The Space Congress® Proceedings

1968 (5th) The Challenge of the 1970's

Apr 1st, 8:00 AM

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Scholarly Commons Citation

Dawson, C. T.; Arndt, G. D.; and Boston, B. H., "An Analysis of the Telecommunication Performance of a Data Relay Satellite System" (1968). *The Space Congress® Proceedings*. 4.
https://commons.erau.edu/space-congress-proceedings/proceedings-1968-5th/session-9/4

AN ANALYSIS OF THE TELECOMMUNICATION PERFORMANCE OF A DATA-RELAY SATELLITE SYSTEM

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Summary

The Data-Relay Satellite System (DRSS) has been proposed as a means of providing a communication capability between a number of earth-orbiting space vehicles and the Mission Control Center-Houston (MCC-H) using earth-orbiting synchronous satellites as relay devices. The purpose of this paper is to report the investigation of the performance characteristics of the relay system and to determine the expected communications capabilities of the DRSS operating with Apollo spacecraft systems and with an advanced spacecraft-systems concept.

When the DRSS is used with the spacecraft high-gain antenna (Apollo or modified spacecraft), positive circuit margins can be expected for all up-link and down-link, pulse modulated (PM) modes, which include pseudorandom noise (PRN) ranging, telemetry, and voice. Wideband frequency modulated (FM) modes (television or 1-Mbps data dump) have positive circuit margins for the modified spacecraft system configuration; however, only marginal performance can be expected with the Apollo system.

When used with the spacecraft omnidirectional antennas (Apollo or modified spacecraft), the circuit margins are negative for all modulation modes except one. Baseband voice communication is possible using the modified system; however, the capabilities of the DRSS are severely limited when used with spacecraft omnidirectional antennas.

Introduction

The DRSS has been proposed as a means of providing communication between several earth-orbiting space vehicles and the MCC-H. This concept involves the use of earth-orbiting synchronous satellites as relay devices. The DRSS would provide continuous communication coverage for target vehicles and, conceivably, could provide the means for the deactivation of many of the Manned Space Flight Network (MSFN) stations.

Several studies have been published recently describing the feasibility of implementing a relay satellite system.[1,2,3] In general, these studies have been addressed to the problem of defining in detail a complex satellite system, the communication performance being analyzed on the basis of broad assumptions concerning the spacecraft and ground-based systems with which the satellite is to operate. It is the purpose of this paper to report an evaluation of the Apollo unified S-band (USB) communication system and a modified Apollo system, used with a relay satellite system of comparable capability to those defined in the referenced studies.

Objectives

In this paper a preliminary analysis of the DRSS is presented, and this analysis is oriented to the following objectives.

1. Determination of the expected communication capabilities of the DRSS operating with Apollo spacecraft and with a modified Apollo S-band communication system
2. Presentation of the basic equations and assumptions used in prediction of communication performance
3. Outline of major problem areas and recommendations for obtaining maximum utilization of the DRSS.

Model Concept

The equations used in calculation of system performance are those used in the Apollo unified S-band mathematical model, modified to account for the effect of transmission of signal and noise from the relay satellite. Calculations of a more general nature may be found in several recently published studies on the DRSS system.

The link analysis and circuit-margin predictions presented here are based on the following basic concepts.

1. Each satellite provides simultaneous access to widely separated spacecraft.
2. Two up-link (ground to satellite to spacecraft) and two down-link radio-frequency (rf) (spacecraft to satellite to ground) carriers are used in the modified spacecraft communication system, but the Apollo system has one up link and two down links.
3. The spacecraft high-gain antenna is used for the primary PM and FM down-link modes as defined in Table I. The spacecraft omni-antenna is used only for backup voice communication.
4. The down-link PM services for the modified spacecraft are the same as in the present Apollo USB system except for an increase in high bit-rate telemetry from 51.2 kbps to 102.4 kbps. The down-link FM channel includes a 1-Mbps telemetry dump-mode which is not in the USB system. A commercial television channel has been added as an up-link FM mode.
5. The modified spacecraft communication system is analogous to the Apollo communication system, but contains improvements in the antenna system, in the rf power amplifier, and a reduction of system losses.

System Description

The system description is divided into five parts for convenience of discussion.

Configuration

It is assumed that the DRSS consists of three relay satellites orbiting at a synchronous altitude of 19 600 n. mi. above the earth. Two of the satellites have direct relay links to MCC-H through a 30-ft ground station (located near Houston) and through high-speed data lines. The third satellite is linked to MCC-H through a remote 30-ft station and high-speed data lines. The spacecraft is assumed to be in a 200-n. mi. orbit with a maximum slant range of approximately 23 000 n. mi. from the satellite.

The communication subsystem within the relay satellite consists of a frequency-translation repeater with a retrodirective phased-array antenna for the satellite-to-spacecraft link and with a parabolic antenna for the satellite-to-ground link.

Frequency Selection

The S-band was chosen as the frequency region for the spacecraft-satellite link, and the X-band was chosen for the ground station-satellite link. The selection of S-band frequencies for the spacecraft-satellite link has minimum impact on existing spacecraft USB equipment. The X-band region was chosen for the ground station-satellite link in order to minimize interference effects between the numerous up-link and down-link S-band carrier frequencies present when the satellite is communicating with more than one spacecraft. The individual frequency links chosen for the Apollo spacecraft and assumed for the modified Apollo spacecraft are shown in Figures 1 and 2. Specific frequency assignments for the DRSS modified spacecraft system are a matter for future discussions between the National Aeronautics and Space Administration (NASA), the Department of Defense (DOD), and the Federal Communications Commission (FCC).

Antennas

An electronically phased array was chosen as the relay antenna for the S-band satellite-spacecraft link. The phased-array antenna system appears to be better suited for the proposed application than does a system with a conventional parabolic antenna. For this study, the array is assumed to have a 40-dB gain with a ±39° scan limit. Beam steering for the array is controlled by a narrowband pilot tone from the spacecraft. Since no directed beam exists prior to acquisition of the pilot tone, the pilot-tone power received at the satellite is determined by the gain of an individual element of the array (usually 10 to 16 dB) instead of by the gain of the full array. This loss in received power is of small consequence since the pilot signal is transmitted as a discrete frequency, making narrowband filtering possible by use of a tracking filter. The narrowband filtering reduces the noise power so that proper operation can be obtained at low signal levels. A detailed description of the array considered is available.[2]

The number of independently steered beams is assumed to be two; that is, two spacecraft within the array scan limits can communicate simultaneously through the satellite. Circuit margins for multiple-spacecraft links are less than those for a single-spacecraft link because of reductions in the satellite transmitter power available for a given channel (not because of a reduction in antenna gain caused by the wide beam-width requirement).

The X-band antenna for the satellite-ground link is a 24-in. parabolic reflector which has a 31-dB transmit gain with a 4.5° beam width. This antenna is rigidly mounted and is dependent upon the stability of the satellite to maintain its orientation towards the ground-based station.

Frequency-Translation Repeater

Two techniques may be used within a relay satellite for reception and transmission of the incoming signal spectra. The first technique, similar to one used in the Lunar Module (LM) Relay Experiment, involves a turnaround transponder which demodulates and then remodulates the signal spectrum onto a coherently derived carrier for retransmission.[4] The second technique involves a frequency-translation repeater which, as its name implies, translates rather than demodulates the signal spectrum. Although a detailed trade-off study has not been performed, the frequency-translation method appears to be superior for the DRSS application.

The translation repeater is a relatively simple device and is quite versatile. It is not overly sensitive to modulation techniques, information rates, or subcarrier frequencies. Up-link and down-link modes can be added without any modifications to the repeater. In contrast, a transponder would have to be designed for a specific modulation technique.

In Figure 3, a simplified diagram of a frequency-translation repeater is shown.[3] The incoming signal is received, heterodyned to intermediate frequency (i.f.) for filtering, heterodyned to the desired frequency, and power-amplified for transmission. The signal spectrum is simply translated from the received carrier frequency to another carrier frequency for transmission.

The translation frequencies can be made coherent with the ground-based transmitter frequency by employing a voltage-controlled oscillator (VCO) phase-locked to the up-link frequency. The VCO would be implemented in a narrowband carrier tracking loop in the satellite receiver.

Transmission Modes and Signal-to-Noise Ratio Requirements

The Apollo S-band modulation schemes are used in the link analysis for making performance predictions. That is, the PRN code, voice, and telemetry data all have the same modulation techniques as are used in the Apollo USB system. The down-link services are consistent with the present Apollo modes for the Apollo spacecraft. However, the telemetry rate for the modified spacecraft communication system was increased to 102.4 kbps, which represents the maximum bit rate possible on the 1.024-MHz telemetry subcarrier without producing interference in the 1.25-MHz subcarrier voice channel. A 1-MHz data-dump service has been added as a down-link FM mode. The data dump is at baseband and has to be time-shared with down-link television. This dump mode lessens the requirements for data management on board the spacecraft. The Apollo spacecraft has only a 51.2-kbps data-dump capability.

The up-link FM services (PRN ranging, updata, and upvoice) are also compatible with the Apollo USB system. An additional up-link mode, of commercial quality television and frequency modulated at the carrier baseband, has been added for the modified spacecraft. This FM mode can support crew functions during the long-duration missions.

The Apollo spacecraft does not have the equipment to receive and demodulate television.

A chart of the up-link and down-link PM and FM modes for both spacecraft, with the modulation parameters and detection requirements, is shown in Table I. The full up-link and full down-link PM modes (PRN, voice, and telemetry) use the present Apollo modulation indices. No attempt was made at this time to optimize the indices. Only the full up-link and full down-link modes are considered when using the spacecraft high-gain antenna, since satisfactory performance for these modes implies satisfactory performance for the less stringent combinations.

The signal-to-noise ratio (SNR) and bandwidth requirements for satisfactory signal detection are based upon existing Apollo requirements. The one exception is in the FM channels in which the required SNR has been reduced from 8 dB to 7 dB. This 1-dB reduction is justified in consideration of Manned Spacecraft Center in-house investigations presently underway for improvements in FM-demodulation techniques.

System Parameters

Parameter values used in the link analysis for antenna gain, transmitter power, and system losses are listed in Table II for the Apollo and the modified spacecraft, the ground-based station, and the relay satellite. Two spacecraft antenna options, the high-gain antenna for normal operations and the omnidirectional antenna for situations in which the high-gain antenna is not available, are provided.

Spacecraft modifications such as increased rf-transmitting power (20 W instead of 11.2 W), reduced system losses (4.0 dB rather than 7.9 dB), and a 10-ft parabolic antenna to replace the present high-gain antenna, are proposed for the modified Apollo spacecraft and are not considered major changes in the basic Apollo electronic system. However, changing the spacecraft reception frequency, as shown in Figure 2, is a major modification of the present Apollo equipment.

The ground-based station parameters, with the exception of the 7-dB SNR requirement in the FM channel, are the same as those presently used for the Apollo system. The system noise temperatures are given in Table III. A cooled parametric amplifier is assumed for the ground-based station. The satellite has a 5.3-dB noise figure which implies a solid-state preamplifier preceding the translation repeater. The 7.5-dB noise figure listed for the modified spacecraft is conservative because a low-noise, parametric amplifier would yield a 2- to 3-dB improvement in the noise figure.

Link Analysis

Sample calculations are provided for various portions of the link analysis.

Analytical Approach

In the analysis of the performance of the DRSS, four separate links were considered. Two of these links, ground to satellite and satellite to spacecraft, form the up-link channel. The other two, spacecraft to satellite and satellite to ground, combine to form the down-link channel. Each of these links can be analyzed separately, and the results combined to provide the total performance analysis. Thus, the approach used here is to calculate (in the usual manner) the total power received at each terminal, to calculate the noise power at each terminal in a common bandwidth, to combine the results of these calculations to form an effective total received power at the ground and spacecraft terminals, and to use these effective values with the Apollo USB mathematical model to determine the performance of the system.

Calculation of Received Radio-Frequency Power

The method used to calculate received signal power is straightforward and is based on known and proven link equations. The total power $\left(P_{Rec}\right)$ at a receiver is found from

$$P_{Rec} = P_{Tr} + L_T + G_T + L_S + G_R + L_R \qquad (1)$$

where

P_{Tr} = transmit power, dBW
L_T = transmit system losses, dB
G_T = transmit antenna gain, dB
L_S = space loss, dB
G_R = receive antenna gain, dB
L_R = receive system loss, dB

The space loss L_S is given by

$$L_S = 37.8 + 20 \log R = 20 \log f \qquad (2)$$

where

R = slant range, n. mi.
f = transmit frequency, MHz

The slant ranges used in the calculations are listed below for a spacecraft in a 200-n. mi. circular orbit.

Spacecraft to satellite	Spacecraft to ground	Ground to satellite
23 000 n. mi.	1200 n. mi.	19 600 n. mi.

The other parameters used in Equation (1) are listed in Table III. The calculations for the up-link received-power levels are shown in Table IV. The down-link received powers are calculated in an analogous manner, as is shown in Table V.

Calculation of Noise Spectral Density

The equivalent system noise temperature T_{Sys} can be found for each system using the equation

$$T_{Sys} = \frac{T_A}{L_L} + \left[290\left(1 - \frac{1}{L_L}\right)\right] + \left[290(NF - 1)\right] \qquad (3)$$

where

T_A = antenna noise temperature
L_L = losses between the antenna and the first-stage amplifier
NF = noise figure of first-stage amplifier and succeeding receiver

The antenna temperature includes all terrestrial and extraterrestrial noise sources plus noise contributions inherent in the antenna structure.

The following assumptions were made in determination of T_A.

1. The ground-based station antenna viewing condition to the satellite is a quiet sky.

2. The spacecraft antenna viewing condition to the satellite is a quiet sky.

3. The satellite viewing condition to the ground-based station is earth-at-zenith.

4. The satellite viewing condition to the spacecraft is earth-at-zenith.

Receiver-noise power calculations are based on the assumption of flat noise spectral density (NSD). The NSD may, therefore, be expressed as

$$\mathrm{NSD} = KT_{\mathrm{Sys}} \tag{4}$$

where

K = Boltzman's constant
T_{Sys} = the total system temperature (as found from Table IV)

Effective Signal Power

The circuit margins presented in this report are based on modulation techniques similar to those used in the Apollo communication system. Thus, the mathematical models developed for the Apollo Program are applicable and may be used as the basis for most of the predictions contained in this report. In the proposed DRSS, the signal is relayed through a frequency-translation repeater in the satellite. This is the most significant difference in the proposed DRSS compared with the Apollo-MSFN system. All incoming signals within the receiver bandwidth are frequency translated by a fixed amount, amplified, then retransmitted. The total transmitted power from the satellite consists of both signal and noise (Eq. (1)). For example, on the down link, power from the 20-W X-band satellite transmitter is divided among the received spacecraft signals and the thermal noise present in the satellite receiver i.f. bandwidth. The effective received-signal power, that is, the usable signal power, at the ground-based station and at the spacecraft receiver is a function of the SNR in the satellite i.f. bandwidth. The expression for the effective received-signal power P_E (derived in appendix A) is as follows.

$$P_E = P_{\mathrm{Rec}} \frac{\mathrm{SNR}_T}{\mathrm{SNR}_R + \mathrm{SNR}_T + 1} \tag{5}$$

where

SNR_T = signal-to-noise ratio in the satellite i.f. bandwidth
SNR_R = received signal-to-noise ratio at the ground-based or the spacecraft receiver in a bandwidth equal to the satellite i.f. bandwidth
P_{Rec} = total received power at the ground-based station or at the spacecraft

Circuit Margin Computations

By using the effective received-signal powers and the Apollo mathematical model (appendix B), the circuit margins may be calculated for each mode. Use of the frequency-translation repeater in the satellite relay eliminates the need to establish channel circuit margins at the satellite. Satellite degradation of the circuit margins is taken into account through the use of effective received-signal power.

The up-link and down-link margins are calculated based on the assumption of transmission to and from a single spacecraft. If the satellite-to-spacecraft radiated power is assumed to be equally divided between two spacecraft, a 3-dB degradation occurs in the up-link circuit margin. This degradation corresponds to the situation in which two spacecraft are within the scan limits of the satellite antenna. The down-link circuit margin degradation, caused by simultaneous transmission from two vehicles, is negligible. This is because of the high SNR present on the satellite-to-ground link.

To calculate a circuit margin, it is necessary to define an SNR requirement at some point (bandwidth) in a receiver channel and then to calculate the actual SNR at that point. The difference between what is required and what is achieved is the circuit margin. The signal-to-noise requirements and the associated noise bandwidths for each channel are given in Table I.

Simplified block diagrams of typical spacecraft and ground receivers are shown in Figures 4 and 5. The circled letters indicate the points at which the circuit margins are calculated in this analysis.

The signal power in a channel (telemetry, voice, updata, and so on) is found by subtracting the modulation loss for the channel from the total received power. The equations for modulation losses in each channel are given in appendix B. For example, the power in the telemetry channel P_{TM} at the ground-station receiver is given by

$$P_{TM} = P_E - ML_{TM} \tag{6}$$

where ML_{TM} is the telemetry channel modulation loss as given by Equation (B8).

The noise power in the channel is found by integrating the noise spectral density over the noise bandwidth (NBW) of the channel. For the case considered, the noise spectral density is assumed to be flat over the range of frequencies involved. Thus, the channel noise power N_X (in dBW) is given by

$$N_X = 10 \log_{10} NSD_X + 10 \log_{10} NBW_X \qquad (7)$$

The subscript X indicates a particular channel.

For the up-link PM voice and data channels, another noise source must be considered when the PRN ranging code is being transmitted. The power spectrum of this code has components in the 70-kHz updata and 30-kHz voice subcarrier bandwidths. Thus, the SNR is given by

$$SNR = \frac{Pe\ ML_X}{N_X + I_X} \qquad (8)$$

where I_X is the interference term in channel X (given by Eqs. (B13) and (B14)).

Limiter effects in the wideband phase detectors of the ground-based and spacecraft receivers produce performance degradations of as much as 1 dB at low signal levels. The expected received signal levels for the DRSS using the spacecraft high-gain antenna are, however, sufficiently strong to prevent limiter degradation. The backup voice is demodulated in the narrowband carrier tracking loop of the ground-based receiver and will not undergo limiter degradation.

Calculations for up-link PM mode 1 and down-link PM mode 1 are shown in Tables VI and VII, respectively.

Circuit margins for all the mode combinations listed in Table II are summarized in Table VIII. The modulation indices used are those for the Apollo system. No attempt has been made to optimize the indices for the DRSS links. It is anticipated that a small improvement in circuit-margin performance can be obtained by optimization of the indices for the DRSS.

Calculations for the pilot-tone circuit margin are shown in Table IX; the spacecraft omni-antenna was used. The pilot signal is the most critical communication link because it must operate satisfactorily before the main beam can be formed and directed from the satellite antenna. As previously stated, the signal power for the pilot tone is determined by the gain of a single element within the array. However, because of the small bandwidth requirement for the tone, a high SNR is possible with a very weak signal.

For this analysis, the pilot tone is assumed to be the S-band PM carrier. It is assumed that no modulation is on the carrier during acquisition procedures. Multipath loss for the pilot tone is reduced from the 12 dB assumed for the voice channel to 3 dB because of the very narrow tone channel bandwidth necessary.[2] This narrow bandwidth results in suppressions of interfering reflections which have a Doppler shift different from the direct wave.

The high-gain antenna on the Apollo spacecraft has three possible beam widths and, consequently, has three possible gains. The maximum gain, that is, the narrowest beam width, is constrained by the tracking rate of the spacecraft antenna. The maximum tracking rate for the Apollo system is specified as 5 deg/sec.[5] The maximum spacecraft antenna tracking rate occurs when the vehicle is directly beneath the satellite (Fig. 1). For a 200-mile orbit, the spacecraft velocity is approximately 25 000 ft/sec.[6] Using a spacecraft-to-satellite distance of 19 400 miles, the maximum rotation rate of the spacecraft antenna is 0.014 deg/sec. Thus, the Apollo high-gain antenna can be operated in its narrow beam-width position. All circuit margins for the Apollo spacecraft are computed using the narrow beam-width antenna gain.

Conclusions

The circuit margin calculations are proof that the DRSS exhibits satisfactory communication performance when operating with the spacecraft high-gain antenna. However, the capabilities are severely constrained when the spacecraft omni-antennas are employed. The circuit margins are summarized in Table VIII. The performance calculations are evidence that the weakest rf link is always between the spacecraft and the satellite. The satellite-to-ground link introduces little or no degradation to the overall system. The capabilities of the DRSS for the Apollo and the modified Apollo USB communication systems are summarized as follows.

DRSS with the Modified Spacecraft

The full down-link PM mode (PRN, voice, and 102.4-kbps telemetry) and the down-link FM mode (1-Mbps data dump or television) perform satisfactorily. These modes use the spacecraft high-gain antenna. Backup voice communication at baseband is possible using the omni-antenna.

The full up-link PM mode (PRN, updata, and voice) has positive margins as does the up-link FM mode (commercial television) when the spacecraft high-gain antenna is used. The minimum uplink (voice only) over the omni-antenna has a negative margin. The up-link voice circuit margins shown in Table VI were calculated for voice frequency modulated onto a subcarrier, which requires considerably more rf power than does baseband voice. Thus, the up-link configuration must be modified to accept a voice signal phase-modulated at baseband to achieve a positive margin using the spacecraft omni-antenna.

DRSS with the Apollo Spacecraft

The full down-link PM mode (PRN ranging, voice, and 51.2-kbps telemetry) performs satisfactorily, but the margin for the down-link FM mode (television) is -1.6 dB. These modes use the Apollo spacecraft high-gain antenna operating in its narrow beam-width position. The down-link PM mode (backup voice) operating with the omni-antennas has a negative margin. The DRSS, using the Apollo spacecraft omni-antenna configuration, will not provide positive circuit margins for any of the up-link modes. Margins for the full up-link PM mode (PRN ranging, voice, and updata) are positive when the spacecraft high-gain antenna is employed.

The margins also prove that the pilot link will operate satisfactorily with the omni-antenna on the modified spacecraft, but will not operate satisfactorily with the omni-antenna on the Apollo spacecraft.

Improvements in the transmission or reception characteristics of the ground-satellite link will not significantly improve the overall system performance. In fact, for all practical purposes, the marginal mode calculations, that is, those based on the omni-antennas, could be made by assuming that the ground-station demodulators are located in the satellite. Thus, the satellite-spacecraft link must be improved if any improvement in total system performance is to be achieved.

It is worth noting that the primary reason for the poor performance of the spacecraft omni-antennas is the rather severe losses attributed to multipath. The 12-dB loss used in this report was based on an analysis which contained the assumption that the omni-antenna was a perfect isotropic radiator.[2] The Apollo omni-antenna system consists of four elements individually switched to provide omnidirectional characteristics. Thus, the active element will have significant directivity toward the satellite and away from earth. This should result in a decrease in multipath effects. Further study of this problem could result in a specification on the multipath loss which will eliminate some of the negative circuit margins that have been discussed in this report.

The data-relay satellite system concept is feasible for establishing communication with manned spacecraft. However, there are many areas which demand further study and analysis before a workable and reliable system can be firmly specified. Particularly, the problems involved in implementation of a suitable multibeam, phased-array antenna on the satellite (if indeed this is the best choice of antennas) must be solved. A trade-off study between transponders and translation repeaters for the satellite electronics must be made. Procedures and techniques for automatic signal acquisition define another problem requiring further attention. Intersatellite communication in a multisatellite system is a capability which could provide significant improvement in the DRSS operation. Little attention has been given to the development of techniques to provide this capability. The experience and knowledge gained during the development and subsequent use of the Apollo communication system should be carefully considered in the final design of the DRSS.

Appendix A

Effects of Finite Transmitted Signal-to-Noise Ratios

The purpose of this appendix is to provide a derivation of an expression for the effective SNR in the i.f. and information bandwidths of a communication receiver when the total transmitted power consists of both signal and noise. This situation arises when a signal is relayed through a frequency-translation repeater.

A simplified system is shown in Figure A1. The spacecraft is assumed to be transmitting the signal to the ground-based receiver. However, the same results would be obtained if the ground-based receiver was transmitting instead of receiving. A signal $s(t)$ from the spacecraft transmitter is received at the repeater. Thermal noise, determined by the repeater system noise temperature, is added to $s(t)$. Thus, a signal-to-noise ratio P_i/N_i exists in the repeater i.f. bandwidth. Both the signal power and the noise power are amplified by the transmitter. The amplification process is assumed to be noise free. Thus

$$P_o = KP_i$$

and

$$N_o = KN_i$$

or

$$\frac{P_o}{N_o} = \frac{KP_i}{KN_i} = \frac{P_i}{N_i}$$

where K is the power gain of the transmitter. Now an apparent signal power P_{Rec} is defined such that $P_{Rec} = P_S + N_R$ is the transmitted noise where P_S is the useful signal and N_R is the transmitted noise. Then

$$\frac{P_S}{N_R} = \frac{aP_o}{aN_o} = \frac{P_o}{N_o} = \frac{P_i}{N_i} \tag{A1}$$

where a is the rf path attenuation. Therefore, based on the assumption that $A(t)$ is a white Gaussian process, the ratio of received-signal power to received-noise power is the same as the repeater SNR when referred to a common bandwidth. This ratio is defined as the transmitted signal-to-noise ratio SNR_T, that is

$$SNR_T = \frac{P_S}{N_R} = \frac{P_i}{N_i} \tag{A2}$$

Solving Equation (A2) for N_R and substituting into Equation (A1) yields

$$P_S = \frac{SNR_T}{1 + SNR_T} P_{Rec} \tag{A3}$$

Similarly

$$N_R = \frac{1}{1 + SNR_T} P_{Rec} \qquad (A4)$$

At this point, it is convenient to define an rf noise bandwidth at the ground-based receiver equal to the repeater i.f. noise bandwidth. Then, the effective or actual signal-to-noise ratio $\left(SNR_E\right)$ in this bandwidth is given by

$$SNR_E = \frac{P_S}{N_R + N_{Th}} \qquad (A5)$$

where N_{Th} is the thermal-noise power contribution as determined by the ground-station system noise temperature. Substituting Equations (A3) and (A4) into Equation (A5) and dividing by N_{Th} yields

$$SNR_E = \frac{SNR_T \dfrac{P_{Rec}}{N_{Th}}}{\dfrac{P_{Rec}}{N_{Th}} + 1 + SNR_T}$$

P_{Rec}/N_{Th} is the received SNR if no noise is transmitted, that is, for an infinite transmitted SNR. Thus

$$SNR_E = \frac{SNR_T \, SNR_R}{SNR_R + SNR_T + 1} \qquad (A6)$$

where SNR_R is the received SNR calculated assuming an infinite transmitted SNR $\left(SNR_R = P_{Rec}/N_{Th}\right)$. Equation (A6) may be rewritten as

$$SNR_E = \frac{P_{Rec}}{N_{Th}} \frac{SNR_T}{SNR_T + SNR_R + 1} \qquad (A7)$$

By assuming the total degradation to be a loss of signal power, the effective signal power can then be written as

$$P_E = P_{Rec} \frac{SNR_T}{SNR_R + SNR_T + 1} \qquad (A8)$$

Appendix B

Apollo Unified S-Band System PM Mathematical Model

The modulation-loss equations for calculation of communication performance of the Apollo unified S-band system are presented in this appendix.[7] These equations are used in the calculation of the DRSS circuit margins given in Tables VI and VII.

For the up-link PM modes, the following equations are applicable

$$ML_C = J_0^{\,2}\left(M_{UV}\right) J_0^{\,2}\left(M_{UD}\right) \cos^2\left(\phi_{UR}\right) \qquad (B1)$$

$$ML_{PRN} = J_0^{\,2}\left(M_{UV}\right) J_0^{\,2}\left(M_{UD}\right) \sin^2\left(\phi_{UR}\right) \qquad (B2)$$

$$ML_{UV} = 2J_1^{\,2}\left(M_{UV}\right) J_0^{\,2}\left(M_{UD}\right) \cos^2\left(\phi_{UR}\right) \qquad (B3)$$

$$ML_{UD} = 2J_0^{\,2}\left(M_{UV}\right) J_1^{\,2}\left(M_{UD}\right) \cos^2\left(\phi_{UR}\right) \qquad (B4)$$

where

M_{UV} = upvoice modulation index, radians
M_{UD} = updata modulation index, radians
ϕ_{UR} = up-link PRN ranging-code modulation index, radians
ML_C = carrier modulation loss
ML_{PRN} = PRN modulation loss
ML_{UV} = voice modulation loss
ML_{UD} = updata modulation loss

The down-link PM mode equations are as follows

$$ML_C = J_0^{\,2}\left(M_{DV}\right) J_0^{\,2}\left(M_{TM}\right) J_0^{\,2}(\gamma) J_0^{\,2}(\beta) J_0^{\,2}(\xi) \cos^2(\alpha) \qquad (B5)$$

$$ML_{PRN} = J_0^{\,2}\left(M_{DV}\right) J_0^{\,2}\left(M_{TM}\right) J_0^{\,2}(\gamma) J_0^{\,2}(\beta) J_0^{\,2}(\xi) \sin^2(\alpha) \qquad (B6)$$

$$ML_{DV} = 2J_1^{\,2}\left(M_{DV}\right) J_0^{\,2}\left(M_{TM}\right) J_0^{\,2}(\gamma) J_0^{\,2}(\beta) J_0^{\,2}(\xi) \cos^2(\alpha) \qquad (B7)$$

$$ML_{TM} = 2J_0^{\,2}\left(M_{DV}\right) J_1^{\,2}\left(M_{TM}\right) J_0^{\,2}(\gamma) J_0^{\,2}(\beta) J_0^{\,2}(\xi) \cos^2(\alpha) \qquad (B8)$$

where

M_{DV} = down-voice modulation index, radians
M_{TM} = telemetry modulation index, radians

α = down-link PRN ranging code modulation index

$$= \mathrm{TRC}\left(\frac{\mathrm{SNR}}{1 + \mathrm{SNR}}\right)^{1/2} J_0\left(M_{UV}\right)J_0\left(M_{UD}\right)\sin\left(\phi_{UR}\right) \tag{B9}$$

γ = down-link modulation index of turned-around upvoice subcarrier

$$= 2\mathrm{TRC}\left(\frac{\mathrm{SNR}}{1 + \mathrm{SNR}}\right)^{1/2} J_1\left(M_{UV}\right)J_0\left(M_{UD}\right)\cos\left(\phi_{UR}\right) \tag{B10}$$

β = down-link modulation index of turned-around updata subcarrier

$$= 2\mathrm{TRC}\left(\frac{\mathrm{SNR}}{1 + \mathrm{SNR}}\right)^{1/2} J_0\left(M_{UV}\right)J_1\left(M_{UD}\right)\cos\left(\phi_{UR}\right) \tag{B11}$$

ξ = down-link modulation index of turn-around white noise

$$= \mathrm{TRC}\left(\frac{1}{1 + \mathrm{SNR}}\right)^{1/2}\left(\frac{2\mathrm{NBW}_R}{\mathrm{NBW}_{IF}}\right)^{1/2} \tag{B12}$$

TRC = spacecraft transponder turnaround gain constant
SNR = signal-to-noise ratio in the spacecraft transponder i.f. bandwidth
NBW = spacecraft ranging channel postdetection-noise bandwidth
NBW_{IF} = spacecraft receiver i.f. noise bandwidth

The PRN interference term used in the up-link calculations is given by the following equations

$$I_{UD} = 2\mathrm{NBW}_{UD}P_S J_0^{\,2}\left(M_{UV}\right)J_0^{\,2}\left(M_{UD}\right) \sin^2\left(\phi_{UR}\right)\frac{\sin^2\left(\omega_{UD} \times 10^{-6}\right)}{\left(\omega_{UD} \times 10^{-6}\right)^2} \tag{B13}$$

for the updata channel and

$$I_{UV} = 2\mathrm{NBW}_{UV}P_S J_0^{\,2}\left(M_{UV}\right)J_0^{\,2}\left(M_{UD}\right) \sin^2\left(\phi_{UR}\right)\frac{\sin^2\left(\omega_{UD} \times 10^{-6}\right)}{\left(\omega_{UD} \times 10^{-6}\right)^2} \tag{B14}$$

for the upvoice channel

where

NBW_{UD} = predetection-noise bandwidth of the updata channel
NBW_{UV} = predetection-noise bandwidth of the upvoice channel
P_S = actual channel power, given in Equation (A3)
ω_{UD} = angular frequency of updata subcarrier
ω_{UV} = angular frequency of upvoice subcarrier

Signal suppression caused by limiter effects at low SNR in the ground-station and spacecraft wideband phase detectors is approximated by a sequence of straight lines, given by the following equations

$$\mathrm{SNR}_{out} = \pi/4\ \mathrm{SNR}_{in},\ \text{for}\ \ \mathrm{SNR}_{in} < 0.035$$

$$\mathrm{SNR}_{out} = \left(0.68\ \mathrm{SNR}_{in} + 0.76\right)\mathrm{SNR}_{in},\quad \text{for}\ 0.035 \le \mathrm{SNR}_{in} \le 0.35$$

$$\mathrm{SNR}_{out} = \mathrm{SNR}_{in},\ \text{for}\ \ \mathrm{SNR}_{in} > 0.35$$

where SNR_{in} is the signal-to-noise ratio into the limiter, and SNR_{out} is the signal-to-noise ratio out of the limiter. The 1.05-dB degradation is based on the work of Davenport.[8] Although the limiter equations do not reveal a 3-dB improvement at strong SNR, a 3-dB improvement is evident when the phase detector which succeeds the i.f. limiter is analyzed. This 3-dB improvement appears in the modulation-loss equations.

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TABLE I.- UP-LINK AND DOWN-LINK MODES FOR THE DRSS

(a) Spacecraft-to-satellite-to-ground (down-link) modes

Mode	Information	Modulation technique	Subcarrier frequency, MHz	Phase or frequency deviation	Ground predetection-noise bandwidth	SNR required, dB
PM 1	Carrier				700 Hz	12.0
	PRN	PM on carrier		[a]α	1 Hz	32.0
	Voice	FM/PM	1.25	0.7 rad	24 kHz	7.0
	102.4-kbps telemetry	PCM/PM/PM	1.024	1.2 rad	350 kHz	8.5
PM 2	Carrier				50 Hz	12.0
	Backup voice	PM on carrier		1.5 rad	2.5 kHz	4.0
FM 1	Television (Apollo)	FM on carrier		1.0 MHz	4 MHz	7.0
FM 2	1-Mbps playback telemetry	FM on carrier		2.0 MHz	6 MHz	7.0

(b) Ground-to-satellite-to-spacecraft (up-link) modes

Mode	Information	Modulation technique	Subcarrier frequency, kHz	Phase or frequency deviation	Spacecraft predetection-noise bandwidth	SNR required, dB
PM 1	Carrier				800 Hz	12.0
	PRN	PM on carrier		0.5 rad		
	Voice	FM/PM	30	1.0 rad	22 kHz	10.0
	Updata	FM/PM	70	.76 rad	22 kHz	10.0
PM 2	Carrier				800 Hz	12.0
	Voice	FM/PM	30	1.85 rad	22 kHz	10.0
FM 1	Commercial television	FM on carrier		6 MHz	20 MHz	7.0

[a] See Equation (B9).

TABLE II.- SYSTEM PARAMETERS

Parameter	Apollo spacecraft	Modified Apollo spacecraft	Ground station	Relay satellite
1. Antenna gain				
a. S-band				
Transmit	HGA: 27.0 dB Omni-antenna: 0 dB	HGA: 33 dB Omni-antenna: 3 dB	43 dB	40 dB (2288 MHz) 39 dB (2106 MHz)
Receive	HGA: 23.3 dB Omni-antenna: 0 dB	HGA: 33 dB Omni-antenna: 3 dB	44 dB	40 dB (2288 MHz) 39 dB (2106 MHz)
b. X-band				
Transmit			54 dB	31 dB
Receive			55 dB	30 dB
2. Transmit power				
a. S-band	11.2 W	20 W		50 W
b. X-band			150 W	20 W
3. System losses (This includes cable, polarization, and pointing losses.)	HGA: 7.9 dB Omni-antenna: [a]6.2 dB	HGA: 4.0 dB Omni-antenna: [a]3.0 dB	0 dB (System loss is included in antenna gain.)	4.5 dB (for both X-band and S-band)

[a] An additional 12-dB loss because of multipath fading is possible when the omni-antenna is used.

TABLE III.- SYSTEM NOISE TEMPERATURES

Communication links	T_A, °K	L_L, dB	NF, dB	T_{sys}, °K
Satellite to ground	60	0.5	0.8	135
Spacecraft to satellite	250	3.0	5.3	970
Ground to satellite	250	3.0	5.3	970
Satellite to modified spacecraft	60	4.0	7.5	1540
Satellite to Apollo spacecraft	60	7.0	13.0	5800

TABLE IV.- UP-LINK SIGNAL-POWER CALCULATIONS

[Ground to satellite to spacecraft]

Line	Calculation	Apollo spacecraft		Modified spacecraft	
		Omni-antenna	HGA (NBW)	Omni-antenna	HGA
1	Ground-based transmitter power, dBW	21.8	21.8	21.8	21.8
2	Ground-based transmitter losses, dB	-.0	-.0	-.0	-.0
3	Ground-based transmit antenna gain, dB	54.0	54.0	54.0	54.0
4	Ground-based station-to-satellite space loss, dB	-201.6	-201.6	-201.6	-201.6
5	Satellite receiving antenna gain, dB	30.0	30.0	30.0	30.0
6	Satellite receiving losses, dB	-4.5	-4.5	-4.5	-4.5
7	Multipath loss, dB	-.0	-.0	-.0	-.0
8	Satellite received-signal power, single link, dBW (sum of 1 to 7)	-100.3	-100.3	-100.3	-100.3
9	Satellite NSD, dBW/Hz (Eq. (4))	-198.7	-198.7	-198.7	-198.7
10	Satellite i.f. bandwidth, dB (NBW = 28 MHz)	74.5	74.5	74.5	74.5
11	Satellite i.f. noise power, dBW (sum of 9 + 10)	-124.2	-124.2	-124.2	-124.2
12	Satellite transmit SNR, dB (8 minus 11)	23.9	23.9	23.9	26.9
13	Satellite transmitter power, dBW	17.0	17.0	17.0	17.0
14	Satellite transmitter losses, dB	-4.5	-4.5	-4.5	-4.5
15	Satellite transmit antenna gain, dB	39.0	39.0	40.0	40.0
16	Satellite-to-spacecraft space loss, dB	-191.4	-191.4	-192.2	-192.2
17	Spacecraft receiving antenna gain, dB	.0	23.3	3.0	33.0
18	Spacecraft receiving losses, dB	-6.2	-7.9	-3.0	-4.0
19	Multipath loss, dB	-12.0	-.0	-12.0	-.0
20	Spacecraft total received power, dBW (sum of 13 to 19)	-158.1	-124.5	-151.7	-110.7
21	Spacecraft NSD, dBW/Hz (Eq. (4))	-191.2	-191.2	-196.7	-196.7
22	Spacecraft i.f. bandwidth, dB (NBW = 28 MHz)	74.5	74.5	74.5	74.5
23	Spacecraft i.f. thermal-noise power, dBW (sum of 21 + 22)	-116.7	-116.7	-122.2	-122.2
24	Apparent spacecraft i.f. SNR, dB (20 minus 23)	-41.4	-7.8	-29.5	11.5
25	Effective spacecraft received-signal power, single link, dBW (See appendix A.)	-158.1	-124.5	-151.7	-113.8

TABLE V.- DOWN-LINK SIGNAL-POWER CALCULATIONS

[Spacecraft to satellite to ground]

Line	Calculation	Apollo spacecraft		Modified spacecraft	
		Omni-antenna	HGA (NBW)	Omni-antenna	HGA
1	Spacecraft transmitter power, dBW	10.5	10.5	13.0	13.0
2	Spacecraft transmitter losses, dB	-6.2	-7.9	-3.0	-4.0
3	Spacecraft transmit antenna gain, dB	.0	27.0	3.0	33.0
4	Spacecraft-to-satellite space loss, dB	-192.2	-192.2	-191.4	-191.4
5	Satellite receiving antenna gain, dB	40.0	40.0	39.0	39.0
6	Satellite receiving losses, dB	-4.5	-4.5	-4.5	-4.5
7	Multipath loss, dB	-12.0	-.0	-12.0	-.0
8	Satellite received-signal power, single link, dBW (sum of 1 to 7)	-164.4	-127.1	-155.9	-114.9
9	Satellite NSD, dBW/Hz (Eq. (4))	-198.7	-198.7	-198.7	-198.7
10	Satellite i.f. bandwidth, dB (NBW = 13 MHz)	71.1	71.1	71.1	71.1
11	Satellite i.f. noise power, dBW (sum of 9 + 10)	-127.6	-127.6	-127.6	-127.6
12	Satellite transmit SNR, dB (sum of 8 to 11)	-36.8	3.5	-28.3	15.7
13	Satellite transmitter power, dBW	13.0	13.0	13.0	13.0
14	Satellite transmitter losses, dB	-4.5	-4.5	-4.5	-4.5
15	Satellite transmit antenna gain, dB	31.0	31.0	31.0	31.0
16	Satellite-to-ground space loss, dB	-201.7	-201.7	-201.7	-201.7
17	Ground receiving antenna gain, dB	55.0	55.0	55.0	55.0
18	Ground receiving losses, dB	-.0	-.0	-.0	-.0
19	Multipath loss, dB	-.0	-.0	-.0	-.0
20	Ground total received power, dBW (sum of 13 to 19)	-107.2	-107.2	-107.2	-107.2
21	Ground NSD, dBW/Hz (Eq. (4))	-207.3	-207.3	-207.3	-207.3
22	Ground i.f. bandwidth, dB (NBW = 13 MHz)	71.1	71.1	71.1	71.1
23	Ground i.f. thermal noise power, dBW (sum of 21 + 22)	-136.2	-136.2	-136.2	-136.2
24	Apparent ground i.f. SNR, dB (20 minus 23)	29.0	29.0	29.0	29.0
25	Effective ground received-signal power, single link, dBW (See appendix A)	-173.0	-135.9	-164.6	-124.7

TABLE VI.- UP-LINK CIRCUIT-MARGIN CALCULATIONS FOR PM MODE 1

Line	Calculation	Apollo spacecraft	Modified spacecraft
		HGA (NBW)	HGA
	Carrier		
1	Effective spacecraft received-signal power, dBW (Table IV, line 26)	-124.5	-113.8
2	Modulation loss, dB (Eq. (B1))	-4.8	-4.8
3	Effective spacecraft received-carrier power, dBW (sum of 1 + 2)	-129.3	-118.6
4	Spacecraft NSD, dBW Hz (Table IV, line 22)	-191.2	-196.7
5	Spacecraft predetection-noise bandwidth, dB (NBW = 800 Hz)	29.0	29.0
6	Spacecraft thermal-noise power in predetection bandwidth, dBW (sum of 4 + 5)	-162.2	-167.7
7	SNR, dB (3 minus 6)	32.9	49.1
8	Required SNR, dB (Table II(b))	12.0	12.0
9	Margin, dB (7 minus 8)	20.9	37.1
	Voice		
10	Effective spacecraft received-signal power, dBW (Table IV, line 26)	-124.5	-113.8
11	Modulation loss, dB (Eq. (B3))	-6.6	-6.6
12	Effective spacecraft received-voice power, dBW (sum of 10 + 11)	-131.1	-120.4
13	Spacecraft NSD, dBW/Hz (Table IV, line 22)	-191.2	-196.7
14	Spacecraft predetection-noise bandwidth, dB (NBW = 27 kHz)	43.4	43.4
15	Thermal noise in predetection bandwidth, dBW (sum of 13 + 14)	-147.8	-153.3
16	SNR, dB (12 minus 15)	16.7	32.9
17	Required SNR, dB (Table II(b))	10.0	10.0
18	Margin, dB (16 minus 17)	6.7	22.9
	Updata		
19	Effective spacecraft received-signal power, dBW (Table IV, line 26)	-124.5	-113.8
20	Modulation loss, dB (Eq. (B4))	-9.5	-9.5
21	Effective spacecraft received-voice power, dBW (sum of 19 + 20)	-134.0	-123.3
22	Spacecraft NSD, dBW/Hz (Table IV, line 22)	-191.2	-196.7
23	Spacecraft predetection-noise bandwidth, dB	43.4	43.4
24	Thermal noise in detection bandwidth, dBW (sum of 22 + 23)	-147.8	-153.3
25	SNR, dB (21 minus 24)	13.8	30.0
26	Required SNR, dB (Table II(b))	10.0	10.0
27	Margin, dB (25 minus 26)	3.8	20.0

TABLE VII.- DOWN-LINK CIRCUIT MARGIN CALCULATIONS FOR PM MODE 1

Line	Calculation	Apollo spacecraft	Modified spacecraft
		HGA (NBW)	HGA
	Carrier		
1	Effective MSFN received-signal power, dBW (Table V, line 25)	-135.9	-124.7
2	Modulation loss, dB (Eq. (B5))	-5.3	-5.4
3	Effective MSFN received-carrier power, dBW (sum of 1 + 2)	-141.2	-130.1
4	Ground-station NSD, dBW/Hz (Table V, line 21)	-207.3	-207.3
5	Ground-station predetection-noise bandwidth, dB (NBW = 700 Hz)	28.5	28.5
6	Ground-station thermal-noise power in predetection-noise bandwidth, dBW (sum of 4 + 5)	-178.8	-178.8
7	SNR, dB (3 minus 6)	37.6	48.7
8	Required SNR, dB (Table II(b))	12.0	12.0
9	Margin, dB (7 minus 8)	25.6	36.7
	Voice		
10	Effective MSFN received-signal power, dBW (Table V, line 25)	-135.9	-124.7
11	Modulation loss, dB (Eq. (B7))	-10.8	-10.9
12	Effective MSFN received-voice power, dBW (sum of 10 + 11)	-146.7	-135.6
13	Ground-station NSD, dBW/Hz (Table V, line 21)	-207.3	-207.3
14	Ground-station predetection-noise bandwidth, dB (NBW = 24 kHz)	43.8	43.8
15	Thermal noise in predetection bandwidth, dBW (sum of 13 + 14)	-163.5	-163.5
16	SNR, dB (sum of 14 + 15)	16.8	27.9
17	Required SNR, dB (Table II(b))	7.0	7.0
18	Margin, dB (16 minus 17)	9.8	20.9
	Telemetry		
19	Effective MSFN received-signal power, dBW (Table V, line 25)	-135.9	-124.7
20	Modulation loss, dB (Eq. (B8))	-4.8	-4.9
21	Effective ground-station received-telemetry power, dBW (sum of 19 + 20)	-140.7	-129.6
22	Ground-station NSD, dBW/Hz (Table V, line 25)	-207.3	-207.3
23	Ground-station predetection-noise bandwidth, dB (NBW = 180, 350 kHz)	52.5	55.4
24	Thermal noise in predetection bandwidth, dBW (sum of 22 + 23)	-154.8	-151.9
25	SNR, dB (21 minus 24)	14.1	22.3
26	Required SNR, dB (Table II(b))	8.5	8.5
27	Margin, dB (25 minus 26)	5.6	13.8

TABLE VIII.- CIRCUIT MARGINS (200-NAUTICAL MILE ORBIT)

(a) Down-link circuit margins (spacecraft to satellite to MSFN)[a]

Mode	Service(s)	Modulation technique	Apollo spacecraft to MSFN	Modified spacecraft to MSFN
PM, mode 1	Carrier		25.6 dB	36.7 dB
	PRN	PM on carrier	15.2 dB	30.9 dB
	Voice	FM/PM	9.8 dB	20.9 dB
	Telemetry	PCM/PM/PM	5.6 dB (51.2 kbps)	13.8 dB (102.4 kbps)
PM, mode 2	Carrier		[b]-0.0 dB	[c]8.4 dB
	Backup voice	PM on carrier	[b]-5.2 dB	[c]3.2 dB
FM, mode 1	Television (Apollo format)	FM on carrier	-1.6 dB	9.6 dB
FM, mode 2	1 Mbps telemetry (data dump)	FM on carrier	N/A	7.8 dB

(b) Up-link circuit margins (MSFN to satellite to spacecraft)

Mode	Service(s)	Modulation technique	MSFN to Apollo spacecraft	MSFN to modified spacecraft
PM, mode 1	Carrier		20.9 dB	37.1 dB
	PRN	PM on carrier		
	Voice	FM/PM	6.7 dB	22.9 dB
	Updata	FM/PM	3.8 dB	20.0 dB
PM, mode 2	Carrier		[b]-19.0 dB	[c]-7.1 dB
	Voice updata	FM/PM	[b]-23.0 dB	[c]-11.1 dB
FM, mode 1	Television (commercial)	FM on carrier	N/A	2.9 dB

[a] All margins calculated by using spacecraft high-gain antenna (except where noted) and a 30-foot antenna/cooled-paramp ground station.

[b] 0-dB spacecraft antenna.

[c] 3-dB spacecraft antenna.

TABLE IX.- PILOT-CHANNEL LINK (SPACECRAFT TO SATELLITE)

Line	Calculation	Apollo spacecraft omni-antenna	Modified spacecraft omni-antenna
1	Spacecraft transmitter power, dBW	10.5	13.0
2	Spacecraft transmitter losses, dB	-6.2	-3.0
3	Spacecraft transmit antenna gain, dB	.0	3.0
4	Spacecraft-to-satellite space loss, dB	-192.2	-191.4
5	Satellite receiving antenna gain, single element, dB	16.0	16.0
6	Satellite receiving losses, dB	-4.5	-4.5
7	Multipath loss, dB	-3.0	-3.0
8	Satellite received-signal power, dBW (sum of 1 to 7)	-179.4	-169.9
9	Satellite NSD, dBW/Hz (Eq. (4))	-198.7	-198.7
10	Satellite pilot-channel noise bandwidth, dB (NBW = 50 Hz)	17.0	17.0
11	Pilot-channel noise power, dBW (sum of 9 + 10)	-181.7	-181.7
12	Pilot-channel SNR, dB (8 minus 11)	2.3	11.8
13	Required SNR, dB (12 minus 13)	6.0	6.0
14	Margin, dB	-3.7	5.8

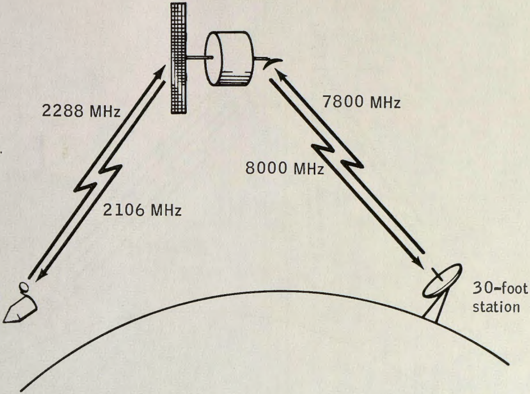

Figure 1. - Transmission and reception frequencies for an Apollo spacecraft.

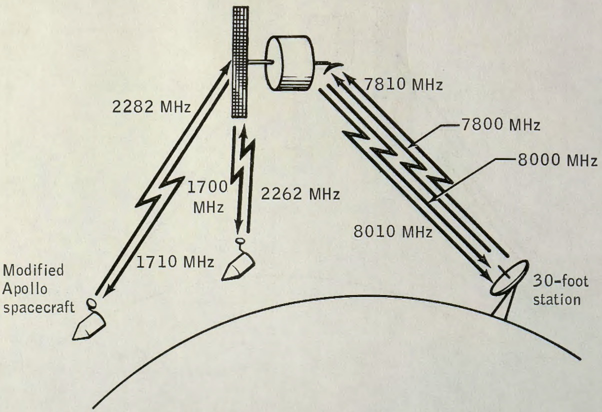

Figure 2. - Transmission and reception frequencies for two modified spacecraft.

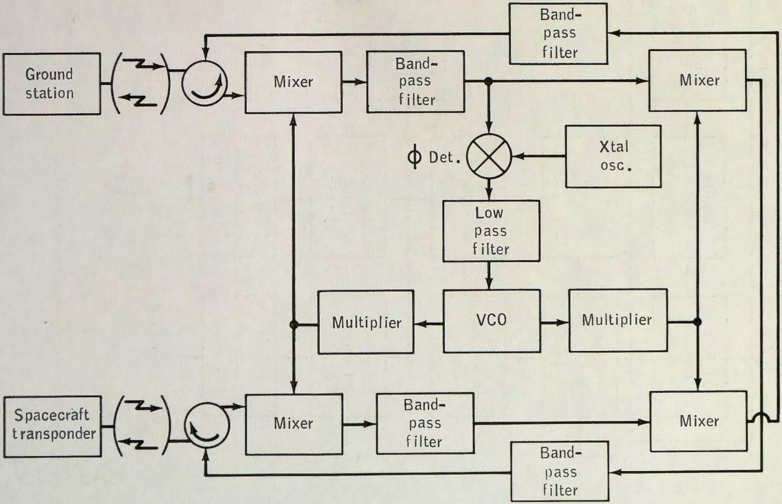

Figure 3. - Simplified diagram of a frequency - translation repeater.

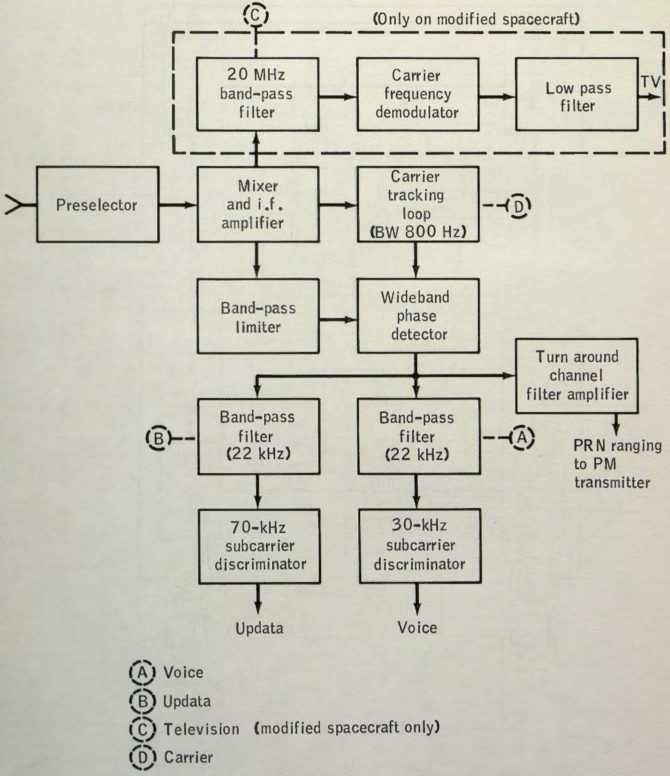

Figure 4. - Simplified block diagram of a typical spacecraft receiver.

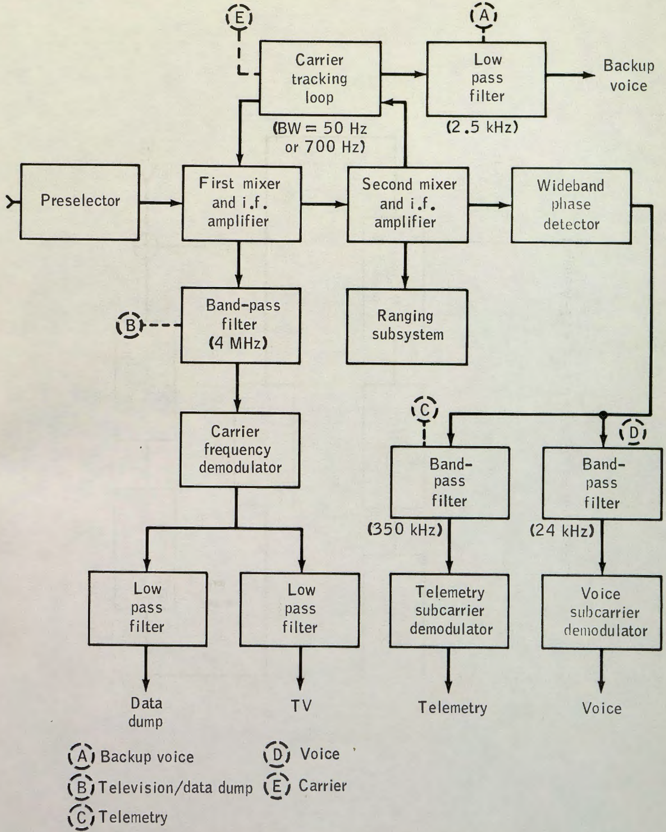

Figure 5. - Simplified block diagram of a typical ground-based receiver.

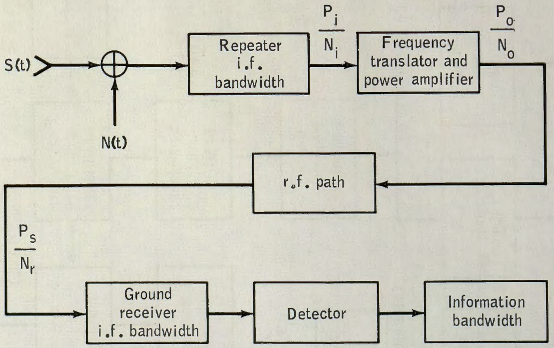

Figure A-1. - Simplified model for relay system.