RADIO CORPORATION OF AMERICA

ASTRO ELECTRONICS DIVISION

~~COMPANY CONFIDENTIAL~~

SUBJECT: PRELIMINARY COMMUNICATIONS SYSTEM DESIGN FOR THE APOLLO LUNAR EXCURSION MODULE

June 9, 1962

Supplied to ACCD through MSD by AED as part of a joint RCA-Grumman Aircraft Company pre-proposal effort.

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An Explanatory Note

The purpose of this memo is to record information supplied to ACCD by Astro-Electronics Division in support of the joint RCA-Grumman pre-proposal effort on the Apollo Lunar Excursion Module.

AED was specifically requested to describe lunar surface operation of the communications systems. In addition, path loss calculations and link system designs were prepared independently of those of ACCD. While in general agreement, these two sets of calculations differ in detail, owing to some differences in initial assumptions.

The AED link designs tend to be somewhat conservative; the nature of the mission is such that the AED engineering feels that such an approach is warranted.

AED was also assigned the task of investigating the frequency netting problem and the multiplexing problem.

The material presented herein was in part prepared at AED and passed to Mr. Levin MSD and Mr. Carlson of ACCD on June 8th. The remainder of the attached material was written at Grumman Aircraft Engineering Corporation (GAEC) for and by request of Mr. Carlson of ACCD on June 8 and 9, 1962.

The outline presented at the beginning of this memo was prepared at AED prior to the Grumman meeting in an effort to coordinate our efforts with ACCD. Copies of the outline were transmitted to ACCD via MSD. Much of the material contained herein was modified to conform to an outline supplied by Mr. C. Carlson of ACCD, and therefore does not conform to the outline included in this memo in all respects.

The material that follows represents work done up to and including June 9, 1962. Further study of the multiplexing and other problems will be covered by future memos.

PRELIMINARY TOPICAL OUTLINE

I. THE LUNAR EXCURSION MODULE COMMUNICATIONS SYSTEM

A. Basic Communications Circuits Required

Fig. Flow Diagram

1. LEV Separation and Descent
   a) 2-way Voice and Data LEM to Apollo
2. LEV Operation on Lunar Surface
   a) 2-way Voice and Data LEM to Apollo
   b) 2-way Voice to Earth, data to Earth
   c) TV to Earth
   d) Man to LEM to Apollo and Earth
   e) Man to man to LEM to Apollo and Earth
3. LEM Ascent, Rendezvous and Dock
   a) Same as 1
4. Emergency Communication Circuits
   a) Descent phase
      Voice only to Apollo
      Voice or C-W to Earth
   b) LEV on Lunar Surface
      Voice only LEM to Apollo
      Voice or C-W to Earth
   c) Ascent phase
      Same as a)

II. COMMUNICATIONS SYSTEM DESIGN

Block Diagram

A. Introduction

1. List three basic links
   a) Apollo-LEM
   b) LEM-Earth
   c) Men to LEM

B. The Apollo-LEM Link

1. Range Limits
2. Frequency selection
    a) Noise vs. free space loss
    b) Equipment feasibility vs. frequency
    c) Duplex voice-data circuit
3. System Design

    Path loss-power-modulation-multiplexing diversity
    Doppler-data rates-noise temperature

C. The LEM to Earth Link

1. TV Circuit
    a) Line and frame rates - TV baseband
    b) Frequency selection

        Window, noise, antenna gains, low noise receivers, range
2. TV Transmission System Design
3. Voice-Data Link Design - Normal and emergency modes

D. The Man to LEM Link

1. Frequency selection
2. Range, multiplexing, voice and data
3. Frequency compatibility for netting
4. System design

E. Overall System Description and Operation

1. General description
2. Switching and control unit

I. THE LUNAR EXCURSION MODULE COMMUNICATIONS SYSTEM

A. Basic Communications Circuits

The Lunar Excursion Module (LEM) communication system design must provide for a number of basic communications circuits, necessary for successful accomplishment of the mission and to aid in assuring the safety of the crew.

Figure 1 illustrates the required flow of information from and to the LEM during the descent to the lunar surface and during the ascent from the Moon to rendezvous with Apollo.

During the in flight phases of the LEM, two-way voice communication between Apollo and the LEM is required. A two-way data link, capable of handling 2100 bit per second real time; PCM telemetry is also required.

Under certain conditions, it may not be possible for the LEM to communicate directly with Apollo due to the interposition of the Moon. This can occur if the LEM does not achieve the desired orbit.

To accommodate this situation an emergency two-way voice link to the Earth from the LEM is required.

Figure 2 illustrates the communications circuits required for operations on the lunar surface. Here, the primary communications links are the lunar vehicle-Earth links. A two-way voice circuit to Earth is required, as well as a real time TV link and a 700 bit/second data link, one way to Earth.

Two-way data and voice communications are required with Apollo, but since Apollo will be orbiting the Moon 100 miles above the surface, it will be above the lunar horizon only about 10% of the time. Consequently, a store and forward mode of operation is required for the data link, with the stored data being transferred to Apollo at a high rate when it appears over the horizon.

It is planned to have one of the two astronauts leave the LEM and move about on the Moon with a TV camera. Video will be transmitted to the LEM via a cable, and a radio link for two-way voice and one-way telemetered biomedical data is required from the man to the LEM, to allow the astronaut to move further from the vehicle than the cable permits.

An emergency may require the second man to leave the vehicle to go to the aid of the first, or because of damage to the vehicle. Under this condition, a two-way voice link between the two men, as well as voice and data links to the LEM from the men, for relay to Earth and to Apollo. The necessary links are shown as dotted lines on the diagram.

Emergency Communications Circuits

Various possible contingencies can place special requirements upon the communications systems. It is desired to provide at least a minimal communications capability for all forseeable eventualities in which communication will be required.

During the descent or the ascent phases, the Apollo and the LEM may become separated by a distance greater than the normal design range of the LEM-Apollo communication system, which is set at about 470 miles by the normal maximum slant range to Apollo with the LEM on the Moon's surface. By reducing bandwidth and transmitting voice only, without the data link, the range of this circuit can be extended to approximately 1000 miles.

Still greater ranges could be achieved if directional antennas were used. However, the use of such antennas requires a knowledge of the direction of Apollo from the LEM and the ability to orient the antennas. Either of these factors are likely to be unavoidable in an emergency situation.

In the event that the line of sight path between the two vehicles intersects the Moon, direct communication between the two vehicles becomes impossible. However, the Earth is in view during a bit more than half of each orbit, and can be used as a relay point. For this case, a voice or cw emergency link, which is not normally used while the LEM is in space, is required to Earth.

Since the Earth is a quite conspicuous object at lunar distances, no difficulty exists in determining its direction, and a directional antenna of moderate gain can be used, providing the spacecraft remains capable of controlling its attitude. Communication with an omni-directional antenna is desirable to provide for communication if control is lost and the spacecraft begins to tumble.

Emergency Communication on the Lunar Surface

If an emergency condition requires power saving, reduced transmitter power for communication on the lunar surface can be accommodated by the same bandwidth reducing the techniques discussed above, that is, by transmitting voice only to Apollo and voice or cw only to Earth.

As has been previously pointed out, an emergency may require both crew members to leave the vehicle at the same time. This situation requires a radio link between the two astronauts, via packsets, which is independent of the LEM itself, as well as links to provide for relay from each man to Earth and to Apollo via the LEM.

2. Operations on the Lunar Surface

As illustrated in figure 2, three principal communication links must be established and maintained once descent to the lunar surface is complete.

Communication will be lost with Apollo shortly after landing, as Apollo sets on the lunar horizon. Consequently, the deep space parabolic antenna (figure 3) must be erected and oriented toward Earth to re-establish communication from the LEM.

Since it may be necessary for a crew member to leave the spacecraft to erect and aim the antenna, the low power VHF set will be activated to permit man to LEM communication during this phase (figure 4).

Since direct communication to Apollo is not possible at this time, the high power (10 watt) VHF transmitters will be shut down to conserve power.

The VHF link to Apollo will be automatically reactivated by a timer, set to the Apollo's orbital period, to prevent accidental loss of communication time to Apollo due to human error.

The telemetry data, which has been transmitted to Apollo over the VHF link in real time during the descent phase, is diverted into a tape recorder. The data rate is reduced from 2100 bits/second to 700 bits/second, as only 1/3 of the sensors are required when the LEM is not in flight.

This tape recorder is played back at 10 times the record speed when Apollo appears above the horizon. In this manner, data continues to flow to Apollo in a store and forward mode.

Operation of the Moon-Earth Circuit

After the UHF parabola is oriented toward Earth, the UHF deep space communications equipment is activated.

Both UHF receivers begin searching in frequency, then lock on to the carrier of whichever of the three Earth transmitters is illuminating the Moon at the time. This AFC search and track operation is necessary because of the doppler shift introduced by the Earth's rotation, as well as possible drift of the receiver local oscillator and Earth transmitter. The receiver receiving the poorer signal from Earth is shut down by the operator to conserve power.

The standby transmitter is activated and its output power is checked with a directional coupler and power monitor provided for the purpose. This transmitter is normally operated without its power amplifier at the 2 watt level, and will handle voice and telemetry only.

The prime transmitter and power amplifier will be used for video transmission.

In the event of equipment failure, the prime transmitter can be substituted for the standby to maintain the voice link. Switching and multiplexing arrangements for the Earth link UHF equipment are illustrated in figure 3, a simplified block diagram.

Since we have continuous operation of the Earth-Moon link, data is transmitted to the Earth in real time.

The 700 bit/second data is multiplexed on the voice transmitter by means of a subcarrier. Use of a separate transmitter for voice and data simplifies the multiplexing and switching problems on this link.

Video will be transmitted as straight frequency modulation using one of the 20 watt power amplifiers. It is expected that TV will only be transmitted for about one-half hour.

Operation of the Man-LEM Link

Communications from the man to the LEM are accommodated by a two-hundred-fifty milliwatt low power VHF set similar to the space suit packsets.

This set avoids the high power drain of the 10 watt Apollo-LEM transmitters, which are unnecessarily powerful for this purpose.

In the description of the links required for lunar surface operations, it was shown that it is desirable to provide communication between both men and between each man and the LEM when both men are outside the spacecraft. This is done by using a three-frequency netting system, illustrated in figure 4.

The packset transmitters operate continuously whenever the men are outside the vehicle to continuously telemeter biomedical data to the LEM. The packset transmitters are operated on different frequencies to avoid mutual interference, and two VHF receivers are provided in the LEM to allow simultaneous reception of both packsets.

Similarly, both packsets are capable of receiving on two frequencies, to allow simultaneous reception of the other packset and of the LEM transmitter, which is used to relay messages to the men from Earth or from Apollo.

Figure 5 is a block diagram illustrating one possible mode of providing the required two frequency operation in a simple packset receiver. The receiver is a superheterodyne so arranged as to have its image frequency fall on the second desired frequency when it is tuned to the first desired frequency. The RF and mixer stages are deliberately designed to offer no image rejection, so both the normal and image frequencies are received equally well.

The FM capture effect results in only the strongest of the two signals being heard when both transmit simultaneously.

However, as will be shown in the section on signal switching and control, both possible frequencies will be modulated with the same information, so the capture effect performs the task of suppressing possible echoes, which might otherwise cause loss of a message.

The VHF-LEM-Apollo Link

The same VHF transmitter receiver equipment that was used during the descent will be used to communicate to Apollo whenever the Apollo spacecraft is within line of sight of the LEM.

However, the mode in which these equipments are used differs from that of the descent phase. Since adequate time exists to switch to standby equipment if a failure should occur once the LEM has landed, the prime and standby equipment will not be operated simultaneously. Only one transmitter and one receiver will be operated at a time to conserve power.

The VHF transmitter to Apollo will be shut down except during the time when Apollo appears above the horizon.

The Apollo VHF receivers will be equipped with an AFC circuit with the same automatic search and lock features provided on the Earth link receivers.

The AFC circuit accommodates the doppler shift caused by the radial component of Apollo's orbital motion as well as actuating a signal when the AFC system locks onto the Apollo signal. This signal will alert the operator when communication becomes possible.

In addition, an orbital timer, set to the Apollo orbital period, can be used to reactivate the VHF equipment in the LEM when Apollo is due.

Data transmission may not be required to Apollo except as a backup mode for the UHF Earth circuit. Consequently, the data channel may be dropped from the VHF circuit by turning off the subcarrier oscillator and reducing the bandwidth. This procedure will increase the link communications reliability at extreme range.

II. COMMUNICATION SYSTEMS DESIGN

B. LEM-Apollo Communications

1. Link Analysis

Frequency band selection

The 250 Mc band is chosen for this link due to the availability of equipment having proven performance. In this band, state of the art receivers with good noise figure performance and using all solid state components are available. As to propagation characteristics, this band has galactic noise comparable to the receivers internal noise, and thus does not degrade a 6 db NF receiver appreciably. This is based on a 400°K sky temperature which excludes the 1% hottest areas. This band is also compatible with the antenna system expected to be carried on Apollo.

The block diagram description of the LEM-Apollo communication link, showing detail of the system, is described elsewhere. The following summary of parameters shows the feasibility and performance of this link:

LEM-Apollo 250 Mc Link Parameters

Transmitter Power - 10 watts	10.	dbw
Diplexer - cable loss - on S/C	- 1.	db
S/C Antenna gain (on Moon) (+2 to +5)	+ 2.	
Free space loss (480 miles)	- 138.	
Polarization loss (RHC on LEM, Linear Apollo)	- 3.	
Apollo antenna gain	- 3.	
Circuit losses - on Apollo	- 1.	
Power received	-134	dbw

Galactic noise temperature	400°K	
Receiver noise temperature	870°K	
System noise temperature (Based on 6db NF receiver)	1270°K (Ts)	
RF Bandwidth B = 60 Kc		
System noise received KT_SB		-150 dbw
IF C/N Ratio		16 db
IF Threshold		10 db
Margin		6 db

The carrier/noise ratio above of 16 db is based on a maximum slant range of 480 miles and an antenna gain of only +2 db at 5° above the horizon. It is possible that this gain can be raised to +5 db, in which case the C/N will increase to 19 db, thus raising the margin from 6 db to 9 db. The calculations are based on the expected maximum slant range while on the lunar surface. In the descent and ascent phases the range may be less, thus improving the circuit margin.

For emergency operation these conditions are assumed; one, that the available antenna gain drops to -2 db above isotropic,- two, that the rendezvous phase involves a range of 1,000 miles - three, that voice communication is all that is required - and four, that the receiver bandwidth is reduced to 10 kc. For this condition the above calculations are modified as follows:

Loss due to antenna +2 to -2	=	- 4 db
Loss due to increased range	=	- 6
Gain due to bandwidth reduction	=	+ 8
Net Loss		- 2 db

This reduces the C/N ratio received to 14 db with 4 db margin.

2. Multiplexing of Voice and Data on 250 Mc Link

This problem has been studied and has not been fully solved at this writing. One possible arrangement studied uses the voice band applied as direct FM on the carrier with a modulation index of 0.6, that is a peak deviation of 1.8 kc. The data channel may then be applied as a subcarrier above the 3 kc voice baseband. A peak deviation of 8 kc can then be used on the carrier for the subcarrier oscillator. The combination of the two peak deviations plus a maximum baseband occupancy of 20 kc allows the two channels to fit in the 60 kc RF band.

$$B_{IF} = 2\ (fd_1 + fd_2 + 20\ kc) = 2\ (1.8 + 8 + 20) = 59.6\ kc$$

A subcarrier bandpass of 5 to 20 kc with a subcarrier centered at 12.5 kc was calculated but found inadequate for the 7000 bit/second data rate. Since this data rate is needed only if the 700 b/s data must be played back at 10/1 speed and since the data may be recorded intermittently, the actual required data rate may drop to as low as 1000 bits/second. In the latter case very reasonable values of subcarrier bandwidth and modulation index can be achieved.

C. The LEM to Earth Link

1. TV Circuit

The TV study has shown that a minimum frame rate of 8 FPS is needed for real time TV transmission. A frame rate of 10 FPS with slight reduction in the number of lines is preferred due to the integral relation to standard TV frame rates.

For the purposes of the TV link design these constants are therefore assumed -

Frame rate	10 per second
Lines	327
Aspect ratio	3:4
Video baseband	500 kc

2. Frequency Band Selection

The 2 Gc frequency band is a logical choice for the TV link from Moon to Earth. A window exists in the broad frequency band of 1 to 10 Gc in which the propagation and galactic noise are optimum for best transmission. At 2 Gc frequency there are existing antennas designs (85 foot) whose gain peaks in this band and there are existing low noise maser receivers. The bandwidth required for the 500 kc video baseband transmission and the extreme range of about 250,000 miles, require the use of all these present state of the art devices. In this frequency band the general availability of proven devices make the choice of operating frequencies near the lower edge of the band desirable.

3. TV Communications System Design

In the block diagram description the basic equipments and the operation of the TV to Earth circuit are described. This section deals only with the basic system parameters that show the feasibility of operation.

a) The basic system parameters are listed below and discussed in the following paragraphs. The system listed here is for TV transmission only.

Frequency - About 2.3 Gc		
Transmitter power 20 watts		+ 13 dbw
Line and diplexer losses		- 2 db
LEM antenna gain (6 foot dish) (RH circular)		+ 30 db
Free space loss 250,000 S. miles		-212 db
Polarization loss (elipticity)		- 0.5 db
Receiving antenna 85 foot dish gain (RH circular)		+ 51.5 db
Receiving Circuit losses		- 0.5 db
Total - power received		-120.5 dbw
Receiver and antenna noise temperature		100°K
Lunar " "		250°K
Galactic		50°K
System noise temperature		400°K
Baseband		0.5 Mc
RF/IF bandwidth		2.5 Mc
Modulation - direct FM		
Modulation Index	1.5	
Received noise power KT_SB		-138.6 dbw
IF C/N ratio		18 db
Receiver FM threshold		10 db
Margin above threshold		8 db
RMS S/N ratio at baseband (min/max)		25 to 33 db
Peak-to-peak video to RMS noise (min/max)		34 to 42 db

b) Discussion of above choice of parameters

Frequency

A frequency channel near 2.3 Gc allows use of existing power tubes, is in a portion of the spectrum for low galactic noise, allows high antenna gains for small sizes on the Moon and for large dishes on the Earth. Low noise phase lock receivers are in existence at this frequency.

Transmitter Power

20 watts is feasible at this frequency and is required for adequate margin.

Line and diplexer losses

A loss of 2 db total for these items is reasonable, based on known characteristics.

LEM 6 foot antenna

Considering the need for a margin allowance above threshold, as well as weight and bulk limitations, this is an optimum size dish.

Receiving Antenna Gain

Existing 85 foot dishes have a peak gain at the assumed frequency. The increased gain that theory predicts at high frequencies is not achieved because of limitations imposed by the mechanical tolerance on smoothness of the parabolic reflector.

Noise Temperatures

The values used are conservative and represent somewhat worst case conditions.

Baseband

The value of 0.5 Mc is dictated by the general requirement of real time TV at 10 frames/second and 327 line resolution.

Modulation - TV

Direct FM modulation of the carrier is chosen over subcarrier modulation because of its higher efficiency. Doppler shift has been considered and will be sufficiently low that it may readily be removed by the phase locked receiver. Analog TV transmission has been chosen over digitalized systems due to its relative simplicity and smaller number of components thus leading to reliability, minimum weight, volume and power drain.

Modulation Index

A value of 1.5 was chosen after considering tradeoffs of bandwidth, noise and power. This value results in a minimum rms S/N of 25 db (34 db peak/peak video/rms noise) with a margin allowance of 8 db. That is, the system can degrade 8 db and still maintain this value.

Receiver FM Threshold

A value of 10 db carrier to noise ratio was assumed for the receiver FM threshold. This is a realizable value for a phase locked detector receiver. The system would still be operable with a conventional FM-limiter receiver having a 12 db threshold, but the margin would be reduced to 6 db.

Signal to noise in video channel

A value of 24 db for rms signal to rms noise was chosen as a minimum value at threshold. This gives a 33 db peak/peak video to rms noise ratio for the video channel. This is generally accepted as a good quality picture.

4. LEM to Earth Communications - Voice and Data Link

Multiplex considerations and voice data link. The TV link as proposed above requires no multiplexing. The voice and data link from the LEM to Earth does require transmission of two distinct, independent channels. The first of these is the voice channel, with 3 kc bandwidth; the second channel for data transmission must accommodate 700 bit/second data. Since the voice channel, in emergency mode, is operated without data transmission, and since the signal to noise requirements for voice are at least as great as those for the data channel, it seems logical to apply the voice as direct FM on the carrier and the 700 bit/second data on a subcarrier above the voice channel. A further consideration for placing the voice channel below the data and on direct FM is that in emergency voice mode no subcarrier source is required and the modulation index for the voice channel may be increased if needed.

These conditions are met by the use of a 3 kc low pass filter for the direct FM voice channel and a 6 kc subcarrier roofed by a 2 kc bandwidth channel filter above the voice channel. Characteristics of the voice/data channel are tabulated below.

The prime or normal voice/data circuit to Earth will use the exciter of the standby 20 watt TV transmitter. An exciter power of 1 watt is used in the following system calculation. However, the margin that this gives is more than required, and a lower powered exciter could be used.

VOICE-DATA-LEM to EARTH LINK

Frequency - About 2.4 Gc		
Transmitter power 1 watt		0 dbw
Line and diplexer losses		- 2 dbw
LEM antenna gain (6°) R.H.C.		+30
Free space loss		-212
Polarisation loss		- 0.5
Receiving antenna gain 85° R.H.C.		+51.5
Receiving circuit losses		- 0.5
Total - Received power		-133.5 dbw
Receiver and antenna noise temperature	100°K	
Moon temperature	250°K	
Galactic noise temperature	50°K	
System Noise temperature Ts =	400°K	
Noise power received KT_sB		-155.8 dbw
IF C/N ratio		22 db
Receiver threshold		10 db
Margin		12 db
S/N Voice channel at threshold		29 db
S/N Data channel at threshold		15 db
Voice channel baseband		3 Kc
Data channel baseband		2 Kc
Data channel subcarrier		6 Kc
Voice channel deviation on carrier		5.4 Kc
Data channel deviation on carrier		4.1 Kc
Data channel deviation on 6 Kc subcarrier		300 cps
RF bandwidth of receiver		48 Kc

For the emergency mode of operation, it is assumed that only a voice link to Earth is required. If the emergency involves loss of the 30 db antenna, the 20 watt amplifier is switched to the voice/data transmitter, the receiver bandwidth is reduced to 10 Kc and its modulation index to unity. The above table of performance characteristics then is modified as follows:

Increase in transmitter power	+ 13 db
Decrease in antenna gain to isotropic	- 30 db
Bandwidth reduction 48 Kc to 10 Kc	7 db
Net Loss	- 10 db

The C/N in the detailed analysis above was 22 db so that the C/N in the emergency mode is thus reduced to 12 db. Under some conditions a 10 db helix antenna gain may be available, which would then increase the C/N to 22 db as in the original system.

E. Signal Combining and Switching

In designing the communications system, the basic philosophy of switching design has been to avoid the necessity of operator intervention, such as operating a transmit-receive switch, as far as is possible. Some operator attention to the communication system is required when changing modes of operation; for example, when going from operation in space to operation on the lunar surface. Once set up, however, the two astronauts in the LEM, the man in Apollo, and the Earth station can communicate as if they were face to face in the same room, without switching, subject, of course, to the unavoidable path delay in the Earth-Moon circuit due to the finite propagation velocity of radio waves.

How this is done isillustrated in the overall block diagram, figure 6.

A separate 3 input audio baseband combiner is used with each of the three link transmitters (Earth UHF circuit, Apollo VHF, and Man VHF transmitters) and with the local intercom set. The Earth link transmitter accepts inputs from the manpack receivers, the Apollo receivers, and the local (LEM) intercom, but not from the Earth link receivers.

Likewise, the Apollo transmitters accept inputs from the local intercom, the Earth circuit receivers, and the manpack receivers. The manpack-LEM transmitter accepts inputs from the local intercom, the Apollo receivers, and the Earth circuit receivers. The local intercom accepts inputs from the LEM-manpack receivers, the Apollo receivers, and the Earth circuit receivers.

KGM-RC:dp

Fig. 1

COMMUNICATIONS FLOW DIAGRAM

DESCENT AND ASCENT PHASES

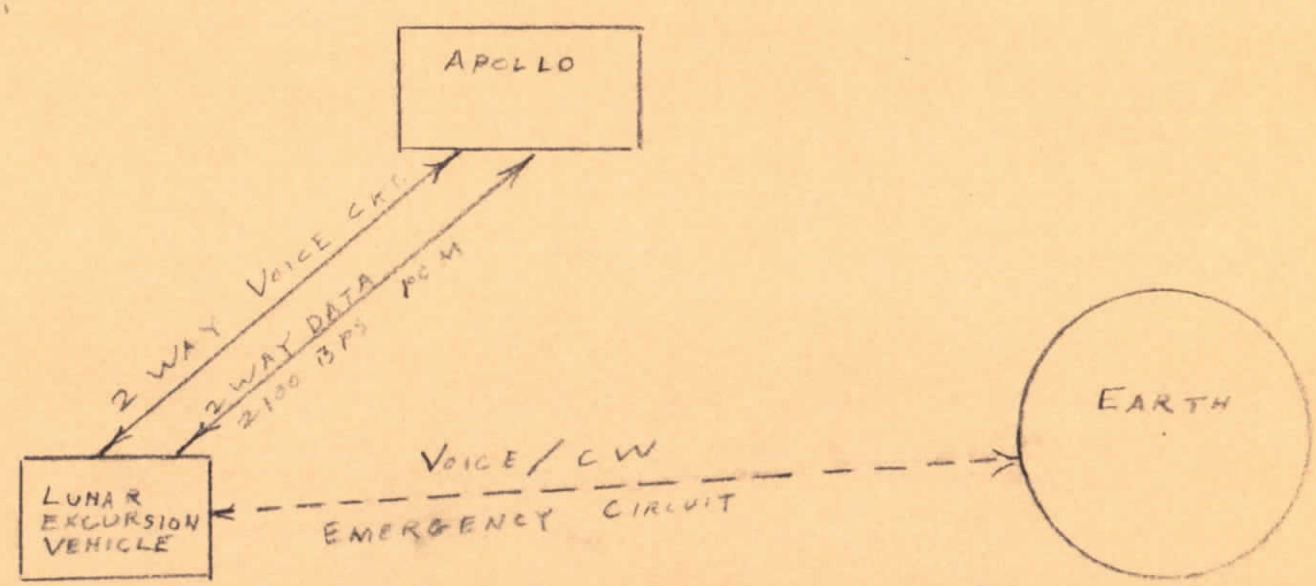

FIG 1

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Fig. 2

COMMUNICATIONS FLOW DIAGRAM

LUNAR SURFACE OPERATIONS

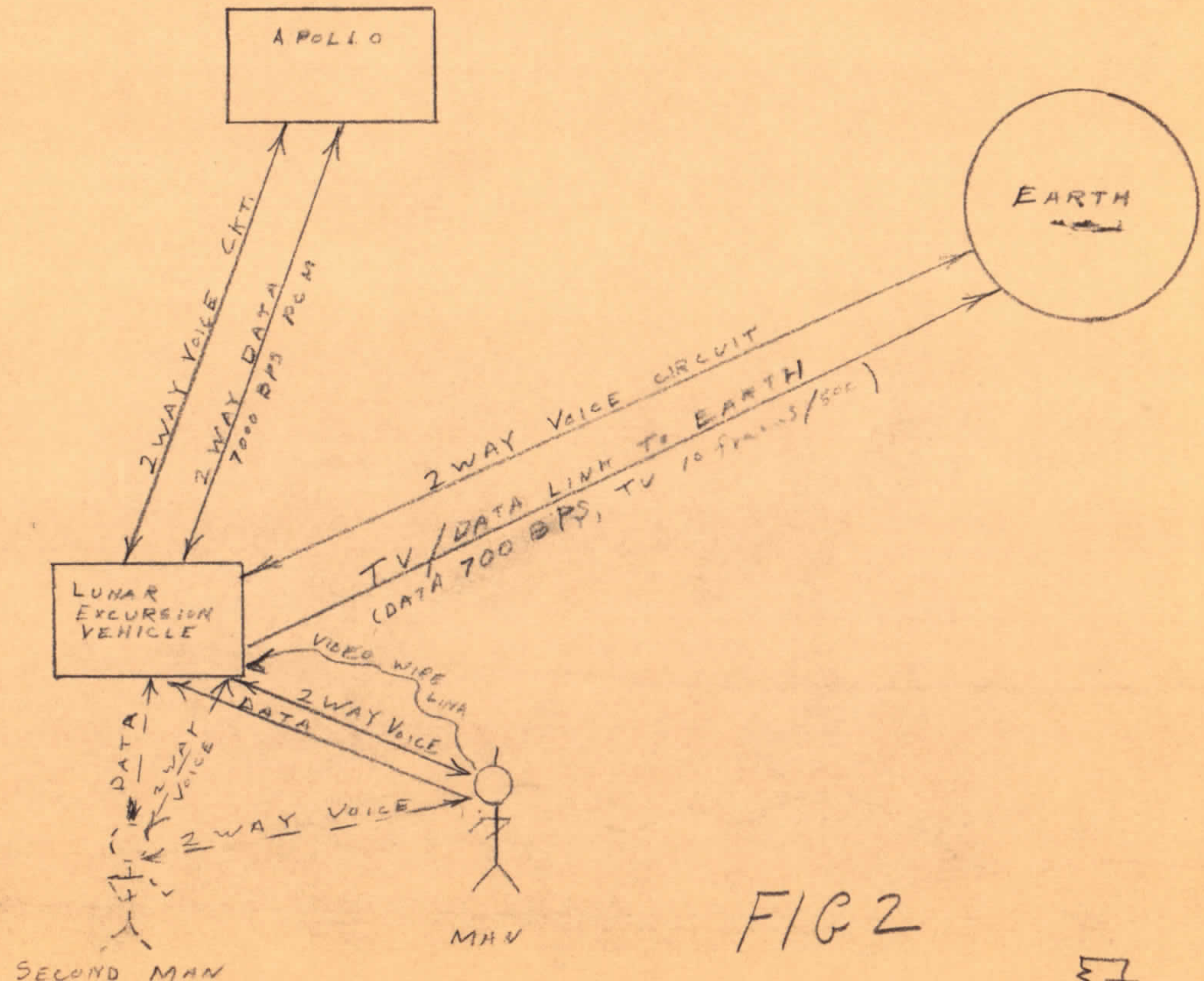

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FIG 2

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UHF BLOCK DIAGRAM

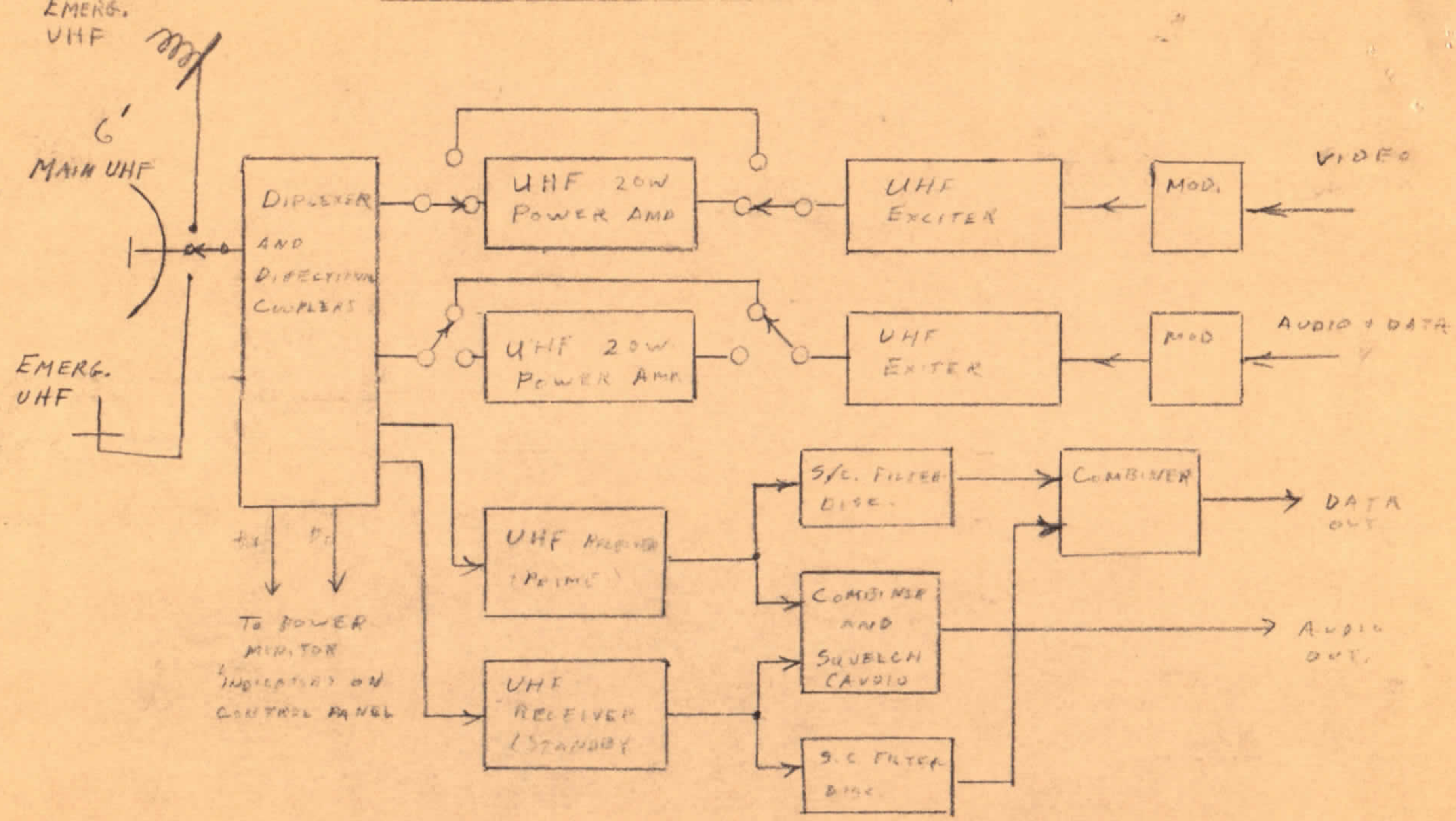

FIG 3

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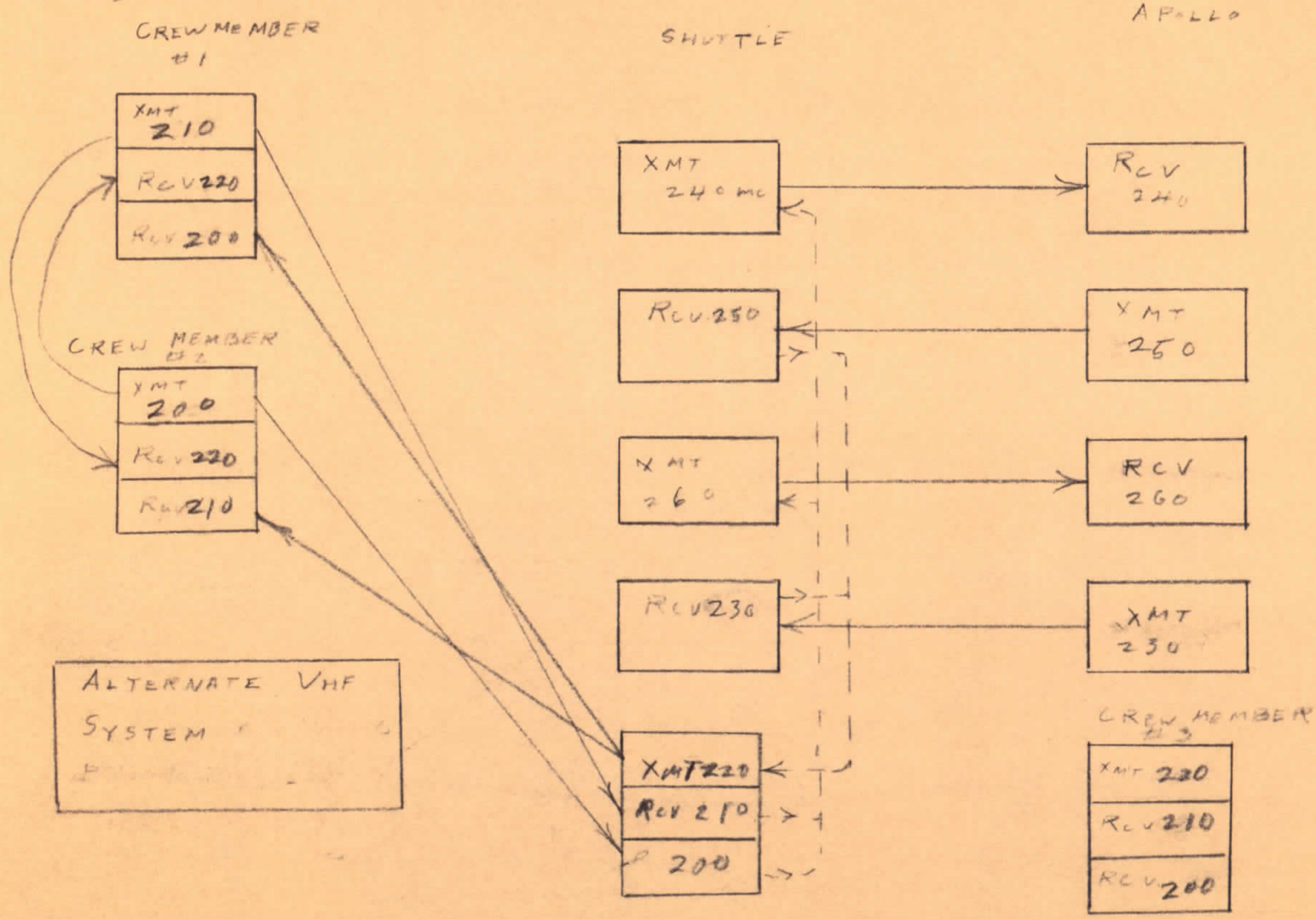

Fig. 4

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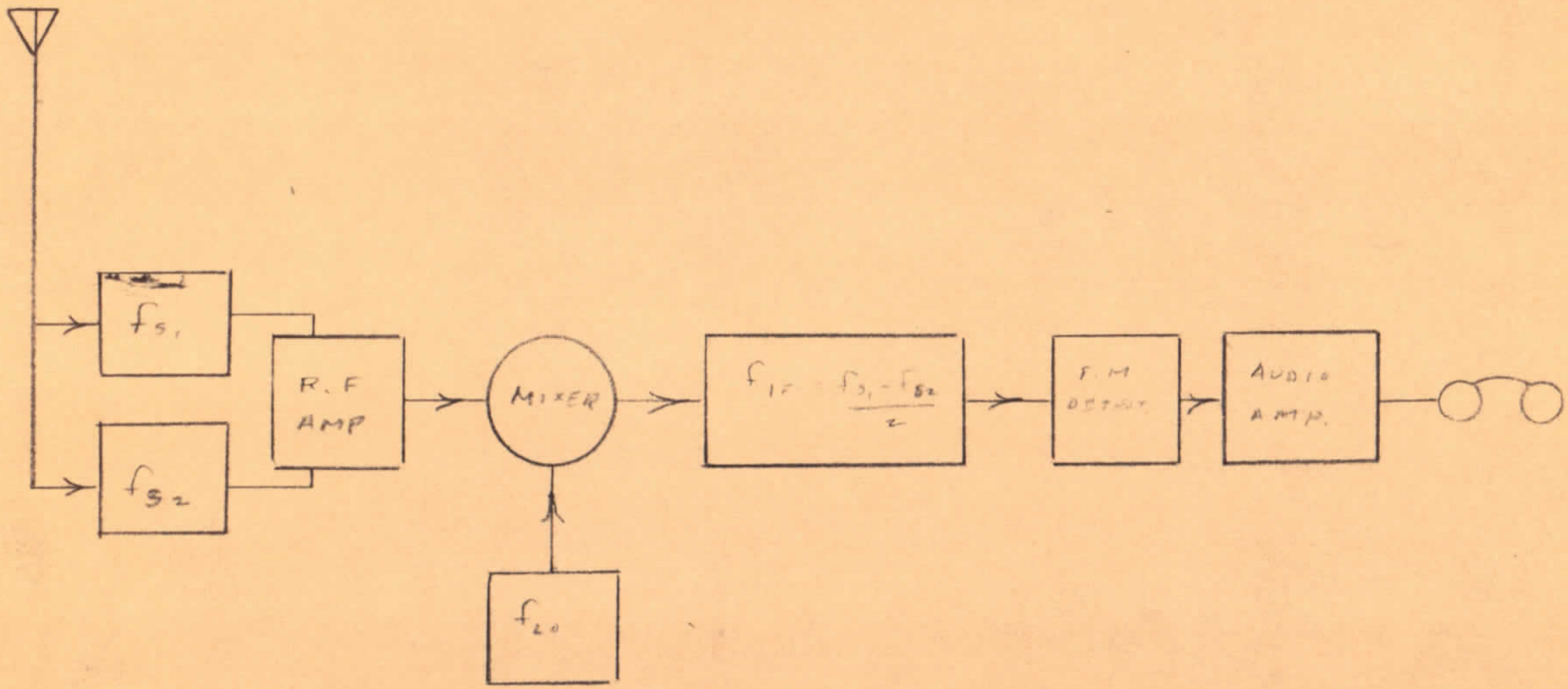

DUAL FREQUENCY RECEIVER
for
PACKSET USE
JUNE 2, 1962

FIG. 5