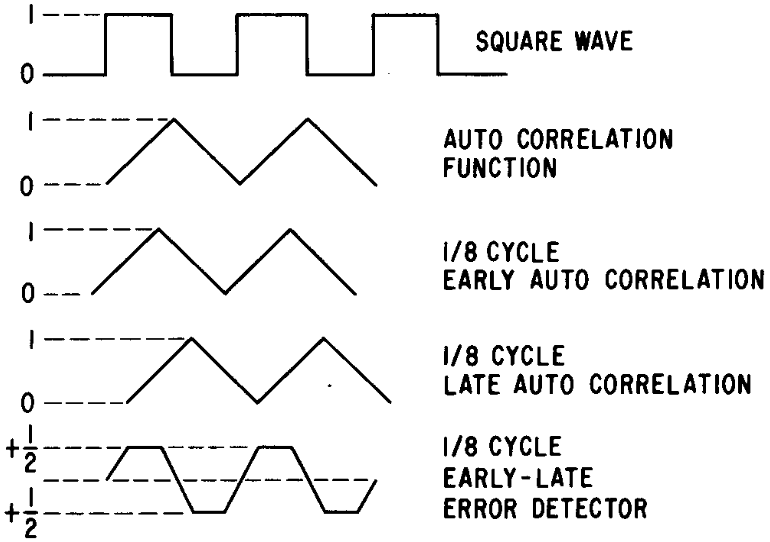


Figure A4. Early/late error detection diagram

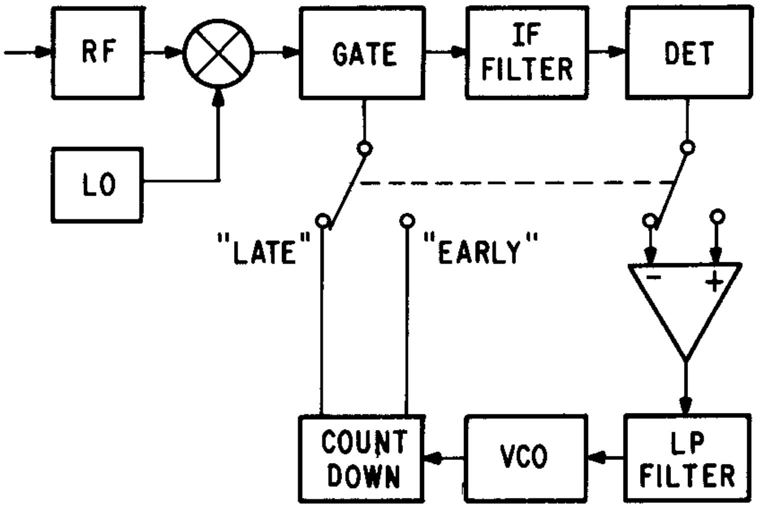


Figure A5. Single i.f. tracking receiver

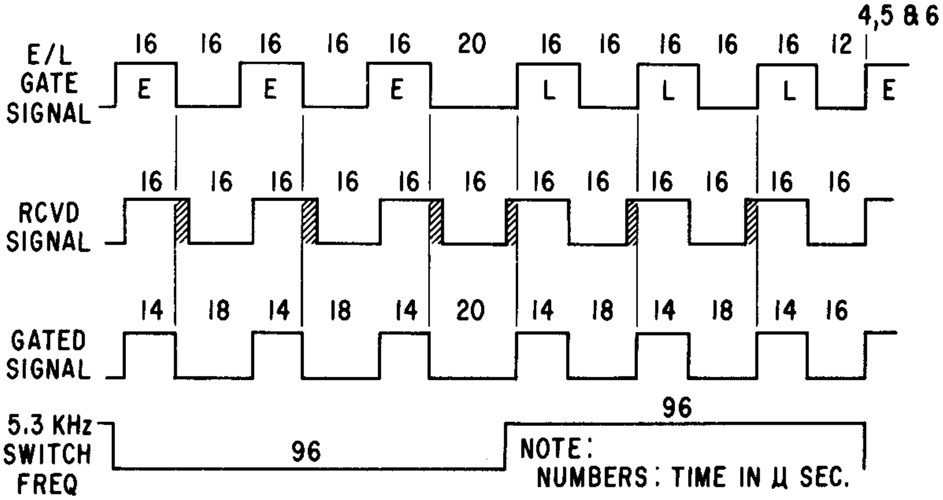


Figure A6. Early/late gating diagram