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TITLE- Communications Reliability for the Apollo Manned Space Flight Network (MSFN) Based on Past NASA Network Performance

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FILING CASE NO(S)- 215

DATE- March 9, 1965

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ABSTRACT

The percentage of circuit availability time, the probabilities of circuit interruptions resulting in total channel outages, and probable error rates for data transmission were considered for voice bandwidth circuits (including teletype and high speed data), and wideband data channels such as are planned for communications in the Apollo Network. Most of the basic information analyzed was obtained from GSFC and NASA documents on the past performance of NASA communication networks primarily for the periods during space missons.

From these data, with the exception of high frequency (HF) radio circuits, it was estimated that the average reliability for non redundant channels of the Apollo Manned Spaceflight Network can be expected to be high for short continuous use (about 99.7 percent for one hour), and that the probability of a complete channel outage increases with time resulting in lower reliability (about 92.7 percent for 24 hours). Error rates for data transmission were estimated to be low (one in 10^5 bits or less). Redundant channels appeared to be justified for very important functions, preferably over geographically diversified facility routes. The calculated reliability is 99.9 percent that at least one of two channels will be an operating state at any time utilizing two independent routes.

(NASA-CR-153119) COMMUNICATIONS RELIABILITY FOR THE APOLLO MANNED SPACE FLIGHT NETWORK (MSFN) BASED ON PAST NASA NETWORK PERFORMANCE (Bellcomm, Inc.) 29 p

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SUBJECT: Communications Reliability for the Apollo Manned Space Flight Network (MSFN) Based on Past NASA Network Performance
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DATE: March 9, 1965

FROM: G. H. Speake

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TECHNICAL MEMORANDUM

1.0 INTRODUCTION

It is well recognized that adequate communications between sites of the Apollo MSFN have a direct relationship to the probability of mission success and crew safety. Since the probability of an outage in a communication network is directly proportional to the period of continued use, the reliability of the network is of increasing concern with the advent of the longer duration missions such as Gemini and Apollo.

The intersite communications of the Apollo MSFN comprise essentially a world-wide private-line network made up for the most part of commercial type circuits in the world wide commercial communication facilities. The reliability of the Apollo MSFN is thus closely related to the quality and quantity of these facilities. Communication reliability may be considered as a measure of ability to transport information when requested, within a desired time interval and with a desired degree of accuracy. These parameters are seldom precisely defined, and when they are, their relation to a particular physical network are probably best determined by actual measurements. Even so, the reliability may vary with time depending upon many factors such as the following: (1) particular units of equipment assigned to a circuit at a given time, (2) facility routing, (3) weather, (4) human error, (5) message loading, (6) equipment failures, (7) protection (i.e. backup) channels available and protection switching arrangements, (8) quality of maintenance, (9) diurnal variation of radio propagation, (10) type of facility and its condition. Thus determining a single overall reliability figure for a communication facility or for a particular private line assignment within a facility is a very complex problem. Rather than attempt to derive such a figure, it is more reasonable to discuss significant aspects of reliability and arrive at a range of values.

2.0 SUMMARY

The basic communication facilities for the Apollo intersite communication network will consist of microwave radio relays, land lines, and undersea cables to all land sites except Ascension Island for the primary (first choice) routing. Geographically diversified first choice communication facilities are also available or planned generally within the continental United States and by undersea cables to Europe, Australia and Hawaii. High frequency (HF) radio is the present primary facility for ships, aircraft, and Ascension Island and, to some extent, provides for backup circuits to all land sites except those in the continental United States. This memorandum considers the reliability of facilities when used for wideband data, high speed data, voice, and teletype. Possible data transmission error rates over operating circuits, as well as total channel outages are discussed. The performance of HF radio circuits is treated separately. Most of the basic data for this reliability analysis was obtained from Goddard Space Flight Center and NASA documents.

It was found for microwave and hard wire facilities that the channel availability (the ratio of satisfactory operating time to scheduled operating time) is consistently about 99 percent or better for voice bandwidth circuits, (including high speed data and teletype circuits). The availability of wide band data circuits was also found to be 99 percent or better.

From consideration of the data transmission error rate, high speed data (about 2.0 kilobits per second) may be expected to have an error rate of about 10^{-5} or less. Wideband data may be transmitted over transcontinental distances within the United States with an error rate of about 10^{-6} or less for over 98% of the time.

Reliability, in accordance with MIL-STD-188B, was defined as the probability of an operating channel continuing in an operating state (without a total outage) over a given time. It was found that, for 90 percent of the time with a confidence of 95 percent, there is a probability of 80 percent that a single typical Apollo voice bandwidth circuit will not incur a total outage within 24 hours of a given time. The corresponding probability for a wideband circuit is 91 percent. For a ten day mission time, any single channel will have little chance of continuous operation without at least one failure resulting in a total outage.

For two channel redundant operation, it is found that the probability of at least one of the redundant channels being in an operating state at any time is better than 99.9 percent for voice bandwidth or wideband data channels. However, this figure is less certain for the wideband case because of the possibility of overlapping repair times.

Considerable uncertainty exists in connection with HF radio facilities. While "operating ratios" may be fairly good, the probability of a channel operating over any 24 hour time period without an outage depends upon terminal locations and a number of widely fluctuating parameters (including the ionospheric parameters), many of which are not under engineering control. HF radio communications have failed during mission times (e.g., to the Pacific Command Ship during the MA8 Mercury mission). It has been predicted (Section 4.3) that data error rates of about 10^{-3} or less may be expected for 90 percent of the time over the direct HF circuit from Ascension to Cape Kennedy.

3.0 Reliability Criteria

The Goddard Space Flight Center in their "NASCOM Network Ground Communications Reliability Report" defines reliability as the ratio of realized circuit operating time to the total scheduled operating time. This definition will be used as "operating ratio" in this memorandum. The operating ratio for hardwire circuits has been found to be constantly high, about 99% or better. It is one way of expressing reliability on a long term basis, and gives a good indication of service received in an economical sense. It tells little though, about the probability of a circuit outage occuring during some future entire mission time, which is of particular interest for Apollo.

Common carrier private line circuits generally exist, within a sufficiently large communication facility cross section, such that one circuit may be substituted for another equivalent circuit for normal maintenance or circuit restoral in case of outage. This usually applies for voice-band, or teletype channels which are normally carried by voice-band circuits. It is also the case for data channels of about 2400 bits per second or less. The reliability of such circuits are therefore not heavily dependent upon whether or not the circuit is required for full time (24 hours per day) service or some lesser amount per day. Also, for these circuits, outages are probably random in nature.

For higher speed data or video circuits, which are specially treated, the situation would be different, since equivalent substitute channels are normally limited for such circuits. In any case, for most channels, it might be expected that once a circuit is set up, its time to failure would be exponential in nature as has been found for most electronic equipments. Considering the above, and for the purpose of estimating the probability of a circuit outage, and the probable outage time as discussed in sections 7 and 8, the following assumptions were made:

(1) Circuit interruptions per month resulting in complete outages may be approximated by a normal distribution function.

(2) Estimated time-to-failure for a typical circuit, within any month may be approximated by an exponential function.

(3) Circuit outage-time-per-interruption for typical circuits may be approximated by a normal distribution function.

(4) It is equally probable that at any time, T, any one circuit of a group of average circuits may fail.

Short time interruptions, such as impulse noise, which affect the quality of data transmissions are not random in nature. It has been found that while some impulse noise may occur at random intervals, long noise bursts and circuit dropouts also occur, resulting in data error rates which are not purely random. Data transmission and possible error rates will be discussed.

4.0 Reliability of General Types of Communication Facilities

4.1 Microwave Radio Relay

The reliability of microwave radio relay depends mostly upon type of equipment, system design, and fade margins. A widely used design objective for microwave fading is 99.99% reliability per hop for the busy hour load conditions. For 40 hops, or about 1000 miles, which is likely to be involved in many Apollo intersite circuits, the reliability, Rn would be $(R_1)^n$=99.63% and does not include allowance for human error or equipment failure. This figure is attainable from a practicable standpoint by using protection channel switching (or frequency diversity) and applies to all Bell System heavy route, long haul type of facilities, and to most light route, short haul facilities. It may not apply where light route facilities have been obtained on a lowest bid basis unless care has been exercised in specifying the requirements.

4.2 Hard Wire

Hard wire facilities may be grouped in decreasing order of their relative reliabilities as: (1) undersea, or under ground cable; (2) aerial cable; and (3) open wire. This grouping is based primarily upon susceptibility to physical damage.

It may be expected that an undersea cable of the newer types will suffer damage about once a year.[1] Aerial cable or open wire routes, in addition to accidental damage, are subject to the weather elements such as sleet, ice, wind and lightning. Yearly outages for all hard wire facilities are strongly dependent on the class of construction and the geographical area, and will vary widely for different routes.

4.3 High Frequency Radio

Regardless of transmitted power or modulation techniques, it is necessary to change frequency periodically in order to maintain communications over an HF radio circuit. It is extremely difficult, if not impossible, because of the above factor, to provide continuous service for long time intervals over any single HF radio channel. This situation is of course improved by using multiple channels combined with diverse geographical routes. Diverse routes are particularly important for east-west directions due to diurnal variations. Forecasting of progagation conditions is also helpful in operating HF radio networks, and techniques such as ionospheric soundings have been used to determine the optimum frequencies of transmission. The better operating techniques, higher transmitter powers, and improved hardware,

[1] R. T. Nichols, "Submarine Telephone Cables and International Telecommunications", Rand Corporation, February 1963, p. 30.

available today, have nevertheless, done little to mitigate the basic problems inherent in HF radio transmission which are largely due to the uncontrollable nature of the transmission medium.

For Apollo, HF radio circuits to aircraft, and to ship locations in the northern and southern areas of the Atlantic and Pacific Oceans, and the Indian Ocean are current requirements. Ascension must also be reached by this type of facility, and has HF radio links to cable or land line terminal points at Antigua and Cape Kennedy. The Air Force Missle Test Center has reported high reliabilities for the Ascension circuits (97 to 99%).[2] However, a statistical study of the AFETR circuits, based on RCA Radio Circuit Performance Summaries for the first eight months of 1963, indicate much poorer operations. This study shows for the Cape Kennedy-Ascension link, P26D, that the average number of quarter-hour outages per day equaled 1.3, but in the time intervals of minus 24 hours plus 24 hours from launch for seven orbital launches the equivalent of 43 quarter-hour outages were reported. This would be about 3.1 quarter-hour outages per day or over twice the long term (212 day) average. This and similar analyses on other HF radio links led to the conclusions of the Aerospace study which stated that monitoring of the AFETR HF radio circuits was undoubtedly heavier during launch times and thus data from the RCA summaries could lead to biased opinions.[3]

A detailed study by NBS, analyzed by ITT Communications Systems, Inc., considered predicted performance of 18 AFETR point-to-point HF radio circuits, and a large number of ship-to-shore links for ships in the north and south Atlantic and the Indian Ocean. The Cape Kennedy-Ascension overall reliability was estimated as 83%. This was based on a data error rate of 1 in 10^6 bits, 71 db S/N ratio in a one cycle band,

[2] E. M. Coombs, "Trip Report-Briefing on Kineplex Data Transmission by High Frequency Radio in Atlantic Missle Range", Bellcomm, Inc. (August 20, 1963).

[3] G. L. Bagg, "Statistical Study to Ascertain the Validity of the AMR Radio Circuit Performance Summaries for HF Radio Outage", Aerospace Corporation, February 29, 1964, (Contract AF04 (695-269).

quadruple diversity, and included a direct path plus an alternate path via Antigua. For the direct path, it was expected that the S/N ratio would exceed 43 db (error rate about $3X10^{-3}$) for 90% of the time. The other point-to-point circuits considered were estimated to give better performance in varying degrees up to 73 db S/N ratio expected to be exceeded 90% of the time for an Asmara-Ascension link.[4]

For the MA-9 mission, NASA reported reliabilities of 85 to 98% with message delay times up to 206 minutes for the HF radio ship to shore circuits.[5]

For the MA-8 mission, it was calculated that HF radio reliability would be less than 90% for about five hours during mission time to the Pacific Command Ship (PCS), and that reliability would be less than 90% for about four hours between Australia and the Indian Ocean ship (IOS). The Indian Ocean Ship lost teletype communications for about a one-half hour period which just preceded its contact with the Mercury capsule on the third orbit. The PCS lost teletype communication for about one hour during the fifth orbit, and was out during the capsule in view time.[6] Fortunately, these outages did not seriously affect the mission.

Forecasting of propagation conditions depends upon the time and the known transmitter and receiver locations. The forecast becomes more accurate as the time the forecast is made and the considered time of circuit use become closer together. It is understood that GSFC can provide propagation services on a monthly, daily, or hourly basis for mission periods. It is likely, however, that reliability generally will vary over a rather wide range for various HF circuits and various conditions, for example, 78 to 98 percent.

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[4] "Analysis of NBS Predictions of Performance AMR HF Radio Circuits", ITT Communication Systems, Incorporated, April 22, 1963, (Contract AF 19 (626)-5).

[5] "Communications Performance Analysis for MA-9", Goddard Space Flight Center, June 20, 1963.

[6] "Project Mercury Ground Communications, Final Report on Observations During the MA-8 Mission September 22, 1962 through October 3, 1962", Bell Telephone Laboratories Incorporated, (October 31, 1962), p. 11 (Contract NAS 5-1434).

In general, HF radio circuits properly designed, and with good operating and forecasting techniques, provide fairly effective communications for voice, teletype, and low speed data. Such circuits are most attractive where real time transmission is not mandatory. Where real time transmission is mandatory, and a transmission time is likely to fall at any time within any 24 hour interval, high probabilities of reliable communications are not attainable.

5.0 Apollo Intersite Facilities

For Apollo, the major ground stations shown in Figure 1 are planned. This figure depicts the basic intersite communication facilities for the primary or first choice routing. First choice type of facilities for alternate geographically diversified routing also exists between NASA centers. But alternate routing for sites outside the continental United States as well as primary routing for Ascension and all ships and aircraft, at the present time, depends upon at least one link of the HF radio type of circuit.

Remote site circuits may be terminated to any NASA center through diversified broadband (4 mc.) facilities. This is further illustrated in Figure 2. This figure shows the many possibilities of alternate routing between the NASA centers via microwave radio relay. Also available, but not shown, are many cable and open wire routes. In general, such communication facilities and routing flexibilities are available throughout the continental United States, with correspondingly high facility and route reliability.

Outside the United States, Apollo network circuits may be diversified through undersea cables. There are three Bell System transatlantic cables to Europe, with a fourth planned for 1965 with total capacity using all cables of 424 circuits. Hawaii may be reached via three undersea cables - capacity 256 voice circuits. Bermuda, Guam, and Australia* at the present time depend upon single cables with capacity of 80, 128, and 80 voice circuits respectively. Canary Island is to be served by undersea cable from Spain being installed in 1965 - voice channel capacity will be 160 circuits. Reliability for these type facilities is very high. The probability is greater for a failure on the open wire routes in Australia, or the open wire route serving Guaymas, Mexico from Tucson, Arizona. However, the likelihood of any site

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* As shown in Figure 1, a second cable route to Australia will be in operation in late 1966.

being completely isolated, because of an entire facility route failure, although possible, is slight. The individual channel performance of Apollo network circuits will be most significant with regard to reliability since this type of failure will occur most often.

6.0 Teletype Performance

Teletype is, of course, a form of low speed data (100 WPM ≈ 75 bits per second), and is usually multiplexed and carried over voice bandwidth circuits. For the Project Mercury MA-8 Mission, it was reported by the Bell Telephone Laboratories that: "The teletype circuits in the overall Mercury network provided service continuity for more than 99% of the total available network time for the live mission. On this day, the network was operated on mission status for 14 hours or 840 minutes. The entire Mercury teletype network consists of 33 two-way circuits or 66 one-way circuits. Therefore, some 55,440 circuit minutes of teletype facilities were involved in the mission. The continuity of these facilities showed only 225 circuit minutes of outage, giving an operating ratio of 99.6%.[7] There is no known reason to suppose that the operating ratio for the Apollo teletype network would be less than about 99%, assuming the continuation of high quality administration and maintenance procedures.

7.0 Voice-Bandwidth Channels

Since voice bandwidth circuits are utilized for voice and high speed data (to about 2.4 kilobits per second), their performance in both categories are of interest. The approach here will be to consider separately (1) circuit interruptions where total outage occurs and (2) error rates over operating circuits for data transmission. For total outages, Table 1 has been compiled from data published periodically by GSFC entitled, "NASCOM Network Ground Communications Reliability Report". The data covers the period from September 1963 through July 1964 by reports dated September 1963, November 1963, December 1963, January 1964, February 1964, June 1964 and July 1964. The data considered is applicable to voice bandwidth circuits between GSFC and the Apollo sites shown on Figure 1 and listed in Table 1.

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[7] "Project Mercury Ground Communications, Final Report on Observations During the MA-8 Mission September 22, 1962 through October 3, 1963", Bell Telephone Laboratories Incorporated, October 31, 1962), p. 11 (Contract NAS 5-1434).

7.1 Probability of Total Outage

It may be seen from Table 1 that while "operating ratios" are high (99.26% average) to all Apollo sites, it is highly probable (100% average) that a circuit to any Apollo site will suffer total outage at some time within any month. The data on interruptions per circuit per month and circuit outage time per circuit has been plotted on Figure 3 and Figure 4, respectively, as percentage cumulative distributions. The solid line for both figures was determined from the means and standard deviations of the samples, and are estimated normal cumulative distributions which are used in determining the estimated reliabilities shown in Table 3 and Table 4.

Table 3 shows that with 95% confidence it can be stated that for 90% of the time that the probability of an average Apollo network voice bandwidth circuit operating without a total outage (from any time t), is 99.08% for one hour; for one day 80.2% and, for 10 days 11.1%.

These results are based on a limited sample necessarily chosen in such a manner that they might not apply to all networks. The numbers, however, do appear to be reasonable. It is well known that individual telephone circuits do fail, but it is also well known that nationwide network for telephone service is highly reliable. This apparent conflict is resolved through use of redundant circuits. There are now over 238,000 long distance circuits which provide for a considerable number of redundant paths between switching centers.[8] For example, circuits are provided between switching centers so that it will be expected that all circuits between any two centers will be busy for only 1.0% of the calls dialed during the busiest hour of the busiest day of the year. It is clear, therefore, that for the majority of the time many circuits are idle and these provide redundant facilities contributing to the high reliabilities which exist. The MSFN may utilize the switched network for voice circuits if a need should occur.

An individual Apollo circuit would not automatically be switched for another circuit in case of a failure. Thus, its time to failure would be related to the number of electronic components in the circuit, which, of course, is related to circuit length. Table 1 indicates that circuit length is, indeed, one factor in reliability. It may be seen in Table 1 that a number of interruptions per circuit months of operation are considerably higher for the longer circuits. (9.5 for Australia-11500 miles vs. 0.6 for Cape Kennedy-925 miles). For the MSFN network reduntant circuits, which are discussed in Section 9.0 are used to increase reliability.

8 R. R. Hough, "The Bell System Construction Program," Bell Telephone Magazine, XLII Number 3, (Autumn 1964).

7.2 High Speed Data Error Rates

Error rates for data transmission over voice bandwidth telephone circuits are affected by such transmission parameters as: (1) circuit bandwidth, (2) frequency response characteristic, (3) envelope delay characteristic, (4) circuit net loss, (5) steady state noise, and (6) impulse noise. These parameters are by no means consistent for all circuits, but vary considerably from circuit to circuit and also from time to time for the same circuit in some cases. Other important factors which influence error rates are the type of data sets used, and whether the data is to be transmitted over the switched telephone network, or private line circuits. Error detection, with retransmission of data in error, or error correction codes would also influence the overall error rate. The Bell Telephone Laboratories have studied the switched telephone network for data transmission capabilities. For one type of data set, and as a general situation, it was found that data error rates of about 10^{-5} for 60% of long distance calls would apply for data transmission speeds of 1200 bits per second.[9] A study by the Lincoln Laboratory showed that error rates of about 10^{-5} were feasible over typical private line telephone circuits. This study considered four different data sets, at 1300, 1000, and 2400 bits per second.[10]

Improvements in data sets and in the telephone network have proceeded since the above studies were made (1959-60). The Bell System data Set 201A is now offered for 2000 bits per second service over the switched telephone network, and the Data Set 201B for 2400 bits per second service over private line systems. Several types of private line circuits are offered for data transmission. These include a Schedule 4B Voice/Data service, which is now provided for high speed data (2000 bits/second) circuits between GSFC and Cape Kennedy, and GSFC and Bermuda. This type of circuit is especially treated or selected, if required, to meet specifications on attenuation, frequency response, envelope dealy, signal-to-noise ratio and impulse noise. GSFC reports that the existing circuits are performing very well.[11] Considering the above, and the fact that experience with data

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[9] A. A. Alexander, R. M. Gryb, and D. W. Nast, "Capabilities of the Telephone Network for Data Transmission", Bell System Technical Journal, XXXIX, (May 1960), 431.

[10] A. B. Fontaine, and R. G. Gallager, "Error Statistics and Coding for Binary Transmission over Telephone Circuits." Proceedings of the IRE, (June 1961), p. 1059.

[11] "NASCOM Network Ground Communications Reliability Report," Goddard Space Flight Center, August 1964, p. 81.

transmission over various circuits (e.g. SAGE) has broadened considerably in the past several years, it is highly unlikely that excessive data error rates will be experienced over the Apollo network private line circuits. This assumes that proper circuit design is followed and appropriate data sets are chosen from those available.

8.0 Wide Bandwidth Channels

8.1 Probability of Total Outage

From a channel outage standpoint, two wideband data services have been informally investigated. One service consisted of 2100 circuit miles in the east-west direction. The other, 1030 circuit miles in a north-south direction. Both services are provided by the Bell System within the continental United States and operate at 40.8 thousand bits per second. The longest circuit has been in service for approximately two years, and the shortest for about four months. As shown in Table 3, and based on the ratio of actual service availability time to scheduled service availability time, it was found that the operating ratios for the longest and shortest circuits, respectively, were 99.5% and 99.8%. Interruptions per circuit per month and the circuit outage time per interruption have been approximated by the normal distribution shown on Figure 3 and 4 respectively. Because of the limited data upon which these distributions are based, it is doubtful that conclusions may be made with a high degree of confidence. It is of interest to note, however, that while wideband data circuit interruptions per month appear to be less than that for voice band-width circuits, the outage time per interruption can be significantly higher. Wideband data service is relatively new. Because of this, and the nature of the service, it is likely that circuit assignments would be most carefully made, resulting in the very best facilities being made available for wideband data trans-missions. Also, less equipment would be required, com-pared to a voice circuit, since interconnections would be made on a group or through basis and no voice channel modems would be required. In addition, it is likely that maintenance forces would tend to be especially alert regarding a wideband data service. These factors could conceivably reduce the number of interruptions to the wideband service. On the other hand, because of the special circuit arrangements, and circuit conditions, it is likely that the number of equal quality spare facilities would be limited. In some cases, therefore, a wideband data circuit could be out until the trouble causing the outage was found and corrected instead of substituting a good circuit for the bad one while repairs were being made.

8.2 Wideband Data Error Rates

Wideband data transmission and probable error rates over Bell System type of facilities is considered in detail in "Transmission Systems for Communications", Bell Telephone Laboratories, Chap. 28. Based on actual noise measurements on Bell System long haul microwave facilities, and other relevant parameters, it is shown that wideband data may be transmitted over transcontinental distances with bit error rates of less than 10^{-6} for 98.5 percent of the time. It was further estimated that reliable data transmission is feasible up to 4000 miles at a rate equivalent to 6 pages per minute of facsimile or 255 kilobits per second.[12] There are no known reasons to challenge these conclusions. It should be emphasized, however, the communication systems considered were Bell System type long haul facilities which will be used for Apollo such as the TD-2 microwave radio relay. Lesser quality facilities would experience higher error rates.

9.0 Redundant Channel Operation

It has been a practice to provide redundant channels over geographical diversified routes for operational critical circuits whenever such routing was or could be made available, for important missions. For Apollo, such routing will be available, and it is of particular interest to determine the reliability probabilities involved.

It has been implied that circuit reliability is related to, among other things, the circuit repair time as well as the number of circuit outages within a time period. This is

[12] Transmission Systems For Communication, Third Edition, Bell Telephone Laboratories Incorporated, (1964), p. 690.

true for redundant channel operation. There is some probability that repair time will overlap overating time, thus causing both channels to be out of service. This problem may be reduced to a first order Markov process with two states for each channel (operating state and repair state) and the channel transition probabilities. Another possibility is that a channel is in a standby state, but for Apollo, it will be assumed that any benefit of longer life attained by a standby condition under reduced stress for electronic equipment would be offset by switching time required to bring the circuit into operational status. The following relations are used:[13]

(1) The probability that both channels are operational at the beginning of any time T is:

$$P_{oo} = \frac{\left(T_o / T_r\right)^2}{1 + 2\frac{T_o}{T_r} + \left(\frac{T_o}{T_r}\right)^2}$$

(2) The probability that one channel is operational and one channel is in repair at the beginning of any time T is:

$$P_{or} = \frac{2\left(T_o / T_r\right)}{1 + 2\frac{T_o}{T_r} + \left(\frac{T_o}{T_r}\right)^2}$$

(3) The probability that both channels are in repair at the beginning of any time T is:

$$P_{rr} = \frac{1}{1 + 2\frac{T_o}{T_r} + \left(\frac{T_o}{T_r}\right)^2}$$

Where T_o is the time interval between channel failure and T_r is the time interval required to repair a channel.

[13] W. B. Rohn, "Reliability Predictions for Complex Systems", Proceedings Fifth National Symposium on Reliability and Quality Control in Electronics, (January 1959), pp. 381-388.

9.1 Redundancy Utilizing Independent Routes

Table 4 is a summary of the probabilities for two channel reliability. It may be seen from this table, that the probability of at least one of two channels being in the operational state for both voice bandwidth circuits and wideband data circuits is very good, about 99.9%. It is also shown that wideband data channels are somewhat less reliable for two channel operation than the voice bandwidth circuits. This is because of more uncertainty in probable repair time for wideband data channels. The probability of both wideband data channels being in an operational state at the beginning of any time T, and for T_o and T_r within two standard deviations of the mean is 93.9% while the corresponding figure for voice bandwidth circuits is 95.6%.

9.2 Redundancy Utilizing Same Route

Redundant channels such as voice or wideband data may be provided over the same communication route. The improvement in reliability obtained by this method depends upon the type of route and the facility components or equipment which are common to the redundant channels. For "L" type carrier, the same group, super group, master group, and line repeaters would be used for many voice or data channels. Group equipment is common to the equivalent of twelve (4KC) voice channels; super group to 60 voice channels; and master group to 600 voice channels. Redundant channels assigned within the same group would result in little immediate reliability improvement. This may be determined from Table 3 by comparing the average voice channel reliability of 99.68 percent for one hour with the wideband figure of 99.86 percent for one hour. The wideband reliability is representative of a channel from input to group equipment to output of group equipment since this service does not utilize voice modems. It is clear that no amount of redundancy of channels assigned within the same group or other common equipment can improve reliability beyond that of the group or common equipment itself. For 10 days of continuous operation, reliability similar to the above would be 46.8 percent for voice and 71.9 percent for wideband.

Undersea cables of 128 (3KC) voice channel capacities require only 8 group and 2 super group equipments for multiplexing. This seriously restricts possibilities of redundant channel assignments for high reliabilities. Line repeaters, and power supplies are common to all channels and place further restrictions on possible reliability improvements by redundancy.

Microwave radio relay and underground cable routes may have many independent channel assignment possibilities. Considerable improvement reliabilities for selected redundant channels over such routes is feasible. Open wire routes have similar possibilities. Careful assignment of facilities for redundant channel operations over such routes should result in a probability of at least one of the redundant channels being in an operating state at any time, T, which approaches the reliability of the route itself.

10.0 CONCLUSIONS

Consideration of the various aspects of the communication network between sites of the Apollo MSFN lead to the following conclusions:

1. The basic communication facility routes between NASA centers and the primary route to Apollo ground sites are of sufficiently high quality, that there is little chance of a site being isolated because of an entire route failure. An exception is Ascension Island which depends solely on high frequency (HF) radio. There is some reservation regarding communication reliability of Guaymas, Mexico, which is served by open wire from Tuscon, Arizona, and the Carnarvon, Australia site.

2. Error rates for data transmission over microwave or hard wire circuits of 1 in 10^5 for voice bandwidth channels, and about 1 in 10^6 for wideband channels in the USA can be expected. Wideband data may be transmitted over transcontinental distances within the Unites States.

3. Availability, (ratio of operating time to scheduled operating time), is 99 percent or better for microwave or hardwire channels, voice and wideband.

4. Reliability, (the probability of a single channel operating without an outage over a given time), decreases sharply with the duration of the operational interval, and there is little chance that a single channel (voice or wideband) would operate continuously for a 10 day mission period.

5. For independent two channel redundant microwave or hardwire operation, there is a high probability, 99.9% or better, that at least one channel of the two will be in an operating state at any time for voice or wideband. There is less certainty associated with this reliability, for wideband as compared to voice circuits.

6. There is considerable uncertainty associated with high frequency radio for real time transmission. High frequency radio circuits are, therefore, not

attractive in cases where real time transmission is a requirement.

G. H. Speake

2021-GHS-mk

Attached:
Figures 1-4
Tables 1-5

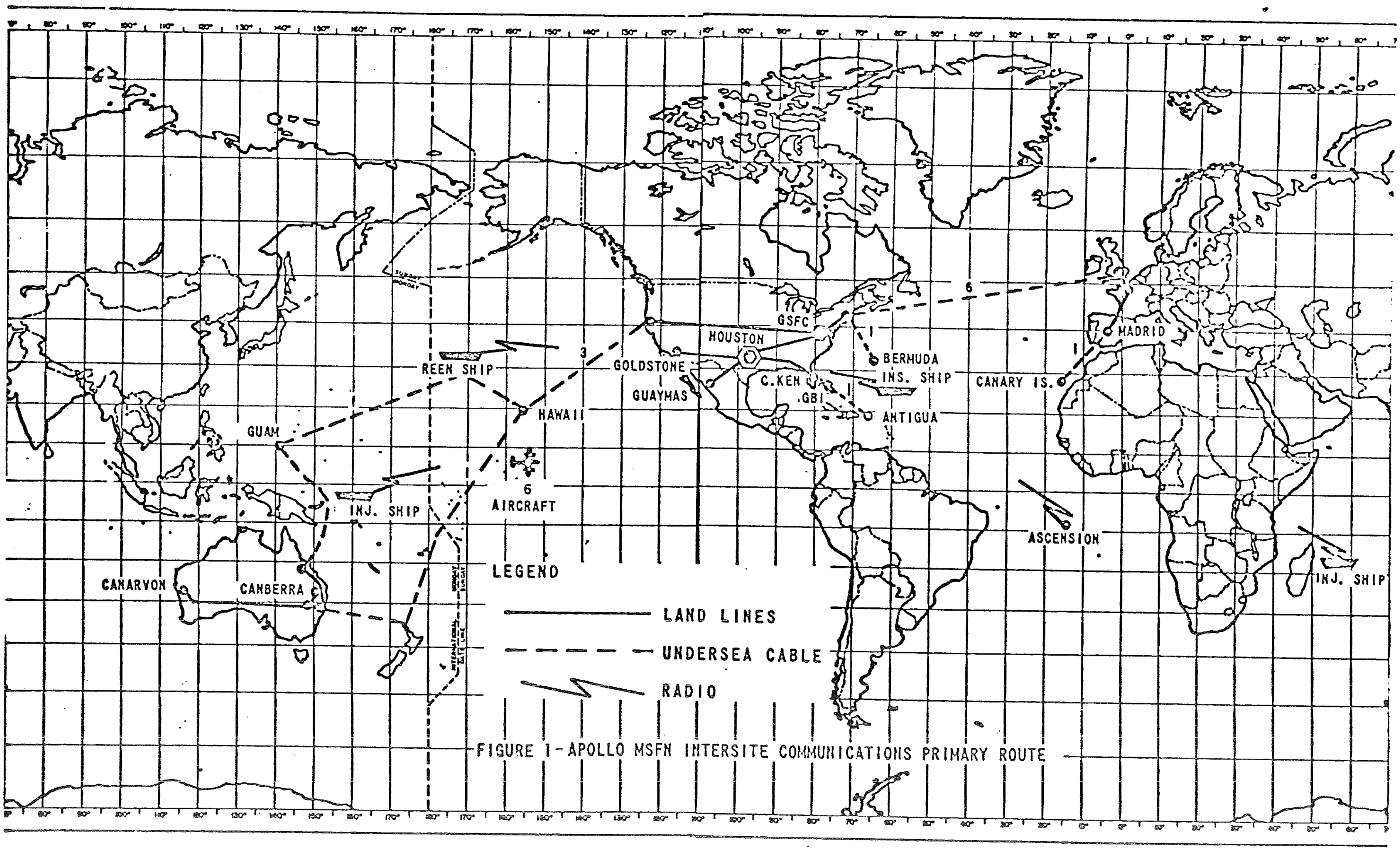

FIGURE 1 - APOLLO MSFN INTERSITE COMMUNICATIONS PRIMARY ROUTE

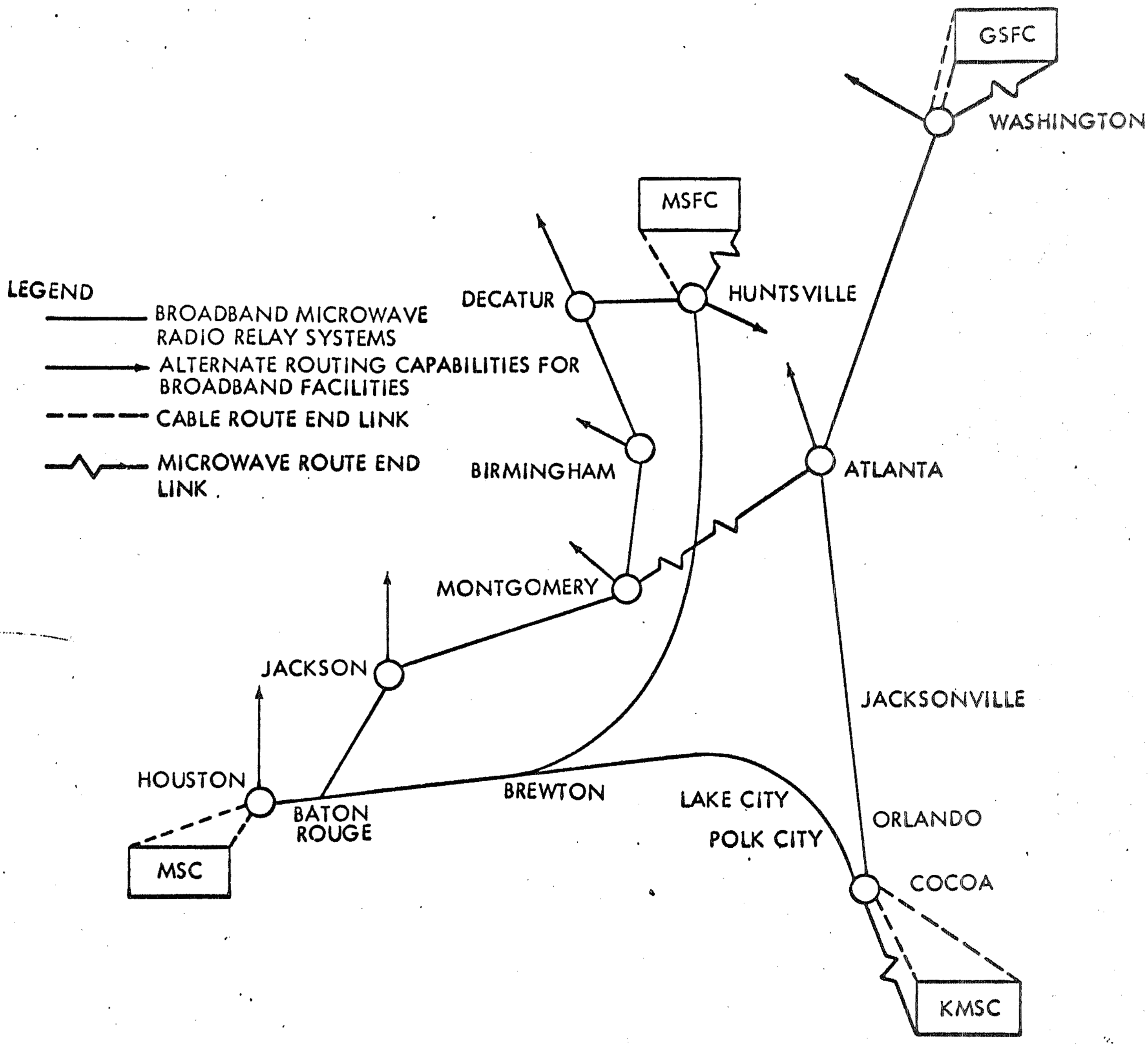

FIGURE 2 PRIMARY COMMUNICATION FACILITIES BETWEEN NASA CENTERS.

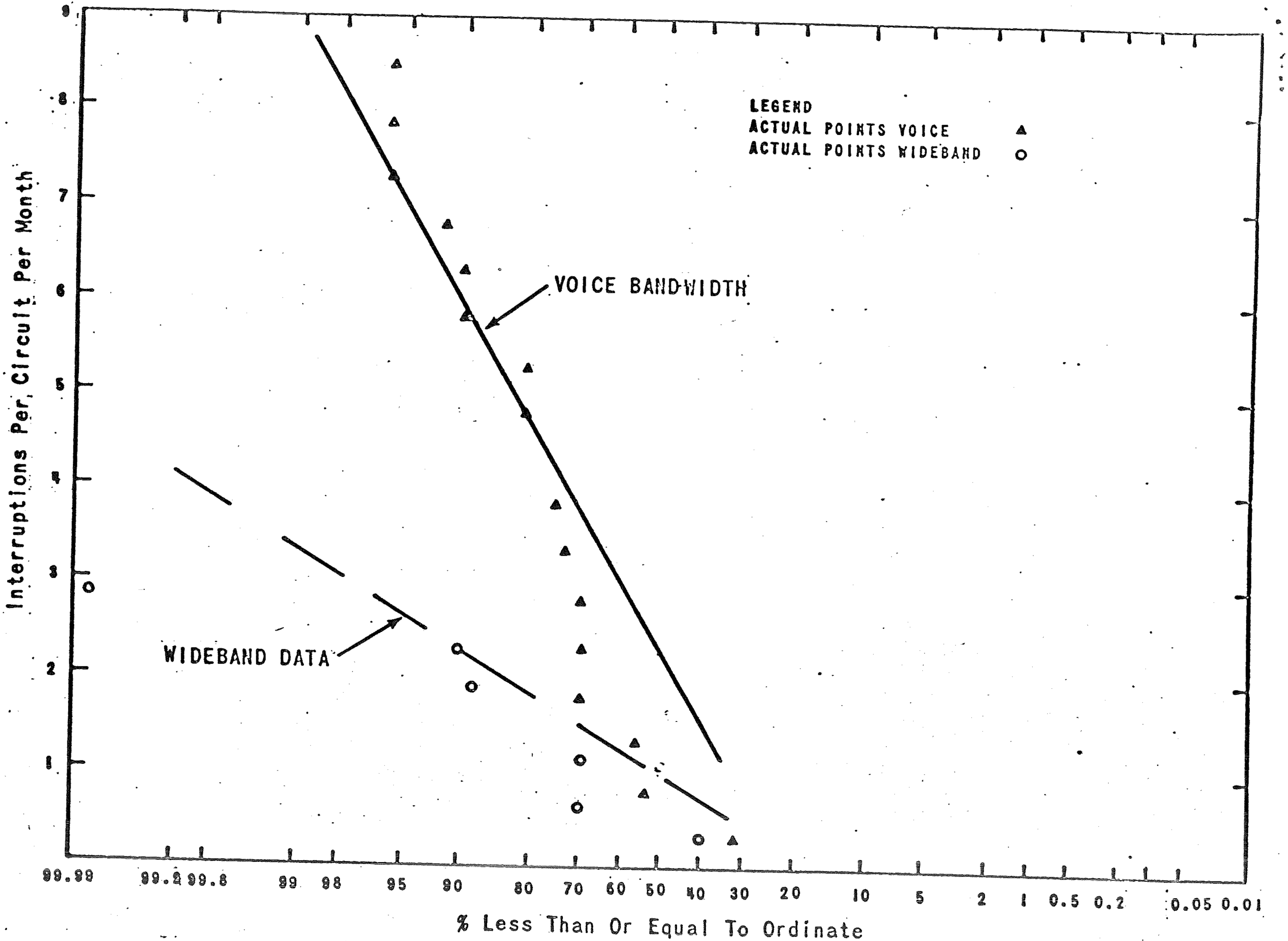

FIGURE 3 ESTIMATED CIRCUIT INTERRUPTIONS APOLLO MSFN

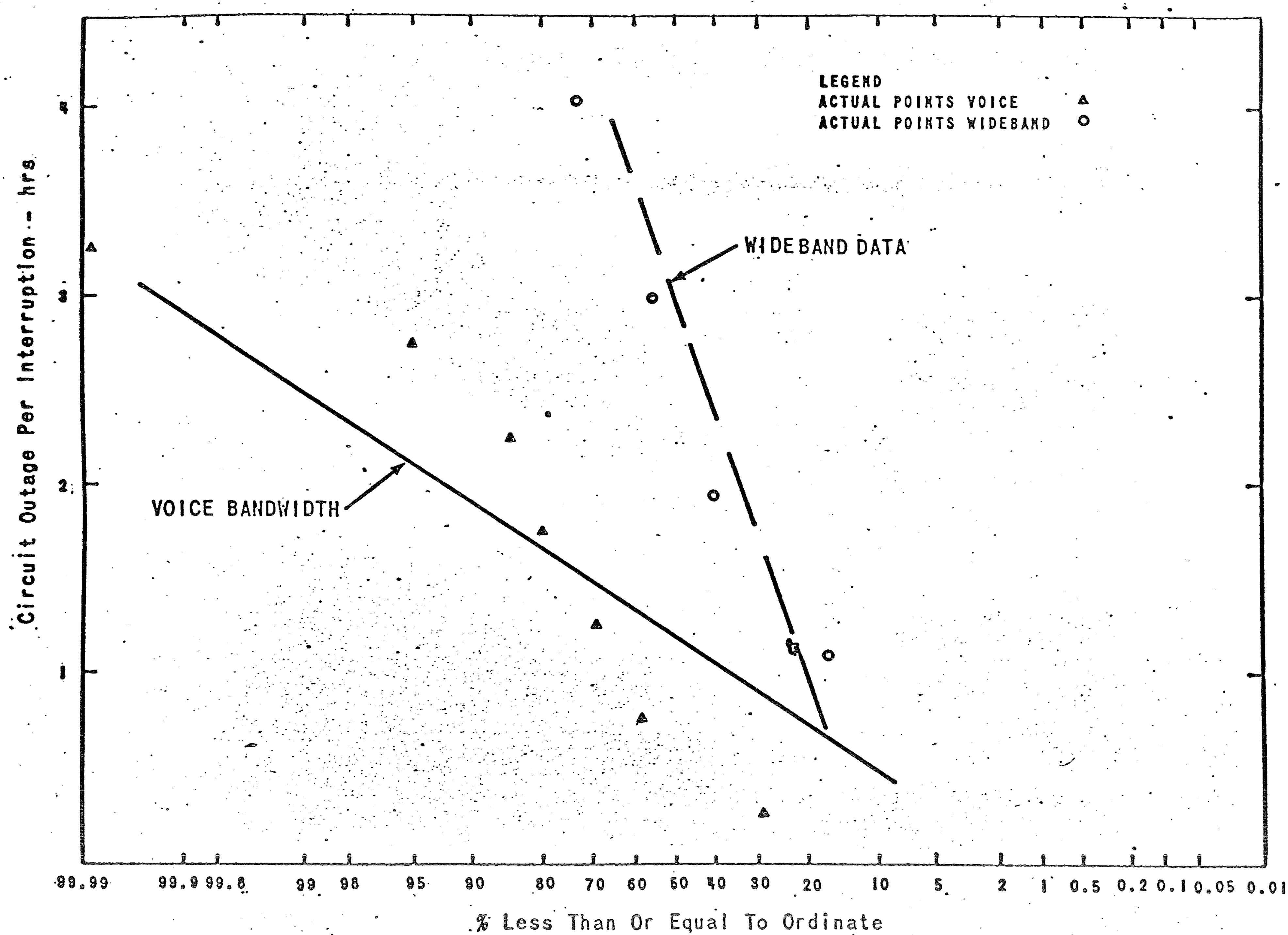

FIGURE 4 ESTIMATED CIRCUIT OUTAGE APOLLO MSFN

TABLE 1

Estimated Average Monthly Performance - Apollo MSFN

Voice Bandwidth Basis

Site	Ckt. Mos. of Opn.	No. of Ints.	Prob. of an Int. Per. Mo.	Scheduled Opn Time Per Ckt.	Out Time Per Ckt	Opn Ratio
Antigua		Comparable to Cape Kennedy				
Ascension		High Frequency Radio				
Bermuda	14	8	57.1%	1137 Hrs.	1.7Hrs	99.85%
Canberra	4	38	100.+	2235	26.2	98.83
Cape Kennedy	56	36	64.3	2433	6.5	99.73
Carnarvon		Comparable to Canberra				
Texas	7	5	71.4	1577	6.0	99.62
Goldstone	12	23	100.+	4368	16.4	99.62
Guam		Comparable to Kauai				
Guaymas	7	20	100.+	4960	30.4	99.39
Kauai	7	12	100.+	2391	9.1	99.58
Madrid*	6	42	100.+	6798	96.4	98.58
Average	14.1	23	100.+	3238	24.1	99.26

*Based on London circuits

Basic data for this table was obtained form the GSFC Nascom Network Ground Communication Reliability Reports.

Table 2

Estimated Average Monthly Performance - Apollo MSFN

Wide Bandwidth Basis

Location	Ckt. Mos. of Opn.	No. of Ints.	Prob. of an Int. Per Mo.	Scheduled Opn. Time Per Ckt.	Out Time Per Ckt.	Opn. Ratio
East - West						
Continental U.S.						
2100 Ckt. Miles	20	20	100%	6480 Hrs	32.7Hrs.	99.49%
North - South						
Continental U.S.						
1030 Ckt. Miles	3	1	33.3	975	1.9	99.80
Average	11.5	10.5	91.30	3727	17.3	99.54

Table 3

Estimated Reliability Apollo - MSFN

Single Channel Operation

For 90% of Time with % Confidence Indicated	Interruptions per circuit per month ≤ X	R(t) Probability of No. Interruption for Continuous time of: one hr.	one day	5 days	10 days	R(10) Prob. of No. Int. for One Hr. In 10 ckt. Grp.	Duration of Outages if Occuring ≤ X hrs.
Voice Band 75%	6.0	99.17%	81.9%	36.8%	13.5%	92.00%	1.9
Voice Band 90	6.4	99.13	81.1	35.9	12.2	91.63	2.0
Voice Band 95	6.6	99.08	80.2	33.3	11.1	91.15	2.1
Average	2.3	99.68	92.7	68.4	46.8	96.83	1.2
Wide Band 75%	2.5	99.65	92.0	66.3	43.6		6.7
Wide Band 90	2.8	99.61	91.1	63.1	39.5		7.2
Wide Band 95	2.9	99.59	90.7	61.9	37.9		7.6
Average	1.0	99.86	96.7	85.2	71.9		3.0

$R(t) = 1-e^{-\lambda t}$ where λ = number of interruptions per month divided by number of days or hours per average month.

$R(10) = R(t)^{10}$

Table 4

Estimated Reliability - Apollo MSFN

Two Channel Redundant Operation

Independent Facilities

Probability of Operating State P_o, or Repair State P_r.	Voice Bandwidth		
	Average	Plus one Std. Dev.	Plus Two Std. Dev.
Both Chs. Opn., P_{oo}	99.23%	97.72%	95.57%
One Opr., One Rpr., P_{or}	0.763	2.27	4.39
Both Rpr., P_{rr}	<0.002	<0.02	<0.06
At Least One Opr. P_c	99.99	99.98	99.94
	Wide Bandwidth		
Both Chs. Opr., P_{oo}	99.17%	97.07%	93.92%
One Opr., One Rpr., P_{or}	0.826	2.91	6.09
Both Rpr., P_{rr}	<0.002	<0.03	<0.10
At Least One Opr., P_c	99.99	99.97	99.90

TABLE 5
APOLLO INTERSITE COMMUNICATION FACILITIES
PRIMARY AND ALTERNATE ROUTES

STATION	APPROXIMATE DISTANCE TO MCC	MICROWAVE AND/OR LAND CABLES		UNDERSEAS CABLE		OPEN WIRE		RADIO	
NEAR EARTH									
CAPE KENNEDY	900 MILES	P	B						
GRAND BAHAMA IS.	1,100	P	B	P	S				B
ANTIGUA	2,400	P	B	P	S				B
BERMUDA	2,200	P	B	P	S				B
ASCENSION	8,500	P	B					P	B
CANARY ISLANDS	6,500	P	B	P	S				B
CARNARVON	11,400	P	B	P	B	P	S		B
GUAM	7,800	P	B	P	B				B
HAWAII	4,000	P	B	P	B				B
GUAYMAS	1,300	P	B			P	S		B
TEXAS	100	P	B						
DEEP SPACE									
GOLDSTONE	1,300	P	B						
MADRID	5,600	P	B	P	B				B
CANBERRA	10,500	P	B	P	B	P	S		B
SHIPS									
INSERTION	3,500							P	B
INJECTION (2)	3,000-12,000							P	B
REENTRY (2)	5,000							P	B
AIRCRAFT									
INJECTION (6)	3,000-12,000							P	B

LEGEND:

- P - PRIMARY
- B - BACKUP DIVERSE ROUTE
- S - BACKUP SAME ROUTE