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APOLLO EXPERIENCE REPORT - S-BAND SYSTEM SIGNAL DESIGN AND ANALYSIS

Harold R. Rosenberg, Editor
Manned Spacecraft Center
Houston, Texas 77058

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16. Abstract

A description is given of the Apollo communications-system engineering-analysis effort that ensured the adequacy, performance, and interface compatibility of the unified S-band system elements (i.e., the command and service module, lunar module, and Manned Space Flight Network) for a successful lunar-landing mission. The evolution and conceptual design of the unified S-band system are briefly reviewed from a historical viewpoint. A comprehensive discussion of the unified S-band elements includes the salient design features of the system and serves as a basis for a better understanding of the design decisions and analyses. The significant design decisions concerning the Apollo communications-system signal design are discussed (i.e., selecting the preferred modulation technique, level of signal processing, and baseband structure and determining the most efficient operational aspects — e.g., ranging technique and acquisition procedure — for a communications-system signal design), providing an insight into the role of systems analysis in arriving at the current configuration of the Apollo communications system. Analyses are presented concerning performance estimation (mathematical-model development through real-time mission support) and system deficiencies, modifications, and improvements.

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CONTENTS

Section | Page

TABLES

FIGURES

Figure		Page

APOLLO EXPERIENCE REPORT

S-BAND SYSTEM SIGNAL DESIGN AND ANALYSIS

By Harold R. Rosenberg, Editor
Manned Spacecraft Center

SUMMARY

During the conceptual design, development, testing, and operation of the Apollo communications system, many significant signal-performance problems and system-interface problems were exposed. To solve a problem, it was often necessary to investigate the problem analytically to determine the source. Sometimes, because of the complexity of the problem, it was necessary to use experimental investigation and data analysis. The analyses described in this report began with efforts by NASA to define a signal design compatible with the unified S-band system and the communications requirements of the Apollo lunar-landing mission and continued through the analysis associated with color television transmission from the lunar surface.

The first section of this report is a brief history of the evolution of the Manned Space Flight Network and the concept of the Apollo unified S-band system. The second section contains a comprehensive discussion of the Apollo communications system and its physical and operational characteristics. Important system design decisions that required supporting analysis are discussed in the third section. In these discussions, the basic issue is outlined and the effect of the decision on the final system configuration is shown. In the fourth section, a discussion is provided on the importance of configuration control in overcoming system-interface problems that occur during the design, development, and manufacturing stages. This configuration control assures satisfactory system performance during the operational phase of the mission.

System analyses concerning the performance of the Apollo unified S-band system are described in the fifth section. These analyses have been divided into two parts. The first part is a description of the development of the tools by which the Apollo communications-system performance is estimated. The development of the unified S-band system mathematical model is discussed first, and a description of the origin and use of the computer-aided analysis system with regard to real-time Apollo mission support follows.

The analyses in the second part of the fifth section concern areas of system performance deficiencies, equipment modifications, and improvements that resulted. These analyses have a common objective, which is to define the problem, the source of the problem, and the best solution to improve the Apollo communications-system performance.

The design criteria for selecting the S-band carrier phase-modulation and frequency-modulation indices and the transponder turnaround ratios are discussed first, followed by a discussion of the S-band receiver noise temperature and its effect on system performance. The subsequent discussion concerns the frequency-modulation mode-performance deficiency that resulted in a change in the Manned Space Flight Network frequency-modulation demodulators and a concentrated effort to reduce command and service module Block II S-band system circuit loss. The spacecraft S-band low-gain antennas are discussed with respect to their impact on radio-frequency coverage and system performance. Finally, discussions of backup-voice interference with the telemetry channel, the signal-design analysis of the extravehicular communications system and the telemetry and voice subcarrier interference with lunar module color television transmissions are presented.

INTRODUCTION

When the Apollo Program was initiated, it was stipulated that as much as possible of the existing Project Mercury and Gemini Program ground network and spacecraft systems were to be used for the near-earth phase. In addition to these systems, it was decided that a transponder should be included in the command and service module (CSM) to perform the ranging operation at lunar distances. The transponder was also to be used for the transmission of voice and telemetry at lunar distances. Because the transponder design chosen was compatible with the Deep Space Instrumentation Facility (DSIF) established by the Jet Propulsion Laboratory (JPL), the JPL technique (pseudo-random code ranging) was chosen by NASA to perform ranging. Thus, for the deep-space phase of communications for the lunar mission, the new spacecraft transponder would perform the communications and tracking functions in conjunction with three deep-space stations resembling the JPL design. For the near-earth phase, however, the very-high-frequency (vhf), ultrahigh-frequency (uhf), and C-band Gemini-type equipment was to be used for the communications and tracking functions. However, a study conducted by JPL personnel indicated that, "under worst conditions," the deep-space stations might not acquire the spacecraft at altitudes lower than 10 000 nautical miles. In addition, computations made by the CSM contractor and the NASA Manned Spacecraft Center (MSC) indicated that the vhf- and uhf-systems range capability would be less than 10 000 nautical miles.

During the early phases of the spacecraft-subsystems design performed by the contractor, it was realized that a problem would arise with the spacecraft weight because the near-earth phases of the mission required several different spacecraft transmitters and receivers as well as backups. This observation, coupled with the limited range capability of the vhf system, indicated that another communications and tracking system should be used during the various near-earth phases.

As a result of NASA intercenter activity to resolve these undesirable conditions, a meeting was held at the NASA Office of Tracking and Data Acquisition Systems (OTDA) in Washington, D.C., in December 1962. At this meeting, OTDA personnel presented plans to representatives of various NASA centers (including the NASA Goddard Space Flight Center (GSFC) and MSC) for a ground network using a unified S-band (USB) carrier system. The ground-based portion of the system was to consist of the three previously mentioned stations, each having an 85-foot Cassegrain-feed antenna for deep-space communications and tracking (separate from those of the DSIF), and several stations with 30-foot Cassegrain-feed antennas for communications and tracking during the near-earth phases of the Apollo lunar missions. This proposed ground network not only would increase the range capabilities for near-earth communications and tracking but also would allow transmission from the spacecraft to be performed by one transmitter during both near-earth and deep-space phases, thus eliminating the vhf, C-band, and uhf systems and backups and consequently reducing the spacecraft weight.

The primary concept underlying the Apollo USB telecommunications system was originally that all communications and data transfer between spacecraft and ground should be made by using one common set of equipment and one radio-frequency (rf) carrier for transmission. For various technical reasons, this concept was not fully implemented in the Apollo system.

Because of the requirement that the spacecraft transmit a stable carrier spectral line (phase coherent with the up-link carrier) to enable two-way Doppler tracking, ranging, and ground-antenna pointing, narrow-deviation phase modulation (PM) was implemented for most of the spacecraft transmission. In subsequent signal designs, the information functions that required a large modulated bandwidth were modulated directly onto the carrier, while other less wide functions were first modulated onto subcarriers. Because the range code and television signals transmitted by the Apollo spacecraft both required large modulated bandwidths and, in some instances, would be transmitted simultaneously, it was necessary to place them on separate carriers using PM for pseudorandom-noise (PRN) ranging and frequency modulation (FM) for the television. Aside from this exception, the basic concept of one carrier and one set of equipment was closely approached in the Apollo communications system. Duplicate standby equipment, both in the spacecraft and on the ground, was required because of failure and redundancy considerations.

SYSTEM DESCRIPTION

By Benjamin H. Hood and Robert W. Moorehead

Successful execution of an Apollo lunar mission (fig. 1) requires continuous tracking information and a capability for analog voice transmission and digital data transmission between spacecraft and earth when line-of-sight viewing conditions exist. The Apollo USB telecommunications system, which consists of special equipment on board the CSM and the lunar module (LM) and in the Manned Space Flight Network (MSFN), provides a variety of communications and tracking functions that fulfill these requirements. In addition, this system has a capability for television transmission from the lunar surface.

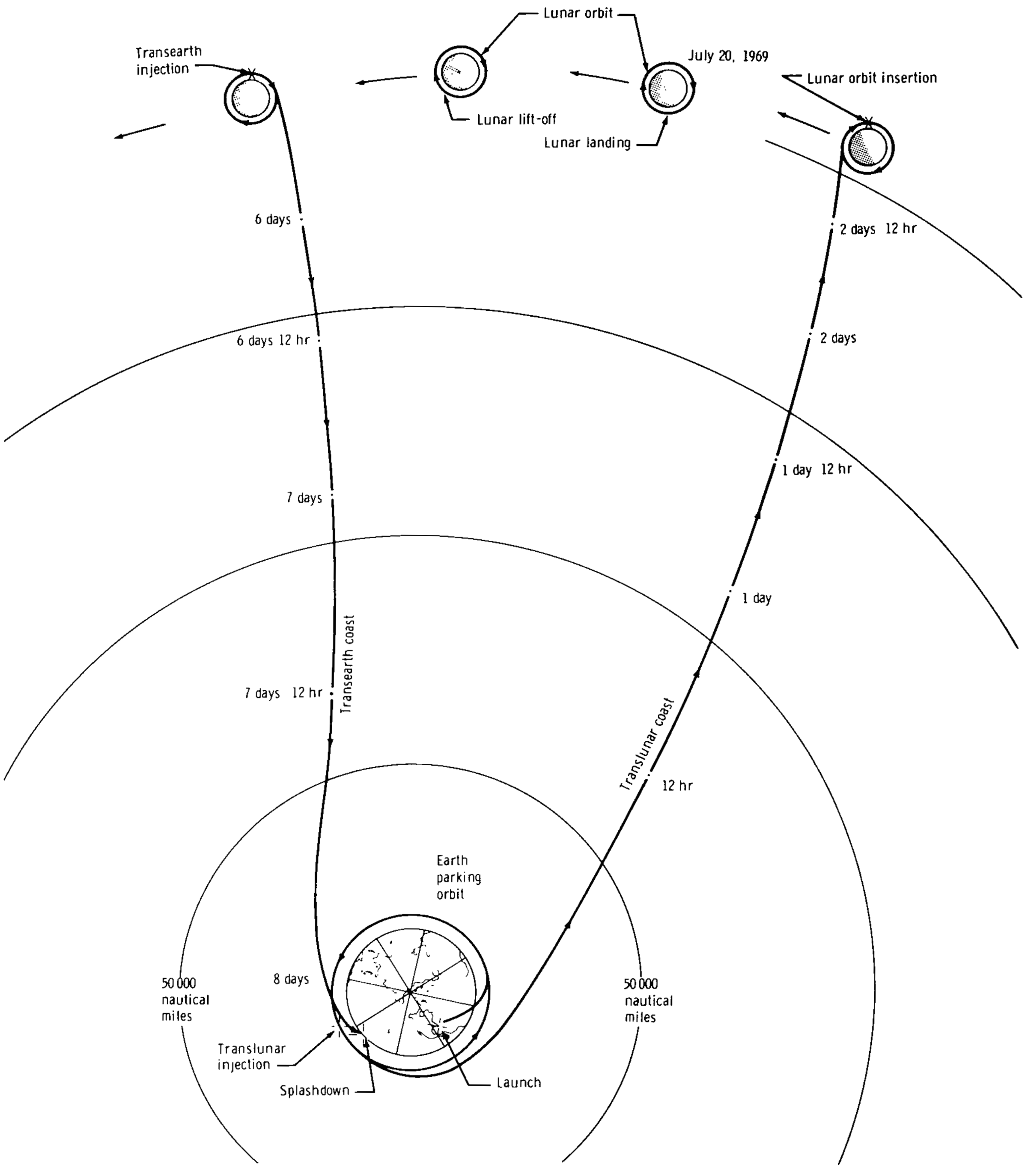


Figure 1. - Graphic profile of the Apollo 11 manned lunar mission.

MODULATION TECHNIQUES AND RADIO-FREQUENCY SPECTRA

The USB system has modulation spectra varying from narrowband voice and telemetry to wideband television and ranging data. The narrowband information channels are modulated onto subcarriers before modulation onto the S-band carrier, while the wideband information is modulated directly onto the carrier.

The full up-link signal consists of a transmitted S-band carrier, phase modulated by two subcarriers, and of a PRN range code. Narrowband PM is used to ensure that a phase-stable carrier component is transmitted to the spacecraft. The two subcarriers, 30 and 70 kilohertz, are frequency modulated by voice and up data, respectively. Up-data transmission of the digital commands is accomplished by using phase-shift keying (PSK) modulation. The composite data waveform is a 1-kilohertz coherent reference signal summed with a 2-kilohertz data signal, which is phase shift keyed by a 1-kilobit binary code. The binary command signal is a 200-bit information signal, subbit encoded 5 for 1. This composite PSK signal frequency modulates the 70-kilohertz subcarrier with a peak deviation of 5 kilohertz. Thus, the total up-data modulation system is pulse code modulation (PCM)/PSK/FM/PM. Similarly, the up-link voice signal is frequency modulated, with a peak deviation of 7.5 kilohertz, onto the 30-kilohertz subcarrier, which is phase modulated onto the S-band carrier. If the 30-kilohertz up-voice subcarrier is lost, an up-voice backup transmission capability is implemented on the 70-kilohertz up-data subcarrier.

The PRN range code was taken from the ranging system developed at the JPL (refs. 1 and 2). The code, generated from a 496-kilohertz clock signal, has a bit rate of 992 kbps for both spacecraft. The total length is 5.4 megabits, as determined from a combination of five shorter codes. The code has an unambiguous range of approximately 540 000 miles, with a theoretical system accuracy of ±15 meters. The signal also has a symmetrical spectral distribution about the carrier, with nulls appearing at the inverse of the bit period (approximately 1 megahertz).

Certain components of the PRN range code interfere with the information on the 30- and 70-kilohertz subcarriers and limit the maximum achievable signal-to-noise ratio (SNR) in these channels. However, it may be shown that the threshold performance of the voice and up data is determined by thermal noise.

The up-link modulation techniques are identical for both the CSM and the LM systems. The two up-link systems are distinguishable only by the difference in carrier frequencies. The up-link range code and subcarrier spectral distributions are shown in figure 2.

The down-link services consist of voice, telemetry, range code, television, and emergency key. These services are transmitted either on the coherent PM carrier derived from the up-link carrier or on a noncoherent FM carrier generated from an auxiliary oscillator in the spacecraft. The two down-link subcarrier frequencies, 1.024 and 1.25 megahertz, are near the first null of the turnaround range-code envelope to minimize ranging interference. When the range code is present, the up-link baseband spectrum is turned around in the spacecraft transponder and phase modulated onto the down-link coherent carrier. The ranging modes are degraded by the turnaround of up subcarriers and channel noise, which modulate the down link and reduce the down-link

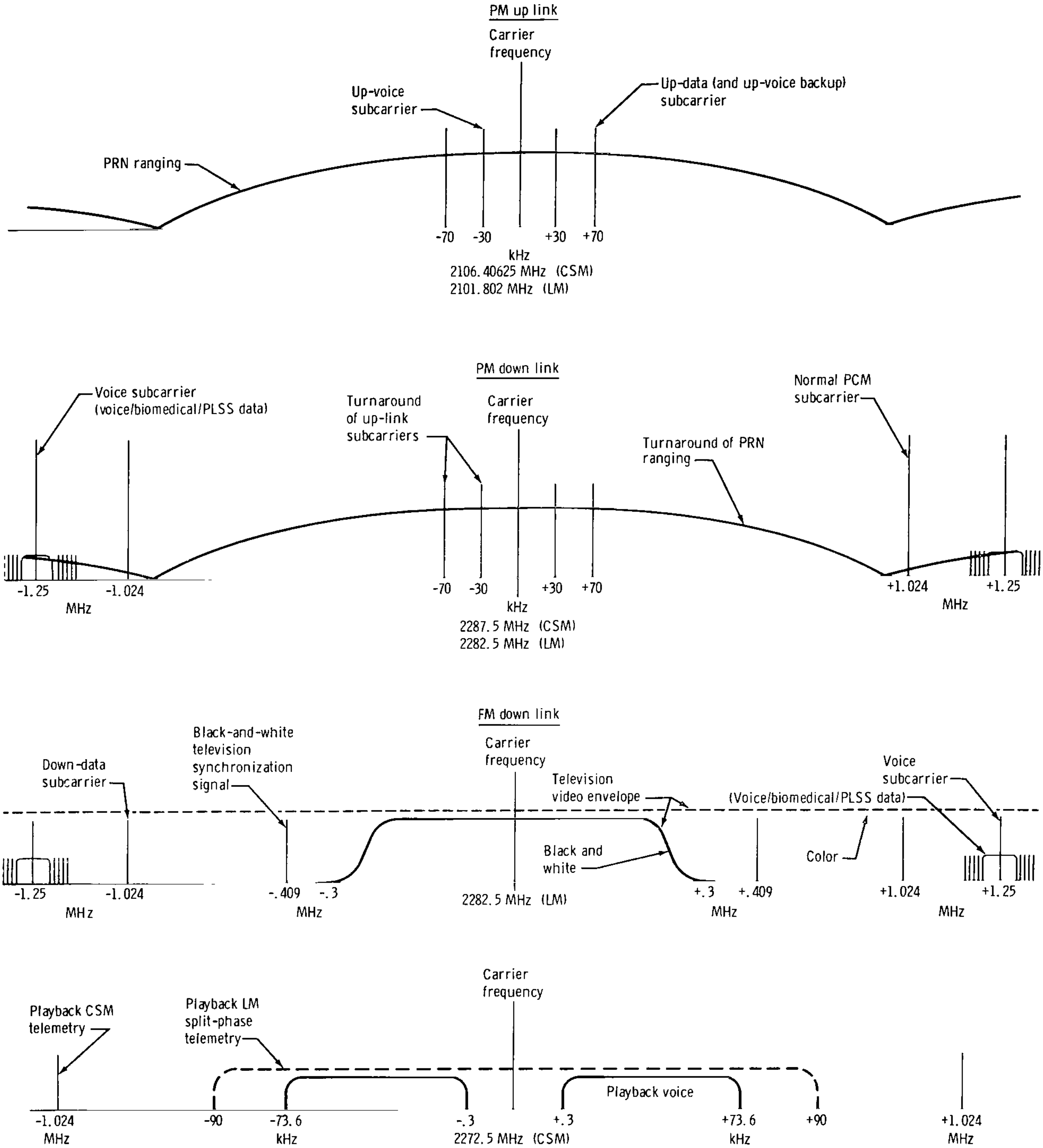


Figure 2. - Up-link and down-link S-band spectra.

carrier-to-noise ratio. In addition, the up subcarriers form undesirable intermodulation products with the down-link baseband components. These effects have been analyzed and are mathematically described in the Apollo USB system mathematical model (ref. 3).

The normal down-link voice signal, which has a frequency response of approximately 300 to 3000 hertz, is frequency modulated onto the 1.25-megahertz subcarrier. This voice signal is sometimes frequency multiplexed with biomedical information before the subcarrier modulation process, as described later. Biomedical data are transmitted by PCM telemetry when the astronauts are in the command module (CM). However, when an astronaut is in the LM or on the lunar surface, low-frequency subcarriers carry the data. While the astronauts are in the LM, a 14.5-kilohertz subcarrier, frequency modulated with electrocardiogram (EKG) data, provides the only biomedical data. However, when the astronauts are engaged in exploration and experimentation on the lunar surface, the biomedical information is transmitted by two subcarriers at 3.9 and 5.4 kilohertz, frequency modulated with EKG data; and a second pair of subcarriers at 7.35 and 10.5 kilohertz is frequency modulated with portable-life-support-system (PLSS) status data from two astronauts. The voice and data subcarriers are summed and amplitude modulated onto a vhf carrier and relayed from the astronauts' backpacks to the LM. (The modifications and improvements necessary to accomplish the dual extravehicular activity (EVA) mode are discussed in the section entitled "Signal Design and Performance Analyses for EVCS." The modulation scheme for dual EVA is depicted in fig. 3.) The vhf links are demodulated and the information is remodulated onto S-band. Thus, the composite signal modulating the LM 1.25-megahertz subcarrier during lunar exploration includes baseband voice and four biomedical subcarriers. The 1.25-megahertz subcarrier can then be frequency or phase modulated onto the S-band carrier, depending on the modulation mode selected. Continuous biomedical data are available from both astronauts simultaneously, but voice transmission is time shared. The frequency spectra for the voice and biomedical subcarriers are shown in figure 2 along with the PM and FM carrier frequency spectra.

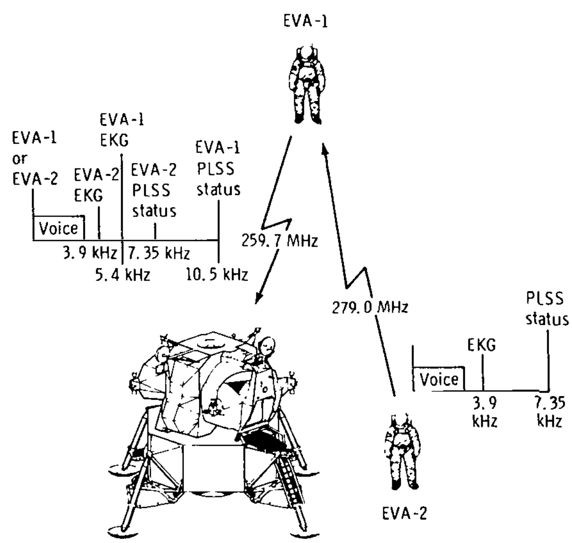


Figure 3. - Dual mode, EVCS/LM link.

Voice capability is required if a failure occurs in either the spacecraft high-gain antenna or the power amplifier. To meet this mission requirement, a backup-voice mode was provided in which the voice signal is heavily clipped and is phase modulated directly onto the carrier. The modulation technique requires approximately 13 decibels less power than the normal voice channel, which is frequency modulated onto the 1.25-megahertz subcarrier. The voice signal in the backup-voice mode is heavily clipped (24 decibels for both the CSM and the LM) to keep the average voice-power level high.

The down-link real-time telemetry systems for the CSM and LM have a nonreturn-to-zero format at bit rates of 1.6 or 51.2 kbps. The PCM telemetry is biphase modulated onto the 1.024-megahertz subcarrier, which is phase or frequency modulated onto the carrier.

An emergency key capability has been included in case both the spacecraft high-gain antenna and the power amplifier fail. The astronauts can transmit Morse code by amplitude modulating (on/off keying) a 512-kilohertz subcarrier that is phase modulated onto the S-band carrier.

Television from the LM is frequency modulated directly onto the S-band carrier. Because of spacecraft power limitations, the video picture does not have the same quality as commercial television. The Apollo black-and-white television system has two possible configurations: mode 1 has a fast-scan low-resolution format sufficient for transmitting images of moving objects; mode 2 has a slow-scan high-resolution format for transmitting detailed pictures for scientific data collection and evaluation. The fast-scan mode, although never developed or used, was a 10-frame/sec, 320-line/frame format as compared to the 0.625-frame/sec, 1280-line/frame format (or 640-line/frame format because only every other line was used) in the slow-scan mode. The synchronization signal consists of horizontal and serrated vertical synchronization bursts at a frequency of 409 kilohertz.

A color television camera was developed and successfully used from the CSM on the Apollo 11 lunar mission. The video bandwidth of the color signal is slightly greater than 2 megahertz, while the bandwidth for the black-and-white television signal is 500 kilohertz. The color television system is operated through the existing Apollo equipment in place of the black-and-white television. Some problems were incurred because the telemetry and voice subcarriers were in the color television video bandwidth. A discussion of the resolution of these problems is presented in the section entitled "Color Television Interference and SNR Requirements." Other CSM baseband FM transmission modes include the 1:1 and 32:1 playback of recorded voice. The CSM also has a 32:1 playback of recorded LM 1.6-kbps split-phase telemetry; that is, during the period after the LM has separated from the CSM and both spacecraft are behind the moon, LM telemetry is transmitted by vhf to the CSM, where the telemetry is recorded and then dumped by the CSM at baseband over the S-band FM link to the MSFN station when line of sight has been restored.

COMMAND AND SERVICE MODULE CONFIGURATION

The equipment of the CSM USB system is shown in figure 4. This equipment includes four basic components: (1) the USB equipment, (2) the premodulation processor, (3) the power-amplifier assembly, and (4) the antenna system. Perhaps the most significant of these units is the USB equipment. This unit consists of redundant PM receivers and exciters and a single FM exciter.

The receivers, which are of the dual-conversion superheterodyne type, exhibit a noise figure of less than 11 decibels and operate at a center frequency of 2106.4 megahertz. A narrowband phase-lock tracking loop in the operating receiver reconstructs the carrier component of the PM signal transmitted from the earth and supplies this

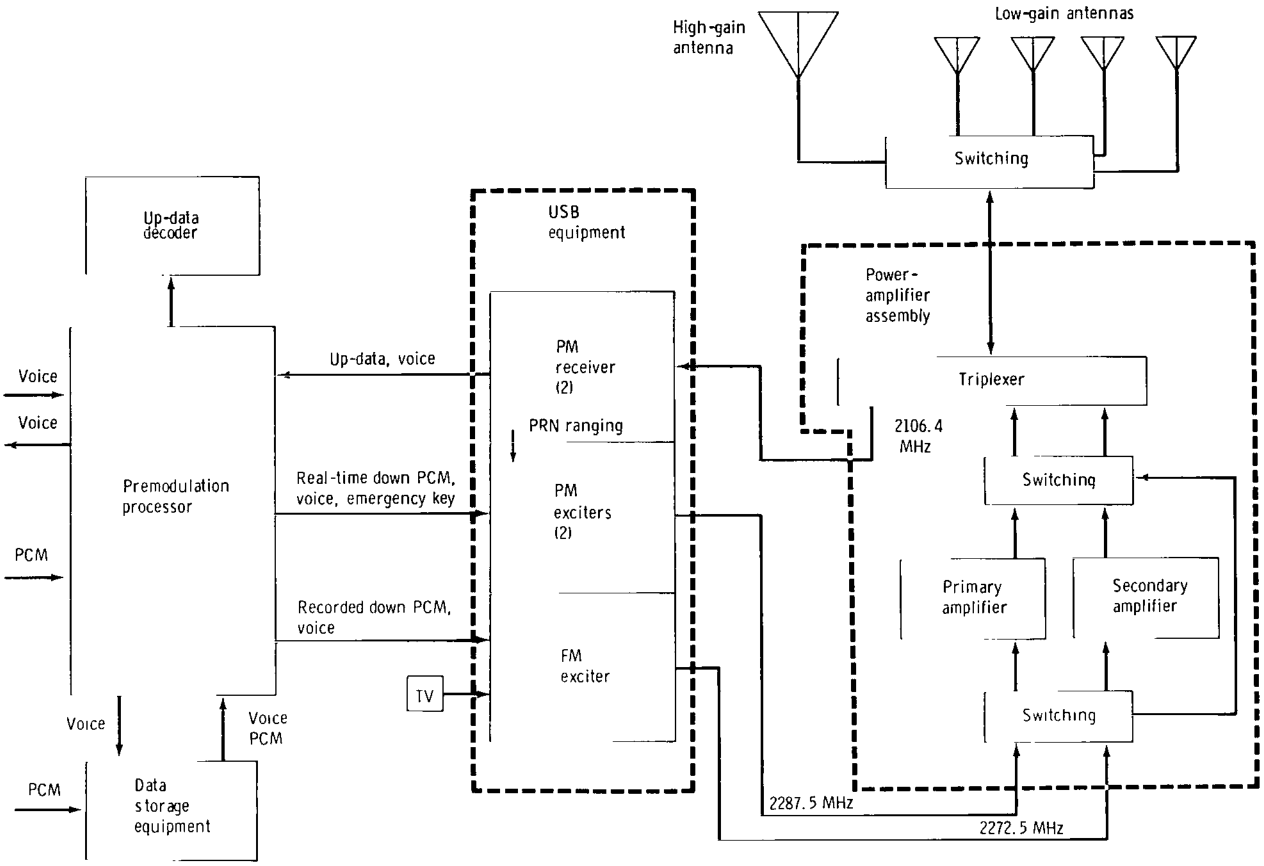


Figure 4. - Command and service module USB system.

signal as a reference for the conversion process and to the wideband phase detector, where the transmitted PRN range code and up-data and up-voice subcarriers are recovered. The up-data and up-voice subcarriers are routed to the premodulation processor for detection, whereas the range code is returned to the operating PM exciter for combination with the real-time down-data channels and is retransmitted to the MSFN. In addition, the reconstructed up-link carrier component is multiplied by the ratio of 240: 221 and then supplied to the PM exciter, thereby providing a down-link carrier of 2287.5 megahertz coherently related to the up-link carrier. Recorded spacecraft data and television signals are transmitted to the MSFN by the FM link, which operates at 2272.5 megahertz.

After detection by the premodulation processor, up voice is routed to the crew, and up data are channeled to the command decoder for decoding before command execution. Both the voice and the up-data signals are detected by using conventional FM discriminators. Additional functions of the premodulation processor include processing the down-data channels, combining them for use by the PM and FM exciters, and interfacing with the vhf equipment for communications between the CSM and LM.

The power-amplifier assembly consists of two 20-watt traveling-wave-tube amplifiers, a multiplexer, and the appropriate switching arrangements. The switches are designed so that any of the USB equipment exciters may be connected to either amplifier, and either of the amplifiers may be connected to any of the five antennas that comprise the antenna system. During normal operation, only the 2287.5-megahertz PM signal is transmitted to earth; thus, only one amplifier is used. However, for those periods when data dump or television (or both) is required, the second amplifier is used in conjunction with the 2272.5-megahertz FM link. It should be noted that the actual power delivered by the power amplifier is reduced because of the multiplexer and switching circuitry. In particular, the assembly output power is 11.2 watts for PM transmission and 12.6 watts for FM transmission. If both amplifiers fail, a 0.125-watt signal, derived from the PM exciter, is provided at the assembly output terminals. Four low-gain antennas (cavity-backed helices) spaced at 90° intervals around the spacecraft periphery provide near-omnidirectional coverage. Only one of the four elements is excited at any one time, providing a resultant gain and coverage of ≥0 decibels over 80 percent of the sphere. Element selection and switching is accomplished manually by the crew.

The high-gain antenna consists of an 11-inch-diagonal wide-beam horn flanked by an array of four 31-inch-diameter parabolic reflectors, as shown in figure 5. Transmitting beam widths of 40.0°, 11.3°, and 4.4° are selectable by manual switch. Reception and transmission gains corresponding to these beam widths are listed in table I. The antenna tracks by using electronic conical scan where the angle-tracking information is encoded as amplitude modulation (AM) on the phase-modulated signal received from earth. This error information is extracted within the USB equipment by a narrowband coherent amplitude detector and routed back to the antenna system, thereby providing angular displacement control.

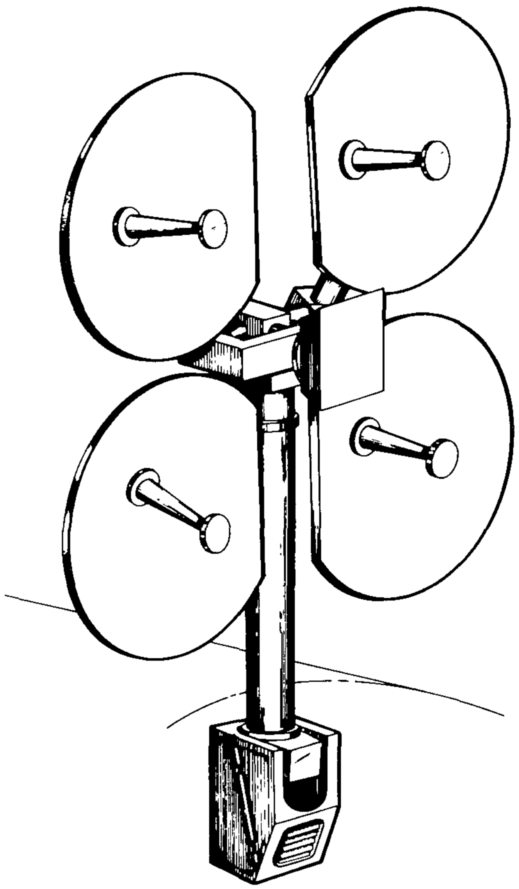


Figure 5. - Command and service module antenna configuration.

TABLE I. - CSM HIGH-GAIN ANTENNA CHARACTERISTICS

Receive		Transmit	
3-dB beam width, deg	Gain, dB	3-dB beam width, deg	Gain, dB
40.0	3.1	40.0	8.0
4.5	22.5	11.3	18.0
4.5	23.0	4.4	25.7

The omnidirectional antenna system is used during earth-orbital operations and during those periods of translunar and transearth coast when spacecraft attitude is constrained so that the spacecraft structure shadows the high-gain antenna from the earth line of sight. In addition, the omnidirectional antenna system is used if the high-gain antenna fails.

LUNAR MODULE CONFIGURATION

For the most part, the equipment that comprises the LM USB system (fig. 6) is functionally equivalent to that of the CSM. Thus, the following discussion is limited to those areas in which the two systems differ significantly. The LM S-band transceiver is capable of transmitting either PM or FM signals. However, unlike the CSM system, the LM system cannot transmit both signals simultaneously. Generally, the FM transmission mode is selected only during those periods when activity on the lunar surface

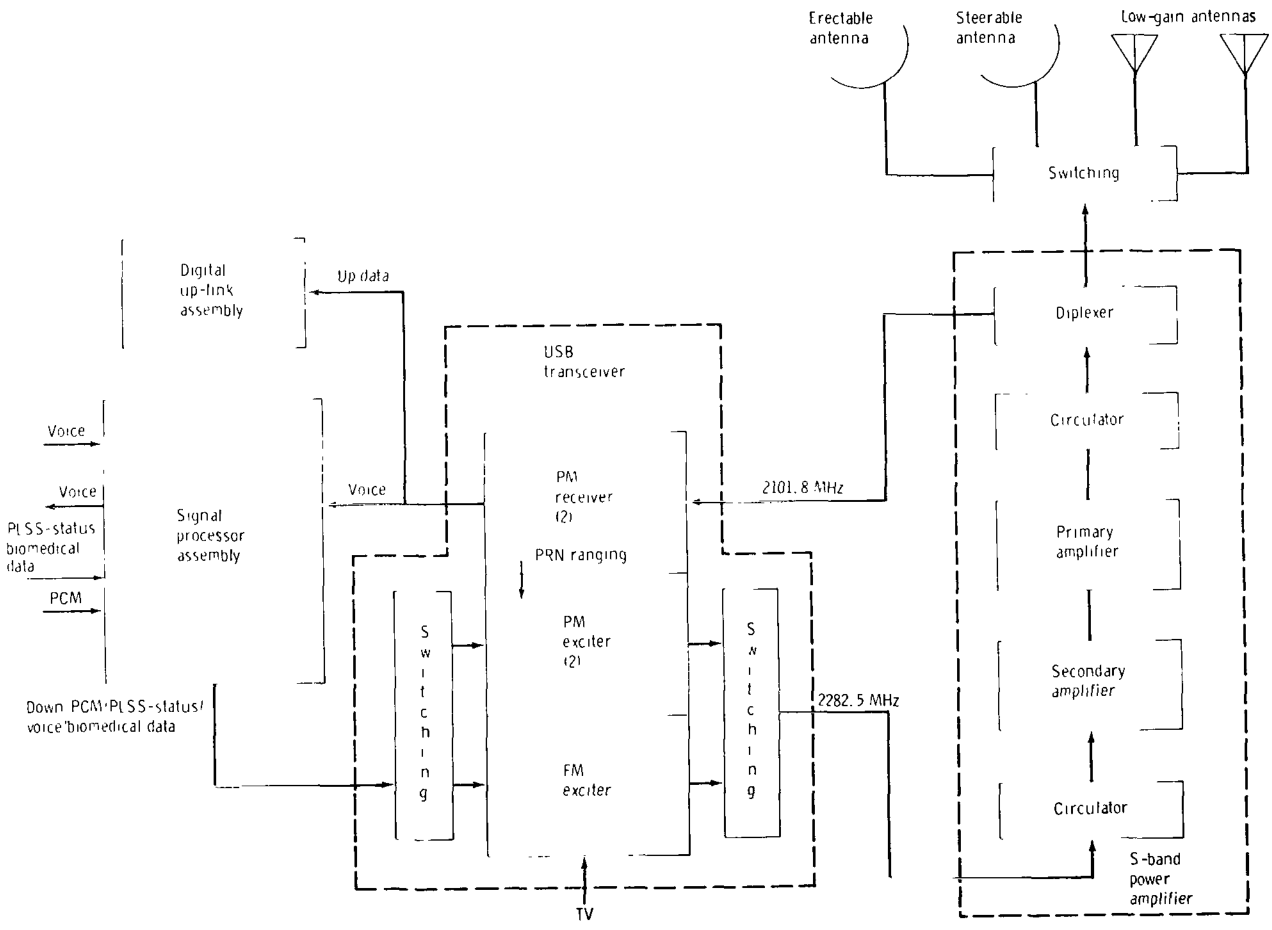


Figure 6. - Lunar module USB system.

requires television. The LM has no capability for dumping recorded data. All S-band transmissions are at 2282.5 megahertz. Rather than using traveling wave tubes for S-band power amplification as does the CSM, the LM uses amplitrons, which provide 20 watts of rf power. In the case of power-amplifier failure or the need to conserve prime power, some modes can be transmitted by routing the 0.75-watt output of the S-band transceiver to the high-gain antenna.

The LM is equipped with four S-band antenna elements. One of these, the steerable antenna, is a high-gain antenna used to maintain line-of-sight communications between the LM and the earth from time of spacecraft occupancy through lunar orbit and descent until the erectable antenna is deployed on the lunar surface. The steerable antenna is used again during lunar ascent and rendezvous. This antenna, with a receive gain of 16.5 decibels and transmit gain of 20.5 decibels, consists of a single paraboloid 26 inches in diameter. Earth tracking is accomplished by an electronic conical-scan scheme similar to the one used in the CSM high-gain antenna.

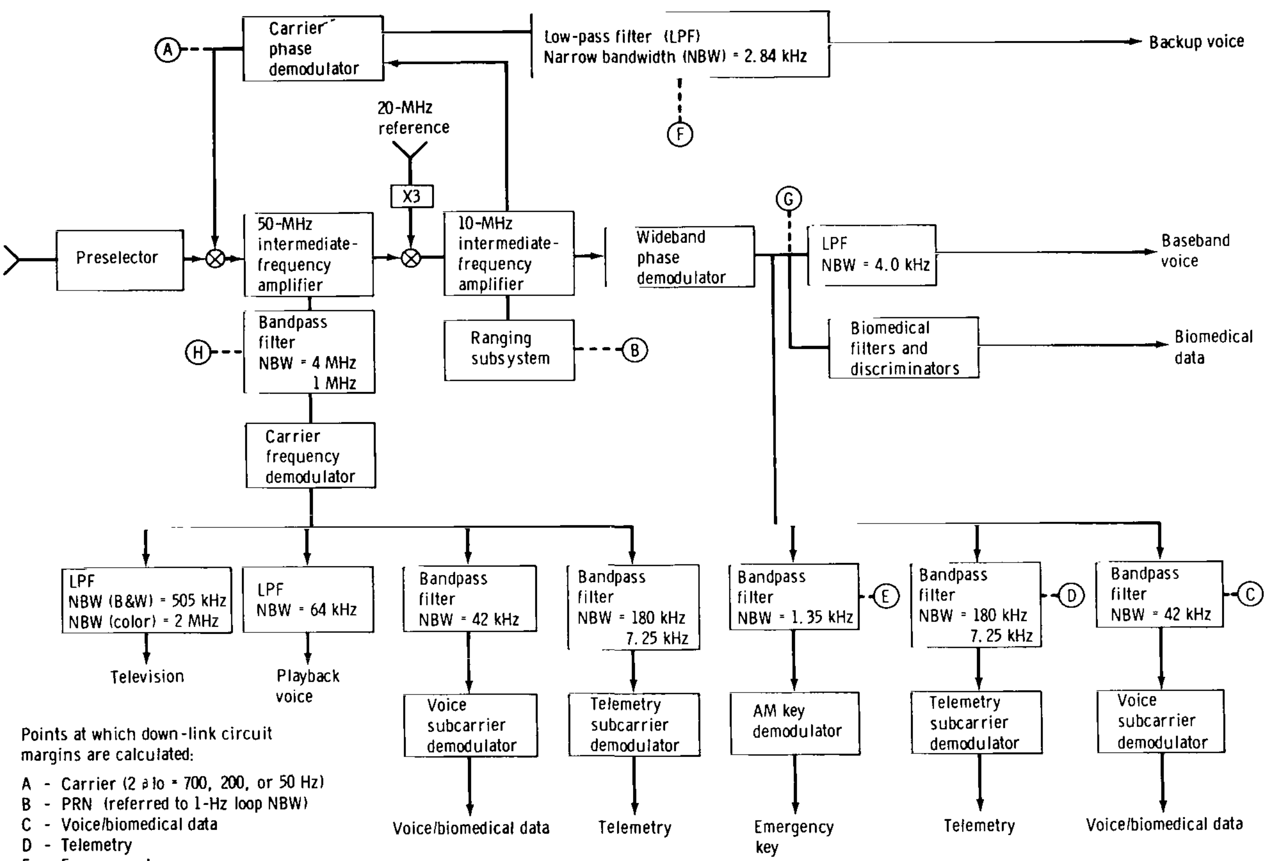
After deployment on the lunar surface, the erectable antenna is used for communications to earth. This unit is a 10-foot-diameter manually erected parabolic antenna with a receive gain of 33.2 decibels and a transmit gain of 34 decibels. If the erectable antenna is not deployed for some reason, the steerable antenna described previously will be used for moon-earth communications.

Near-omnidirectional coverage with -3-decibel gain is provided by two helices spaced 180° apart on the spacecraft surface. Element selection is accomplished manually by the crew.

GROUND-STATION DEMODULATION SYSTEM

The Apollo spacecraft provides communications and ranging data to the MSFN, which consists of specially equipped ships and aircraft, 11 ground stations (Merritt Island Launch Area; Bermuda; Grand Bahama Island; Antigua; Ascension Island; Canary Island; Guam Island; Carnarvon, Australia; Hawaii; Guaymas, Mexico; and Corpus Christi, Texas) with 30-foot-diameter antennas, and three stations (Goldstone, California; Madrid, Spain; and Canberra, Australia) with 85-foot-diameter antennas. The 210-foot-diameter antennas available at Goldstone, California, and Parkes, Australia, are also used to support LM powered descent and color television transmission from the moon. The 85-foot antennas provide communications and tracking capabilities at lunar distances, while the 30-foot antennas are used during the earth-orbital and preinjection phases of the missions and for carrier Doppler extraction during lunar descent and ascent to supplement data derived from the 85-foot-antenna sites. To enhance the USB system sensitivity, cooled parametric amplifiers with noise temperatures of 33° K are used in the front end of the receiving systems for the 85-foot-antenna stations and for several of the 30-foot-antenna stations. Uncooled parametric amplifiers with 142° K noise temperatures are used at the remaining 30-foot-antenna stations. Because the MSFN has been described previously in other literature (ref. 4), only the demodulation portion of the ground-station system will be discussed in detail in this report.

The S-band signal is detected in the phase-lock, double-superheterodyne receiver shown in figure 7. The receiver uses a "long" phase-lock loop (PLL) configuration for coherent detection; that is, the coherent reference, as derived in a narrowband tracking loop, is applied as the local oscillator signal into the first mixer rather than into the wideband phase detector. The PM modes are routed through a 10-megahertz intermediate-frequency (i.f.) channel, while the FM modes use a 50-megahertz i.f. channel. Each channel uses a separate set of signal-data demodulators. The ranging data are routed to the range-code receiver where the signal is detected and correlated. The range measurements are made by counting the reference oscillator cycles during the delay period between the transmitted and received range code and then adjusting the cycles in accordance with the motion of the spacecraft.



Points at which down-link circuit margins are calculated:

A - Carrier (2 βlo = 700, 200, or 50 Hz)
B - PRN (referred to 1-Hz loop NBW)
C - Voice/biomedical data
D - Telemetry
E - Emergency key
F - Backup voice
G - Baseband voice/biomedical data
H - All FM circuit margins

Figure 7. - Diagram of MSFN receiver and identification of points at which the down-link circuit margins are calculated.

In the PM channel, a wideband phase detector strips off the 1.024- and 1.25-megahertz subcarriers. The normal voice and biomedical data are then demodulated in a 1.25-megahertz PLL FM demodulator. The voice is routed to an audio system while the biomedical subcarriers are subsequently demodulated using standard Inter Range Instrument Group FM detectors.

The backup voice is demodulated in the carrier tracking loop of the MSFN receiver. The narrowband phase detector preceding the carrier loop demodulates the baseband signal, and the voice is taken out through a low-pass filter ahead of the loop filter. The carrier loop will tend to track out the low-frequency components of the voice. However, tests indicate that only with the 700-hertz loop bandwidth (fig. 7) and under strong signal conditions will there be any noticeable degradation to the voice. The 50- and 200-hertz loop filters do not affect the voice. The 1.024-megahertz telemetry subcarrier is demodulated using a PLL detector. The phase reference for demodulating the subcarrier is derived by first squaring the incoming signal to remove the modulation. The PLL removes any excessive noise from the squared signal before it is frequency divided by 2 to obtain the stable reference. The reference and telemetry subcarriers are routed into a balanced detector, and the resultant PCM bit-stream output is routed to the bit synchronizer and matched filter. The degradation in the total telemetry subsystem (the subcarrier demodulator, the bit synchronizer, and the matched filter) has been measured in spacecraft/ground-station compatibility tests to be approximately 2 decibels. For the PM modes, a 10^{-6} bit-error rate (BER) requires 12.5 decibels SNR in the bit-rate bandwidth.

The 512-kilohertz emergency key subcarrier is translated to a 1-kilohertz on-off tone by mixing with a 513-kilohertz oscillator. The 1-kilohertz signal is demodulated with a diode detector and is routed through a switchable, low-pass output filter (135 or 20 hertz) for audio detection. The 20-hertz output bandwidth is used when no Doppler-frequency offsets exist, such as the period during which the spacecraft is on the lunar surface.

The FM channels are demodulated in a PLL FM demodulator. Both the FM and PM channels are band limited by a 5.3-megahertz rf-interference filter at the output of the first mixer in the MSFN receiving system. The FM demodulator has two loop bandwidths. The narrow loop is approximately 3.6 megahertz, and the wide loop is approximately 10 megahertz.

The wide-loop filter is used for LM and CSM television modes, and the narrow-loop bandwidth is used for CSM modes 1, 2, and 3. Mode contents are listed in table II. The performance of the FM channels is constrained by the large carrier-frequency drifts (±455 kilohertz) and by the multiplicity of possible modulation spectra that do not permit optimization of the predetection and loop-filter bandwidths for the individual modes.

TABLE II. - INFORMATION CONTENT OF CSM S-BAND DOWN-LINK MODES

(a) Down-link PM modes

Information	Mode														
	1	2	3	4	5	6	7	8	8A	9	10	11	12	13	15
Carrier	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Voice/extravehicular mobility unit	X	X	X	X								X	X		
Telemetry (high bit rate)	X	X												X	X
Telemetry (low bit rate)			X	X	X			X	X	X					
PRN		X	X				X		X	X		X			X
Voice backup								X	X		X				
Key						X									

(b) Down-link FM modes

Information	Mode			
	1	2	3	4
Carrier	X	X	X	X
Playback voice (1:1)	X			
Playback 51.2 kbps telemetry (1:1)	X			
Playback voice (32:1)		X		
Playback 1.6 kbps telemetry (32:1)		X		
Playback LM 1.6 kbps telemetry (32:1)			X	
Television (black and white or color)				X

IMPORTANT SYSTEM DESIGN DECISIONS

PSEUDORANDOM NOISE AND TONE RANGING

By Benjamin H. Hood

The method of determining spacecraft range (distance) from a ground-based station has been the subject of much debate. Pulse radars were used during Project Mercury and the Gemini Program. The range measurement for the pulse system was determined by measuring the time required for a high-power pulse to travel to the spacecraft and to be retransmitted to earth. The USB system, however, operates in the continuous-wave mode and a different scheme must be used for range determination. Two ranging schemes were proposed: The JPL PRN range code and the GSFC range and range-rate (RARR) system.

The JPL PRN ranging system uses a digital sequence that is deliberately constructed to exhibit several properties characteristic of random processes. The code is periodic with a period sufficiently long to allow the unambiguous measurement of spacecraft range. The measurement of round-trip transit time (range) is performed by comparing or correlating a locally generated replica of the transmitted signal with the returned signal, then time shifting the local replica by some amount and again correlating, and so on. This procedure is repeated until a maximum autocorrelation value is observed. The time by which the local signal replica has been time shifted to yield this maximum correlation is then equal to the round-trip transit time. The use of long code lengths and correlation detection makes the PRN ranging system well adapted to ranging, at extremely long ranges, on power-limited spacecraft transponders. The time required to obtain an accurate range measurement is a function of the received power level. As the power level goes down, the required integration time for the correlation detector increases.

In the RARR system, a set of sinusoidal tones is used for ranging. The range measurement is determined by the phase delay of the sine wave. Using this technique, the maximum unambiguous range is determined by the lowest frequency tone, and the resolution capability of the system is determined by the highest frequency. This system is better for shorter range, higher resolution, and faster acquisition applications than the PRN system. It can be used at longer ranges if a coding scheme is used to resolve range ambiguities.

The JPL PRN ranging system was chosen for Apollo missions because of its long-range minimum-power characteristics. The performance of the PRN ranging system has been good, but acquisition times have been somewhat longer and the acquisition procedure somewhat more complex than desired. Therefore, if a new ranging system were designed, it is very possible that a hybrid could be designed that would have the good features of both the PRN and RARR systems. A short digital code to resolve range ambiguities and a tone to provide high resolution would be used in the hybrid system. The questions of acquisition time and complexity would have to be considered.

MODE-SELECTION FLEXIBILITY

By William E. Teasdale

In the early stages of the Apollo hardware development, the communications system was designed to have multiple operating modes to accommodate the transmission of different types of information (e.g., voice, telemetry, television, recorded data, biomedical data, etc.), but not all simultaneously. These different combinations (or modes) provided a certain degree of information-transmission flexibility, but some functions invariably were transmitted, regardless of whether they were really required, simply because they were part of a fixed combination or grouping of information channels (e.g., transmission of a subcarrier even though the information it carried (if any) was not required). This situation was recognized as inefficient in terms of required effective radiated power (ERP) needed to achieve acceptable reception at the ground station and in terms of the rf spectrum used. Also, the system was inflexible from the standpoint of alternatives for equipment contingencies.

It was decided on this basis that greater mode-selection flexibility was needed. The communications-system equipment design was then changed to allow basically any communications function or combination of these functions (voice, telemetry, etc.) to be selected for transmission. This selection flexibility — coupled with the capability of independently selecting transmission power level, antenna, and telemetry bit rate — provided a complete matrix of possible communications-system operating modes.

The down-link communications modes currently used for the CSM and LM are listed in tables II and III, respectively, and the CSM and LM up-link mode selections are listed in table IV. As shown in table IV, eight up-link modes may be selected to transmit various combinations of voice, up data, and PRN ranging. In addition, one of these up-link modes allows transmission of voice over the up-data subcarrier (70 kilohertz), which provides an up-link voice backup capability. Some of the indicated down-link modes (e.g., table III, LM down-link PM modes 12, 13, 14, and 15) are not currently described in the S-band Performance and Interface (P&I) specifications nor in the MSFN Program Support Requirements Document; however, the capability does exist for configuring to these modes with present Apollo hardware.

Several function switches perform the switching necessary to obtain the wide variety of modes; for example, PCM and voice on-off switches, a backup-voice on-off switch, a PCM bit-rate switch, a power-amplifier selection switch, and so forth. However, the system does not have total flexibility because, in a few instances, selection of one function will inhibit the selection of another function. Such is the case when LM backup voice is selected; transmission of PRN ranging is thereby inhibited. The rationale for this implementation was based on the belief that, if both were transmitted simultaneously, the backup voice (a baseband transmission) and ranging spectra would overlap and cause performance degradation to both functions. Systems tests have since shown that this is not the case and that very little if any degradation results to either channel.

TABLE III. - INFORMATION CONTENT OF LM S-BAND DOWN-LINK MODES

(a) Down-link PM modes

Information	Mode												
	1	2	3	4	5	6	7	[a]8	11	12	13	14	15
Carrier	X	X	X	X	X	X	X	X	X	X	X	X	X
Voice/hard-line biomedical/extravehicular mobility unit	X	X					X	X		X		X	
Telemetry (high bit rate)	X	X									X		X
Telemetry (low bit rate)			X	X			X	X					
PRN ranging		X							X			X	X
Voice backup[a]				X	X								
Key						X							

[a]Voice is on baseband.

(b) Down-link FM modes

Information	Mode			
	9a	9b	10a	10b
Carrier	X	X	X	X
Voice/extravehicular mobility unit/biomedical	X	X	X	X
Telemetry (high bit rate)		X		X
Telemetry (low bit rate)	X		X	
Television (black and white or color)			X	X

TABLE IV. - INFORMATION CONTENT OF LM AND

CSM S-BAND UP-LINK PM MODES

Information	Mode							
	1	2	3	4	5	6	7	8
Carrier	X	X	X	X	X	X	X	X
Voice		X		X		X	X	
Up data			X		X	X	X	
PRN ranging	X			X	X	X		X
Voice backup[a]								X

[a]Up-voice backup modulates the 70-kHz subcarrier and is thus time shared with up-data transmissions.

Although the expanded flexibility greatly enhanced the Apollo communications-system efficiency in terms of power and bandwidth and also provided backup capability for contingency situations, it placed a heavy workload on the flight crew, who had to perform the communications-system configuration management function manually in real time in addition to their other duties. It seems imperative that, for future space programs and manned spacecraft, the communications-system management function not be performed by the flight crew, although a high degree of operational flexibility must be maintained. One possible solution is automatic switching of all functions (with manual override for safety and reliability) by means of some combination of onboard and ground-based control.

Because of the time frame in which the change in the Apollo concept was initiated, automatic switching of all functions was considered impractical from the standpoint of effects on cost, weight, and schedule and consequently was not pursued.

UNIFIED S-BAND VOICE PROCESSING

By James A. Porter

The design goals for the Apollo S-band voice links were 90-percent word intelligibility for the primary communication modes and 70-percent word intelligibility for backup modes. (Intelligibility refers strictly to understanding the spoken word; the term does not imply identification of the speaker, high fidelity, etc.) Because of the redundancy in speech, a channel scoring 90-percent word intelligibility yields nearly 100-percent sentence intelligibility, and a channel scoring 70-percent word intelligibility produces better than 90-percent sentence intelligibility.

Because the upper and lower frequency components of speech contribute little to intelligibility, large segments of the normal speech frequency spectrum, particularly at the higher frequencies, can be filtered out. Accordingly, the Apollo USB communications-system down-link voice spectrum is band limited to approximately 300 to 2500 hertz. (Earlier in the program, the upper limit was 3000 hertz but the limit was reduced to remove noise and the 3.9-kilohertz EKG data subcarrier from the voice and thus improve overall voice quality.)

Other voice processing used in the Apollo Program, besides filtering, includes preemphasis (differentiation) and clipping. Investigations early in the Apollo Program indicated that clipping should be preceded by approximately 6-dB/octave preemphasis. Increasing the power in the higher frequencies by preemphasis minimizes the effect of noise caused by clipping and generally results in better intelligibility. These early investigations also indicated that, in the absence of complete detailed knowledge of all factors that will ultimately affect the quality of the voice link, 12 decibels of clipping is a good design compromise between too little and too much.

This combination (6-dB/octave preemphasis and 12-decibel clipping) was implemented on the CSM for normal (subcarrier) voice from the CSM to the ground stations. Normal (subcarrier) voice, for the LM-earth link, was implemented with no preemphasis and no clipping, partly because some of the factors involved in LM design were different from those for the CSM (such as the greater cabin noise in the LM).

The combination of 6-dB/octave preemphasis and 24-decibel clipping was implemented on both spacecraft for backup (baseband) voice. Backup voice was not only to be used in case of a failure of the normal-voice subcarrier oscillator but also to permit voice communications over the spacecraft omnidirectional-antenna system at lunar distance if the high-gain antenna should fail. Use of the omnidirectional antennas meant a much weaker signal and prompted the selection of 24 decibels of clipping for backup voice, because weak signal conditions are one instance where greater amounts of clipping can be advantageous. As for the ground stations, it was decided that preemphasis and clipping were not needed because the high transmission power and large antennas already assured a strong voice signal at the spacecraft.

Generally, the overall results of voice processing in the Apollo USB system have proved to be satisfactory. In retrospect, some conditions exist that, on the basis of accumulated experience, might be treated differently. The LM backup-voice function could probably be improved by lowering the 24-decibel clipping to 12 decibels or even 0 decibel. Cabin noise in the LM is relatively loud and enters the microphone along with the astronauts' voices; this is one instance where clipping usually does more harm than good.

More research on methods to improve baseband voice would probably indicate further changes. Another area in which improvements could be made involves the ground links between the Mission Control Center (MCC) at Houston and the receiving stations. It has never been a serious problem, but degradation over the ground links causes the deviation of the 30-kilohertz up-voice subcarrier to vary considerably from station to station.

TRACKING DYNAMICS OF SPACECRAFT AND GROUND STATION

By William E. Teasdale

The velocity of the spacecraft relative to the ground station introduces a Doppler shift in the up- and down-link S-band carrier frequencies, resulting in an uncertainty in the received frequency both at the spacecraft and at the ground station. Both the spacecraft and the ground-based receivers are equipped with PLL frequency-tracking receivers that lock onto and track the received frequency so that the received carrier may be coherently detected.

Because of the varying amounts of Doppler shift (from the relatively low rates encountered in lunar orbit to the higher rates encountered in earth orbit and during portions of translunar and transearth coast), different carrier-tracking-loop bandwidths are required. It is desirable to keep the tracking-loop bandwidth as narrow as possible (reducing the dynamic phase error) while providing a broad enough bandwidth to accommodate the maximum expected frequency jitter of the carrier. Therefore, the ground receiver was designed to have a selectable loop bandwidth (50, 200, or 700 hertz). The 50-hertz bandwidth was used at lunar distance and the 700-hertz bandwidth during earth-orbital operations.

The CSM and LM had only a 700-hertz carrier-tracking-loop bandwidth. This bandwidth requirement is not as stringent as the ground-station requirement, because the up-link received signal power at lunar distance is sufficiently high to overcome the added phase error caused by the increased noise power resulting from the 700-hertz loop bandwidth.

During the course of the spacecraft-receiver design effort, considerable discussion and controversy arose between NASA and the spacecraft contractors regarding what the gain and the bandwidth of the spacecraft-receiver PLL should be to accommodate the automatic acquisition function (i. e., to interface properly with the MSFN frequency-sweeping transmitters). In addition, the question of whether it was better to specify the spacecraft-receiver PLL tracking capability or the PLL parameters (gain and bandwidth) was debated. Finally, it was agreed that the tracking capability required for the spacecraft-receiver PLL, in terms of minimum sweep range and minimum sweep rate, would be specified to assure spacecraft/ground-station operational compatibility.

The performance of the spacecraft tracking loop, in terms of maximum allowable static phase error, was also specified to be 24°. This requirement ensured that the spacecraft receiver would operate on the linear portion of the phase-transfer characteristic curve of the phase detector. The phase-transfer curve is actually sinusoidal, but an approximately linear characteristic can be obtained by limiting the input phase error to less than 25°.

ACQUISITION PROCEDURES

By William E. Teasdale

When developing the S-band ground stations, NASA engineers used the experience acquired by JPL personnel in their unmanned space effort and patterned the Apollo MSFN after the existing JPL stations in basic design and operation. Because of the similarity between the NASA MSFN stations and the JPL stations, the rf acquisition procedures for the Apollo USB system were developed jointly by NASA and JPL engineers.

Radio-frequency acquisition of the Apollo USB system involves: (1) spacecraft rf (carrier only) illumination by a line-of-sight ground station and (2) up-link and down-link rf carrier acquisition followed by PCM data acquisition and PRN ranging acquisition. During initial carrier acquisition, the ground antenna is driven in a program-track mode, which results in real-time positioning in accordance with predicted spacecraft-position coordinates. During the initial pass (launch phase), the spacecraft-position coordinates are computed on the basis of predicted flight-profile data. After the launch phase, updated coordinate predictions are provided by the C-band tracking-radar stations to all stations for use during the preacquisition programed tracking phase. In earth orbit, a 3-foot-diameter broad-beam acquisition antenna attached to the side of the 30-foot dish is used during the spacecraft-illumination phase to account for inaccuracies in prediction of spacecraft position. (Because very accurate pointing predictions are available for the 85-foot antennas during the translunar, transearth, and lunar-orbit phases, a special acquisition antenna is not used.)

Following initial spacecraft illumination, the two-way rf acquisition phase is initiated. During this phase, the ground-transmitter frequency is swept over a predetermined range at a predetermined rate. (The original acquisition procedure was to sweep the ground-transmitter frequency over a range of ±90 kilohertz at a rate of 35 kHz/sec. Based on CSM-MSFN compatibility tests at MSC, it was determined that the sweep rate could be increased to 70 kHz/sec without degrading system performance.) The system is constrained to establish up-link lock before establishing down-link lock because the ground-based receiver will lose down-link lock when the spacecraft receiver acquires the up link if down-link lock is established first. Up-link rf acquisition is also constrained to be performed only while an up-link carrier is being transmitted. If this were not the case, the spacecraft could conceivably lock onto either the 30-kilohertz voice subcarrier or the 70-kilohertz up-data subcarrier because these subcarriers fall inside the ±90-kilohertz frequency-sweep range normally used for acquisition.

A problem similar to the up-link acquisition constraint just described plagued down-link rf acquisition during Apollo compatibility tests. This problem, known as the "telemetry spur problem," was one in which the ground-based receiver would lock onto an unwanted spectral component appearing inside the frequency-sweep range about the S-band carrier. The component of primary concern appeared at 51.2 kilohertz about the S-band carrier because of the 51.2-kbps telemetry modulation.

Spectral components also appeared at multiples of 51.2 kilohertz for high-bit-rate telemetry and at multiples of 1.6 kilohertz for low-bit-rate telemetry. The amplitude of the components falling inside the ± 90-kilohertz range about the carrier, except for the one appearing at 51.2 kilohertz, was sufficiently low to prevent false acquisition during tests. To prevent false acquisition (acquisition of the telemetry spur instead of the S-band carrier) during Apollo flights, one of two possible changes to the acquisition procedure was required — (1) constraint of the down-link signal spectrum during acquisition to preclude transmission of high-bit-rate telemetry, or (2) reduction of the frequency-sweep during acquisition to a value of less than ± 51.2 kilohertz.

The latter option was selected because it was less constraining on spacecraft operations (i.e., it would not increase astronaut activity). The sweep range was reduced from ± 90 kilohertz to ± 37 kilohertz, and the sweep rate was reduced from 70 kHz/sec to approximately 30 kHz/sec. However, reduction of the sweep range increases the uncertainty of acquisition during periods of large Doppler shifts, which situation in turn increases the nominal acquisition time. The capability to revert to wider sweep ranges was maintained as an alternate to the revised acquisition procedure.

BASEBAND VOICE MODES

By William E. Teasdale

As a part of the communications-system operating-mode-selection flexibility (discussed in the section entitled "Mode-Selection Flexibility"), several so-called baseband voice modes were provided (LM modes 4, 5, and 8; CSM PM modes 8 and 10).

On the basis of theoretical analyses performed by NASA, JPL, and other engineers, it was determined that the performance of baseband clipped voice in general would allow transmission with reduced ERP (low power or omnidirectional antenna or both). This transmission was desirable during periods of low activity to conserve spacecraft electrical power and to provide acceptable performance during contingency situations that result in reduced ERP (i.e., failure of the power amplifiers or the high-gain antenna or both). With the exception of LM mode 8, the baseband voice modes were implemented with 24-dB clipping to allow transmission of voice (and, in certain cases, low-bit-rate telemetry) during the contingency and low-activity periods. The phrase "backup-voice modes" is often used to describe these modes.

The baseband voice modes consist of voice that is phase modulated directly onto the S-band carrier. By phase modulating the voice signal at baseband, the FM threshold requirement that exists for the normal voice modes (in which the voice signal is frequency modulated onto a subcarrier) no longer must be met. In addition, a further reduction in required received-power-level is obtained by reducing the voice word-intelligibility requirement from 90 to 70 percent, because a considerable reduction in the transmission bandwidth is realized with the baseband voice-only modes (LM mode 5 and CSM mode 10). The other baseband voice modes do not achieve a significant bandwidth reduction because the telemetry subcarrier modulation is present at 1.024 megahertz.

In general, the backup-voice modes have performed marginally with respect to the normal voice channel. The voice sounds garbled and distorted, even at high received-signal levels, as a result of the clipping action. In addition, when telemetry was transmitted along with voice on one of these modes, severe telemetry degradation was encountered. The telemetry degradation (in the form of data dropouts or burst error) was present only during periods when voice was being transmitted. This interference problem is discussed in more detail in the section entitled "Backup Voice Interference With 1.6-kbps Telemetry."

Lunar module mode 8, also a baseband voice mode, was not designed for the same purpose as the other baseband voice modes but rather to serve as a full-service backup mode for use in the event of a failure of the LM 1.25-megahertz (voice) subcarrier oscillator. This mode provides for the transmission of not only voice by means of the baseband but also of the hard-line biomedical subcarrier and the EVA biomedical and PLSS-status data subcarriers.

On the basis of circuit margin, LM mode 8 requires more ERP for a given level of performance (voice intelligibility) than do the other baseband voice modes. (Mode 8 voice is not clipped.) Therefore, it is not useful as a backup mode for the condition in which both the steerable antenna and the power amplifier have failed. Mode 8 also exhibits telemetry degradation because of the presence of the baseband modulation.

FREQUENCY-SHIFT KEYING OR PHASE-SHIFT KEYING FOR THE UP-DATA LINK

By Pamela Bankston

No agreement could be reached between NASA George C. Marshall Space Flight Center (MSFC) and MSC personnel on the selection of PSK or frequency-shift-keying (FSK) modulation. Therefore, in early 1963, it was decided that (1) the MSC would use PSK for the spacecraft command systems, (2) the MSFC would use FSK for the launch vehicle, and (3) the MSFN systems would be made compatible with both PSK and FSK. In view of the apparent costs to the ground-based systems and possible operational problems, the Command Subpanel, at the ninth meeting of the Instrumentation and Control Panel in early 1964, was asked to reconvene and rereview the entire command concept and report all findings to the Instrumentation and Control Panel.

The general request to the subpanel was to compare PSK and FSK on the basis of modulation techniques, operational considerations, costs, and reliability and to make a recommendation on findings to the Instrumentation and Control Panel.

The investigating committee was comprised of four major participants — GSFC, MSFC, MSC, and a contractor. The first Command Subpanel meeting for this purpose was held in April 1964. The assignment of tasks was made and a tentative schedule was established for accomplishing the tasks. Assignments were made to MSFC, MSC, and the contractor for modulation techniques; to MSFC and MSC for operations; to MSC, MSFC, and GSFC on costs (later changed to financing, scheduling, and weight); and to GSFC and the contractor for reliability.

It was agreed that both systems should be evaluated in the following areas.

1. Performance capabilities

   a. Effects of thermal noise above and below carrier threshold

   b. Effects of interference from all sources

      (1) Pulsed carriers

      (2) Continuous-wave-type signals

   c. Propagation effects

      (1) Plasma

      (2) Multipath

      (3) Doppler

      (4) Lunar reflections for lunar-orbit phase

   d. Nonuniform receiver characteristics

      (1) Filter amplitude ripple

      (2) Filter phase nonlinearities

      (3) Amplitude-to-phase conversion in carrier amplitude limiter

      (4) Limitations of receiver dynamic range

   e. Limitations on multiplex baseband design

      (1) Spectral properties and bandwidth requirements

      (2) Characteristics of intermodulation and cross-modulation products

      (3) Sensitivity of multiplexed spectra to noise and distortion

2. Implementation

3. Flexibility

a. Compatibility with other systems

b. Adaptability to integration with other functions

c. Amenability to expansion to meet increased demands on performance or future needs

4. Cost and scheduling implications and reliability

Upon completion of the study, it was concluded that neither system had any significant technical advantages, but the use of the PSK system by both MSC and MSFC would prove to be more adaptable and economical than the FSK system when MSFN implementation and operational aspects were considered. The PSK system was therefore selected.

CONFIGURATION CONTROL

By Harold R. Rosenberg

Configuration control is discussed in terms of a group of Apollo communications-system interface documents (refs. 5 to 10). The generation of these documents evolved from a program need to control and integrate the related activities of the NASA centers and the numerous Apollo contractors and subcontractors responsible for the design and fabrication of the Apollo communications equipment. These interface documents consist of two types: (1) the spacecraft/ground S-band P&I specifications, which contain all the critical rf/equipment-interface parameters affecting total system performance, and (2) the S-band circuit-margin Interface Control Documents, which contain the Apollo communications-system mathematical model and system-performance predictions based on parameter values in the P&I specification and which provide a means for judging and controlling deviations from the P&I specifications values. The availability and use of these documents throughout the developmental and operational phases of the Apollo Program played a significant role in the successful performance of the Apollo communications system and the Apollo Program itself. The placement of the P&I specifications high on the contractors' "spec tree" was a major factor in this success.

S-BAND P&I SPECIFICATIONS

The generation of the P&I specifications was a mutual effort by personnel from MSC, GSFC, MSFC, JPL, and several contractors. Initially, pertinent system parameters were collected by the CSM contractor and MSC to form the CSM Block I P&I specification (ref. 5). Following NASA-contractor negotiations, this document was approved by NASA and published by the contractor as a contract specification subject to configuration-management change-control procedures.

The preparation and format of the CSM Block II and LM S-band P&I specifications (refs. 6 and 7) were based on the Block I specification (ref. 5) with the required upgrading of coverage in the area of system-parameter definition. Although the preparation and publication of the P&I specifications in the Apollo Program was a contractor responsibility, considerable coordination effort from MSC communications-system engineers was required to fill the gap between the spacecraft contractors and other NASA centers (e.g., to acquire, evaluate, and negotiate MSFN, Apollo range instrumentation aircraft, and vhf Government-furnished-equipment system parameters for inclusion in the P&I specifications). Once available, the P&I specifications served as a firm control medium for all communications-system parameters that could not be adequately controlled by "black box" specifications. For example, parameters impacting total system performance (such as cable loss; transmission power; system temperature; antenna-pointing loss and on-axis gain; acquisition procedures; allowable incidental PM (IPM) and incidental AM (IAM); required signal-to-noise ratios, bandwidths, modulation indices; etc.) could now be controlled, and performance could be predicted with some degree of confidence.

Because of the late start in preparing the P&I specifications, they contained parameter values that were required by existing equipment performance. (Some hardware had already been designed and built.) This situation resulted first in an overall system performance somewhat below the level required and second in continuous activity throughout the program to upgrade other areas of the system to compensate for the identified deficiencies and to emphasize the need to maintain status in other areas. The latter situation often caused significant cost increases and delays in equipment delivery.

For the P&I specifications to be realistic and effective in future programs, it is thought that P&I specifications should be more of a NASA-generated specification than a NASA-approved-but-contractor-generated specification.

Without the P&I specifications in the Apollo Program as a NASA control point, the required CSM, LM, and MSFN overall communications-system performance capability would not have been realized, because, in a program as large as Apollo, many equipment items are built, tested, and accepted on an individual basis. Often, many small, isolated changes are requested (black-box-specification relaxations) for the various system components. These changes are considered acceptable at the black-box level and seem insignificant to overall system performance. Experience has shown that these changes often degrade system performance; therefore, any and all black-box changes, regardless of apparent insignificance to overall system performance, must be investigated for effect on the integrity of the overall systems-performance capability. To this end, system-level specifications, such as P&I specifications, are essential for controlling contractor-proposed modifications and for maintaining the overall system capability dictated by mission requirements.

Experience has shown that this type of documentation serves a dual purpose: (1) it provides NASA management with a tool to control the overall communication-systems configuration and performance and assures interface compatibility between spacecraft/ground-based terminals, and (2) it makes available to all MSC organizations, other NASA centers, and the spacecraft contractors and subcontractors a working document that contains all the critical system parameters used in predicting communications-system performance. The effectiveness of these documents depends on the degree to which they are accepted by management as the final word in defining overall system performance and the degree to which they are used by the responsible persons for preparing overall vehicle specifications (e.g., Master End-Item, Contract End-Item, etc.), vehicle test documentation, and equipment-acceptance criteria.

S-BAND CIRCUIT-MARGIN INTERFACE CONTROL DOCUMENTS

As stated in the discussion on P&I specifications, the effect of changing system parameters required an evaluation of total system performance before acceptance of any recommended change. The circuit-margin Interface Control Documents provided the medium and tool for this evaluation through the publication of an approved mathematical model of the Apollo communications system and the acceptance of the calculations by the contractor as the official performance capability of the system. The Interface Control Documents thus added uniformity and, therefore, consistency to both contractor and NASA calculations and became the official source for emphasizing performance deficiencies.

The circuit-margin Interface Control Documents also served as a management tool for mission planning and as a working document among the many contractors and NASA centers involved in the Apollo Program. Because of the tight relationship with the P&I specifications, the Interface Control Document (ICD) had a basic drawback in that, when official changes were made to the P&I specifications, their implementation in the applicable ICD would, in most cases, require a complete rework of the ICD. To compensate for the delay in published up-to-date circuit-margin information, MSC programed the mathematical model and published circuit-margin data in accordance with the latest known values of system parameters. This effort is discussed in more detail in the section entitled "Performance Estimation and Operational Inputs."

ANALYSIS OF THE APOLLO COMMUNICATION SYSTEM

The Apollo USB system has been extensively analyzed, and mathematical models have been developed that accurately describe the system performance. The analysis may be divided into two categories — (1) the mathematical models that describe the operating performance of the individual communications channels, and (2) the mathematical analyses of specific problem areas.

The operating performance of the individual channels is usually in the form of circuit margins (communications-performance predictions) as a function of mission elapsed time. A circuit margin is defined as the difference in decibels between the required SNR (SNR_{req}) and the actual SNR (SNR_{act}) calculated in the predetection bandwidth of the channel concerned. For example, in the telemetry (TLM) data channel, the circuit margin is defined by

$$\text{Circuit margin (TLM)} = SNR_{act}(\text{TLM}) - SNR_{req}(\text{TLM})$$

The specific problem-area analyses pertain to system performance and interface incompatibilities that arose during spacecraft-MSFN compatibility tests at MSC, in actual mission environments, or during a design or systems-performance analysis.

The Apollo USB communications system has been extensively and accurately analyzed. These analytical efforts have been reflected in mission success.

PERFORMANCE ESTIMATION AND OPERATIONAL INPUTS

The development of the tools by which the Apollo communications-system performance is estimated (predicted) is discussed in this section. The development of the USB system mathematical model is discussed first. A discussion of the origin and use of the rf coverage documents that have been prepared for each Apollo mission follows. Finally, the development and subsequent use of the computer-aided analysis system (CAAS) with regard to real-time Apollo mission support are discussed.

Development of USB System Mathematical Models

By G. Dickey Arndt

The performance of the Apollo system was first analyzed and documented in a series of contractor reports (refs. 3, 11, and 12). The derivations of the modulation-loss equations, the range-code interference terms, and the spacecraft-transponder turnaround effects as elements of the USB system mathematical model are included in the contractor reports for both the up-link and down-link PM modes. The design philosophy and optimization procedure for selecting the modulation indices (PM modes) and the carrier-frequency deviations (FM modes) are also discussed in reports. Further development in the mathematical model included other reports by another contractor (refs. 13 and 14). These reports include a detailed analysis of the Apollo FM channels and the backup-voice/telemetry modes. The FM analysis is a detailed treatment of the threshold-extension phenomenon achieved by PLL demodulators in place of conventional discriminators. Modulation-loss expressions were derived for the backup-voice/telemetry modes, including the effects of voice clipping to increase signal power. Additional refinements, such as the inclusion of suppression effects of limiters at low signal conditions, were later added. The various mathematical models were incorporated into one analysis program, which was implemented on the 1108 computer. The effects of increased noise temperature at strong levels were also added to the mathematical model. This program, which provides an analysis of the USB system, served as the basis for computerized calculations of rf communications-coverage analysis and compatibility-test predictions. The vhf relay links and their interfaces with the USB system were later analyzed and implemented into the computer calculations. It is now possible to trace the signal performance through the vhf links, the spacecraft, and the S-band relay to the MSFN. The accuracy of the calculations is usually within 1 decibel when comparing theoretical results with experimental data involving compatibility tests between spacecraft and ground-station equipment. The theoretical calculations also agree closely with measured Apollo mission performance.

Radio-Frequency Coverage Analysis

By Carroll T. Dawson and Theodore W. Eggleston

Apollo 1 (AS-201/SC-009). - Beginning with the Apollo 1 mission, a concerted effort was established to automate performance predictions for the Apollo communications system. The object was to use a simulation of the spacecraft trajectory and attitude sequence in conjunction with measured spacecraft-antenna patterns, specified system parameters, and a mathematical model of the system to calculate a predicted time history of circuit margins at all applicable ground stations.

In late 1964, computer programs existed (programs written for Project Mercury and the Gemini Program and updated for the Apollo Program) that could provide slant range and elevation and azimuth-angle data for the ground station, time-referenced to lift-off; however, none satisfied the immediate need for the computation of the spacecraft look angles θ and ϕ time-referenced to lift-off. The angles θ and ϕ are defined as follows: (1) θ is the angle between the tracking-station line of sight and the vehicle roll axis (measured from the positive X-axis), and (2) ϕ is the angle between the X-Z plane (pitch plane) and a plane through the tracking-station line of sight and the X-axis (measured in a plane normal to the X-axis). The angular parameters of the Apollo spacecraft coordinate system (figs. 8 and 9), as just defined, are spatially identical to the angular-coordinate system used for the omnidirectional-antenna-system-pattern data (i.e., the gain of the omnidirectional antenna varies with θ and ϕ).

The implementation of θ and ϕ calculations into an existing computer program was considered only the first step toward a fully automatic program that would, in the final version, compute and plot the signal level received at the ground station along the flight trajectory as a function of time referenced to lift-off. Spacecraft look-angle calculations were implemented in one of the available programs and used to predict communications-system performance for the AS-202 and AS-204 flights. Unfortunately, the size and inflexibility of the program resulted in a very long turnaround time in obtaining performance data. Each time a change in flight trajectory was made, the process had to be started again. To alleviate this situation, a task was undertaken by MSC in September 1966 to develop a new and flexible computer program. This program was called the Apollo Unified S-Band Circuit Margin Program (AUSBCM) and is discussed in more detail with regard to the Apollo 4 rf coverage analysis.

For the early flights, the prediction technique was simply a correction based on changes in spacecraft-to-ground-station range and spacecraft-antenna gain applied to a reference margin. This model was used for both the vhf and USB systems. Antenna patterns used for the early flight predictions were based on one-third-scale measurements of the slotted scimitar antennas used on the Block I spacecraft. Gain variations in these patterns were large. As a result, the plots of circuit margin as a function of mission time resembled a random-noise process. Unfortunately, very little correlation

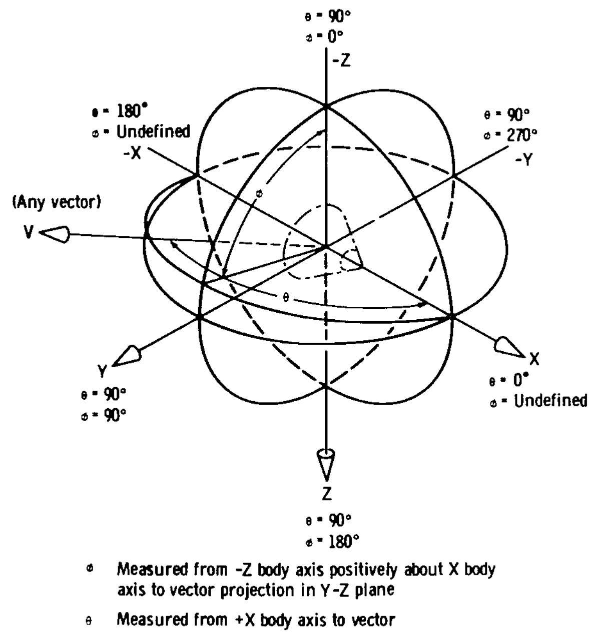


Figure 8. - Command and service module θ / ϕ body coordinate system.

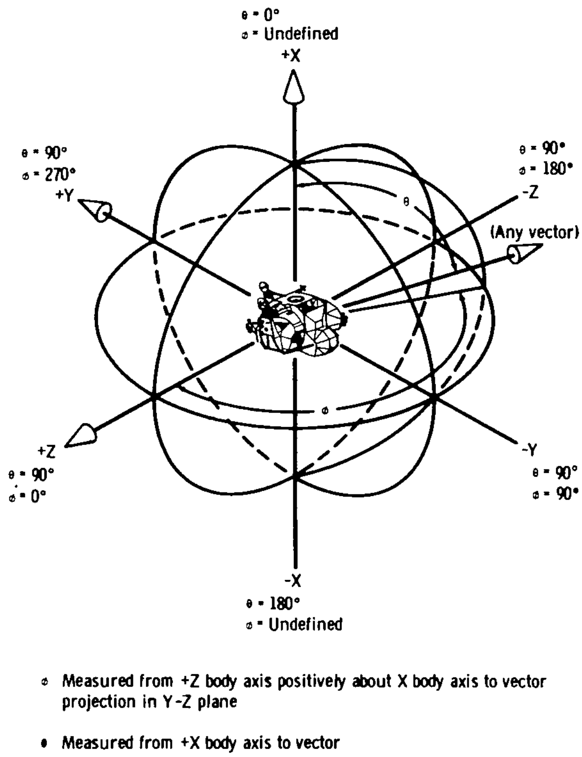


Figure 9. - Lunar module θ / ϕ body coordinate system.

between the prediction and the actual performance could be established. Measured data from AS-201, which used vhf only, were extremely sparse, and thus little was learned about making performance predictions from the flight. Between the AS-201 and AS-202 missions, work was begun on a computer program for automating and improving the accuracy of communications-system performance predictions. (This effort was to continue beyond the first lunar-landing mission.) One of the first steps was to transform antenna-pattern data into a form that could be used efficiently by a computer. To accomplish this, a program was developed for the Univac 1218 computer that read antenna-pattern data from paper tape (a standard storage medium) and output the data onto magnetic tape in a FORTRAN-compatible format. This program was used to convert hundreds of antenna patterns for many organizations before being replaced later in the Apollo Program by a more complex version that was compatible with the MSC computation center system.

With the problem of rapid access to tens of thousands of discrete antenna gains solved, the next step was to improve the mathematical models. The vhf system was a standard off-the-shelf configuration, and the simple models being used were adequate. The USB system was a different situation. Many factors not accounted for in the simple model affected the USB performance. One such factor was the dependence of the receiver-noise figure on the received carrier power. (The section entitled "S-Band Receiver Noise Characteristics" contains further information.) The net result of this dependence (an increase of noise figure with an increase of carrier power beyond a certain value) was a limit to the maximum possible received SNR and, thus, the maximum obtainable circuit margin. The USB model was modified to account for this effect, and the first circuit-margin predictions for AS-202 were generated.

Apollo 2 (AS-202/SC-011). - The maximum circuit margins calculated for AS-202 were negative, resulting in a change in an attenuator setting in the ground-station receiver that shifted the knee of the curve for noise figure as a function of carrier power to a point well above the power required for positive circuit margins.

The first rf-coverage-analysis report was published on August 9, 1966. The report contained performance predictions for all vhf and S-band links. Recommendations for switching between the Block I CSM surviving and nonsurviving slotted scimitar antennas during the flight were given in the report.

Postflight analysis of the AS-202 data revealed large discrepancies in predicted and actual performance during the launch phase. However, sufficient data were available to pinpoint some of the prediction problems. As a result, flame effects and effects of booster shadowing of the CSM antennas during the launch phase were to be included in subsequent predictions. Agreement between predictions and observations during other parts of the mission was better; most discrepancies were attributed to inaccuracies in antenna-pattern data, trajectory-simulation data, or operational procedures at the ground stations.

Apollo 3 (AS-204/SC-012). - Work on the coverage analysis for the original AS-204 (spacecraft 012) mission was beset by many problems. The length of the mission itself presented the major problem. Obtaining a usable trajectory simulation proved extremely difficult. Furthermore, the fact that it was to be a manned mission made it possible to obtain good spacecraft-attitude data only for periods near critical mission events. However, a document containing recommended antenna switching and, for the first time, Doppler-frequency-shift predictions to aid in USB acquisition procedures was ready for publication on January 20, 1967. Because of the spacecraft 012 fire, the report was never distributed.

Apollo 4 (AS-501/SC-017). - The 6 months between the Apollo 3 fire and the launch of Apollo 4 were spent updating coverage documents based on changes in mission planning for Apollo 4. During this period, the efforts to computer-mechanize the mathematical model of the USB system were completed.

The AUSBCM provided accurate performance predictions for all operational USB modes. Calculations could be made for both the Block I and Block II CSM and for the LM systems. Because all system parameters were input variables, the program was very flexible with respect to respecification of parameters. For this reason, it was decided to add the capability of circuit margin as a function of mission time to AUSBCM.

The final Apollo 4 coverage analysis was published on June 5, 1967. This report included an analysis of all communications links — S-band, C-band, vhf, and uhf. For the first time, outputs from AUSBCM were used for USB predictions, and computer-generated plots were used directly in the document; this innovation saved many man-hours in document preparation.

The Apollo 4 spacecraft was a Block I spacecraft, but it provided the first test of the Block II CSM low-gain S-band cavity-backed helix antenna. The omnidirectional-antenna system consisted of four low-gain elements spaced 90° apart around the periphery of the CM near the heat-shield end. The elements were paired by connecting two diametrically opposite elements in parallel. Command switching was not available on the Block I CSM spacecraft; therefore, the antenna pair that would provide the best coverage had to be selected before launch. Based on the coverage analysis, pair A was chosen.

An unexpected problem that degraded telemetry performance occurred because of the difference in cable lengths feeding the elements of pair A. This difference in cable lengths caused a skewing of the total spectrum. Despite this problem, significant confidence was gained in the ability to predict accurately the communications-system performance for a given mission.

Apollo 6 (AS-502/SC-020). - When the preparation of the Apollo 6 coverage analysis was begun, the usual problems were encountered with obtaining measured parameters and good trajectory data. However, the first publication was distributed by mid-February 1968. Following the initial publication, several events occurred that required a revision of the entire document.

Data from the Apollo 4 mission indicated good vhf performance at slant ranges near 10 000 nautical miles. Predictions indicated that data should be good only to approximately 4000 nautical miles. It was determined that ground-station capabilities were far better than specified in the applicable Interface Control Documents. Further, it was determined that bit-error rates of 10^{-3} were being considered acceptable, compared with the 10^{-6} requirement in the P&I specifications. When these changes were incorporated in the prediction model, good agreement was achieved with the measured data. New vhf predictions were thus indicated for the Apollo 6 mission.

The expected improvement in vhf performance proved to be very valuable as the countdown to the Apollo 6 mission continued. The launch date was slipped, and it became necessary to define a new trajectory. Unfortunately, a spacecraft-attitude profile could not be found that satisfied all constraints. The thermal constraints dictated one attitude and good communications, another. When any apparent compatibility was approached, the selected attitude was ruled out because of the constraint on the middle gimbal angle on the guidance platforms. After approximately 17 iterations, a trajectory was selected that satisfied the thermal requirements and the gimbal-angle constraints and that, with judicious use of the vhf system, apparently would give reasonable communications. With regard to the backup S-band system, pair B fortunately provided the best coverage, thus eliminating the problem encountered on Apollo 4 with pair A; that is, skewing of the S-band spectrum.

Apollo 5 (AS-204/LM-1). - After the tragedy of the spacecraft 012 fire, the decision was made to use the AS-204 launch vehicle for an unmanned LM mission. This mission was designated Apollo 5 and was to be the first operational checkout of the LM subsystems. The mission was flown on January 22 and 23, 1968. The communications-systems performance analysis for the Apollo 5 mission started many months before the ultimate launch date.

This early communications-systems analysis was based on a preliminary (reference) trajectory; however, several important decisions were made as a result of this work. Analysis of the S-band system indicated that the aft (-Z) LM antenna would provide optimum S-band communications coverage during the mission. (Only one of the S-band omnidirectional antennas could be used because the capability to command switch between opposite omnidirectional antennas was not incorporated into the LM system.) However, it was shown that continuous communications could not be provided with only the aft antenna and that loss of communications could be expected whenever the antenna was shadowed by the spacecraft. This prediction was later verified when most of the S-band system problems encountered during the mission were traced to poor spacecraft attitudes.

The results of this analysis were published in a document, based on the premission reference trajectory, entitled "Apollo Communication Systems Performance and Coverage Analysis for Mission AS-204/LM-1." This document was distributed in early December 1967.

As soon as an operational trajectory was available, work began on the publication of an addendum to this document. This addendum contained signal-strength predictions based on the best premission trajectory available. These predictions agreed favorably with the signal levels observed during the mission until midway through the third revolution, when a premature shutdown of the descent propulsion system forced the selection of an alternate mission. However, postmission predictions based on the best-estimate trajectory agreed to within ± 3 decibels of actual signal-strength measurements.

Apollo 7 (AS-205/CSM-101). - The Apollo 7 mission was the first manned Apollo mission and thus provided the first opportunity to demonstrate satisfactory performance of all operational and backup communications modes. Also, because S-band omnidirectional antenna switching was performed by the crew, the Apollo 7 mission provided a good opportunity for accurately checking premission communications-system predictions against actual flight performance. In previous missions, the outputs of the omnidirectional antennas were paralleled. This arrangement caused interference between the individual antenna radiation patterns, which made accurate signal-strength predictions difficult. On the Apollo 7 mission, the low-gain antennas would be switched individually.

Because this mission was to be the first flight test of a manned Block II CSM, the MSFN provided certain communications modes for the first time. For example, the up-link and down-link voice channels provided actual voice transmissions whereas voice transmission was simulated on previous Apollo missions. On the Apollo 7 mission, voice communications were provided over both the S-band and vhf/AM links, with the vhf link being primary. Also, command, telemetry, and tracking services were provided by only the S-band system for the first time. On previous missions (using Block I CSM's), the S-band system had provided a backup capability to the uhf up-data link, the vhf telemetry link, and the C-band tracking system. In the Block II CSM, the uhf up-data link, vhf telemetry link, and C-band systems had been eliminated because of weight considerations.

The Apollo 7 performance and coverage-analysis document began a trend away from previous coverage-analysis documents, which mainly predicted communications-systems performance, toward documents that were more mission oriented. For the first time, signal-level plots were analyzed to determine antenna-switching and ground-station-handover times. As long as the mission trajectory remained unchanged, these predicted times were very useful; however, any change from the premission operational trajectory made premission predictions useless. This problem was not corrected until Apollo 9 and the advent of CAAS and real-time mission support. (The section entitled "Computer-Aided Analysis System Support" contains further information.)

From previous missions, it was known that launch-vehicle flame effects and shadowing would degrade communications at the Merritt Island Launch Area during launch. As a result of this knowledge, a recommendation was made to hand over to the Grand Bahama Island station early in the launch phase. This procedure eliminated the loss of signal encountered in earlier missions.

As on each of the previous Apollo missions, signal-strength predictions were based on the premission operational trajectory. These predictions were in very good agreement with measured signal levels until the trajectory being flown deviated from the operational trajectory. Because this situation occurred early in the Apollo 9 mission, only a few revolutions existed for which the premission predictions were useful. The degree of accuracy of the premission predictions is indicated in figures 10 and 11. It can be seen from these figures that the premission predictions were usually within 1 to 2 decibels of the measured carrier power and indicated the correct trend. Thus, plots of this type were very useful in planning major communications events such as television transmissions.

The first television broadcast from an Apollo spacecraft was telecast during the Apollo 7 mission. This telecast was received by the Texas and Merritt Island ground stations during the 45th revolution. Picture quality ranged from fair to excellent.

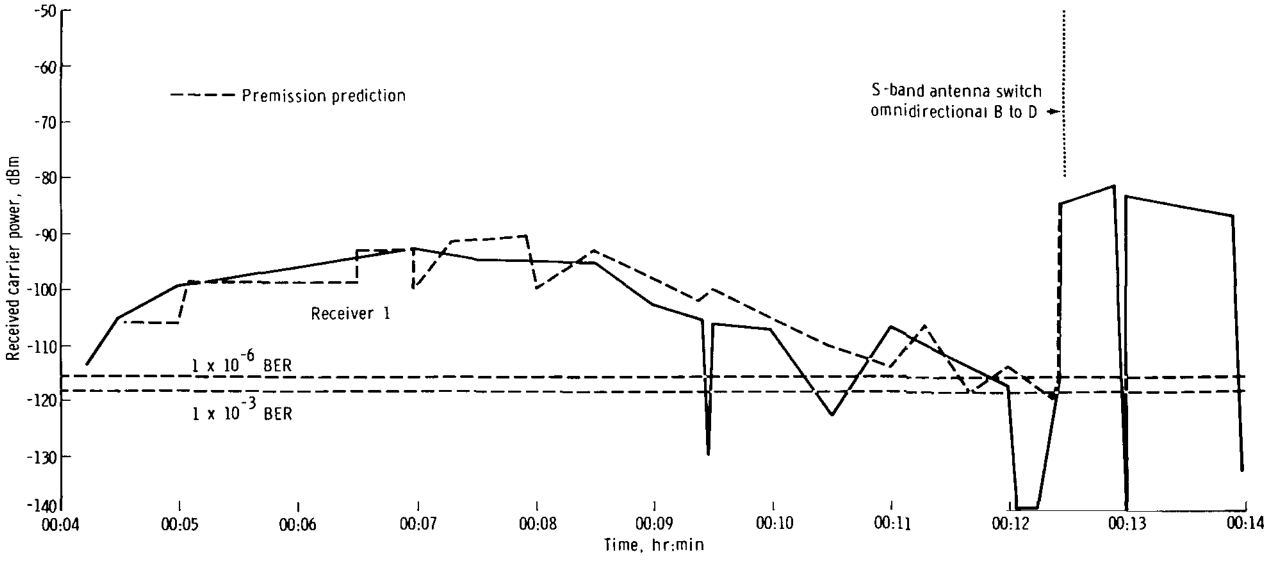


Figure 10. - Apollo 7 MSFN-received S-band carrier, Bermuda (launch).

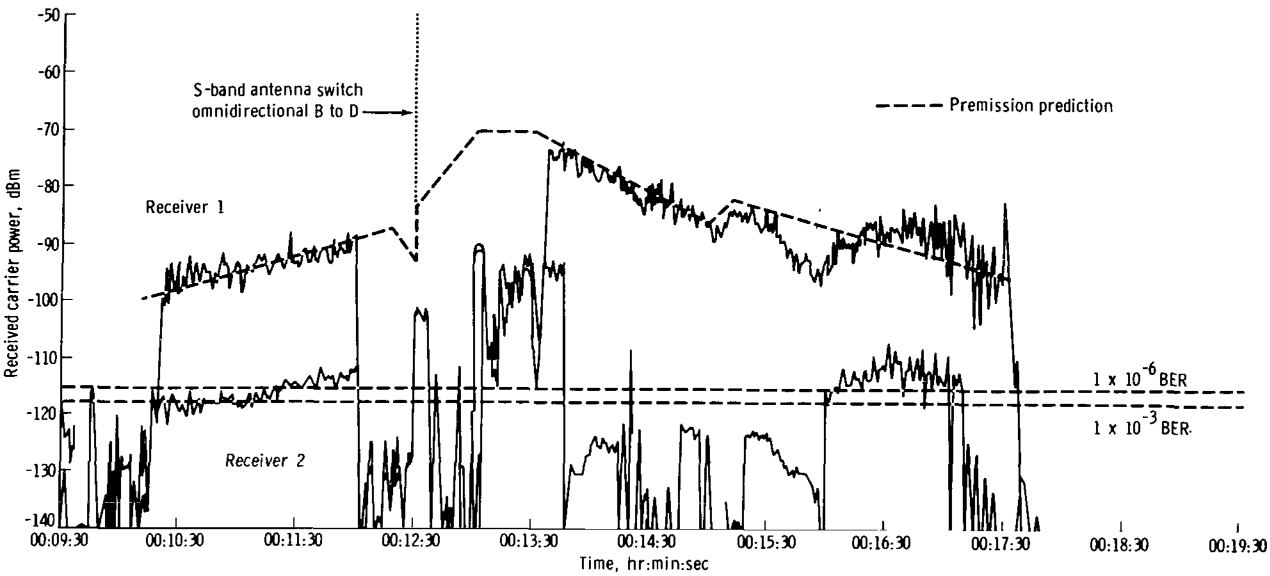


Figure 11. - Apollo 7 MSFN-received S-band carrier power, USNS Vanguard (launch to orbit insertion).

Apollo 8 (AS-503/CSM-103). - Apollo 8, the first mission to send men around the moon and return them safely to earth, was launched from the NASA John F. Kennedy Space Center (KSC) on December 21, 1968. The major communications-systems objectives for the mission were checkout of the S-band high-gain antenna and evaluation of CSM/MSFN communications capabilities at lunar distance while using the S-band omnidirectional antennas. The S-band omnidirectional antennas were a backup for the high-gain antenna and were used whenever the high-gain antenna to the MSFN line of sight was shadowed by the spacecraft.

During the translunar and transearth coasts, the spacecraft was rotated so that no one side would become overheated by the sun. This maneuver, called passive thermal control (PTC), placed severe restrictions on the operation of the high-gain antenna. During early mission planning, the possibility was investigated of orienting the spacecraft so as to achieve uninterrupted high-gain-antenna coverage. However, when all constraints placed upon spacecraft orientation during PTC were considered, the region in which this coverage was available became quite small (only a few degrees off the forward and aft ends of the spacecraft). It was also known that sloshing of fuel in the propellant tanks during PTC caused the spacecraft to precess away from a preset orientation and would thus require spacecraft attitude control. Thus, it was difficult to maintain a spacecraft attitude such that uninterrupted high-gain-antenna coverage was available.

The task of determining a spacecraft attitude that would satisfy all mission constraints while optimizing communications was assigned to MSC. As a result of the analysis performed in preparing the communications-systems performance and coverage-analysis document for Apollo 8, a PTC attitude was selected that optimized the coverage available from both the S-band omnidirectional and high-gain antennas. This optimum PTC attitude resulted in loss of high-gain-antenna coverage once during each rotation of the spacecraft and placed a much less severe constraint on spacecraft attitude than did other methods considered. By optimizing the the spacecraft attitude to achieve maximum omnidirectional-antenna gain, it was possible to communicate at lunar distance while using the omnidirectional antennas. This communications mode was used quite extensively during the Apollo 8 mission and has been used successfully in subsequent Apollo lunar missions.

Several changes were made in the communications-systems performance and coverage-analysis document for the Apollo 8 mission. For the first time, plots generated entirely by computer were used throughout the document. This procedure resulted in less time being spent preparing the plots and allowed more time for analysis. Also, for the first time, the document was arranged according to mission phase instead of communications system. This change made it possible to present results of the communications-systems analysis in a more unified form.

The trend toward a more mission-oriented document continued with the Apollo 8 document. Several appendixes were added that could be used as guidelines in making real-time decisions. These appendixes included antenna patterns to be used in determining optimum spacecraft attitudes for communications, an analysis of possible high-gain-antenna failure modes, tables giving communications-systems capabilities, and an analysis of the Apollo S-band FM modes. By the time of the Apollo 8 mission, confidence had been established in the communications-system mathematical models to predict accurately the performance of the Apollo communications system, given an accurate trajectory and correct parameters. Although the appendixes were useful in answering general questions concerning the communications system, a method of updating communications-system performance predictions during the mission was needed. Thus, the decision was made to support the Apollo 8 mission directly on a real-time basis. This support was made possible by the development of a CAAS that provided a man/computer interface. Trajectory data based on the latest tracking data were used to provide communications-system predictions in a near-real-time basis. Whenever the mission trajectory changed, these predictions were updated to account for any attitude changes resulting from the revised trajectory. These predictions could then be used to determine the optimum omnidirectional antenna and the optimum communications mode and to schedule ground-station-handover times.

As with any new system, some problems developed during the support of the Apollo 8 mission. Most of these problems involved obtaining trajectory tapes early enough to be useful in the generation of performance plots. However, the system operated successfully, and some useful inputs were made to flight controllers. Real-time support of the Apollo 8 mission was a qualified success, and continued support was requested for subsequent missions.

Before the Apollo 8 mission, it was known that the FM communications system would be operated below system threshold at lunar distance when working with the 85-foot-antenna station. Because it was planned to use the FM system to transmit television while the CSM was in lunar orbit, it was desirable to improve the FM-system performance for the Apollo 8 mission. A study to determine methods of improving FM-system performance had been initiated sometime before the Apollo 8 mission. (The section entitled "Frequency-Modulation Demodulators — Threshold Extension" contains further information.) As a result of this study and other similar studies, modifications were made to the MSFN stations in time to support the mission. In addition, the 210-foot-antenna JPL station was requested to support the mission. As a result of this effort, high-quality television pictures were received from the moon on Christmas Day, 1968.

Apollo 9 (AS-504/CSM-104/LM-3). - Apollo 9 was a 10-day earth-orbital mission and was the first mission to include both manned CSM and manned LM operations. Because this was the first manned LM mission, most of the mission communications objectives involved the LM communications system. The most important of these objectives were to demonstrate the capability of the various LM communications modes, to demonstrate proper operation of the LM communications equipment, to use the S-band antenna-select switch to select the optimum LM omnidirectional antenna, and to demonstrate the successful operation of the LM steerable antenna. The Apollo 9 mission also presented the first opportunity to demonstrate the integrated communications systems of the LM and CSM and to determine the performance of the S-band, vhf, and EVA communications systems in preparation for a lunar-landing mission. Because the CSM high-gain antenna had performed so well during the Apollo 8 mission, it was not tested during the Apollo 9 mission.

Tests of the LM communications system revealed several problems that affected the Apollo 9 mission. Some of these problems are described in the following paragraphs.

The success of the relay-mode communications was primarily dependent on proper configuration of communications systems and experienced operation of voice-operated circuit (VOX) and squelch sensitivity settings. This mode required an exact setting of VOX and squelch. Too high a setting on either the VOX or squelch would cause a loss of relay voice communications, and too low a setting on either the VOX or squelch could introduce unwanted noise into the relay communications.

With LM down-link modes 8 (baseband voice and high-bit-rate telemetry) and 4 (backup voice and low-bit-rate telemetry) and with CSM down-link mode 8 (backup voice and low-bit-rate telemetry), telemetry was inhibited during speech periods.

Despite these problems, the LM and CSM communications systems operated very well during the mission, and most of the problems that did occur were attributed to operator unfamiliarity with the LM communications system.

The Apollo 9 communications-systems performance and coverage-analysis document was similar to the Apollo 8 document except that, because of the length and complexity of the mission, the Apollo 9 document was larger. Some method of reducing the length of the document was needed. The received-carrier-power plots had been changed to a small extent. For the first time, the carrier powers for opposite antennas were plotted on the same graph, which made it easier to determine the optimum S-band omnidirectional antenna.

The Apollo 9 mission was supported by the CAAS on an as-requested basis. The system was used to select the optimum LM S-band omnidirectional antenna during EVA and during the LM ascent propulsion system (APS) burn-to-depletion maneuver. Because the crewman in the LM during EVA was not close to the antenna switch, it was not possible to switch omnidirectional antennas as the LM changed attitude. Thus, it was necessary to select an antenna that provided adequate communications during the entire maneuver. A similar situation existed for the APS burn-to-depletion maneuver. It was desired that communications be maintained for as long as possible after the APS burn. The CAAS was used to determine which LM omnidirectional antenna the crewmen should select before leaving the LM. In both of these cases, the selected antenna provided good communications throughout the maneuvers.

Apollo 10 (AS-505/CSM-106/LM-4). - The Apollo 10 mission, the first lunar mission to include both CSM and LM operations, provided the opportunity to evaluate LM omnidirectional- and steerable-antenna performance at lunar distance. This mission was also the first during which color television was transmitted from the CSM.

Because Apollo 10 was only the second mission on which the LM steerable antenna was to be used and the first on which it was to be used at lunar distance, it was desirable to have a ranging mode using the LM omnidirectional antennas. To provide a ranging capability when using the LM S-band omnidirectional antennas, it was necessary to provide a special ranging-only mode designated LM PM mode 11. (Simultaneous ranging and voice transmission was not possible because the selection of backup voice disabled the ranging channel.) Mode 11 was selected by setting the voice and PCM switches to the "off" position and by turning on the ranging channel. Preflight analysis indicated that, at lunar distance, LM PM mode 11 would have a positive circuit margin of approximately 4 decibels when the LM S-band omnidirectional/85-foot MSFN antenna combination was used.

Premission analysis for the Apollo 10 communications-systems performance and coverage-analysis document indicated that signal strengths would be too low to provide good quality color television from the CSM in lunar orbit if the high-gain antenna and an 85-foot MSFN antenna were used. Thus, it was decided to use the 210-foot antenna at Goldstone to receive television transmissions from lunar distance.

The Apollo 10 communications-system and coverage-analysis document provided more than signal-strength predictions. The document also provided omnidirectional-antenna selection recommendations, predictions of when CSM high-gain- and LM steerable-antenna blockage would occur, ground-station handover-time recommendations, and operational aids that could be used to determine the optimum communications for a given spacecraft range. The operational aids were used during the translunar and transearth coasts not only to determine the optimum communications-system configuration but also to check system performance.

As in previous communications-systems analysis documents, it was recommended in the Apollo 10 document that CSM omnidirectional antenna B be selected at lift-off and that omnidirectional antenna D be selected at approximately 6 minutes after lift-off. During the Apollo 10 launch, this antenna switching from B to D was not performed until approximately 10 minutes after lift-off. This delayed switching resulted in low signal levels and the loss of some data at Bermuda. However, received up-link and down-link S-band signal levels corresponded to predictions throughout most of the mission.

During the translunar and transearth coasts, communications were maintained by crew switching between omnidirectional antennas or between omnidirectional and high-gain antennas, by ground-command switching between omnidirectional antenna D and the high-gain antenna, or by ground-command switching between omnidirectional antennas B and D. The latter procedure had been recommended in the Apollo 10 communications-systems analysis and rf coverage document and was used with excellent results during crew rest periods.

The Apollo 10 mission was actively supported by the CAAS, but several problems occurred with the system during this mission. Most of these problems were caused by unfamiliarity with the system; however, a few major problems included input-trajectory tape errors, CAAS program errors, and slow plot production. Some of these problems were corrected during the mission, and the rest were corrected in time to support the Apollo 11 mission.

Despite minor problems encountered with the system, several contributions to the mission were made by the CAAS. Plots were generated that were useful in determining system performance and in selecting ground-station-handover times. A recommendation to use an 85-foot antenna instead of the 210-foot antenna for the last translunar-coast television transmission was made on the basis of CAAS data. This recommendation was accepted, and the resulting television pictures were excellent.

Apollo 11 (AS-506/CSM-107/LM-5). - Apollo 11, the first manned lunar landing, was launched from KSC on July 16, 1969. This mission was the most complex ever attempted in the history of space flight and was a severe test of the Apollo communications systems.

It was highly desirable that the first lunar-landing attempt be successful. However, a mission rule required that the landing be aborted if voice and high-bit-rate telemetry were not available throughout the lunar-landing phase of the mission. It was recognized that because of low signal levels, these channels could not be maintained when using an omnidirectional antenna and an 85-foot ground antenna. However, because the 210-foot antenna had been requested to support the mission, a performance analysis was initiated to determine if a 210-foot antenna would increase the down-link signal power enough to provide the required communications if the LM steerable antenna lost lock. This analysis showed that voice, high-bit-rate telemetry, and biomedical data (LM PM mode 1) could be received and processed by a ground station using a 210-foot antenna. As a result, it was recommended that the lunar landing be delayed one revolution to obtain 210-foot Military Affiliate Radio Stations (MARS) coverage. A procedure was then developed for switching to an omnidirectional antenna should the steerable antenna lose lock and should the spacecraft fail to reacquire the signal using the steerable antenna. During LM descent, the steerable antenna did lose lock, resulting in a drop in signal level to a level comparable to that from an omnidirectional antenna. The MARS 210-foot site provided the necessary voice and high-bit-rate data, and the lunar landing was not aborted.

Omnidirectional-antenna switching recommendations for all mission phases were provided by the Apollo 11 communications-systems performance and coverage-analysis document. These recommendations were given in the form of bar charts and tables that provided optimum-antenna information, antenna-blockage information, and recommended antenna-switching times. The Apollo 11 document also contained plots of LM steerable-antenna coverage during powered descent and ascent. The descent and ascent trajectories were plotted on a diagram of the LM steerable-antenna blockage region. Examples of these plots are shown in figures 12 and 13. By using these diagrams, it was possible to determine when tracking of the steerable antenna would be impaired during the ascent and descent phases of the mission.

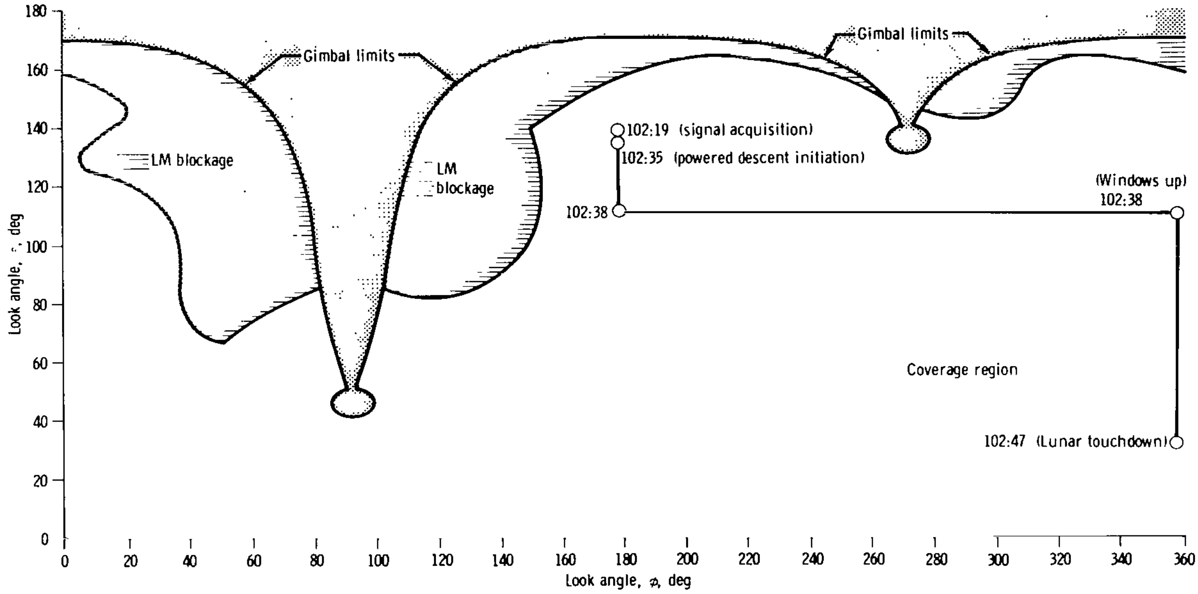


Figure 12. - Apollo 11 LM steerable-antenna coverage (powered descent period).

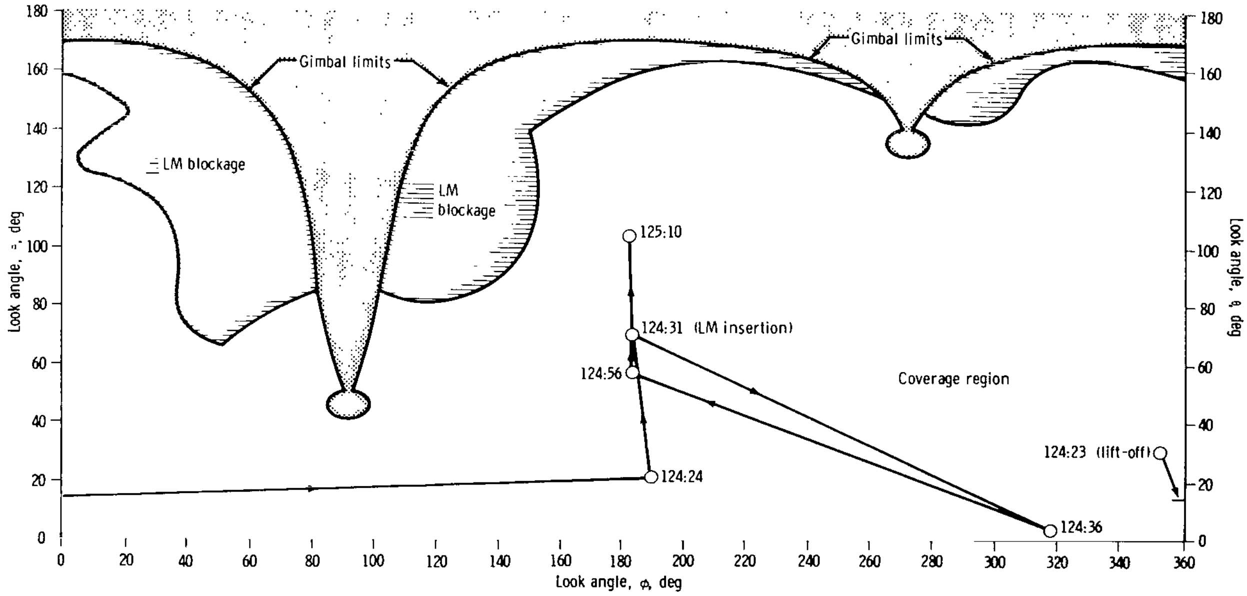


Figure 13. - Lunar module steerable-antenna coverage (ascent period).

As can be seen from figure 12, the Apollo 11 descent trajectory was not expected to result in structural blockage of the steerable-antenna line of sight. However, as mentioned previously, the steerable antenna did lose track during LM descent. An analysis of the LM received-signal level during descent indicated that the loss of track was probably caused by the steerable-antenna tracking into or near the LM structure. The LM manufacturer was requested to update the vehicle-blockage plot. Plotting the Apollo 11 descent trajectory on this graph (fig. 14) shows that the steerable-antenna loss of track could have been predicted, and thus prevented, if a correct vehicle-blockage diagram had been available. Corrected blockage plots were used in the analysis for Apollo 12 and subsequent missions.

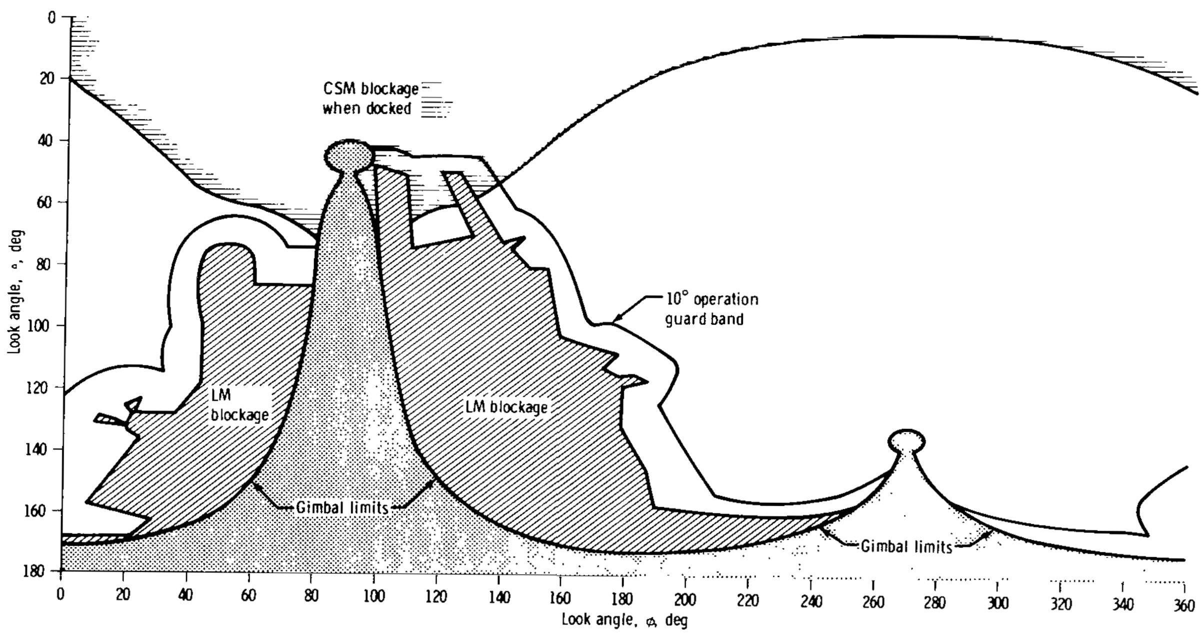


Figure 14. - Lunar module steerable-antenna vehicle blockage diagram (θ / ϕ).

The Apollo 11 communications-systems performance and coverage-analysis document was different from the Apollo 10 document in several respects. Whereas the Apollo 10 document had been published as one large volume, the Apollo 11 document was published in five volumes. A different aspect of the mission was covered in each volume. Also, the operational aids were expanded and published as a separate volume. The operational aids were rapidly becoming the most important part of the document. Because the only portion of lunar missions that changes significantly from mission to mission is the lunar-operations phase, the communications-systems analysis and rf coverage documents for future missions would consist of only the operational aids and communications-performance analysis for portions of the lunar-operations phase (LM descent, LM ascent, etc.). This change in the scope of the document reduced the size and preparation time without sacrificing usefulness.

The CAAS was used extensively both before and during the mission. Before the mission, the system was used in the analysis that showed that LM PM mode 1 would provide satisfactory communications from the LM during descent when an omnidirectional antenna was used in conjunction with a 210-foot ground antenna. During the mission, the CAAS was used to support flight control and the mission-evaluation team. Plots of spacecraft elevation were supplied to MCC for each ground station that had contact with the spacecraft at a specified time. The plots were used by MCC to inform the ground stations of expected acquisition and loss-of-signal times and to determine times when the received signal strength could possibly be reduced because of low elevation angles or ground-station tracking limits. Plots of received carrier power (signal strength) were provided to MCC and the mission-evaluation team. These plots were used to determine if the spacecraft communications systems were operating as expected.

For the most part, the CAAS operated successfully throughout the mission. This fact is probably best exemplified by a quote from the system log: "Mission Control said the data we are giving them is excellent and working out very well. No other action occurred during this shift other than 'The Eagle landed.'"

The Computer-Aided Analysis System

By Carroll T. Dawson

The problem experienced in responding quickly to requests for performance predictions for the Apollo 6 mission brought into focus a long-recognized need for a more efficient method of generating coverage predictions. At this time, the Systems Analysis Branch was in the process of developing a generalized communications-system modeling capability using computer graphics as an interactive interface with a large-scale computer. This project became known as the CAAS.

It was decided to redirect the initial CAAS effort toward providing an efficient and flexible method of providing mission communications-performance predictions. This decision meant that maximum effort had to be devoted to implementing a special-purpose system capable of generating plots of circuit margin or carrier power as a function of mission time. A deadline for implementation was established that would allow for support of the Apollo 8 mission in December 1968. To meet this date, it was necessary to use existing capability where possible. This necessity led to use of the IBM 360/44 computer and the digital television display system (DTDS), both of which were a part of the data-systems development laboratory.

Additional hardware and peripheral computer equipment available for use included a large-scale Gerber X-Y plotter, two continuous-loop random-access-memory (RAM) units, and three tape-drive units for the computer. The DTDS included a console with a three-screen cathode-ray-tube (CRT) display and alphanumeric keyboard for interface with the computer.

The basic plan for implementation required that software be developed for the IBM 360/44 that would use only existing equipment to provide communications-performance predictions based on the latest available spacecraft-trajectory and spacecraft-attitude information for any anticipated or desired communications mode and antenna/power configuration.

The computer programs necessary to accomplish these objectives were divided into three general areas: machine-dependent subprograms, graphics and control generation, and analytical calculations. The machine-dependent programs included those subroutines necessary to perform the following functions.

1. Convert Univac 1108 FORTRAN-compatible magnetic tapes to IBM 360/44 FORTRAN-compatible tapes

2. Command the DTDS to perform various functions such as clear a display, draw a vector, or print an alphanumeric character

3. Generate an output tape capable of driving the Gerber plotter to make a hard-copy graph of the output data

4. Store and retrieve background display data from the RAM units

The graphics and control subprograms included all routines necessary to control the interaction between man and machine. These routines were written in the FORTRAN IV language to make them as machine-independent as possible. The basic functions provided were input, output, and postanalysis.

The input program was designed to accomplish three basic functions. First, the program was to display concise instructions to the analyst working at the display console. These instructions enabled proper sequencing of control and eliminated the need for any programing expertise on the part of the analyst. Second, the input program accepted parameters input to the computer by the analyst at the console. Finally, the input program included an error check to ensure that the desired system was configured properly and then set up the necessary flags and parameters in the computer to begin the performance analysis.

The output program was designed to accept data from an array in the computer memory, to scale these data, and to display them on one of the CRT display screens. All pertinent parameters and configuration information were written on the output display.

The postanalysis program provided the capability to change parameters, configuration, or the graphic display without a complete restart of the system. As an example, the spacecraft transmitting power, the mode of operation, and the scaling of the graphic display could be changed simply by making the proper selections from the postanalysis displays.

The analytical calculations were of two types: communications-system performance modeling and trajectory-related parameters. The mathematical model implemented was an extension of the comprehensive model discussed earlier. The basic calculations for a particular spacecraft system were made using AUSBCM on the computation-center processors. The results of these calculations were output onto magnetic tape and used as an input to the CAAS. As in AUSBCM, the basic calculations are modified according to the changes in spacecraft-antenna gains and actual range. However, in the CAAS, the calculations are further modified to reflect parameter changes input through the console.

The second type of calculation relates to spacecraft trajectory and ground-station location. All trajectory and ground-station information used in the initial CAAS implementation plan was generated by the Apollo Reference Mission program. The spacecraft-to-ground-station range, elevations, and azimuth and the spacecraft look angles were all input to CAAS by means of magnetic tape. Thus, all that remained was for the CAAS programs to search the proper data for the conditions defined by the analyst.

The CAAS was ready for operation shortly before the Apollo 8 mission. However, because of the many procedures being implemented for the first time, it was impossible to check out the system capability thoroughly. Arrangements had been made with the Real Time Auxiliary Computing Facility to provide trajectory- and attitude-related parameters updated at regular intervals. Further arrangements had been made with the Data Reduction Complex (DRC) to obtain trajectory parameters based on telemetered spacecraft attitude. These data were to be provided at 4-hour intervals throughout the mission. These interfaces were not completed in time for any simulations; in fact, no data were received from the DRC during the mission. Difficulty in obtaining accurate attitude predictions for the 12-hour trajectory simulation seriously reduced the effectiveness of the CAAS activity during the Apollo 8 mission.

The experience gained during Apollo 8 produced several modifications to the CAAS structure. The primary change was the introduction of the capability to simulate spacecraft attitude through input from the console and to generate data only for the selected ground station. This procedure substantially reduced the required data storage and eliminated the problems involved in predicting attitude for long periods. Most significantly, however, this procedure reduced the required trajectory-data input from external sources to the spacecraft position in inertial geocentric coordinates as a function of time. These data are readily available from virtually every trajectory source.

Other modifications to the CAAS increased its utility and efficiency. By the time of the Apollo 11 mission, the operating structure was considered a major milestone in communications-performance prediction capability. A summary of the selections and options provided at the time of the Apollo 11 mission is given in table V.

TABLE V. - SUMMARY OF CAAS SELECTIONS AND OPTIONS

Selection	Option
Spacecraft	LM or CSM
Link	Up link or down link
Mode	All defined operational modes
Antenna system:	Omnidirectional or high gain
Omnidirectional	Any combinations
High gain	Beam width
Spacecraft or ground-station transmit power	Keyboard input
System temperature source	Quiet sky or moon at zenith
Ground station	Any
Station pass time	Keyboard input or choice from calculated pass time
Output objective	Carrier power, circuit margin (for selected channel), elevation, azimuth, θ, ϕ, or Doppler[a]
Trajectory source	Tape dish file
Attitude source:	From trajectory source on keyboard
Keyboard	Time function on constant yaw, pitch, and roll.
Reference stable member matrix	Keyboard on card input
Interpolation	Minimum desired points per time period
Spacecraft configuration for antenna patterns	CSM: CSM/spacecraft-LM adapter/Saturn IVB; CSM/LM descent stage; CSM/LM ascent stage; CSM; CM
	LM: Docked or undocked

[a]Ground-station terrain obstructions or keyhole constraints are indicated on each plot.

SYSTEM DEFICIENCIES, MODIFICATIONS, AND IMPROVEMENTS

The analyses in this section concern the areas of system-performance deficiencies and equipment modifications and the improvements that resulted. The design criteria for selecting the S-band-carrier PM and FM modulation indices and the transponder turnaround ratios are discussed first. The S-band receiver noise temperature and its effect on system performance are discussed next. The third discussion is of the FM-mode performance deficiency that resulted in a change in the MSFN FM demodulators and a concentrated effort to reduce CSM Block II S-band circuit loss. The spacecraft S-band low-gain antennas are discussed with respect to the effect on rf coverage and system performance. Finally, discussions of backup-voice interference with the telemetry channel, the signal-design analysis of the extravehicular communications system (EVCS), and the telemetry- and voice-subcarrier interference with LM color television transmissions are presented.

Selection of S-Band Carrier Modulation Indices

By G. Dickey Arndt

The Apollo USB system has a modulation spectra varying from narrowband voice and telemetry to wideband television and ranging data. The narrowband information channels are modulated onto subcarriers before modulation onto the S-band carrier, while the wideband information is modulated directly onto the carrier. Early in the Apollo Program, an analysis for selecting the modulation indices of the various information channels was undertaken by MSC and three contractors. The results of the study, as documented in the original issue of the CSM and LM P&I specifications, defined the optimum modulation indices for both the up-link and the down-link S-band communications modes (refs. 5 to 7). In addition, the spacecraft-transponder turnaround ratio also was defined during the modulation index (MI) optimization analysis.

The optimization study was based on the mathematical model that describes the performance of each information channel in the S-band system and the study that grouped the information channels into modes or carrier-transmission combinations. Using the following guidelines as the design philosophy, the individual modulation indices were selected for each channel in each mode defined.

1. The up-link and down-link subcarrier modulation indices shall yield maximum first-order sideband power and equal communications margin for each subcarrier.

2. The up-link subcarriers are (because of the system design) remodulated onto the down-link carrier along with the range code and, consequently, degrade the down-link performance. Therefore, this degradation to the down-link channels will be minimized by selecting the up-link modulation indices and the transponder turnaround ratio in some optimum manner. (Although this guideline leads to degradation of the up-link performance, the rationale for improving down-link performance at the expense of the up-link channels is justified because the up link is considerably stronger as a result of the large transmitter on the ground.)

The design criteria, as given in references 5 and 7, were intended to yield equal circuit margins for the CSM and LM information channels (voice and telemetry) within a particular PM communications mode. Thus, the information channels would nominally have the same minimum power requirement within a particular up-link and down-link mode. Because of equipment tolerances, however, this condition was not realized in practice.

The optimization procedure for the down-link FM channels differed from that of the PM channels. Generally, the FM design criterion was that the carrier-frequency demodulator should reach threshold at the same rf level for all channels within each communications mode. The FM signal power would then be distributed among the various channels in relation to the threshold characteristics of each channel. This design criterion would maximize the communications range for the FM modes. Additional FM signal-design guidelines were as follows.

1. The carrier-frequency demodulator and the subcarrier demodulator must reach threshold at the same input-signal level. (This criterion determines the peak frequency deviation of each channel.)

2. The predetection bandwidth BW of the carrier-frequency demodulator is determined by Carson's rule; that is, $BW = 2(\Delta f + f_m)$ where Δf is the peak frequency deviation and f_m is the maximum modulation frequency. (Carson's rule applies to sinusoidal modulation and allows 98 percent of the signal energy to pass. Thus, the wideband television signal is band-limited by the predetection bandwidth; however, the associated degradation is negligible.)

3. For modes with multiple subcarriers, the peak carrier deviation caused by all subcarriers is equal to not more than one-half the predetection bandwidth.

In retrospect, the Apollo PM-communications-channels performance indicates that the signal-design philosophy and subsequent selection of the S-band carrier modulation indices for the PM modes in the Apollo S-band system represented good engineering judgment and analysis.

The FM signal design probably would have different criteria for selecting the peak frequency deviations. The characteristics of threshold-extension demodulators, such as the PLL of the frequency-modulated feedback demodulators, would be taken into consideration when designing new FM systems.

S-Band Receiver Noise Characteristics

By James A. Porter

Radio noise, much like the static commonly heard in AM radios, is inherent to every radio receiver. Receiver noise is thermal in nature, and communications engineers often use a quantity called the "effective noise temperature" to compare different receivers. In general, the higher the noise temperature, the more noise power present and the stronger the received signal must be to recover the transmitted information (voice, telemetry, etc.). The selection of receivers for the Apollo USB spacecraft and ground stations was based on minimizing the noise temperature within the constraints imposed by reliability, weight, volume, cost, and availability. Obviously, the constraints were much more restrictive for the spacecraft than for the ground stations; hence, the noise temperature of the spacecraft receivers was higher than that of the MSFN receivers. Spacecraft-receiver design resulted in typical noise temperatures of 2600° K for the CSM and LM receivers. These values were not cause for major concern, because the ground stations could be equipped with powerful transmitters (10 000 watts) and provide a strong up-link signal to the spacecraft. The down link was the critical link; it had to carry more information with much lower transmitter power (approximately 20 watts). The low-noise receivers required at the ground stations to recover the weak signals from the spacecraft — signals that would travel approximately 215 000 nautical miles from the moon to earth — are discussed in the remainder of this section.

The ground receiver was designed to receive the weak signal coming from a spacecraft near the moon. Consequently, the gain distribution in the receiver was originally set to provide the lowest noise temperature possible at weak signal levels. Subsequent tests showed that the receiver noise temperature was constant, and minimum, for carrier power levels less than approximately -125 dBm. (Signal levels as low as -140 to -145 dBm could be anticipated for some low-power modes, such as CSM emergency key with bypass power.) As the carrier signal level increased above -125 dBm, the noise temperature also increased, as shown by the upper curve in figure 15.

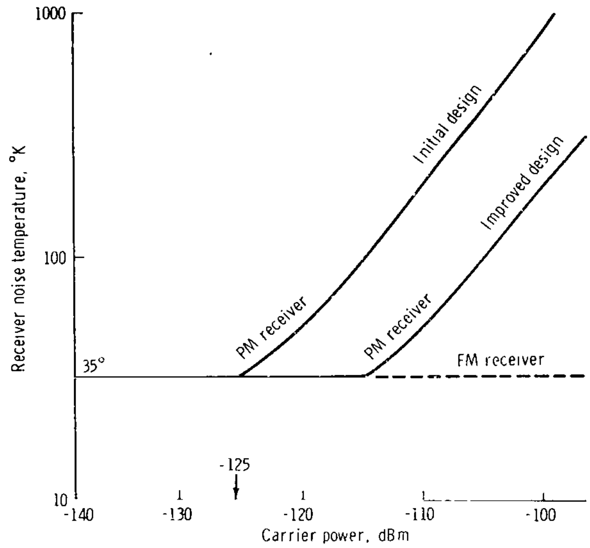


Figure 15. - Receiver noise temperature, cooled parametric amplifier ground station.

The -125 dBm breaking point, or "knee," of the curve was found to be very important. At -125 dBm, the SNR was adequate for PRN ranging, emergency key, and low-bit-rate telemetry. When increasing the carrier signal level above -125 dBm, the SNR still continued to increase, though at a diminishing rate (because the receiver thermal noise was beginning to increase nearly as fast as the signal), up to the point at which any further increase in carrier power produced a corresponding increase in noise. This final improvement above -125 dBm was sufficient to ensure good voice communications. However, the maximum-attainable SNR was not adequate for high-bit-rate telemetry (51.2 kbps). Thus, the knee of the curve posed a serious design deficiency.

Subsequent analyses and tests by JPL, GSFC, and MSC personnel presented several alternate proposals for redistributing the gains of the receiver to shift the knee of the curve toward the right (fig. 15). The gain-distribution plan subsequently adopted, which eliminated the design deficiency, is shown by the lower curve in figure 15.

These curves are applicable to the PM receiver; the FM-receiver noise temperature, as illustrated by the dashed lines in figure 15, remains constant because it is not a function of the received-carrier signal level. The problem discussed pertained only to the PM receiver.

Frequency-Modulation Demodulators — Threshold Extension

By Frank J. Loch

A special FM test series conducted in 1966 at MSC indicated that the CSM FM channels exhibited negative circuit margins at lunar distance under worst-case conditions. A negative circuit margin implies that the operational performance requirements for a particular information channel will not be satisfied. Circuit-margin values of approximately -1.5 decibels were obtained from these early test results for the CSM playback-voice and telemetry modes (CSM FM modes 1 and 2) and the CSM television mode (CSM FM mode 4). The negative margins were based on an 8-decibel mode-as-a-whole SNR required in the predetection bandwidth of the MSFN carrier-frequency demodulator.

Two primary factors contributed to the degraded CSM FM channel performance: (1) the CSM cable losses were excessively high, reducing the ERP from the vehicle, and (2) the MSFN carrier-frequency demodulator did not meet the specified performance requirements. The cable-loss problem was later minimized by the installation of new low-loss cables in the spacecraft. (The section entitled "System Circuit Loss" contains further information.)

A solution to the MSFN FM-demodulator performance problem was more difficult to obtain and, consequently, both MSC and GSFC initiated programs early in 1967 to improve the performance of the CSM FM modes.

The degraded performance of the MSFN FM demodulator was primarily related to the threshold characteristics of the device for each of the information channels. Therefore, the following discussion is presented to clarify the meaning of FM threshold and its significance relative to the performance of the Apollo communications system.

By definition, the criterion for evaluating the performance of an FM demodulator is based on the ability of the device to provide a linear relationship between the output and input signal-to-noise ratios. The useful operating range of all FM demodulators, however, is limited by the fact that this relationship, or transfer characteristic, becomes nonlinear below a certain value of input signal-to-noise ratios. This value of input SNR is called the "point of threshold" for the demodulator.

Because it is difficult in most cases to determine the exact value of input SNR that divides the linear and nonlinear regions of the performance curve, it is necessary to define a reasonable criterion for determining the threshold point.

One accepted definition of FM threshold is based on the graphical determination of the specific input-SNR value the corresponding output SNR of which occurs exactly 1 decibel below an extension of the linear portion of the transfer curve. This method of defining FM threshold is illustrated in figure 16 and will be used consistently throughout this discussion.

The occurrence of threshold in an FM system can also be defined in terms of the demodulator output-noise characteristics. In general, when the demodulator is operating with values of input SNR greater than 10 decibels, the output-noise spectrum is parabolic, and the amplitude distribution has a characteristic called "Gaussian." As the input SNR decreases, the output-noise voltage is punctuated with occasional high-amplitude noise spikes having either positive or negative polarity. These noise impulses become more frequent as the input SNR is reduced below 10 decibels. For the region of input signal-to-noise ratios between 0 and 10 decibels, the output-noise power increases at such a rate that the slope of the SNR transfer curve becomes much more severe than the slope of the linear portion. This implies that a small change in input SNR results in a relatively large change in output SNR (fig. 16).

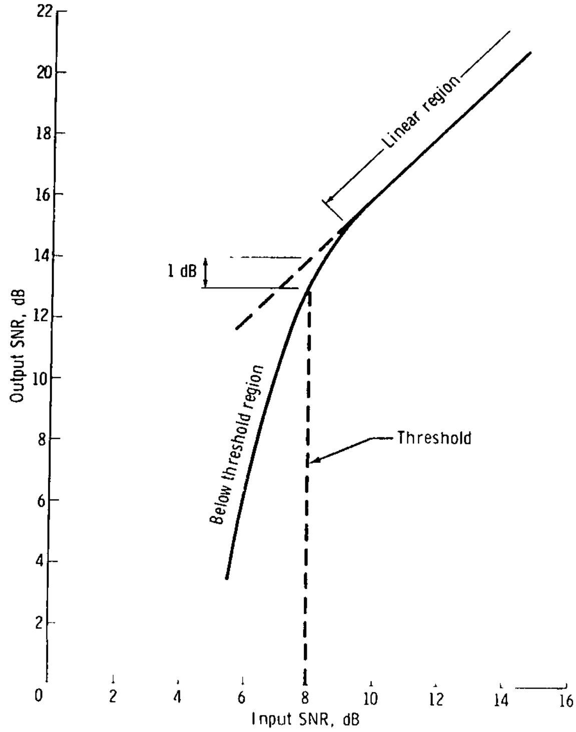


Figure 16. - Graphical determination of FM threshold for a typical demodulator SNR transfer curve.

The energy in the individual noise spikes (called click noise) at the output of an FM demodulator contributes significantly to the total output-noise power. In addition, the impulsive nature of click noise causes it to be much more degrading to the demodulated signal than is the Gaussian output noise. Click noise is a primary factor contributing to the occurrence of threshold in an FM system.

The FM optimization program initiated by MSC personnel in 1967 consisted of two main efforts.

1. To investigate the FM threshold phenomenon with the purpose of developing threshold-extension techniques that could be implemented at the output of the MSFN demodulator to provide improved performance

2. To investigate alternate demodulation systems with the purpose of obtaining a replacement for the MSFN demodulators that would improve the performance of the Apollo FM modes

The MSC FM optimization study resulted in the development of a threshold-extension device that could be implemented at the output of the MSFN demodulator to provide improved SNR performance. The device provides SNR improvement through the detection and elimination of threshold-noise impulses in the demodulator output. Elimination of click noise reduces the effective output-noise power, which in turn increases the output SNR.

A series of tests was conducted at MSC to evaluate the performance of the threshold-extension device using actual CSM equipment and a simulated rf path in conjunction with actual MSFN equipment. These tests indicated that the device could provide a threshold extension of approximately 2 decibels for the CSM playback voice and television modes.

As a result of the performance-evaluation tests, a program was initiated to fabricate six operational threshold-extension devices similar to the engineering unit tested. The six devices would be made available to GSFC for possible implementation at the three 85-foot-antenna MSFN sites to support Apollo 8 and subsequent lunar missions. Construction of the six units began in 1968, and they were made available to GSFC before the Apollo 8 mission.

At the same time that the threshold-extension device was being developed at MSC, an effort was being made to obtain an alternate demodulator for the MSFN stations that would provide the required threshold performance.

As one possible solution, MSC personnel initiated a developmental contract early in 1968 to modify a Lunar Orbiter frequency-modulated feedback demodulator to be compatible with the Apollo FM modes. Extensive systems tests at MSC indicated that the modified frequency-modulated feedback demodulator provided a 5-decibel threshold improvement of the CSM playback voice modes compared with the original MSFN demodulator. This improvement was more than sufficient to provide the required 70-percent word intelligibility for the CSM playback voice modes at lunar distances. Cost and schedule constraints, however, prohibited the procurement of the modified frequency-modulated feedback units in time for the Apollo 8 mission.

A developmental contract for the design and fabrication of an FM-demodulation test set was also initiated at MSC. This test set was to be used to determine the maximum threshold improvement for the FM channels. If the frequency-modulated feedback demodulator did not provide significant threshold extension, the FM test set was to be used to ascertain what improvements were possible using the latest PLL techniques.

The test set has extreme flexibility and incorporates the latest concepts of FM-demodulators optimization. Specifically, the test-set demodulator includes the following features: (1) an automatic frequency control for the input, (2) a selectable-limiter/automatic gain control (AGC) i.f. amplifier that provides maximum signal conditioning for various modulation characteristics, (3) an automatic loop stress circuit that compensates the voltage-controlled-oscillator drift and offsets, and (4) a complex phase-lock demodulator with selectable predetection and loop bandwidths. This demodulator has a "multiple loop filter" configuration that incorporates a low-pass loop filter for the baseband signals (baseband voice or television) and narrow bandpass filters for the telemetry and voice subcarriers. It is also possible to select either first- or second-order loop filters.

Because of its versatility, the test set is being used as an analytic tool for determining optimum demodulator configurations for advanced programs.

A GSFC study in 1968 indicated that the MSFN demodulators were not optimally alined for the Apollo FM signal characteristics. The improper alinement was considered a primary cause of the MSFN-demodulator degraded threshold performance; therefore, GSFC personnel initiated a program to realine the MSFN demodulators. Systems tests were performed on a GSFC-realined MSFN demodulator at MSC. The tests indicated that a slight improvement (approximately 1 decibel) in threshold performance was obtained over an untuned MSFN unit. This improvement, however, was not sufficient to justify the designation of the realined demodulators as a solution to the CSM FM circuit-margin problem. In addition, the MSC tests performed in June 1968 (in conjunction with GSFC) uncovered a compatibility problem between the realined demodulator and the MSFN isolation amplifier used for the playback voice modes.

In a later series of tests, GSFC and MSC engineers also evaluated a new PLL demodulator to determine its performance capability as part of the MSFN system. These MSC tests, conducted in September 1968, indicated that the new demodulator provided a significant performance improvement over the original MSFN demodulator for the CSM FM modes. However, the tests also indicated that a possible compatibility problem existed between the new demodulator and the MSFN receiver. The GSFC personnel initiated special actions to resolve the demodulator/receiver compatibility problem and, although full compatibility was not achieved, the new demodulators were successfully used at the three 85-foot-antenna MSFN stations to support the Apollo 8 mission.

An MSC threshold-extension device was also used in series with a new demodulator at the 85-foot- and 210-foot-antenna MSFN stations at Goldstone during the Apollo 8 mission.

Tests performed shortly before the mission indicated that the device could provide additional SNR improvement for the CSM playback voice modes. However, the threshold-extension device was not used during subsequent missions for two reasons.

1. The new demodulator provided sufficient performance enhancement for the CSM FM modes such that additional improvement provided by the threshold-extension device was not necessary.

2. Because the MSC threshold-extension device was designated primarily for operation with the original MSFN demodulator, it was not completely compatible with the new demodulator. This incompatibility reduced the performance-improvement capability of the threshold-extension device.

After the Apollo 8 mission, further modifications to the new demodulators made the units more fully compatible with the MSFN stations. The modified demodulators have been successfully used to support all missions since Apollo 8.

System Circuit Loss

By Harold R. Rosenberg

The importance of system circuit loss (including cable loss) is indicated by its effect on sizing the required performance characteristics of transmitters, receivers, and high-gain antennas. During the Apollo Program, a major conflict evolved concerning the Block II CSM cable losses with regard to their effect on circuit-performance margins. The effort to resolve the deficiency in the performance of the FM mode resulted in MSFN FM-demodulator modifications and in significant trade-offs between CSM cable losses, high-gain-antenna on-axis gain, and FM-transmitter output power. (The latter also led to the selection, as far as possible, of the higher performance black boxes for the lunar missions.) With regard to the Block I CSM circuit losses, the measured values agreed with the specified values and did not effect required overall systems performance.

The LM spacecraft circuit losses were essentially stable throughout the program. Some net changes did evolve because of weight-reduction programs; that is, cables were rerouted and some cable types were changed, but no specific tasks were undertaken to reduce LM circuit loss to alleviate a performance deficiency.

Following the definition and specification of the CSM Block II system-performance parameters, analysis indicated that the performance of the CSM Block II FM playback modes (FM modes 1 and 2) was unacceptable (negative circuit margins) based on calculations using worst-case specified system parameters. (The section entitled "S-Band P&I Specifications" contains further information.) A concentrated effort evolved within NASA and the contractor organization to upgrade the performance of the MSFN FM demodulators, antenna gains, and applicable spacecraft parameters to overcome this deficiency. During the latter part of 1966 and in early 1967, the actual performance capability of the CSM Block II system began to become evident when measured performance data on manufactured black-box equipment became available and overall system compatibility tests began. These measured data indicated that a serious circuit-loss problem existed, that the specified CSM high-gain-antenna narrowbeam on-axis gain was not realizable without major cost and equipment changes, and that the majority of FM transmitters exceeded the specified output power by at least 1.0 decibel. At this time (according to test results), the MSFN demodulator was performing below the specified level, and antenna-gain measurements on the 85-foot antennas were too inconsistent to allow an upgrading of the specified on-axis gain.

After a contractor request to increase the specified high-gain-antenna circuit loss was rejected by NASA, a series of correspondence and negotiations was begun between NASA and the contractor and continued through 1967. The outcome was that the specified high-gain-antenna circuit losses were reduced and the specified FM transmit-power output was upgraded 1.0 decibel, compensating for the NASA/contractor-approved relaxation of high-gain-antenna narrowbeam on-axis gain specification, which was done to alleviate production (fabrication and testing) problems. Before the Apollo 8 mission, the FM demodulators had been changed by NASA to upgrade the threshold performance characteristics. (The section entitled "Frequency-Modulation Demodulators — Threshold Extension" contains further information.) After the Apollo 8 mission, an evaluation of the measured data indicated that the 85-foot-antenna gains were 1 to 2 decibels better than the specified worst-case value. Essentially, the critical performance parameters of the Apollo communications system had "matured" and resulted in acceptable performance of all the Apollo FM modes.

As indicated in the preceding discussion, circuit loss is an important system parameter when overall system performance capability is computed. Although specified system parameters may be used to predict preflight system performance at an early stage of development, it is the measured system parameters that provide confidence in predicted system performance during the actual flight. Circuit-loss measurements on installed cables are not only difficult but impossible to make under expected environmental conditions. Thus, cable losses were measured during preinstallation tests, and environmental effects were compensated for analytically by adjusting the measured cable losses in accordance with manufacturer's data on the cable. A side effect of this technique is that the accuracy of the transmitter power-output measurements is decreased; that is, transmitter output power is monitored (measured) at the antenna input terminal (connector) and is adjusted according to the "measured" circuit loss between the transmitter output terminal and the antenna input terminal. Fortunately, in the Apollo Program, the overall communications-system performance has been adequate to account for any measurement inaccuracies.

Incidental PM and Incidental AM rf Interface and Compatibility Performance Analysis

By Harold R. Rosenberg

Various degradations in Apollo USB communications-system performance are directly attributable to incidental (or inadvertent) PM on the down-link S-band carrier and IAM on the up-link subcarrier and S-band carrier.

Incidental PM of the down-link S-band carrier results from structural vibrations, power-supply ripple, and other similar perturbations that act as band-limited noise at the input to the spacecraft PM modulator. This IPM will appear as noise on the coherent carrier reference in the MSFN receiver. Significant amounts of this narrowband noise degrade communications performance, particularly telemetry bit error rates. The presence of IPM on the down-link S-band carrier also causes degradation in other information channels (such as voice, PLSS, and EVA biomedical data, and hard-line biomedical subcarrier data), but these degradations are not as severe as those present in the PCM channels.

Because of the many contributing sources of IPM and the difficulty in determining what level to specify for each source, a total-allowable system specification is necessary. An effort was initiated at MSC to determine the maximum allowable level to be imposed on the spacecraft contractors as a total-system specification. The criterion used to define the maximum allowable IPM was based on accepting not more than 2 decibels degradation of the telemetry 10^{-4} BER threshold. Based on this criterion, test data showed that IPM could not be allowed to exceed 28° rms within a band from 20 hertz to 5 kilohertz. To ensure minimum degradation of the down-link PCM data, MSC engineers requested the contractors to add this new requirement to the LM and CSM P&I

specifications. This value was negotiated with the contractors and was later analyzed by them and included in the LM- and CSM-MSFN S-band P&I specifications. The CSM contractor determined that the expected total S-band system phase jitter caused by the antenna system, S-band power amplifier, USB equipment, transmission line, and rf tracking system would be 5.35° rms. Since the time the initial value of total-system IPM was imposed on the LM contractor, the specified value for the LM has been reduced to 20° rms.

Because the primary up-link and down-link carrier-modulation schemes were PM, the initial emphasis was in the area of IPM and its effects on the quality of the signals. Hence, when the rf tracking system replaced the infrared tracking system for the LM and CSM high-gain antennas, a comprehensive and detailed analysis followed to determine the effects of the rf tracking system on the communications-system performance. Computer solutions, based on design-review information on antenna characteristics, were obtained for the LM and CSM antennas. As proven later, it was correctly concluded that — with the values of null depth, coupling factors, and squint angle used in the LM and CSM rf tracking systems — the effects of IPM and IAM (generated by the rf tracker) on the ranging and communications channels were negligible.

The LM and CSM rf tracking systems were also analyzed for their possible effect on MSFN tracking and acquisition. A meeting was held at JPL in January 1966 to discuss and run demonstration tests that were indicative of spacecraft MSFN acquisition and tracking performance in the presence of down-link IAM and IPM inherently generated by the rf tracking system. Again, no obvious problem was uncovered.

It is unfortunate that, in these initial investigations of the effects of the rf tracker on the USB system, the effect of the PRN ranging and communications channels on the rf tracking system itself were not considered in detail.

The effects of IPM on rf tracker performance, if any, presented no problem; however, the presence of IAM on the up-link subcarrier or on the up-link S-band carrier results in tracking errors in the LM and CSM antenna tracking systems.

At the February 1966 USB meeting at MSC, both spacecraft contractors were requested by the chairman to discuss the testing that was planned to verify the S-band antenna and spacecraft receiver interface performance. The plans of the CSM contractor were to deliver an S-band receiver to the antenna subcontractor so that the CSM high-gain antenna and USB receiver could be properly interfaced during developmental testing by the subcontractor. The plan of the LM contractor was to perform this test during communications-systems integration testing at their subcontractor's plant. It was during these tests in the latter part of 1966 that the IAM problem was discovered.

During the integration tests, a preproduction-model antenna was interfaced with a preproduction transceiver, and the tracking performance of the antenna was observed under simulated up-link conditions. The test results were documented in "Preliminary Test Report of the Effects of Up-Link on the Steerable Antenna Tracking Requirements," January 4, 1967, Action Item C-161. It was observed that, to meet the specified ±2° tracking error, the allowable IAM on the S-band carrier was as follows.

1. 0.5 percent maximum at 50 or 100 hertz

2. 2.0 percent maximum at 60 or 120 hertz

3. 5.0 percent maximum at other discrete frequencies

The allowable IAM on the up-link subcarriers was determined to be as follows.

1. 0.1 percent maximum at 50 or 100 hertz

2. 0.5 percent maximum at 60 or 100 hertz

3. 1.0 percent maximum at other discrete frequencies

4. 2.0 percent maximum peak AM for normal voice

The NASA was officially notified by the LM contractor soon after and apprised of the related effect on the antennas tracking performance in the presence of up-link IAM. The 0.1-percent IAM level given by the contractor as the maximum allowable on the MSFN up-link subcarriers resulted in a major conflict because the existing subcarrier-oscillator (SCO) specified up-link IAM was 5 percent (no discrete frequencies mentioned).

The effort to reduce the SCO IAM to an acceptable level was the prime reason for the analysis and tests that followed. (The test aspects of this problem are discussed in a separate report concerning the MSC Electronics Systems Compatibility Laboratory test activity.)

The CSM contractor was apprised of the LM rf tracker problem and requested to analyze the CSM rf tracker performance in the presence of up-link IAM. Engineers at GSFC were also notifed of the problem and requested to investigate ways to reduce the existing up-link IAM on the 30- and 70-kilohertz subcarrier oscillators. Coordination meetings were held with MSC, GSFC, and several contractors in an effort to define the problem better and to define a course of action that would lead to a solution.

A contractor, with inputs on PRN range-code components from JPL and on the rf tracking-system performance from MSC, did a detailed analysis of the up-link-signal characteristics and the interaction of the up-link signal with the rf tracking mechanism. This analysis and others and the associated system testing at MSC confirmed the seriousness of the incompatibility between the USB-system up-link signal and the LM and CSM rf tracking systems.

It was proposed that the spacecraft coherent AGC detector, used in deriving the tracking error, be replaced by a noncoherent detector. This substitution would have solved the problem but would have resulted in a major equipment modification and a completely new test program for the modified equipment. Because this approach was impractical and because static rf tracker tests at MSC had shown that a reduction in the up-link modulation indices suppressed the tracking error to an acceptable level, a decision was made to reduce the up-link modulation indices. Also, GSFC personnel had determined that decoupling the power-supply circuits in the existing subcarrier oscillators would reduce the IAM to approximately 3 percent maximum. A comprehensive analysis was performed by MSC personnel to define the possible sets of up-link modulation indices that would suppress the rf tracker problem and, at the same time, maintain adequate circuit-performance margins.

Action was then initiated by MSC personnel officially to reduce the modulation indices for LM and Block II CSM up-link combinations 4 and 5 to 0.38 radian for PRN and 1.2 radians for the voice/up-data subcarrier. In addition, the indices were reduced for up-link combination 6 (PRN and two subcarriers) to 0.44 radian for PRN and 1.0 radian for each subcarrier. These reduced indices were made effective on LM-1 and on subsequent Apollo flights.

Although system analysis and supporting tests had shown that reduced modulation indices would result in LM and CSM tracking errors that were within specification, no guarantee existed that the errors would always be within specification because an up-link IAM of 0.1 percent on existing subcarrier oscillators was not acceptable.

The GSFC personnel considered the level of IAM that could be maintained on site to be approximately 2 percent. In addition, it was estimated that, with existing test equipment, the accuracy with which IAM could be measured was approximately 1 percent. Also, with respect to an up-link IAM specification, GSFC personnel could only specify the areas that they controlled (e.g., the combined output of the 30- and 70-kilohertz subcarrier oscillators with controlled inputs (individual tones)). The PRN ranging or voice inputs had too many variables to use them as reference inputs. Consequently, no guarantee existed that the IAM levels would always be insignificant. The GSFC personnel were made aware of this potential problem and, after considerable negotiation, agreed to provide improved subcarrier oscillators with much more stringent IAM specifications.

Personnel at MSC were aware that a technique to detect such low levels of IAM (0.1 percent) did not exist and that, therefore, such a specification was impractical. To alleviate this deficiency, a conceptual analysis was conducted on possible techniques for measuring low levels of IAM. A method was conceived, and it was verified by analysis that it was practical to implement. (An envelope detector and a wave analyzer were used in this method, which allowed an accurate measurement of percent IAM for values considerably less than 0.1 percent.)

Subsequent laboratory measurements of up-link IAM at the critical frequencies of 50 to 100 hertz showed that the subcarrier IAM levels were approximately 0.1 percent for the original MSFN up-link subcarrier oscillators that were tested. Tests have also been performed on the new 30- and 70-kilohertz subcarrier oscillators. These results show that no significant levels of IAM exist at 50 and 100 kilohertz during periods when normal up-link modulation (voice and PRN ranging signals) is applied at the specified deviation.

S-Band Low-Gain Antennas

By Harold R. Rosenberg

Low-gain antennas are normally grouped together to constitute what is referred to as the omnidirectional-antenna system. This system is used as the primary antenna system in the near-earth phases of the mission and as a backup system during the lunar phase. The S-band omnidirectional-antenna system for the Block I CM consisted of two individually switched, diametrically opposite slotted scimitar antennas. (The scimitars were designed for vhf transmissions, but had a slot cut in the forward end with a separate feed line to the S-band diplexer.) The S-band omnidirectional-antenna system for the Block II CM consists of a set of four cavity-backed helix antennas, each encased in a quartz rod for thermal protection. In the final configuration, these antennas were equally spaced between the Z- and Y-body axes around the base of the CM and were switched individually.

The S-band omnidirectional-antenna system for the LM consists of two conical spirals, individually selected, that radiate in the direction of the +Z (forward) axis and -Z (aft) axis. Because these antennas do not have to survive entry, no thermal protection is required, and the design was thus simplified considerably.

Block I-CM S-band low-gain antenna. - The integration of the S-band low-gain antenna with the vhf scimitar antenna resulted in a low-performance S-band omnidirectional-antenna system. The ablative material required to protect the scimitar caused deep nulls in the S-band pattern and poor distribution of the radiated energy that was further aggravated by the antenna location on the CM.

A basic problem, encountered not only on the Block I CM antenna but also on the Block II CM and LM antennas, was in generating antenna radiation-pattern data that were representative of the antenna performance in free space. Compounding this problem in the Block I antenna was the difficulty encountered in the fabrication of the slotted scimitar antenna.

The early pattern data on the Block I antenna were taken with a one-third-scale model of the CM on the contractor's antenna range. The applicability of one-third-scale pattern data is often challenged because of the conditions under which the data are taken and the low confidence level in duplicating the configuration and properties of the antenna used in the tests.

These uncertainties resulted in the construction of full-scale models of the CSM and LM and the use of the MSC anechoic chamber for the taking of low-gain-antenna radiation patterns.

Block II CM S-band low-gain antenna.- The design for the Block II low-gain antennas was based on the successful performance of the C-band tracking antennas. The initial location of these antennas was similar to that on the Block I CSM — approximately midway between the apex and the base of the CM. Based on the poor radiation distribution of the Block I scimitar slot and the excellent radiation distribution of the C-band antenna system, NASA engineers requested the contractor to locate the S-band omnidirectional-antenna system in the same Z-Y plane as the C-band antenna system (around the base of the CM). Because of the increase in diameter of the S-band antenna over that of the C-band (2:1) and because of the potential thermal and structural problems associated with such a relocation, analysis was first required to show that relocation was possible.

The original hookup of the four S-band low-gain antennas was with opposite antennas paired (radiating and receiving together). Because of the need for more power at the ground to enhance system performance, NASA engineers requested the contractor to implement individually switched antennas. The contractor agreed, and the change was made, resulting in the existing configuration (used on Apollo 7 and subsequent missions). Subsequent operational experience indicates that, combined with their other duties, the switching of the four low-gain antennas places a burden on the astronauts. During the translunar and transearth coasts of the Apollo 8 mission, antenna switching was minimized by spacecraft attitude hold and ground-command switching between opposite antennas.

Lunar module S-band low-gain antenna.- The design and development of the LM S-band low-gain antenna proceeded under considerably different guidelines than did the CM low-gain antennas. For example, the LM antenna did not have to survive entry nor operate as a primary rf radiator in earth orbit (i.e., LM-1, LM-2, and LM-3 had research-and-development communications systems on board that were to serve as a primary link during systems checkout in earth orbit). However, because weight was a critical item for the LM, the antennas were to be as lightweight as possible.

The conical spiral design that was used on the LM met all these conditions and, in addition, provided a broad pattern for even distribution of the rf energy.

The only limiting feature was the placement of the antennas on the body of the LM. The LM, serving as the ground plane for the low-gain antenna, greatly affected the radiation pattern because of the many surface discontinuities. Also, the LM rendezvous-radar antenna blocked a portion of the radiated energy when it was oriented in the direction of the descent stage ($\theta > 90°$). When the LM was on the lunar surface (also during lunar ascent and descent), the radiated energy in the direction of the earth was not optimum and the function of the low-gain antenna as a backup to the LM steerable antenna (the LM S-band high-gain antenna) was limited. Because of these difficulties, it is thought that, on future spacecraft not requiring entry capability, the low-gain antenna placement should be thoroughly investigated for deleterious effects from both body-surface discontinuities and physical blockage.

Backup-Voice Interference with 1.6-kbps Telemetry

By Sidney W. Novosad

The Apollo USB communications system has several down-link transmission modes using PM by a telemetry subcarrier and baseband voice. These modes have low-bit-rate (1.6 kbps) telemetry biphase-modulating a 1.024-megahertz subcarrier, which is summed with baseband voice to phase-modulate the down-link S-band carrier. While undergoing initial compatibility testing of these modes in both LM and CSM equipment, serious degradations occurred in telemetry-channel performance during periods of simultaneous speech and telemetry transmissions. Subsequent theoretical and experimental investigations indicated a basic incompatibility between the spacecraft modulation technique and the ground-station demodulation process. In particular, LM down-link PM mode 4 (baseband voice and 1.6-kbps telemetry), LM down-link mode 8 (baseband voice, PLSS status data, biomedical information, and 1.6-kbps telemetry), and CSM down-link PM mode 8 (baseband voice and 1.6-kbps telemetry) contained significant telemetry degradations for nominal ground-station receiver configurations and spacecraft-transmitted signal parameters.

Initially, telemetry channel degradation was attributed to several possible sources. One possible source was the received baseband voice signal appearing as noise in the carrier reference loop of the ground-station receiver. A similar source was a noisy subcarrier reference to the telemetry subcarrier phase detector. Another possible source of degradation was the carrier demodulator, consisting of a quadrature product phase detector, which provides a "linear" phase-detection scheme only for small modulation phase deviations.

Telemetry degradation was attributed to the modulation scheme that was used. Inherent in the modulation process, whereby a baseband signal is summed with a modulated subcarrier to phase-modulate a carrier, is the mathematical result that harmonics of the baseband signal appear about the subcarrier. For certain modulation indices, these baseband-signal harmonics have significant power in relation to the subcarrier-channel power, resulting in direct interference to the subcarrier.

Following detailed testing of the spacecraft-ground communications system using both the CSM and LM equipment, definite conclusions concerning the degraded telemetry performance were established. The telemetry degradations were a function of the baseband voice MI and the carrier-reference (tracking) loop bandwidth. Lower voice modulation indices reduced or eliminated the problem. Actual CSM PM mode 8 baseband voice indices are sufficiently low to prevent interference to 1.6-kbps telemetry, provided the carrier-tracking-loop bandwidth is in the 50-hertz position. (However, a nonstandard CSM down-link mode consisting of baseband voice and 51.2-kbps telemetry used during the Apollo 8 mission experienced telemetry dropouts during speech transmission even when the 50-hertz carrier tracking loop was used.) Also, actual voice modulation indices in LM PM modes 4 and 8 are high enough that telemetry interference will occur for any carrier-tracking-loop bandwidth when baseband voice is simultaneously transmitted. Measured curves (for the CSM and LM) of telemetry BER performance as a function of total received power, for different values of voice MI, using the 50-hertz carrier-tracking-loop bandwidth, are illustrated in figures 17 to 19.

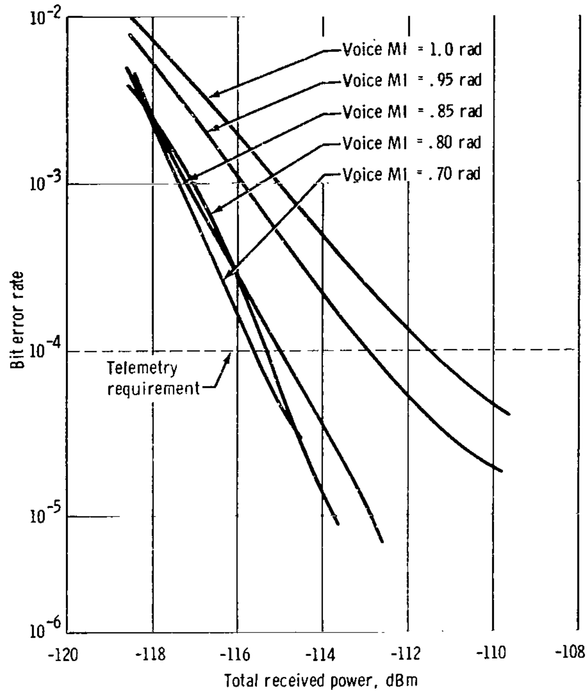


Figure 17.- Bit error rate as a function of total received power, CSM mode 8 (baseband voice and 1.6-kbps telemetry).

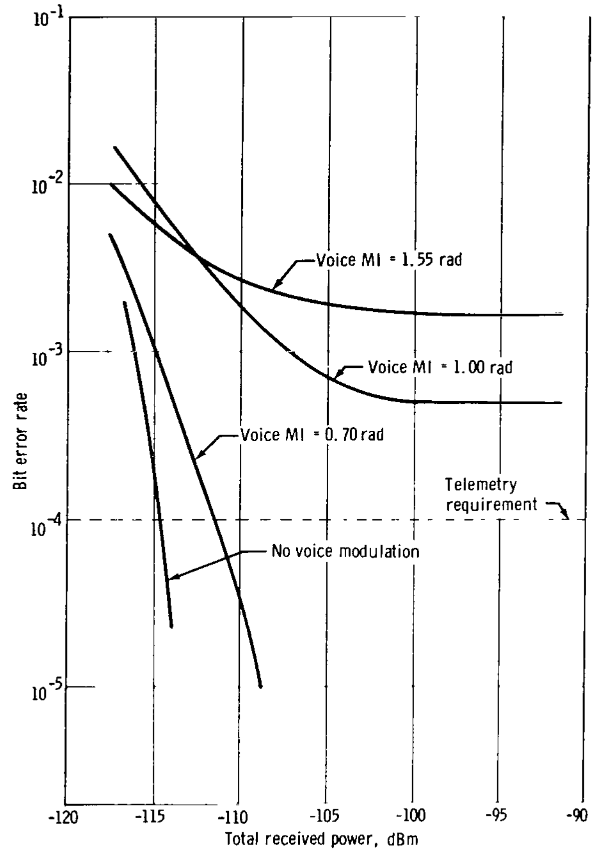


Figure 18.- Bit error rate as a function of total received power, LM mode 8 (baseband voice, EVCS subcarriers, hardline biomedical data, and 1.6-kbps telemetry).

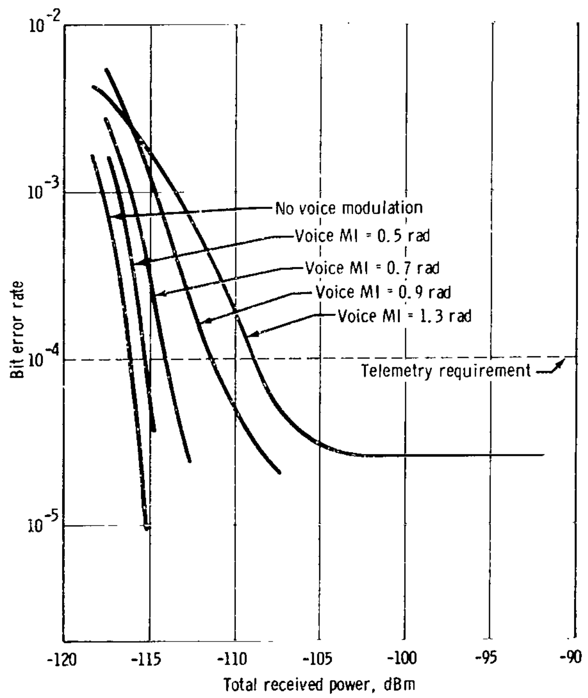


Figure 19.- Bit error rate as a function of total received power, LM mode 4 (baseband voice and 1.6-kbps telemetry).

Several solutions to the problem were initially presented; these solutions ranged from modifying the LM-transmitter equipment to imposing operational constraints on these modes. Suggested modifications included removing the voice signal from baseband or changing the signal-processing equipment to reduce the voice MI. The operational approach included transmitting either baseband voice or telemetry, but not both simultaneously, or simply to accepting telemetry dropouts during speech periods. At the LM Configuration Control Board meeting at MSC in June 1968, a decision was made to accept telemetry degradations during speech transmissions because cost and schedule effects resulting from spacecraft-equipment modifications were too severe.

However, further investigations were undertaken by MSC personnel into possible ground-station demodulation techniques that would eliminate the telemetry degradations. Two methods involving minor modifications to the ground station were designed and successfully tested. Both methods involved reducing the baseband voice MI in the carrier-demodulation process. In one method, a negative feedback loop (consisting of a loop filter, amplifier, and phase modulator) is incorporated around the existing MSFN wideband carrier phase demodulator. In the other method, an external FM demodulator is preceded by a composite filter consisting of three high-Q bandpass filters in parallel. The use of one of these techniques allows acceptable telemetry (1.6 or 51.2 kbps) performance in either the 50- or 700-hertz carrier-tracking-loop bandwidth for LM PM modes 4 and 8 and CSM PM mode 8. One of these methods was recommended to GSFC personnel for implementation in the MSFN stations for Apollo mission support.

Signal Design and Performance Analyses for EVCS

By C. Kenneth Land

Before the Apollo 11 mission, a significant improvement was made relative to communications capability between astronauts on the lunar surface and the MSFN. Originally, the astronaut carried, as a part of his PLSS, a spacesuit communicator (SSC) that transmitted his voice and seven analog data subcarriers over a 259.7-megahertz AM carrier to the LM. At the LM, the AM carrier was demodulated and the voice and seven subcarriers were remodulated on the USB system carrier or subcarrier for transmission to the MSFN. This system was completely adequate for supporting communications between a single astronaut and the MSFN; but, because of the LM equipment and the SSC design, the capability for simultaneous voice and data transmission relayed from two astronauts did not exist. Approximately 2 years before the Apollo 11 mission, this dual capability was made a requirement. The new EVCS was designed to fulfill this requirement and has been documented in an MSC internal note dated May 1969, entitled "Performance Analyses of the EVCS."

The dual EVCS mode of operation itself involves a relay, in that one astronaut's transmissions are relayed by the second astronaut's extravehicular communicator to the LM. Two relays are thus involved in transmitting the first astronaut's voice to the MSFN, as indicated in figure 20. The information transmitted in the dual mode is shown in figure 3. Using a 279.0-megahertz frequency-modulated carrier, the first astronaut (EVA-2) transmits his voice; EKG data frequency modulated onto the 3.9-kilohertz subcarrier; and PLSS-status data — such as suit pressure, oxygen pressure, water temperature, battery voltage, and battery current — frequency modulated onto the 7.35-kilohertz subcarrier. (The PLSS status data are commutated at a rate of 45 samples per second before subcarrier modulation.) The second astronaut (EVA-1) then receives and demodulates the 279.0-megahertz carrier. The received voice and two subcarriers are combined with the second astronaut's voice on a time-sharing basis, with EKG data frequency modulated onto the 5.4-kilohertz subcarrier, and with PLSS-status data frequency modulated onto the 10.5-kilohertz subcarrier. The resulting voice

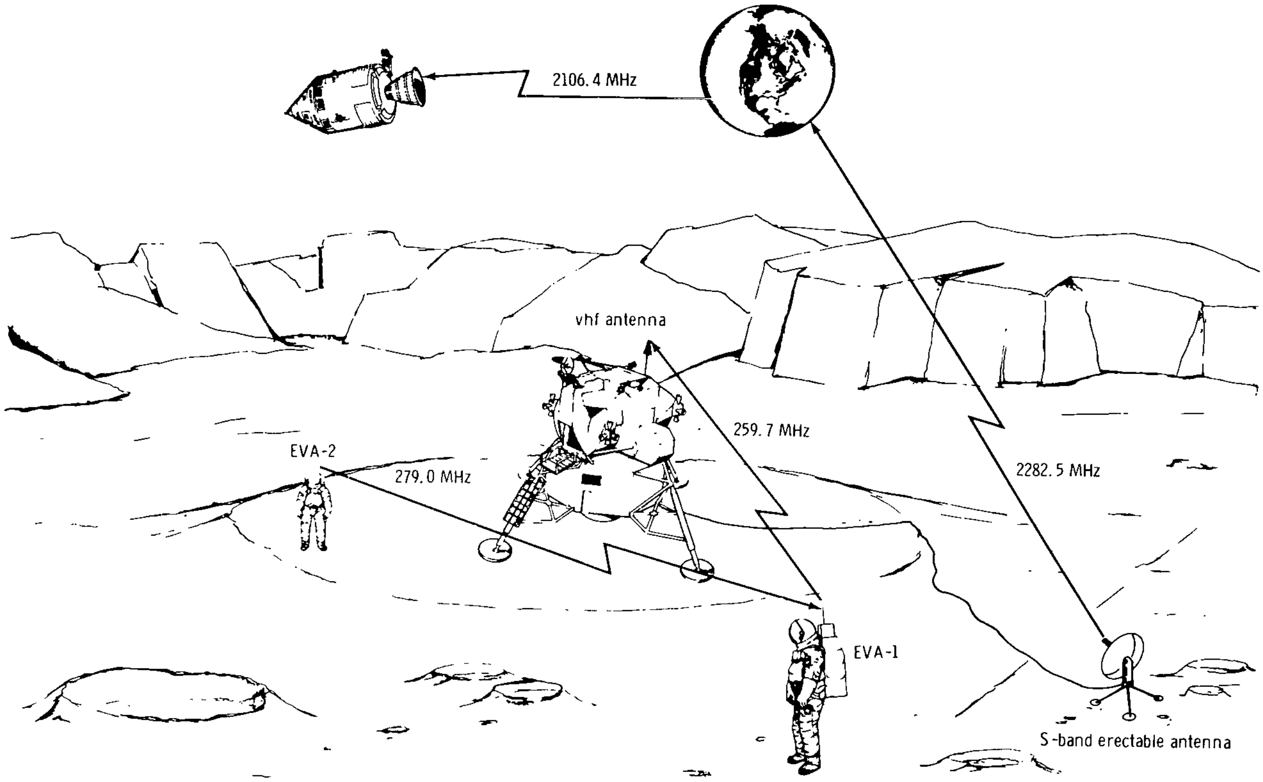


Figure 20. - Relay communications system, extravehicular astronaut (EVA) to MSFN.

and four subcarriers amplitude modulate a 259.7-megahertz carrier, which is transmitted to the LM and relayed on S-band from there to the MSFN and from the MSFN to the CSM by way of the MSFN relay. The equipment involved in the dual EVCS-to-MSFN links is shown in more detail in the block diagram of figure 21.

Because the LM equipment was designed to operate with the SSC, several signal-design analyses were required to define the new rf interface requirements before designing an EVCS compatible with the LM. The first analysis involved mathematically modeling the various relay links such that EVCS design options could be analyzed and evaluated. The mathematical modeling included such factors as the final effect of adding noise and interference at several points along a multiple relay link — a significant consideration in the EVCS design. Also, the actual equipment operation was included. Although models were readily available for most of the EVCS, LM, and MSFN equipment, some had to be developed — specifically the model for the LM AGC amplifier and taper circuit shown in figure 21. Because these circuits set the EVCS voice- and data-subcarrier modulation levels in the LM USB system as a function of the EVCS-to-LM link AM levels, the analysis and mathematical modeling of their operation were required for the overall link model. Once this model had been completed and tested, a set of optimum EVCS AM levels was chosen.

It was found that, even after optimum EVCS signal design, the MSFN reception of EVCS voice and data subcarriers of sufficient signal strength could not be guaranteed

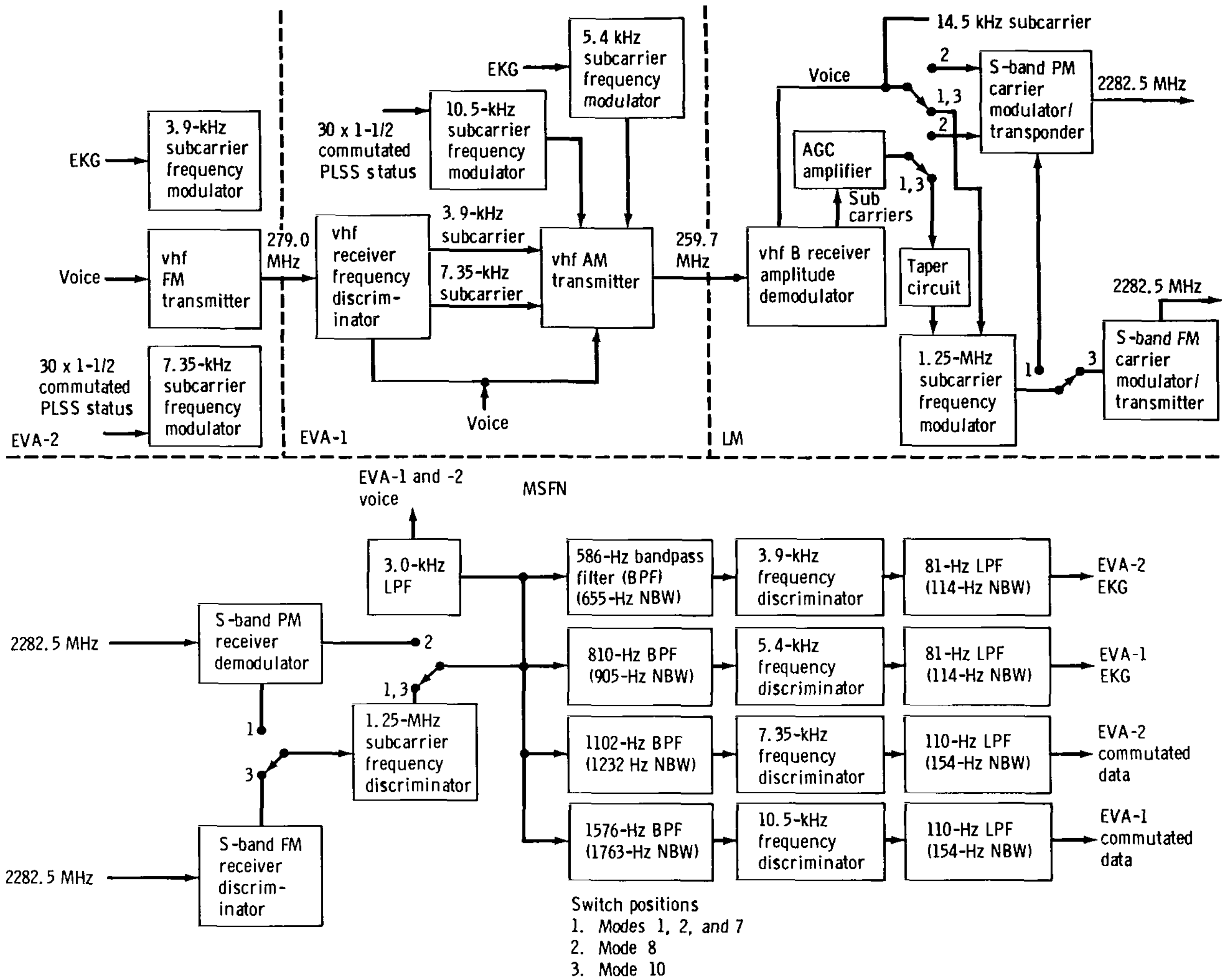


Figure 21. - Communications-system configuration, EVCS to MSFN (dual-EVCS mode).

because of the nature of the existing LM equipment with which the EVCS was required to operate. Furthermore, the cost and schedule effects involved in changes to the LM equipment made such changes virtually impossible in this situation. After evaluation of the measured data on the actual modules (transceivers, power amplifier, and signal processor assembly) that composed the LM communications system, the problem was resolved. The solution consisted of the careful selection of each module based on measured characteristics of that module and of the remaining communications equipment. In this manner, improved LM equipment performance could be attained, and the minimum MSFN requirements could be met.

With the solution of these and other, smaller problems, the EVCS was made to operate successfully for Apollo 11 and subsequent missions.

Color Television Interference and SNR Requirements

By G. Dickey Arndt

The Apollo USB system was originally designed for black-and-white television that had a limited frequency response (500-kilohertz). Because of the limited bandwidth, the video picture could not have the same quality (i. e., motion rendition and picture resolution) as commercial television. However, color television with a 2.5-megahertz modulation bandwidth, that approaches commercial quality, was successfully used on the Apollo 10 and 11 missions and was scheduled for all subsequent missions. The increased modulation bandwidth produces interference problems with the 1.024-megahertz telemetry subcarrier and the 1.25-megahertz voice subcarrier in the LM system. A composite signal spectrum for the LM color television mode is shown in figure 22. (The CSM transmits television alone, so no color-television/subcarrier interference exists.)

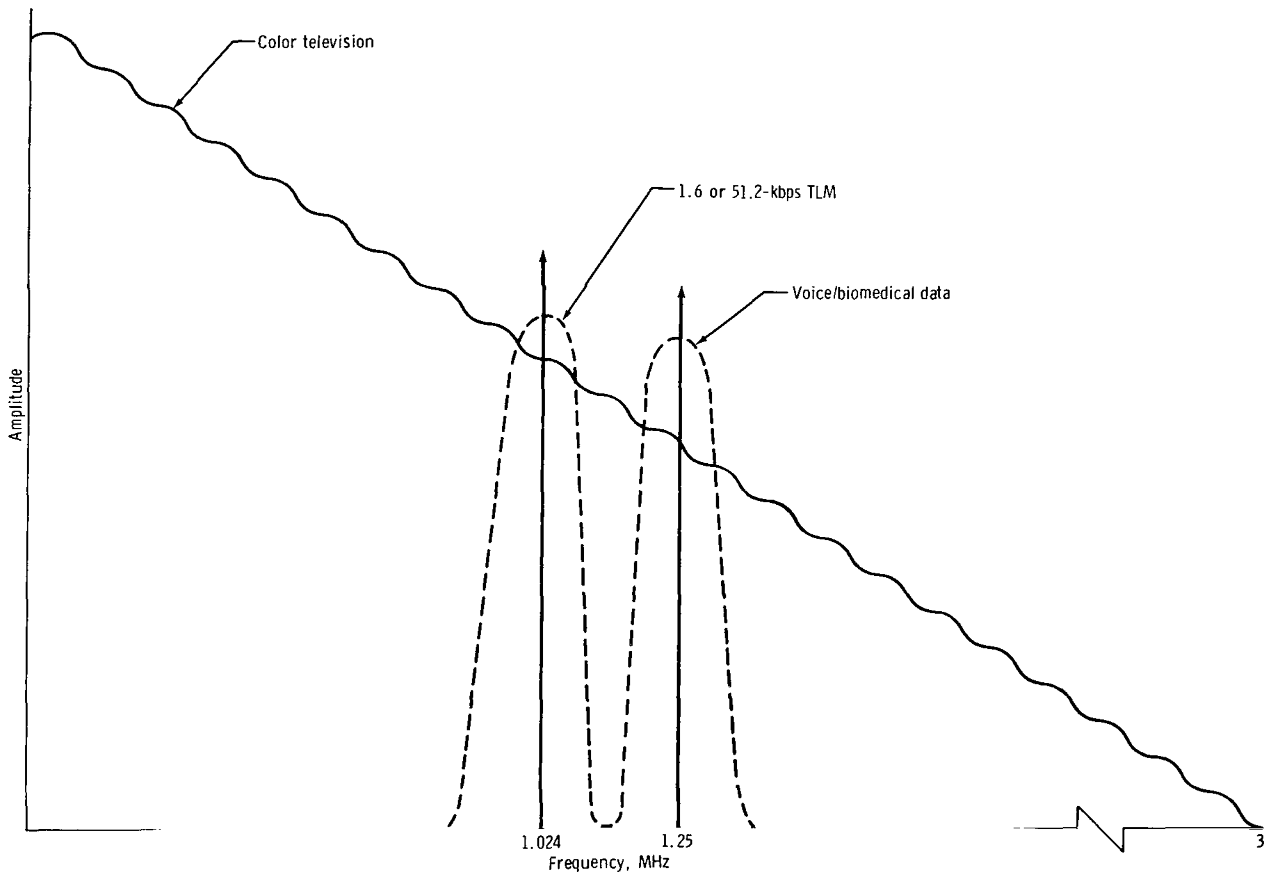


Figure 22. - Composite signal spectrum for LM FM mode 10 (color television, telemetry, and voice).

Two interference problems must be considered: (1) the degradations in the telemetry and voice channels caused by television, and (2) the television degradation caused by the telemetry- and voice-subcarrier-channel interference. The former problem was analyzed by personnel working under a NASA research grant. Their theoretical findings indicated that the energy in the video spectrum around the 1.024- and 1.25-megahertz subcarriers is negligible in comparison to the subcarrier signals. Experimental tests at MSC and at KSC later verified the analysis that television would not degrade the telemetry- or voice-subcarrier performance.

However, the subcarrier interference with television is not negligible. The interference is observed in the television picture as a "herringbone." Several methods for removing the subcarrier interference from the television spectrum are being investigated. These techniques process the television signal after it has been demodulated in the MSFN ground station and do not require any modifications to the spacecraft equipment. In the most promising, though costliest, technique, an amplitude and phase extractor (APEX) system is used to reduce the subcarrier interference. Basically, the APEX system derives an optimal estimate of the subcarrier signals (interference) while minimally disturbing the adjacent television-baseband spectrum. This estimate of the interfering signal is inverted and summed out of phase with the composite television-plus-subcarriers spectrum. The difference between the input interference and the inverted estimate is that which remains to disturb the television picture. The herringbone interference is reduced approximately 20 decibels by using this technique.

In the second technique, a passive-notch filter is used to attenuate the 1.024- and 1.25-megahertz subcarriers. The interference is reduced by approximately 20 decibels with this method, although part of the television spectrum is also eliminated. In the last, and least desirable, technique, a low-pass, 900-kilohertz filter is used to attenuate the interfering subcarriers. However, the television spectrum above the filter cut-off is also attenuated. The result is a degraded video picture with indistinct (fuzzy) contours. The high-frequency video information is eliminated by the low-pass processing filter. Of these three techniques, the notched-filter approach was recommended by MSC personnel and subsequently implemented by GSFC personnel.

The color television signal requires a significant increase in the required input-signal level as compared to the black-and-white television. The input SNR required in the 5.3-megahertz predetection filter of the MSFN FM demodulator is increased from 6 to 16 decibels for color television. An output SNR of approximately 16 to 18 decibels is needed for a good quality video picture. The increase in the required input-signal level is in part a result of the small FM improvement obtained in the demodulation process. Because the FM improvement in output SNR for the color-television channel is only 1 to 2 decibels, a high-input SNR is needed to achieve the output-signal requirements. A 210-foot JPL antenna in conjunction with either the LM or CSM steerable antenna provides the necessary system gain to support color television at lunar distance. An 85-foot MSFN antenna is also adequate when the LM erectable antenna is used for down-link transmission of color television from the lunar surface.

CONCLUDING REMARKS

The success of the Apollo unified S-band communications system throughout the Apollo Program can be attributed in part to the intense systems-engineering analyses and configuration-control efforts conducted during the conceptual design, fabrication, testing, and operational phases of the communications-system development. The numerous parallel analytic efforts initiated early in the program resulted in (1) the timely availability of a representative mathematical model with which overall communications-system performance (spacecraft/ground) could be predicted, and (2) the formation of the basis for many important unified S-band system design decisions required early in the program; for example, the selection of pseudorandom-noise ranging in preference to tone ranging and of phase-shift keying in preference to frequency-shift keying, the generation and implementation of acceptable ground-station acquisition procedures, the need for mode-selection flexibility, voice-processing techniques, and the use of baseband voice as a backup-voice mode.

The performance of the PRN ranging system, developed by the Jet Propulsion Laboratory and chosen for its long-range minimum-power characteristics, has been good; but acquisition times have been somewhat longer and the acquisition procedure somewhat more complex than desired. If a new ranging system were to be designed, it is very possible that a hybrid system would be considered that incorporated the best features of both the pseudorandom-noise and range-and-range-rate systems. Although the mode-selection flexibility that was implemented greatly enhanced the Apollo communications-system efficiency in terms of power and bandwidth and provided backup capability for contingency situations, it placed a heavy workload on the flight crew, who had to perform the communications-system mode-configuration functions manually in real time in addition to their other duties. In future systems, the selection of information to be transmitted by the communications system should be automated by some combination of onboard and ground control, with manual override for safety and reliability.

Generally, the overall results of voice processing in the Apollo unified S-band system have proven to be satisfactory. In retrospect, some items exist that, based on accumulated experience, might be treated differently; for example, lunar module backup voice could probably be improved by lowering the 24-decibel clipping level to 12 decibels (or even 0 decibel), because lunar module cabin noise is relatively loud and enters the microphone along with the astronauts' voices.

The tracking dynamics and radio-frequency acquisition procedures implemented for the Apollo communications system met the basic program requirements. However, the need for operational restrictions, namely the absence of up-link modulation during radio-frequency acquisition and the reduction of carrier sweep rate and offset range because of false locks caused by the 51.2-kbps telemetry, sometimes delayed signal acquisition and resulted in the loss of data. In the design of future spacecraft/ground-communications systems, this limitation should be eliminated.

The use of baseband modulation for the backup-voice channel accomplished its objective. However, because of its interference with the telemetry-channel performance, a different modulation or detection technique should be implemented in future system designs if backup voice and telemetry are to be transmitted simultaneously.

Concerning the trade-off study of frequency-shift keying and phase-shift keying, the use of phase-shift-keying modulation by personnel at the Manned Spacecraft Center and the George C. Marshall Space Flight Center proved to be more adaptable and economical than frequency-shift keying when Manned Space Flight Network implementation and operational aspects were considered.

The communications-system configuration-control documents generated in the Apollo Program provided NASA management with a tool to control overall system configuration and performance. These documents were responsible for the interface compatibility between the spacecraft and the ground-based terminals and for the successful performance of the Apollo communications system and the Apollo Program itself. The Performance and Interface specifications served as a firm control medium for all communications-system parameters that could not be adequately controlled by "black box" specifications. The placement of the Performance and Interface specifications high on the contractors "spec tree" was a major factor in this success. In future programs, the circuit-margin Interface Control Documents and the Performance and Interface specifications should be NASA documents instead of contractor documents.

The capability to predict (calculate) the communications-system performance at an early stage in the unified S-band system development was significant to the control of specified spacecraft and ground-station hardware performance and interface parameters.

Because the Performance and Interface specifications were prepared after some prototype hardware had been built, certain specified system parameters were inadequate for providing acceptable overall communications-system performance in some of the frequency-modulation transmission modes. Subsequent analysis and modification by Manned Spacecraft Center and Goddard Space Flight Center personnel and contractor engineers resulted in a final communications-system configuration that provided acceptable performance for all phases of the lunar-landing mission.

The radio-frequency coverage documents prepared for each mission were invaluable assets for premission planning and for selecting antennas for optimum mission communications. These documents, through their wide distribution and use, served to educate people throughout the Manned Space Flight Network, contractor facilities, and other NASA centers as to the mission particulars and coordination of the efforts of mission personnel.

Because the radio-frequency-coverage documents were based on predicted trajectory data, any significant departure from the scheduled trajectory made certain plots in the document invalid. This particular problem was overcome with the computer-aided analysis system, which provided real-time prediction information that was extremely useful to flight controllers and mission managers. Several of these prediction outputs were subsequently incorporated into the Real Time Computer Complex for Mission Control Center personnel.

The contributions of system analyses in the areas of system deficiencies, modifications, and improvements were numerous and significant to the success of the Apollo Program. The design and construction of new network frequency-modulation demodulators to resolve the frequency-modulation problem and the associated theoretical analyses of threshold-extension phenomena significantly advanced the state of the art in frequency-modulation threshold-extension techniques. The analyses and tests associated with the backup-voice interference with 1.6-kbps telemetry problem extended the theoretical base of knowledge concerning the mechanics of interference introduced by baseband voice modulation and signal-detection techniques, as well as providing a recommended solution for the Apollo problem. The extravehicular communications-system signal-design analysis and supporting tests provided the basic design information for an adequate design and emphasized the need for tight tolerances on the system parameters involved in the relay of voice and data.

Analyses conducted to define a proposed hardware change or to understand a problem observed during system tests also contributed to the success of the Apollo Program. The color television, modulation indices selection, S-band receiver noise characteristics, and the incidental phase-modulation and incidental amplitude-modulation radio-frequency interference analyses are typical examples of the many analyses conducted throughout the program that provided a better understanding of equipment-performance limitations and the extent of required changes before actual implemention of the changes.

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National Aeronautics and Space Administration
Houston, Texas, July 23, 1971
914-50-50-17-72

REFERENCES

1. Levine, S.; Spafford, M. L.; Shaffer, H. W.; and Tagler, R. T.: A Study of the JPL Mark I Ranging Subsystem. NASA TM X-55346, 1965.

2. Baumert, L.; Easterling, M.; Golomb, S. W.; and Viterbi, A.: Coding Theory and Its Applications to Communications Systems. Tech. Rept. 32-67, Jet Propulsion Laboratory, Mar. 1961.

3. Hill, J. D.: Design Philosophy of Modulation Indices for Apollo Unified S-Band Modes with Ranging. TM 65-2021-3, Bellcomm, Inc., Mar. 1965.

4. Anon.: Proceedings of the Apollo Unified S-Band Technical Conference. NASA SP-87, 1965.

5. Anon.: GFE Command and Service Module — Manned Space Flight Network Signal Performance and Interface Specification, Block I. SID 64-1866, North American Aviation, Feb. 1965.

6. Anon.: GFE Command and Service Module — Manned Space Flight Network Signal Performance and Interface Specifications, Block II. SID 64-1613, North American Aviation, Feb. 1965.

7. Anon.: LEM - MSFN S-Band System Signal Performance and Interface Specification. LSP-380-17, Grumman Aircraft Engineering Corp., June 1965.

8. Anon.: LM-S-Band Communications Circuit Margins. LIS 380-15006, Grumman Aircraft Engineering Corp., Dec. 1965.

9. Anon.: CSM S-Band Circuit Margins ICD, Block II. MH01-13001-414, North American Aviation, Dec. 1967.

10. Anon.: Block II CSM S-Band Circuit Margins. MH01-13021-414, North American-Rockwell, June 1969.

11. Hill, J. D.; and Selden, R. L.: Design Philosophy for the Frequency Modulated Modes of the Apollo USB Communication System. TM 65-2021-5, Bellcomm, Inc., April 1965.

12. Hill, J. D.; Raleigh, J. T.; and Selden, R. L.: Unified S-Band Communication Margins Calculations for One-Way Links. TM 65-2021-1, Bellcomm, Inc., Feb. 1965.

13. Ridgeway, R. I.: Threshold in Modulation Tracking Loops Employing Periodic Phase Detectors. Tech. Rept. 2231-6009-RU-00, TRW, Inc., July 1966.

14. Anon.: Unified S-Band Communication and Ranging Performance Study. Tech. Rept. 2231-6004-SU-00, TRW, Inc., Nov. 1965.

NASA-Langley, 1972 —— 31 S-288

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