NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report No. 32-809

Unified S-Band Receiver-Exciter Subsystem

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ABSTRACT

This report summarizes the functional capabilities and physical arrangement of the receiver-exciter subsystem, a part of the unified S-band *Apollo* communications and tracking ground-station system. The report is based on a talk given at the *Apollo* Unified S-Band Technical Conference held at Goddard Space Flight Center, Greenbelt, Maryland, on July 14 and 15, 1965.

The functional operation is initially described, in relation to the other interfacing equipment, by separate explanations of four relatively independent capabilities: doppler extraction, two-way communications, angle-tracking, and ranging.

Somewhat more detailed information is then covered for the main receiver phase-lock and AGC loops and the ranging receiver phase-lock loops, since an understanding of these loops is fundamental to a comprehension of the equipment design concepts.

Finally, the report gives a brief physical description of the equipment layout and control panel functions.

I. INTRODUCTION

The communications and tracking requirements to support the *Apollo* program are similar to those of the *Mercury* and *Gemini* programs in the vicinity of the earth, but, in addition, the functions must be provided at trans-lunar and lunar distances. To fulfill these requirements at the increased distance, a system concept similar to that used in the Deep Space Network (DSN) was adopted for the Manned Space Flight Network (MSFN). This unified S-band concept (USB) fulfills the requirements at trans-lunar and lunar distances, and during the near Earth orbit phases. The system concept is based upon the use of an S-band receiver/exciter ranging subsystem which provides separate high precision phase stable RF carriers for each vehicle on which there are information channels superimposed in the form of phase modulation. Tracking information is simultaneously obtained by reduction of two-way precision doppler information on the carriers (range rate), angle tracking data, and precision CW ranging information.

This report describes the functions and physical makeup of the receiver/exciter subsystem. The operation of the receiver/exciter subsystem is explained by a description of the following four major capabilities.

A. Doppler Extraction

The subsystem provides a signal whose frequency is proportional to the doppler shift occurring on the two-way transponded carrier. The doppler shift is a result of spacecraft motion with respect to the ground equipment.

B. Two-way Communications

The subsystem contains an S-band transmitter exciter that processes the up-data and voice modulation for the *Apollo* spacecraft, and also contains two functionally identical receivers that process the modulated received carriers from the *Apollo* spacecraft. The received modulation consists of spacecraft TV and data telemetry, as well as voice information.

C. Angle Tracking

The subsystem contains dual-channel angle receivers which operate in conjunction with the antenna feed and antenna control and drive equipment to form an antenna position tracking servo system.

D. Ranging

The subsystem contains a ranging receiver and other associated subassemblies that operate in conjunction with the digital ranging subsystem to provide continuous range data between the *Apollo* spacecraft and the ground station.

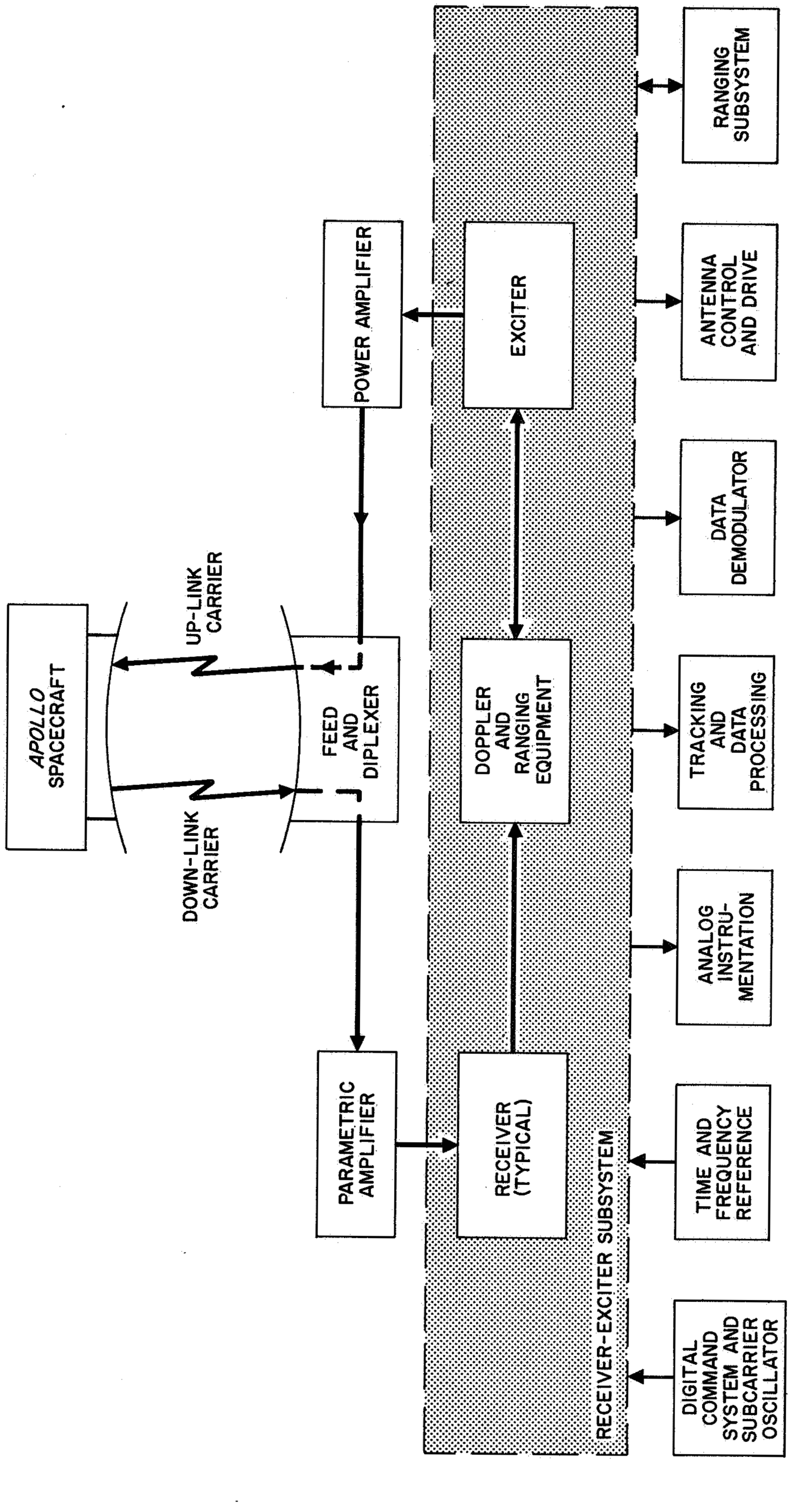

Fig. 1. Fundamental S-band two-way carrier path

The fundamental S-band two-way carrier path is diagrammed in simplified form in Fig. 1. Excitation from the exciter is applied to the power amplifier. The amplifier output is transmitted as the up-line carrier via the diplexer, antenna feed, and antenna. At the spacecraft, the up-line carrier is received, coherently transponded, and retransmitted as the down-link carrier. This carrier is received by the antenna and feed, passed through the diplexer, and amplified by the parametric amplifier. The amplifier output is applied to the receiver.

The receivers and exciter interconnect with the doppler and ranging equipment to perform the listed functions. In the paragraphs that follow, the mechanization of these four major functional capabilities are discussed in detail.

II. MAJOR SUBSYSTEM FUNCTIONS

A. Doppler Extraction

In the doppler extraction function diagrammed in Fig. 2, the exciter output carrier frequency (F_T) at S-band (2100 to 2110 mc) has a precision based upon the accuracy of the 1-mc reference supplied by the timing and frequency reference assembly. The output frequency is amplified and transmitted to the spacecraft where it is coherently transponded by the ratio 240/221 and then retransmitted to the ground station. At the ground station, the received signal is preamplified by the parametric amplifier and appears at the receiver input as the frequency:

$$F_R \doteq (240/221)\, F_T + D \tag{1}$$

The factor D is the two-way doppler-shift frequency, and has a maximum value of about 200 kc at Earth-escape velocity.

The receiver reference loop is phase-locked to this received frequency, and receiver reference signals containing frequencies coherently related to the received frequency are applied to the doppler extractor. Similarly, frequencies coherently related to the transmitted frequency are also applied to the extractor.

Within the doppler extractor, the transmitter references are suitably combined and shifted coherently to simulate

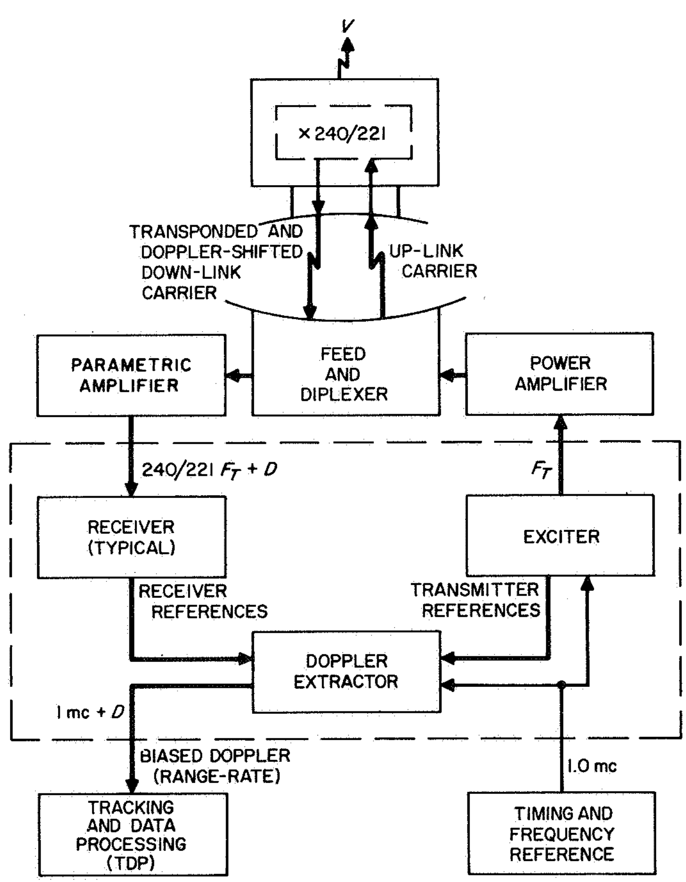

Fig. 2. Doppler extraction function

the 240/221 ratio occurring in the spacecraft. The resulting signal is functionally differenced with the receiver references to obtain the difference, that is, the doppler frequency D. Finally, this doppler frequency is added to a 1-mc bias from the timing and frequency reference assembly, and the resulting biased doppler or "range-rate" signal is supplied for further reduction to the tracking and data-processing (TDP) subsystem. The purpose of biasing is to supply the doppler signal in a form convenient for further reduction by a computer.

Frequency D is approximately related to the spacecraft radial velocity vector and transmitter frequency by the expression:

$$D \approx \frac{240}{221} \times F_T \times 2 \frac{V}{C} \quad (2)$$

where V is considered positive when the range is increasing. Thus, if the spacecraft is moving away from the ground station, the biased doppler frequency will be greater than 1 mc, whereas if the spacecraft is approaching the ground station, the biased doppler frequency will be less than 1 mc.

B. Two-way Communications

A typical operational configuration using both receivers is shown in Fig. 3. Up-data and voice frequency-modulated subcarriers from the subcarrier oscillators are applied to the exciter phase modulator (PM). The phase-modulated carrier from the exciter drives the power amplifier which in turn feeds the phase-modulated "up-link" carrier to the spacecraft lunar excursion module (LEM) or command service module (CSM) via the antenna and microwave equipment. Within the spacecraft, the carriers are suitably demodulated to provide up-link information for the in-flight equipment and personnel. Frequency- and phase-modulated carriers are generated within the spacecraft (LEM, CSM, or *Saturn* IV-B stage) and transmitted to the ground station.

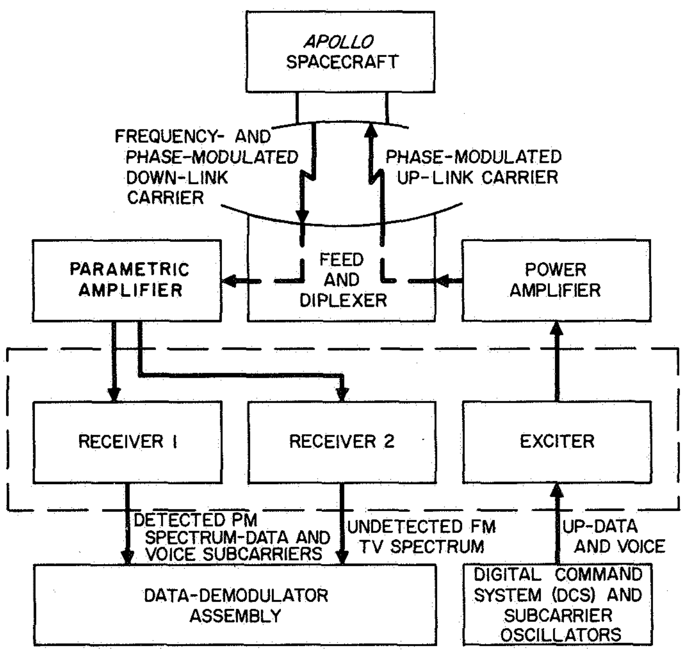

Fig. 3. Two-way communication function

In the configuration shown, the separate carriers are amplified through the multichannel parametric amplifier and applied to the separate receivers. Receiver 1 operates as phase-lock double-conversion equipment and coherently detects the phase-modulated carrier. The resulting detected spectrum consists of information subcarriers, frequency-modulated by voice and data information. This spectrum is supplied to the data-demodulator assembly for subcarrier demodulation.

Receiver 2, in the example shown, operates in an open-loop single-conversion wide-band mode. It supplies a gain-controlled FM spectrum (usually TV information) around a center frequency of 50 mc, the receiver first intermediate frequency. This spectrum is also supplied to the data-demodulator assembly for demodulation of the FM carriers.

Receivers 1 and 2 are not limited to the modes of operation shown in Fig. 3. They can be simultaneously operated either singly or together in either the open-loop or closed-loop configuration on any one of four received channel frequencies in the 2270- to 2290-mc band. The receiver internal configuration is identical except that only one source of reference signals is required, and this is included in receiver 1 for use by both receivers.

C. Angle Tracking

The receiver carrier from the spacecraft is split by the antenna feed equipment into three channels: the sum channel Σ, and X channel, and the Y channel (Fig. 4).

The sum-channel signal is amplified by the parametric amplifier, and is the main received carrier for the reference loop of the receiver.

The X and Y channel signals are not preamplified, but are applied directly to the dual-channel angle receiver. Using reference signals generated by the receiver reference loop, the angle channels operate as dual-conversion

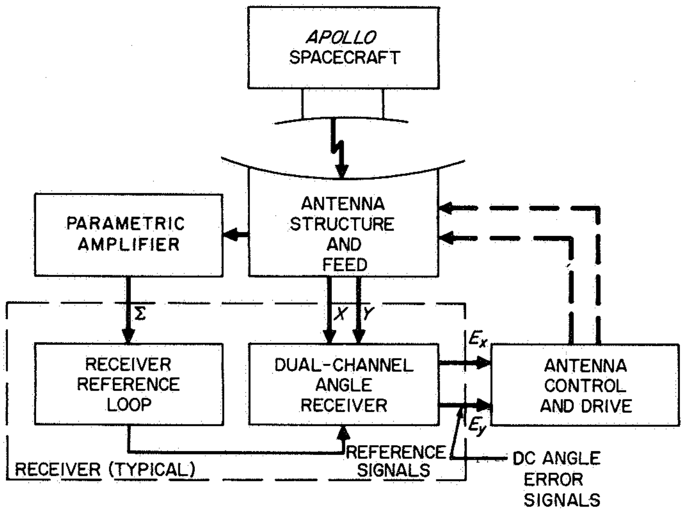

Fig. 4. Angle-tracking function

receivers. They produce dc outputs (E_x and E_y) with magnitude proportional to the amplitude of the channel input signal.

The antenna pattern associated with each channel is such that, when the radial axis of the antenna is perpendicular to the plane of the incoming wavefront, the sum channel amplitude is maximum, but the angle channel inputs are minimum or null inputs. Under this condition, the error signal dc outputs E_x and E_y are also at a minimum.

When the antenna is slightly displaced from radial alignment in either the X or Y tracking planes, as occurs during angular tracking, the angle channel input amplitude increases. The detected error voltages then take on dc values proportional to the angular displacement or tracking error. The polarity of the error voltage is a function of the phase of the channel input signal which, in turn, is dependent on the direction of the angular tracking error. The antenna pattern associated with the angle channels is essentially biphase; that is, the phase goes through a 180-deg reversal at the null (alignment) position of the antenna.

The error signals thus contain information as to the direction and magnitude of the angular tracking error, and the angle channels function as the amplifiers and detectors in the antenna tracking servo loop. The other elements of the loop are the antenna feed, which performs the *sensing* function, and the antenna control and drive equipment, which actuates the motions of the antenna structure.

The standard single configuration contains two complete angle channel receivers, one associated with each of the reference loops. Receiver 1 is ordinarily used with the main (30-ft or 85-ft) antenna, while receiver 2 is ordinarily associated with the small, wide-beam acquisition antenna. When the acquisition antenna is not in use, receiver 2 reference loop is ordinarily switched to receive via the large antenna through the multichannel parametric amplifier.

D. Ranging

The major signal paths associated with the ranging function are shown in Fig. 5. Although not a part of the receiver-exciter subsystem, the digital ranging equipment, known as the ranging subsystem, is shown in the diagram to aid in clarifying the ranging function.

A pseudo-random-noise code spectrum containing a "clock" component is applied from the ranging subsystem as phase modulation (code-X clock) to the exciter. The resulting modulated carrier is transmitted to the spacecraft, turned around, and retransmitted to the ground receiver. Within the receiver reference loop, the carrier containing the received code-X clock modulation is translated to an intermediate frequency of 10 mc and applied to the ranging receiver.

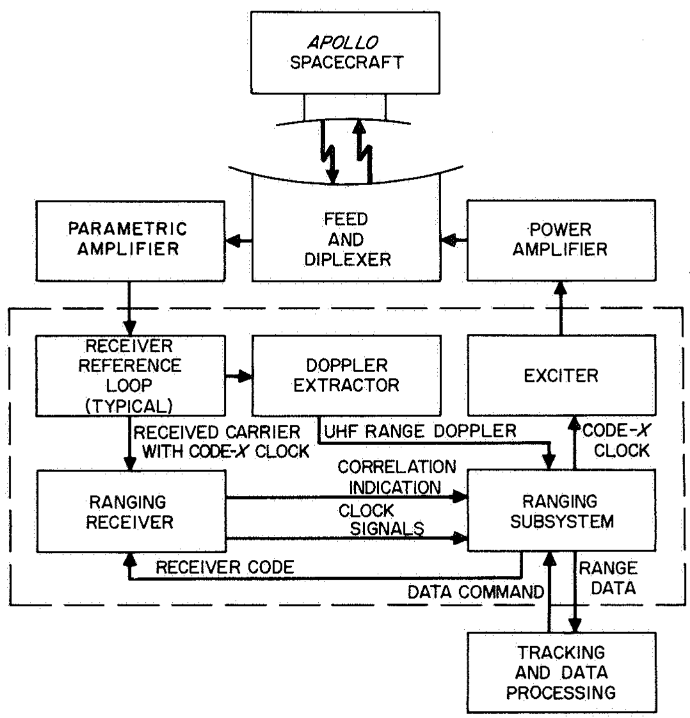

Fig. 5. Ranging function

Within this receiver, the received code-X clock is correlated with a locally generated code from the ranging subsystem.

The correlation process is functionally subtractive, yielding an output of clock signal alone, the amplitude of which is proportional to the degree of correlation. This signal is tracked by a receiver phase-lock loop, and its amplitude is detected to appear as a dc correlation indication. This indication is routed back to the ranging subsystem as a primary information input.

The ranging receiver also supplies clock frequency reference and clock doppler signals, while the reference loop supplies a UHF range doppler signal (at one-fourth the S-band doppler value or $D/4$) for use by the ranging subsystem. Using these various inputs, the ranging subsystem programs an acquisition sequence from which is obtained data proportional to the range of the spacecraft. Upon completion of the acquisition program, the ranging subsystem delivers up-dated range information to the tracking and data-processing subsystem upon command from that subsystem.

III. THE RECEIVER REFERENCE LOOP

A. Function

The reference loop of a typical receiver is particularly important as an element of the subsystem since it contains equipment that is operational in all four of the major functions. The loop and its associated branches are shown in detail on Fig. 6.

The S-band RF input, at one of four carrier center frequencies in the 2270- to 2290-mc range, is applied to the first mixer and preamplifier. At the mixer, the signal is differenced with the local oscillator (LO) chain injection signal, which is 50 mc lower in frequency than the received signal. The resulting 50-mc IF signal is preamplified and applied to the 50-mc IF amplifier which has automatic gain control (AGC).

During open-loop operation, when the carrier is frequency-modulated by television information, the 50-mc spectrum is branched off at this point, passed through a gain-controlled wide-band 50-mc IF amplifier, and supplied as an undetected spectrum to the data-demodulator assembly.

In closed-loop operation, the signal is next gain-controlled through a series of 50-mc AGC-controlled IF amplifier stages and then differenced with a 60-mc reference signal in the second mixer to produce the second IF of 10 mc. The IF amplifier is capable of a total gain control range of 91 db, operating at an overall gain between +51 db and −40 db. The phase and gain changes across this range must be carefully controlled during manufacture to assure compatible operation with parallel units in the angle receiver channels.

The 10-mc output is applied to a distribution amplifier, where telemetry channel IF and range-receiver channel input signals are branched off. Operation of these channels is covered in more detail in Section IV.

The reference-loop signal is next applied to a 10-mc IF amplifier where a crystal filter establishes the loop predetection noise bandwidth of about 7 kc. After the signal has been filtered, it is split into two channels. The first operates at high gain and contains a limiter whose output is applied to the loop phase detector. The second channel operates at lower gain without limiting, and this channel output is applied to the loop AGC detector.

Within the loop phase detector, and assuming loop phase lock, the limited-output signal frequency is differenced with a 10-mc reference signal. The resulting output is a small dc voltage proportional to the angular phase error in the loop. This dc output is applied to the reference loop filter within which time constants are selected

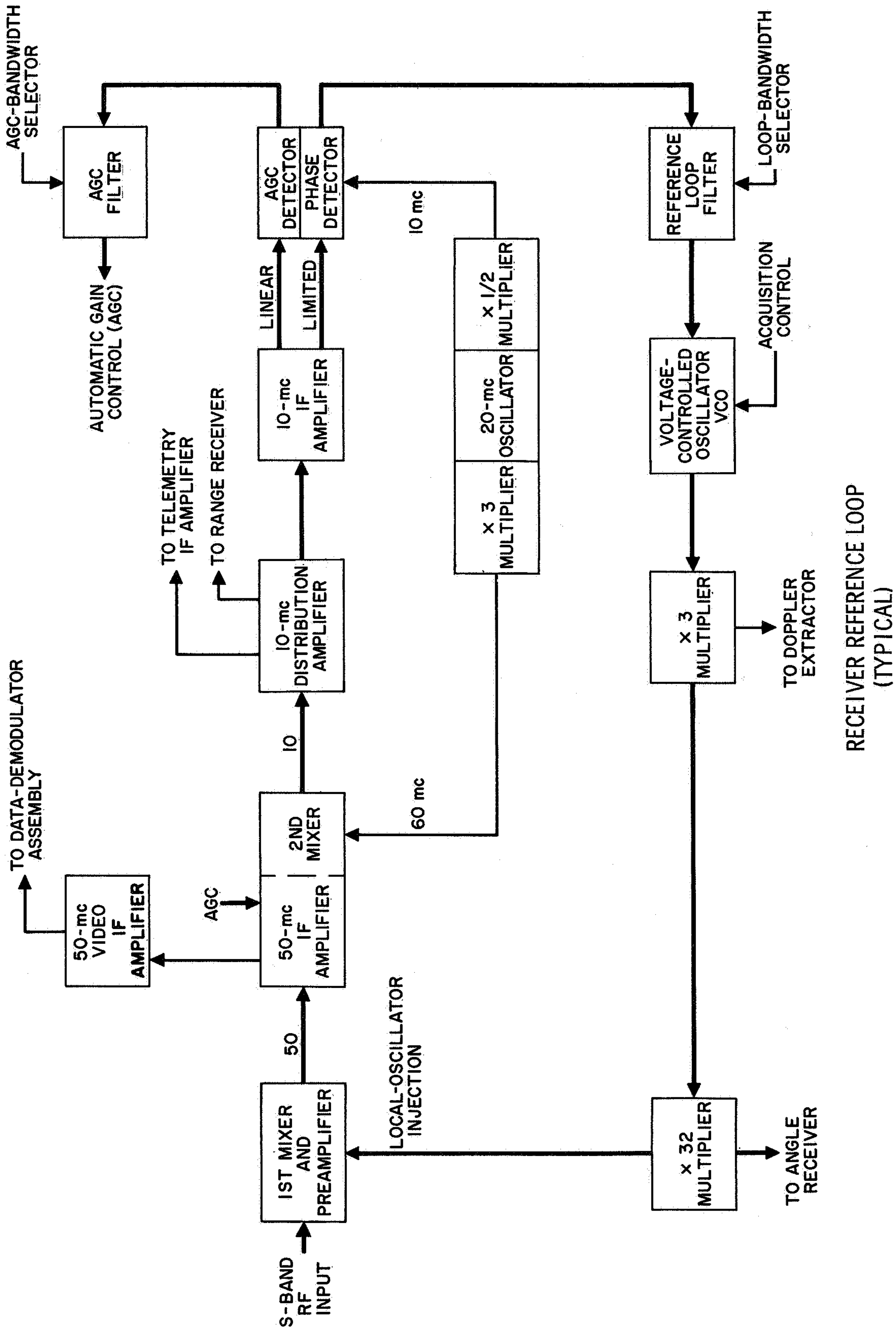

Fig. 6. Receiver reference loop

manually to control the overall loop-noise-bandwidth ($2B_L$). Threshold values for this bandwidth ($2B_{L_0}$) of 50 cps, 200 cps, and 700 cps may be selected.

The loop filter output, known as the loop static phase error (SPE), is a small and relatively noise-free dc voltage. This voltage is applied to the voltage-controlled oscillator (VCO) where, during phase lock, it automatically adjusts the VCO frequency to maintain lock during input signal frequency variations.

An acquisition input voltage to the VCO is applied manually by the operator to obtain initial lock (acquisition), and then to balance out the residual phase error when acquisition has been accomplished. This latter function is indicated by a reduction of the SPE to zero.

The VCO output is next multiplied by 3, and a coherent reference signal for the doppler extractor is branched off from the multiplier. Then the VCO signal is multiplied by 32 for a total multiplication of 96 and applied as the local-oscillator injection signal to the first mixer, thus closing the loop. LO injection signals for the angle channel receiver are also branched off at the X32 multiplier output.

Returning to the AGC path, the detector output is applied to the AGC-loop filter. Within the filter, the AGC-loop bandwidth is selected by the control operator for one of three values, designated narrow, medium, or wide.

These values are ordinarily paired with the corresponding reference loop $2B_{L_0}$ settings, although this is not necessary for proper operation.

The filter output is the dc AGC voltage with a dynamic range of 10 volts. This voltage is applied to the gain-controlled stages in the 50-mc IF amplifiers in the reference loop and to the parallel angle-receiver channels. It is also displayed and recorded by the analog instrumentation equipment because it varies with and is a measure of the input-signal level.

The 60- and 10-mc reference frequencies are both derived from a 20-mc crystal oscillator. The 60-mc signal is obtained through a X3 multiplier while the 10-mc signal is derived from a X½ multiplier. This reference generation equipment is present only in one of the receivers. Reference signals for the second receiver, the angle channels, the telemetry channels, the range receiver, and the doppler extractor are all branched off of the X3 and X½ multiplier outputs.

In summary, the reference phase-lock loop is of second order, with the dual-phase integration occurring through the loop filter and VCO, while the AGC loop is of first order with single integration occurring through the AGC filter.

B. Variation in Loop Noise Bandwidth

The reference-loop gain varies with the input signal level, primarily because of the suppression of signal by noise within the limiter preceding the phase detector. The increased loop gain at high signal levels results in an increased damping and widening of the bandwidth. The values of 50 cps, 200 cps, and 700 cps mentioned earlier are values occurring at the system signal threshold; the strong-signal bandwidths are much wider.

This effect is shown on Fig. 7. Note that in the 700-cps position, the bandwidth rises to about 2 kc when the

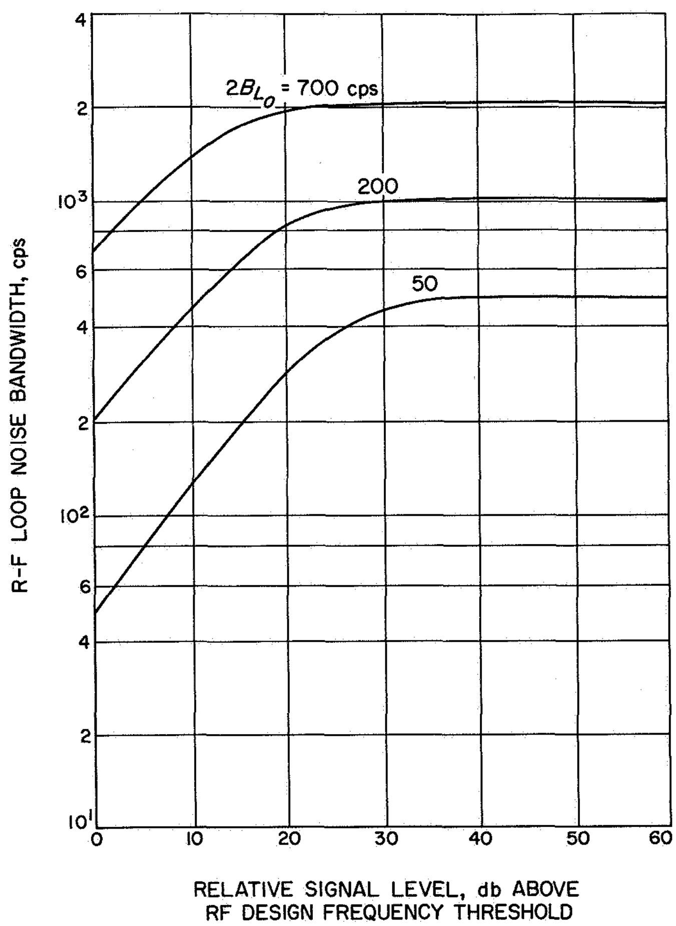

Fig. 7. Effect of variation in loop noise bandwidth on relative signal level

signal exceeds the threshold value by about 30 db. This wide bandwidth is desirable for tracking the high doppler rates encountered during the Earth orbital phase of the *Apollo* missions and will ordinarily be used during these passes.

Carrier phase modulation within the loop bandwidth cannot be properly demodulated since the loop "tracks out" these frequencies. This is of little concern for the *Apollo* program, however, because all modulation other than emergency voice information is on subcarriers at frequencies greater than 1 mc, well beyond the low-frequency cutoff of the loop.

The 50-cps position, reaching a maximum bandwidth of 500 cps, is intended for use during the lunar phases of the mission. Doppler rates will be low during these phases, and the increased sensitivity and narrow bandwidth will assure an adequate communications margin for the expected received signal levels, even if the emergency modes must be used.

The FM television spectrum will contain energy within the tracking bandwidths shown. However, the receivers are in open-loop condition during FM reception, and no attenuation occurs because the tracking loop is inoperative.

IV. RANGING RECEIVER AND DETECTED TELEMETRY CHANNELS

The 10-mc IF distribution amplifier in the receiver channel branches off signals for the ranging receiver and the detected telemetry channel. These two signal paths, which are important to the basic functions of the subsystem, are shown in greater detail on Fig. 8.

The ranging-receiver input from either receiver as selected by the control operator consists of code-*X* clock modulation on the 10-mc IF. This modulation occupies a wide spectrum containing significant sideband components as far as 2 mc from the carrier. This spectrum is applied to a wideband phase detector which has code-*X* IF as a reference. The code-*X* IF is a modulated spectrum centered at the intermediate frequency of 10 mc. The spectrum is derived from a phase switch within which the 10-mc IF reference signal is periodically switched ± 90 deg by the code signal, also shown as the receiver code. This code is supplied by the ranging subsystem.

The phase detector differences the two signals to produce a resultant output spectrum which always contains some energy at the clock frequency. The amplitude of this energy is directly proportional to the degree of correlation between the received code and the receiver code.

The energy at the clock frequency, known as the clock signal, is filtered and amplified through a dual-channel IF amplifier. The channel outputs are applied to a loop phase detector (limited output), and a correlation detector (linear output). The correlation detector develops the dc correlation indication for the ranging subsystem.

The phase-detector output drives a loop filter and VCO which, in turn, serves as reference for the two detectors. These units together define the ranging receiver phase-lock-loop. The loop bandwidth, as in the main receiver, is established by manual selection of the time constants

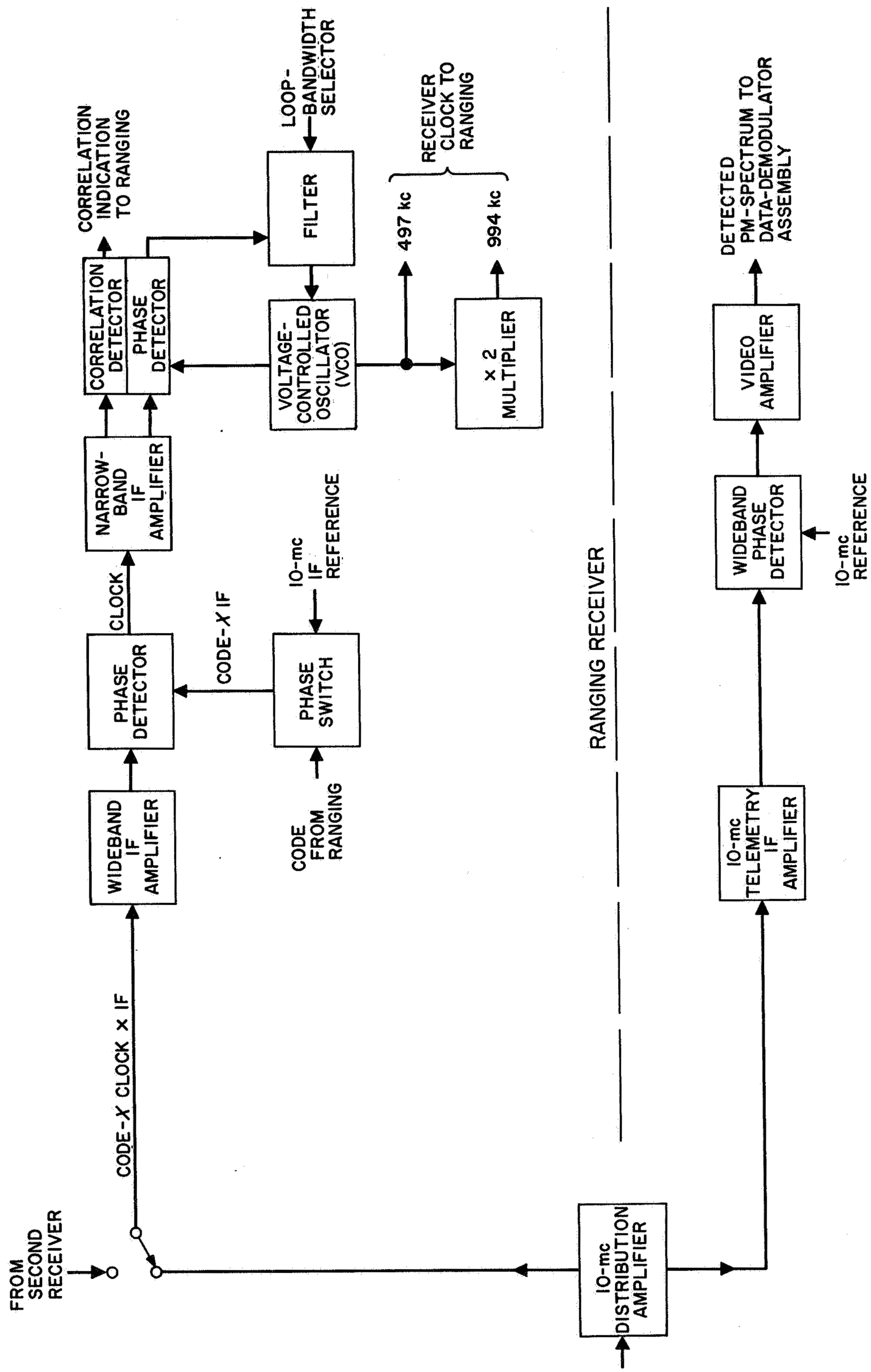

Fig. 8. Ranging receiver and detected telemetry channel

in the loop filter. This bandwidth has threshold values of 4 cps, 16 cps, and 40 cps. Inasmuch as these are considerably narrower than the bandwidths of the main loop, ranging threshold is not ordinarily reached during operation.

The receiver loop acts as a narrow-band tracking filter, providing relatively noise-free frequency references at the clock frequency and its second harmonic. These frequencies are supplied to the ranging subsystem to drive the receiver coder.

The detected telemetry channel is a simple series arrangement of IF amplifier, wideband phase detector, and video amplifier. The phase detector is mixed with a 10-mc signal from the reference signal generator in the receiver. The detected signal is supplied at a level of 0 dbm and a −1-db bandwidth of 1.25 mc to the data-demodulator assembly.

V. EQUIPMENT LAYOUT

A. Component Cabinets

Control-room cabinets containing the receiver-exciter equipment are shown on Fig. 9. Cabinets 1 through 3 contain subsystem control panels and monitoring equipment, tilted and arranged for convenience by a seated control operator. Cabinets 4, 5, and 8 each contain two rollout frames that mount subassemblies of the subsystem. Over 70 different types of subassemblies are used, and the total count exceeds 180.

In Fig. 9, one frame of cabinet 4 is rolled out to show the subassembly packaging and mounting methods. All of the interconnecting coaxial cabling is routed on the outer surface of the mounting plates, while the power, dc, and low-frequency signal paths are all wired with shielded leads on the inner surface of the plates within the frame. Each subassembly is individually removable for quick replacement. Connections to the wiring within the frames is made through multipin connectors mounted at the ends of the subassemblies. Intracabinet cabling is routed through floor channels beneath the cabinets, and all connections to these cables are made through connector plates at the base of the cabinets.

Subassembly power supplies are rack-mounted beneath the rollout frames, and ac convenience outlets are placed on the cabinet lower lips.

Cabinets 5 and 8 contain the subassemblies for receivers 1 and 2, respectively. Each receiver thus housed consists of the reference loop, the angle channels, and the telemetry channels.

Cabinet 4 contains subassemblies of the exciter, the doppler extractor, and the range receiver, as well as other minor equipment used with the range receiver during the ranging program. The exposed plate contains subassemblies of the doppler extractor.

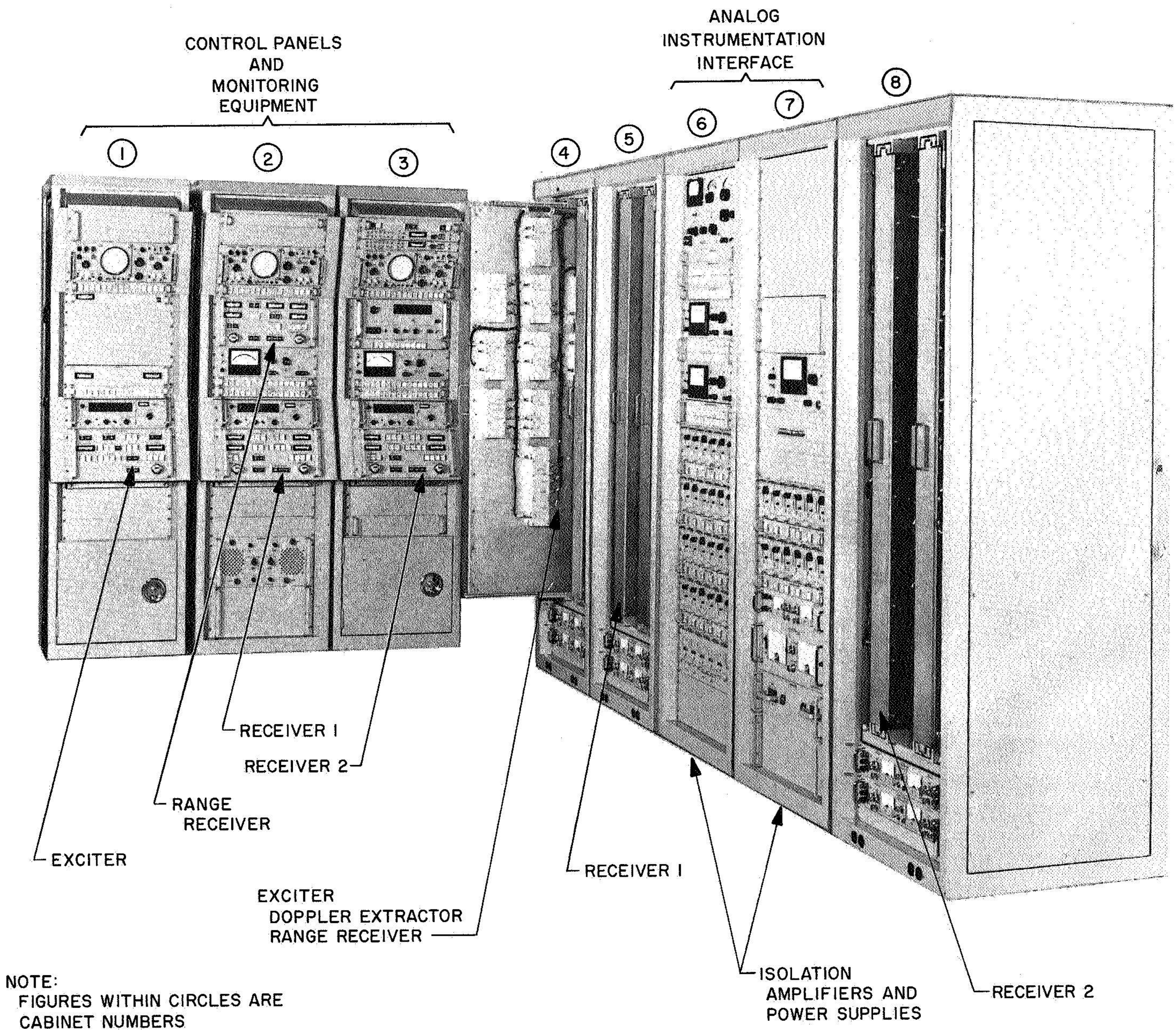

Fig. 9. Receiver-exciter subsystem components and functions

Additional subassemblies containing equipment capable of operating within the S-band are normally mounted near the antenna and do not appear in Fig. 9.

Cabinets 6 and 7 contain isolation amplifiers and power supplies that preprocess monitoring signals before they are fed to the analog instrumentation subsystem. All of these signals have a normal peak-to-peak level of 10 v from the low-impedance output of the isolation amplifiers. The cabinets also contain instrumentation used while testing and evaluating the performance of the subsystem equipment.

Locations of the system control panels for the exciter, the two S-band receivers, and the ranging receiver are indicated on racks 1, 2, and 3. Figures 10, 11, and 12 show these control panels in greater detail.

B. Control Panels

The exciter control panel contains all operational controls and indications for the exciter and doppler extractor. Controls for a phase-lock loop that locks one of four exciter VCO's to a system frequency synthesizer are included, together with controls for selecting the modulation source and the receiver input to the doppler extractor. The panel also contains controls for an automatic sweep generator that acts as an aid during acquisition of down-link carriers by the receivers. The exciter VCO's may also be automatically frequency-swept to aid in the two-way carrier acquisition process.

The receiver control panel contains all operational controls and indications for the receiver reference loop, angle channels, and telemetry channels. Also included are pushbutton controls for selecting the reference-loop noise bandwidth and the AGC-loop bandwidth, as well as controls for selecting one of four VCO's for the corresponding four received carrier frequencies. Coarse and fine manual adjustment controls for the VCO acquisition voltage are located conveniently in the lower right corner of the panel.

The ranging-receiver control panel is not ordinarily used during system operation inasmuch as all operational control of the ranging equipment except bandwidth and input selection is transferred to the digital ranging subsystem. However, during test of the receiver-exciter equipment, this panel is used to control and monitor operation of the ranging receiver and associated equipment. Typical controls are those for selecting the ranging-receiver bandwidth and selecting the main receiver from which the ranging-receiver input is derived.

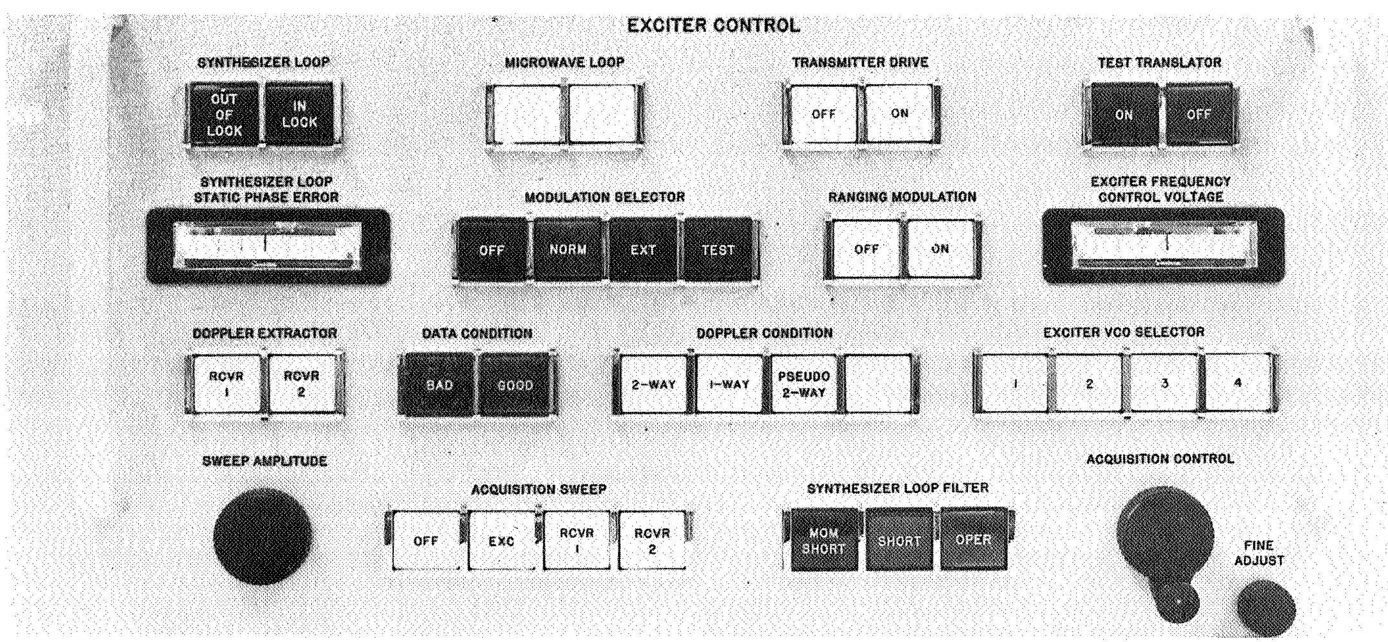

Fig. 10. Exciter control panel

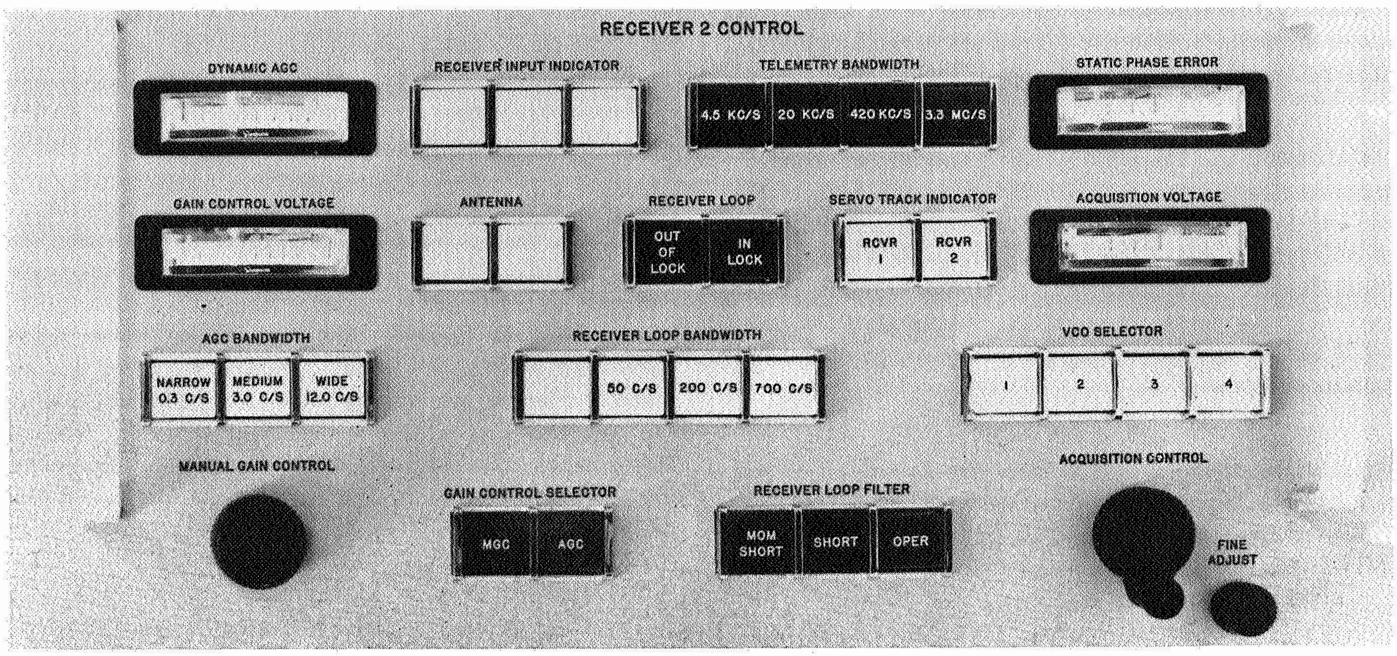

Fig. 11. Receiver control panel

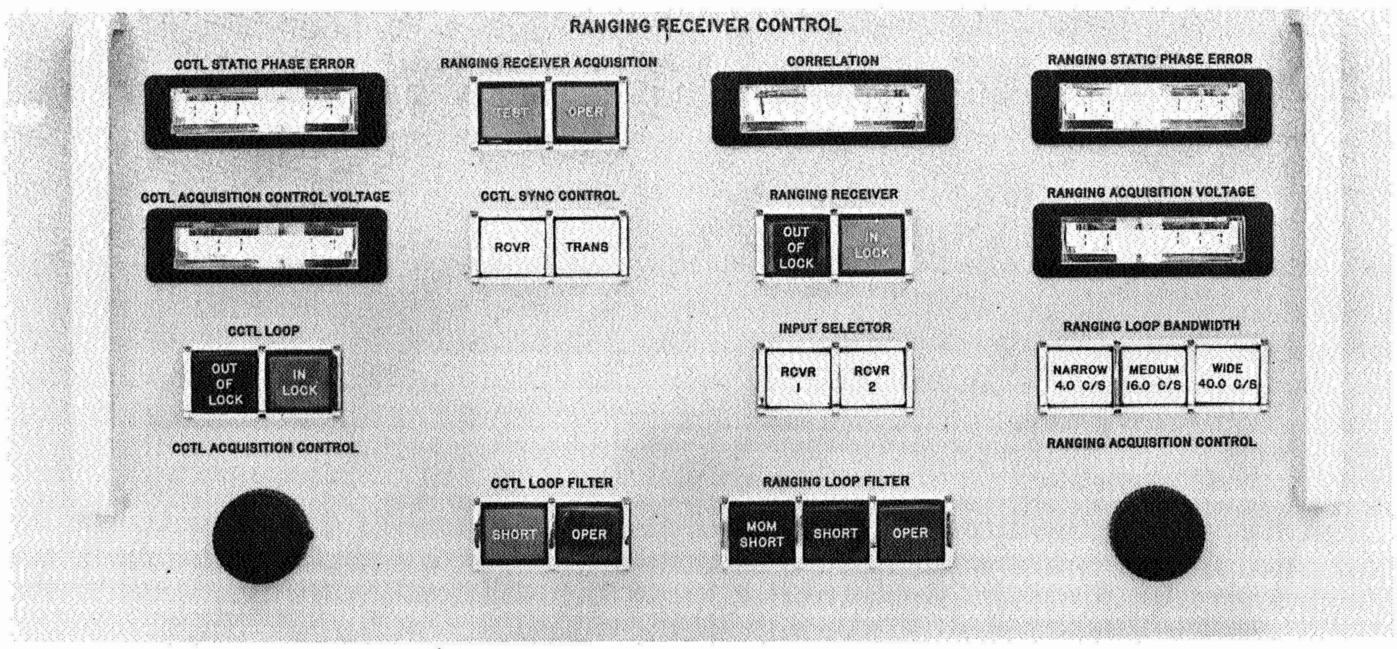

Fig. 12. Ranging-receiver control panel

VI. SUMMARY

The S-band receiver/exciter with doppler, range and angle track functions are described; the receiver/exciter subsystem is the basic element in the unified S-band concept. The subsystem interfaces with other subsystems to meet the *Apollo* Mission requirements for spacecraft position and velocity information, two-way data and voice communications, and accurate antenna tracking. The subsystem integrates into complete USB land and shipboard stations in both a functional and physical sense, performing a fundamental role in meeting the *Apollo* Lunar program communications and tracking requirements.