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PROJECT APOLLO

SHIP-SHORE COMMUNICATIONS USING RADIO SATELLITE RELAY

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SHIP-SHORE COMMUNICATIONS
USING RADIO SATELLITE RELAY

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ABSTRACT

This report assesses the requirements for antennas, radio equipment, and other terminal equipment aboard Apollo communication and tracking ships in order to communicate with land stations via satellite relay. The information capacities of two specific satellite systems that may become operational within the next five years are examined. One system would employ a satellite (the so-called "Early-Bird") in a 24-hour synchronous orbit, and the other would employ satellites in 6000-mile altitude orbits. For both systems, results are given for the case when an Apollo ship and land station are the only users of the satellite, and for cases when there are several pairs of simultaneous users.

Assuming a 30-foot diameter antenna and state-of-the-art receiving and transmitting equipment aboard a ship, it is concluded that an estimated requirement for two voice channels, two teletype channels, and one data channel (the latter equivalent to one voice channel in bandwidth) can be met by either the synchronous-altitude or lower-altitude satellite system. This result holds for as many as four simultaneous pairs of users. If an Apollo ship and land station are permitted exclusive use of the satellite, the capacity can be increased to include several hundred kilobits per second of data. Alternatively, in the case of the medium altitude system, the diameter of the ship's antenna could be reduced to about 15 feet.

Visibility statistics of the 6000-mile altitude system are presented for a number of potential pairs of ship and land station locations. These statistics give a feel for the amount of time that a useful circuit can be maintained, based solely on the geometry of the satellite orbits relative to the locations of the two stations in each pair.

Author

1.0 INTRODUCTION

Ships will be located in the Atlantic and Pacific Oceans to provide tracking data and communication with the Apollo spacecraft during and immediately following its insertion into an Earth parking orbit, following injection into the translunar orbit, and during re-entry. Information received aboard the ships from the spacecraft must be relayed to the Manned Spaceflight Control Center (MSCC) for an evaluation of the performance and condition of the spacecraft and crew. The ships must also be capable of receiving information from the MSCC. This two-way transfer of information will require some form of radio communication between ships and land stations.

The minimum distances between the probable locations of ships and the nearest land stations appropriate as communications terminals are in the order of 1000 to 2000 nautical miles in both the Pacific and Atlantic Oceans. Of the several techniques examined in Reference 1*, only two appeared to offer significant advantages over high-frequency radio for ship-shore communications at these distances. These techniques were: aircraft radio relay, and satellite communication relay. The characteristics of an aircraft relay system to meet the requirements for an Apollo ship-shore circuit were studied in Reference 2.

In the present paper, the feasibility of using satellite radio relay for ship-shore communications is investigated. The principal objective of this work is to define the technical characteristics of shipboard equipment needed to implement such a system. Both synchronous-orbit and medium-altitude (6000 nm) satellites are considered.

A major assumption that dominates this memorandum is that NASA will not implement its own, separate satellite system. Instead, if Apollo circuits are to use satellite relay facilities, they must share the satellite, or satellites, with other users. Indications are that operational communication satellites launched during the next few years

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*References, generally denoted by postscripts, are listed at the end of the report.

will be developed and operated under auspices of the Communication Satellite Corporation (Comsat Corporation).** Some attempt will probably be made, within practical limits, to accommodate the differing needs of many users in the design of such satellites. Nevertheless, it is likely that each user will have to tailor its ground terminal facilities to be compatible with the satellite's characteristics.

The above assumption leads to the approach used in this study: hypothesize one or more satellite configurations that may be implemented in the foreseeable future, based on the best information available to us concerning Comsat Corporation's plans, and then determine the performance of a similarly hypothetical shipboard receiving and transmitting terminal to work with these satellite configurations. Assumptions must also be made concerning certain transmission parameters of the cooperating land terminal, and concerning the required communication capacity and quality of the ship-shore circuits. The latter, discussed in Section 3, are based on estimates supplied by Bellcomm, Inc.

The satellite systems considered are these:

1. A synchronous-orbit satellite, based on characteristics of the "Early-Bird" satellite as reported, for example, in Reference 3. An expected launch date of mid-1965 would make this satellite the first available for operational use.

2. A 6000-nm altitude system, consisting of about 18 satellites in near-polar orbits, the spacing of the satellites being random. The assumed characteristics of these satellites are based on the plan proposed in Reference 4. A contract was recently awarded by Comsat Corporation to AT&T and RCA, as associate contractors, to conduct design studies of this satellite. No decision has yet been made whether or not this system will eventually be implemented. If it is, an operational date of 1966 to 1967 is probable.

**Near the end of the studies reported here, an announcement was made by the Department of Defense of its intention to develop and operate a separate satellite system. No attempt has been made in this report to determine the possible impact DOD plans might have on plans for Apollo communications.

Further characteristics of the synchronous-orbit and 6000-mile orbit systems are given in Sections 7 and 8, respectively. Either system could be used by more than one pair of ground stations simultaneously. There are a number of operational and technical problems inherent in such "multiple-access" operation, and these are discussed in Section 4.

One of the principal operational problems faced by a non-synchronous orbit system concerns the visibility statistics applying to a given pair of ground stations. Continuous visibility of one or more satellites cannot be guaranteed, and it is important to know what to expect in the way of times and durations of communication outages. This subject is discussed in the Appendix.

Section 9 provides a brief assessment of potential improvements in transmission performance of satellite systems beyond the first-generation designs assumed in Sections 7 and 8.

As a final introductory note, the possibility of a medium-altitude (again, about 6000 nm) system of phased-orbit satellites should be mentioned. Such a system has been proposed jointly by Thompson-Ramo-Woodridge's Space Technology Laboratories and International Telephone and Telegraph Corporation. The STL-IT&T team has been awarded a design study contract similar to the AT&T and RCA award for study of the random-orbit design. We do not have information on the characteristics of the proposed phased-orbit design. However, since this proposal was made in response to the same Comsat specifications for launch booster capability, ground station transmission characteristics, and general circuit requirements, it is perhaps fair to assume that the phased-orbit satellite design will have electrical characteristics comparable to those of the random-orbit design. Thus, transmission performance could be assumed similar to that calculated for the random-orbit satellite in this report, and the principal differences would involve specific implementation and visibility statistics. The appendix includes a sample of visibility calculations for a configuration of phased-orbit satellites to permit comparison with the case of the random-orbit system.

2.0 SUMMARY

The bandwidth requirements for an Apollo ship-shore circuit are stated in Section 3 as 12 kc in either direction. This bandwidth can accommodate two voice channels, two teletype channels, and one data channel (the latter equivalent to one voice channel in bandwidth). Assuming state-of-the-art ship and land terminal equipment, transmission calculations indicate that this capacity can be provided by either the Early-Bird synchronous satellite or the 6000-nm altitude satellite proposed to the Comsat Corp. by BTL and RCA. However, the medium-altitude satellite is shown to be significantly better from a transmission viewpoint than the Early-Bird satellite.

The ship terminal receiving system assumed for the transmission calculations includes a 30'-diameter parabolic, Cassegrainian antenna coupled to a cooled parametric amplifier mounted near the antenna's feed structure. The total system noise temperature is assumed as 130°K. With these receiving characteristics for both systems, transmission performance on the down link from the satellite to the ship is expected to be about 5.5 db better in the case of the 6000-mile altitude system than in the synchronous orbit system. When there are four pairs of earth stations operating simultaneously, the margins above FM threshold for the down link to the ship are calculated as 12 db and 6.5 db for the 6000-mile and synchronous orbit systems, respectively. A margin of 6 db is suggested as adequate to allow for propagation variations and equipment losses beyond the assumed normal values. In the case of the medium-altitude system, the extra margin could be used to reduce the ship antenna size to about 15 feet.

The difference in margin between the two systems would be greater except for the fact that the transmitting antenna of the particular synchronous satellite assumed in this study has about 8 db more gain than the lower-orbit satellite. This almost exactly offsets the maximum path loss difference in the two systems (about 8.3 db). The 5.5 db difference in margins is then due almost entirely to the use of two transmitting power amplifiers in the 6000-mile orbit design, each of somewhat greater power output capability than the single power amplifier in the Early-Bird design.

Baseband capacity in the ship-to-shore direction using the Early-Bird synchronous satellite could be over 500 kc - enough for about 400 kilobits per second of data transmission - if an Apollo ship and land station were permitted exclusive use of the satellite when needed. When as many as four pairs of stations use the satellite at once, the capacity in the ship-to-shore direction is reduced to a baseband width of about 17 kc, little more than the assumed 12-kc requirement. In the case of the medium-altitude satellite system, a baseband capacity of about 400 kc is possible in this direction of transmission when a 30-foot ship antenna is used, even when there are as many as four pairs of users. The capacity would be reduced to about 100 kc if the antenna size were reduced from 30 to 15 feet.

Transmission calculations presented in Sections 7 and 8 assume common use of a satellite repeater by several earth stations, of which one would be an Apollo communication and tracking ship. Such operation requires a well-defined plan for regulating access to the satellite, including specific frequency assignments and control of the power transmitted by each station so that power levels at the satellite are as nearly equal as possible. Even when these measures are properly recognized, there will exist in the satellite cer tain noise sources due to interactions of the radio carriers from the several earth stations. These added noise contributions are taken into account in the transmission calculations in an approximate manner, since their effects are not yet fully understood.

The equipment needed for an Apollo ship terminal is basically the same as for any land terminal, with added requirements for facilities to compensate for the effects of ship motion in pointing an antenna. These facilities include a three-axis antenna mount.

If the satellite repeater is in a synchronous orbit, only one antenna is needed aboard ship to maintain continuous communication. If a lower-orbit system is implemented, outages due to loss of visibility must be expected occasionally. To keep these outages to the minimum set by visibility statistics alone, two antennas and a fast means of switching from one to the other would be required. However, it is pointed out in Section 8.3 that the added outage time entailed in transferring from one satellite to another when only one antenna is available probably would be no more than about 12 to 15 seconds. This is expected to be a small percentage - less than 10% - of the total time that the Apollo spacecraft would be visible to a ship, and since the time of occurrence is accurately predictable well in advance of the event, the second antenna does not appear warranted.

Section 9 discusses the improved transmission performance that can reasonably be expected with satellites beyond the first-generation designs principally considered in this report. By about 1970, increased satellite antenna gain, coupled with some increase in primary power capability and higher compoenet efficiencies, indicates a potential improvement in terms of communication capacity of about 10:1. Alternatively, some or all of the advantage might be taken in terms of reduced shipboard antenna size. For example, a 10:1 improvement in satellite transmission performance would reduce the required ship-antenna diameter from 30 feet to about 10 feet, for approximately the same communication capacity. Beyond about 1970, further significant gains are likely to come primarily from the development of new primary power sources.

Visibility statistics of a 6000-nm altitude, random-orbit satellite system are discussed in the Appendix. It is concluded that adequate coverage during the earth-orbit insertion and reentry phases can be provided by either of two configurations analyzed: a system of three equi-spaced orbit planes with six randomly-spaced satellites per orbit plane, or a system of eighteen random-orbit planes with one satellite per plane. However, the coverage is somewhat better in the case of the three-plane system. Typical of land stations that would be suitable as terminals in a ship-shore link during the insertion phase is Rosman, N. C.. During the reentry phase, assuming a landing in the Hawaii or Samoa areas and ships stationed accordingly, appropriate land terminals would be Hawaii and Canberra, respectively. Neither of the medium-altitude configurations analyzed offers as good coverage as is considered desirable during the post-injection phase, assuming ship locations in the Indian Ocean and land stations having good communication facilities to the U. S. Adequate coverage during this phase could be provided by a properly-stationed synchronous orbit satellite; however, as pointed out previously, the particular synchronous satellite system examined in this report (the Early-Bird) has rather marginal transmission capability associated with the ship-to-satellite link. The latter deficiency need not apply generally to synchronous-orbit satellites.

3.0 CIRCUIT REQUIREMENTS

The circuit capacity required is estimated as two voice channels, two teletype channels, and one data channel (2000 to 3000 bits per second) in each direction of transmission. Considerably higher capacity could be used to good advantage if available, particularly in the ship-to-shore direction. The estimates have been supplied by Bellcomm, Inc., and are the same as those adopted in an earlier evaluation of an airborne relay system for ship-shore communications.[2] It is assumed that each voice channel and the data channel occupies a signal bandwidth of 3 kc, and each teletype channel 0.2 kc. With appropriate guard bands, the total channel complement can be multiplexed in a baseband extending from about 0.7 kc to 12 kc.

The following paragraphs discuss the quality requirements for each type of channel and for the baseband as a whole.

3.1 Voice Channels

One of the two duplex voice channels is to be used to relay communications between the MSCC and the spacecraft. The other is intended for traffic between MSCC and ship personnel. For reasons of flexibility and standardization, it is desirable to have both circuits engineered to meet the same voice quality requirements.

A generally-accepted objective for voice channel quality on Apollo communication circuits is a minimum rms speech-to-rms noise ratio of 10 db at the output of the channel. This objective applies to speech that has been clipped 12 db at the input to the originating transmitter, resulting in a speech wave having a peak-to-rms ratio of about 9 db. Thus, the ratio of speech peaks to rms noise at the channel output should be at least 19 db, i.e., the sum of the speech peak-to-rms ratio (9 db) and the required minimum rms speech-to-rms noise ratio (10 db). Expressed in terms of a sine-wave test tone having the same peak value as that of the clipped speech wave - a standard method of loading a transmission system for test purposes - the objective for the voice channel can be stated as an output rms tone-to-noise (T/N) ratio of 16 db. Both voice channels should be engineered to meet these requirements.

Typical transmission calculations for the Apollo spacecraft-to-ground link[5] have allotted the entire signal-to-noise objective to that link, implying that any degradation due to connecting links between a remote site and the MSCC would be negligible. When these connecting links are commercial-grade landlines, submarine cables, or comparable facilities, this is a reasonable engineering approach. However, it may not be so for the case at hand.

Figure 1 is a sketch showing the links that would be involved in a circuit between the spacecraft and the MSCC. Here, the down links from the spacecraft and the communication satellite are both limited by power availability, the latter more than the former when first-generation operational satellites are considered. When the radiated powers, ship and land terminal antenna sizes, and path losses for the two down links are all taken into account, it is found that under some circumstances of practical interest*, the two links would be of comparable transmission quality. It is appropriate, therefore, to allot equal noise contributions to these two links. The up-link from the ship to the satellite has the advantage of much higher available transmitter power than the down links. A net transmission advantage of more than 10 db in terms of signal-to-noise ratio is likely, as will be seen later. Thus, its contribution to the total noise on the over-all circuit would be only a small fraction of a db. Ignoring this contribution and that of any landlines connecting to the MSCC, the voice channel rms tone-to-noise ratio objectives for the satellite-to-land link and the spacecraft-to-ship link will be assumed 19 db each, resulting in the over-all circuit objective of 16 db.

In the reverse direction - MSCC to the spacecraft - it is the down link from the satellite to the ship that controls the over-all circuit performance. Again, this is due to the low power output capability of the satellite relative to that of the ship and land terminals. Assuming an rms

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*For example, during the interval after the second SIV-B burn, and prior to acquisition of the spacecraft by deep-space stations, when the communication range to the spacecraft may be of the order of 5 to 10 thousand miles.

tone-to-noise objective of 16 db at the output of the spacecraft receiver, consistent with the objective at the MSCC in the opposite direction of transmission, a reasonable breakdown of the objective among the several links would be:

Voice Link	Min. T/N
MSCC to satellite land terminal	30 db
Satellite land terminal to satellite	30 "
Satellite to ship	17 "
Ship to spacecraft	25 "

In summary, the voice channel T/N objectives for the satellite relay links are:

	Ship-to-Shore	Shore to Ship
Up Link:	29 db	30 db
Down Link:	19 "	17 "

To assure the speech quality indicated, speech volume at the point of origination - whether at the spacecraft or at a ship or shore station - should be regulated. By this means, weak speech will be brought up to the proper level, and excessively strong speech will be prevented from spilling over into other channels and causing crosstalk or data errors. The volume should be regulated before the speech peaks are clipped.

3.2 Teletype Channels

Two duplex teletype channels are desired between the ship and the MSCC. It is assumed that each teletype channel would be multiplexed with one of the voice channels into a standard 4000 cps band, the total band for two voice and two teletype channels thereby occupying a total of 8000 cps.

The signal-to-noise requirement for these circuits depends on the maximum error rate that can be tolerated (which in turn depends on the type of traffic being handled), on the type of modulation, and on the characteristics of the specific equipment that is used. None of these features has been specified, but some reasonable guesses can be made.

One of the teletype channels probably would be used for administrative traffic transmitted in plain English. The other might be used to carry tracking data from ship to MSCC, and a variety of mission coordination data in the opposite direction. Assuming that the tracking data are frequently up-dated, and that there is redundant transmission (perhaps also error-checking) of the data sent to the ship, a character error rate of about one in $(10)^4$ characters would seem to be satisfactory on either channel and in either direction. Based on a 7-bit code, this translates (with a little margin) to a permissible bit error rate of about one in $(10)^5$ bits.

Standard non-synchronous, frequency-shift keying appears to be suitable for these teletype services. With such a system, it should be possible to maintain the error rate within one in $(10)^5$ bits with an rms signal-to-noise ratio (also tone-to-noise ratio here) of 14 db in a channel bandwidth of 0.2 kc. This ratio is required at the output of the radio receiver (input to the teletype terminal decoder).

Ignoring the noise contributions of the landlines between the MSCC and the satellite land terminal, and recognizing again that the noise contribution of the satellite up links can be made negligibly small relative to that of the down links, the teletype T/N ratio allottments for the up and down links of the satellite relay system become:

	Ship-to-shore	Shore-to-ship
Up Link:	24 db	24 db
Down Link:	14 db	14 db

Note that the difference between the up and down link objectives in the shore-to-ship direction is 10 db, compared to 13 db in the case of the voice channels. This is because no allowance for the spacecraft-to-ship link is needed on the teletype circuit (or on the following data circuit).

3.3 Data Channel

As in the case for the teletype channels, the specific functions of the data channel have not been spelled out. In the shore-to-ship direction, the channel might be used to transmit MSCC commands intended for the spacecraft, acquisition data for the ship's radar and communication antennas, etc. In the ship-to-shore direction, the channel probably would be used to relay telemetry data from the spacecraft. However, a channel with a capacity of about 3000 bits per second cannot handle in real time all the telemetry data that will be received from the Command Module, the SIV-B, and the Instrumentation Unit. (The Command Module alone may be transmitting at a rate of 51.2 kilobits per second.) Either the information must be stored and then relayed at a slower rate, or it must be processed and summarized in such a manner that real-time relay has some meaning.

The minimum signal-to-noise ratio required for the data channel depends on the type of modulation and data transmission equipment employed and on the tolerable error rate. As an example of a type of data system that would be satisfactory, the Bell System's 205A data Set employs phase modulation and is capable of handling 2400 bits per second in a 3-kc channel. With this set, the required minimum signal-to-noise ratio into the receiving decoder, in a 3-kc band of random noise and for a bit error rate of one in $(10)^6$ bits, is about 16 db. At the 2400 bits-per-second transmission rate, this is equivalent to about one bit error in seven minutes. The critical character of the data assumed to be carried by this channel probably warrants this accuracy and it will be so assumed; in fact, it might even be considered desirable to employ error checking to reduce still further the chance of encountering an undetected error.

Again assuming negligibly small noise contributions from the landlines between the MSCC and the satellite land terminal, and from the satellite up links, the T/N ratio allottments for the data channel on the up and down links of the satellite relay system become:

	Ship-to-Shore	Shore-to-Ship
Up Link:	26 db	26 db
Down Link:	16 "	16 "

3.4 Total Baseband Signal-to-Noise Ratio

The voice, teletype, and data channels are assumed multiplexed as shown in Table 1. Assuming a flat band of noise, the fourth column shows the relative noise powers in each channel relative to the noise in one 3-kc voice signal bandwidth. The values of tone-to-noise ratios listed in Column 5 apply specifically to the satellite-to-ship link, the most difficult link of the satellite relay system. The last column shows the level of the test tone power in each channel relative to the power of the test tone for one voice channel.

TABLE 1

SATELLITE-TO-SHIP LINK
RELATIVE TEST TONE LEVELS OF
VOICE, TELETYPE, AND DATA CHANNELS

(1) Nominal Band, kc	(2) Function	(3) Signal Bandwidth, kc	(4) Relative Noise, db	(5) Required T/N Ratio, db	(6) Relative Tone Level, db
0-0.7	Unused				
0.7-4.0	Data	3	N	16	-1
4.0-7.3	Voice	3	N	17	0
7.3-8.0	TTY	0.2	N-12	14	-15
8.0-11.3	Voice	3	N	17	0
11.3-12	TTY	0.2	N-12	14	-15

The total load, relative to one voice channel, is the sum of the signals in the last column. The combined load amounts to about 4.6 db more than the test tone power for one voice channel. Thus, a single test tone 4.6 db greater than the test tone required for one voice channel would represent the full 12-kc baseband rms signal power. However, a tone at this level would not simulate the occasional in-phase voltage addition of the signals on the several channels, which would tend to overload the system.

Considering just the two voice channels, each carrying speech regulated to the same volume and employing 12 db of peak clipping, the instantaneous combined voltages would exceed the peaks of one channel by about 4.6 db for 0.85% of the time.(6) The resulting distortion would probably be unnoticeable - or at least would be acceptable - on the speech channels. However, the effect on performance of the teletype and data channels would be of some concern in view of the objectives for bit error rates mentioned earlier: one in $(10)^5$ and one in $(10)^6$ for teletype and data, respectively. This suggests that the test tones representing the individual channels in column (6) of Table 1 ought to be added more nearly on a voltage basis to determine the level of a single test tone representing the entire baseband.

Figure 2 illustrates the relative levels of test tone powers that would represent various combinations of channels, and also the relative peak voltages of various channel combinations. The maximum peak voltage of the combined voice, data, and teletype signals is about 10.2 db above the peak voltage of one voice channel, as contrasted with the 4.6 db difference in the peaks of full-baseband and single-channel test tones calculated on a power basis. A compromise value of +8 db relative to the test tone for one voice channel will be chosen as the test tone level to represent the multiplexed baseband.

The total noise in the 12-k c. baseband, relative to the noise in 3 k c is

$$N + 10 \log 12/3 = N + 6 \text{ db}.$$

Thus, the required single test tone-to-noise ratio for the complete baseband on the satellite-to-ship link is

17 db (single voice channel T/N ratio)

+ 8 db (multiplexed baseband T/N ratio relative to single voice channel ratio)

- 6 db (ratio of 12 k c to 3 k c noise bands)

= 19 db

The tone-to-noise ratio objectives assigned to the other satellite links are calculated in a similar manner, using the objectives for voice, data, and teletype channels applying to those links as given earlier. The final results for all links are listed in Table 2.

TABLE 2

TONE-TO-NOISE OBJECTIVES FOR
12-KC BASEBAND MULTIPLEX ON EACH LINK

Link	T/N Objective, db
Shore-to-Ship:	
Up-Link	32
Down Link	19
Ship-to-Shore:	
Up-Link	30
Down-Link	20

Should the capacity of the system in either direction turn out to be greater than 12 kc., the added capacity would very likely be used to transmit a greater amount of data. Since the tone-to-noise objective for data in a bandwidth equal to a voice band is only one db less than the objective for speech, and since the load contributed by the two teletype channels is negligible, the tone-to-noise objectives for a baseband wider than 12 kc would be very nearly the same as those indicated in Table 2, regardless of how much wider the band might be.

4.0 MULTIPLE-ACCESS CONSIDERATIONS

The term "multiple-access" implies the multiplexing of signals from several earth stations through a single satellite repeater. The output of the repeater is some frequency or time combination of the input signals. To avoid interference between the signals entering the satellite repeater, they must arrive with appropriate coordination in frequency for frequency-division multiplexing, or in time for time-division multiplexing. Compensation for Doppler effects must be included in either case.

4.1 The Need for Multiple Access

A legitimate question immediately is: Why worry about multiple access? Why is this feature necessary? The answer involves consideration of the alternatives. These are:

1. A completely separate satellite system for the exclusive use of a pair of earth stations;
2. Use of each satellite in a multiple-satellite system by only one pair of earth stations at a time;
3. Provision of separate repeaters in each satellite for each pair of simultaneous users (separate RF frequencies for each repeater).

Basically, the arguments against these alternatives so far as most potential users are concerned boil down to costs.

As stated in the Introduction, Section 1.0, the position is taken in this report that the potential uses of satellite communications in an Apollo mission do not support a need by NASA for a separate satellite system. Thus, the first alternative must be discarded.

The second alternative suggests some degree of sharing of the several satellites comprising a system. This approach requires a considerably higher total number of satellites than does a multiple-access system, to provide equivalent circuit availability. Thus, cost looms as a basic negative factor. It should be noted that this second alternative is not meant to include the familiar time-division PCM multiplexing arrangement where several stations share the transmission medium on a short-term, nearly real-time basis. This technique will be discussed further in the following section.

The third approach involves multiple receivers and transmitters in each satellite. As a purely technical solution to the transmission problem, this approach might be preferred over any of the systems of multiple-access that have been proposed, for it would eliminate or minimize problems of signal distortion and interference. The practical difficulty, however, is that the weight, space, and power supply requirements of the multiple radio equipment units would place higher demands on launch vehicle capability. Here again, the penalty is unreasonably high cost.

These qualitative arguments lead to a conclusion that plans to use communication satellites in support of Apollo missions should assume sharing with other users.

4.2 Types of Multiple-Access

The next question is: what method of multiple-access is likely to be adopted for satellite communications? In general, an optimum technique would permit simultaneous use by a large number of earth stations while at the same time making optimum use of the frequency spectrum and satellite transmitter power. Savings in power and bandwidth can result if channels can be assigned among earth stations on a dynamic basis in response to demand for service, or on a programmed basis in accordance with known load variations, rather than as fixed assignments. The extent to which flexibility of access and of channel assignments is possible depends significantly on the modulation techniques that are used on the up and down links.

Of the variety of multiple-access techniques that can be conceived, only three have been proposed as serious contenders:

1. Single-sideband (SSB) transmission by each earth station on its up link (separate radio frequency assignments for each station), with the signals from all stations frequency-division-multiplexed together in the satellite and then retransmitted as one broadband FM signal.

2. PCM transmission from all earth stations, so synchronized that the signals from all stations can be time-division multiplexed at the satellite and retransmitted on one carrier.
3. Frequency (or phase) modulated transmission by each earth station on separate RF carrier assignments, followed by a frequency translation in the satellite and retransmission of the separate carriers.

The SSB up, FM down technique has certain advantages--frequency conservation being one of the more important--but also has the following serious disadvantage. Each earth station is forced to receive and detect the entire broad-band FM signal transmitted from the satellite, even if it wishes to receive only the information transmitted to the satellite by one other earth station. This means, in general, that each station must have a much better receiving system than is warranted by the portion of the total information that it wishes to extract from the satellite's transmissions. For example, it has been calculated that an 85-foot diameter parabolic antenna and an over-all receiving system noise temperature of about 80°K would be needed at each ground station if the satellite systems discussed in Sections 7 and 8 employed this method of multiple-access. Clearly, the antenna size required is not feasible for a shipboard installation; in fact, the cost implications of this receiving system would not generally be tolerable by users other than those having very large capacity requirements.

The PCM time-division multiplex techniques that have been advanced have a similar drawback. In order to accommodate a large total information capacity (whether required by one or many pairs of users), the pulse length must be very short and the system bandwidth correspondingly wide. This again leads to more demanding requirements on a receiving system than are feasible for a shipboard installation, or for users having small bandwidth requirements.

The last modulation technique listed above--FM up and FM down on separate carriers for each pair of users--appears to be the current favorite. The carrier transmitted by each earth station would be frequency-division multiplexed with the carriers from other earth stations in a common satellite receiver, converted to an IF frequency for amplification, then converted back to a different RF frequency for transmission by a common satellite power amplifier. Thus, an earth station receiver needs to detect only the information band transmitted by its associated earth station. This arrangement is clearly better suited to users having small communication needs and limited receiving system capabilities than either of the first two techniques discussed.

It is understood that Comsat Corporation plans to use the FM up-FM down technique in its Early-Bird synchronous orbit system, and probably also in the earliest lower-orbit system that subsequently may be implemented. This technique of modulation and multiple-access therefore will be assumed in the remainder of this report. As might be expected, there are certain operational problems entailed in this as in any other technique of multiple access, and there are in addition certain technical problems that affect planning of the transmission parameters of a land or ship terminal. These are discussed in the following two sections.

4.3 Operational Considerations in a Multiple-Access System

The principal problem under this heading involves the assignment of RF channels among the users of the satellite system to assure that no two stations employ the same carrier frequency simultaneously, and that the total capacity of the system is used efficiently.

Consider first a synchronous-orbit system. Here, the movement of the satellite relative to any specified latitude-longitude coordinates is likely to be small enough that the configuration of earth stations which can be served is constant. Any variation in the number of stations simultaneously using the satellite, or in the proportion of the satellite capacity assigned to each pair of stations, would be due primarily to variations in the communication loads handled by the stations. If these variations are small, the RF carrier and bandwidth assignments might be kept fixed; if the loads are expected to vary widely, some means of re-assigning carrier frequencies among stations and of adjusting the bandwidth allocations would be required in order to make best over-all use of the satellite. It seems likely that a central coordinating facility would be established to monitor and regulate the use of the satellite by all earth stations, but we are unaware at this time of any specific plans for such a facility.

Control of access to the satellites of a non-synchronous orbit system will be more complicated. Not only will there be the load variation factor as in the synchronous-orbit example above, but the continually changing satellite visibility pattern may require re-assignments of the carriers and bandwidths of all the satellites in the system as they pass in and out of view of earth stations. Even if there are only a few stations and their total communication needs permit fixed carrier and bandwidth assignments, transfers of antennas from one satellite to another must be coordinated between stations communicating together.

The problems cited are fundamental to the use of a satellite communication system regardless of what or where the using earth stations may be. It can be expected that plans for a common-use system will include means for controlling and coordinating access to the satellites. Any Apollo ship terminal expected to communicate via a satellite repeater therefore should be engineered to be compatible with whatever procedures are selected to regulate satellite access. As mentioned earlier, no specific plans to our knowledge have been adopted as yet.

4.4 Transmission Impairments in Multiple-Access FM Systems

Transmission degradation by a satellite in single-carrier FM operation is caused by amplification and phase distortion as well as thermal noise. The effects of the amplitude and phase distortion do not become evident until the FM carrier is detected. Therefore, the threshold of the system is undisturbed, and the effects show up only as added noise (interchannel modulation or crosstalk) in the output of the system.

In the multiple-access FM systems, additional degradation is caused by intermodulation and intelligible crosstalk. The following paragraphs indicate the sources of these impairments and their effects on system operation.

4.4.1 Intermodulation Noise

One source of intermodulation arises from devices that have nonlinear input-output characteristics, such as limiters and traveling-wave tubes (TWT's). Another source of intermodulation arises from amplitude modulation to phase modulation (AM-PM) conversion. This is a process whereby variations in the amplitude of a composite input wave consisting of two or more FM carriers are converted to phase variations at the output. The amplitude variations arise from the random addition of carriers of different frequencies. Although this characteristic is exhibited by limiters and traveling wave tubes, the effect is much more pronounced in a TWT.

While nonlinearity intermodulation and AM-PM intermodulation cannot be measured separately, there are independent mathematical theories which account for the two phenomena and which jointly provide good agreement between theoretical and experimental results.(7) The important, distinguishing characteristic between these forms of intermodulation and others is that the distortion products appear directly in the RF band prior to detection. Hence, these types of intermodulation add to the thermal noise at the input to a ground receiver and must be included in establishing the system threshold. In addition, they reduce the useful power output of the satellite, since some of the available power goes into the distortion products.

The amount of intermodulation is a function of the number of carrier groups and the total input power to the satellite repeater. As the number of carrier groups in a given IF band increases, it can be shown that the distortion power increases but reaches a limit when the number of carrier groups is about twelve. An underlying assumption in the last statement is that the total input power to the repeater remains the same for any number of carriers.

In the case of single-carrier operation, the input power at the satellite should be such that the maximum TWT output is obtained. However, if the TWT were operated at this same maximum output during multi-carrier operation, an intolerable amount of intermodulation noise would be generated. At least, it would be intolerable in terms of achieving maximum capacity and/or high circuit quality since the C/N ratio at the ground receiver would be lowered. By reducing the total carrier power input to the TWT, it can be operated in a more linear region. Intermodulation then decreases, but so does the useful output power. Thus, from the standpoint of intermodulation and not considering thermal noise, the TWT input power should be such that operation is in the linear region. However, there must be a certain amount of output power to satisfy the thermal noise requirements. The simultaneous consideration of both the thermal and intermodulation noise requirements determines the input power necessary for maximum capacity. In general, the total input power must be reduced as the number of carriers increases in order to maintain the same circuit quality.

The amount that the total useful output power is decreased from the single-carrier output power when the input power is reduced is referred to as the "backoff factor," or simply "backoff." It should be noted that the backoff factor consists of two components: (1) the amount of reduced output power resulting from the decrease in input power; and (2) the loss of output power arising when some of the available power is converted into intermodulation.

It has been found[7] that at the optimum operating point of the TWT, which is below the point of maximum output, the intermodulation from AM-PM conversion and nonlinearity are about equal. At the point of maximum output, AM-PM intermodulation is relatively small; the main contribution to intermodulation is from nonlinearity. The converse is true when the input power to the TWT is less than the optimum value.

In summary, the effect of intermodulation is to lower the system capacity due to three interrelated occurrences:

1. The input power to the nonlinear device must be reduced from the point of maximum output power so that intermodulation noise can be kept at a tolerable level. As the number of carriers entering the satellite increases, the input power must be reduced still further in order to maintain the same noise level.

2. Even at this lower input level some of the available power is taken up by the distortion products.

3. The addition of intermodulation noise in the detection band lowers the received C/N ratio at the ground station and automatically lowers the system capacity.

An additional point worth mentioning in connection with multiple-access is that any difference in carrier powers at the input to the nonlinear device will be even greater at the output, when operating in the nonlinear region. However, with the total input power low enough to keep the intermodulation at a reduced level, the power difference between carriers will be about equal in the input and output.[7]

4.4.2 Intelligible Crosstalk

Intelligible crosstalk occurs in a multiple-access system when a non-uniform gain versus frequency characteristic is followed by AM-PM conversion. The non-flat gain versus frequency characteristic (which might exist, for example, in the IF amplifier ahead of the TWT) gives rise to amplitude modulation of the carriers. When they pass through a device such as a TWT, the amplitude modulation is converted to phase modulation in such a way that the frequency modulation structure on one carrier is imposed on each of the other carriers. When the carriers are received at their respective ground receivers, intelligible crosstalk results. This type of distortion should not be confused with the AM-PM intermodulation discussed in the previous section, which finds its origin in the amplitude modulation due to random addition of carriers of different frequencies.

Two important characteristics of the crosstalk effect are that it is proportional to the baseband frequency and to the total input power.(7) Thus, the intelligible crosstalk will decrease as the number of carriers increases in the same RF band since the top baseband frequency on each carrier will be less, and since the input power will have to be reduced by the amount of the backoff factor as mentioned above.

4.4.3 Multiple-Access Considerations Applicable to Apollo Stations

It should be noted that the Apollo ship-shore circuits have less stringent over-all noise objectives than those used in engineering commercial circuits, and hence could tolerate more intermodulation noise arising from nonlinearity and AM-PM conversion. However, it is the stations having the more stringent objectives that determine the amount of backoff needed in the satellite, and hence the levels of the carrier powers allowable at the input to the satellite. In other words, these other users will demand a particular C/N ratio at the output of the TWT in order to satisfy their noise objectives, and this will determine what the total input power can be. The satellite input power from an Apollo ship or land station must be controlled to approximately the same level as that from other stations to avoid increasing the intermodulation noise in those circuits. Thus, the backoff factor must be considered to apply to Apollo stations as well as to other stations using a satellite.

Intelligible crosstalk due to AM-PM conversion need be of no concern for Apollo stations since the magnitude of the crosstalk is proportional to the baseband frequency and will be very small in the baseband widths being considered here.

5.0 RF CARRIER-TO-NOISE REQUIREMENTS FOR FM TRANSMISSION

In Section 3.4 the tone-to-noise ratios required in the up and down links of the satellite relay system were determined. It was established that when transmission is in the shore-to-ship direction, 32 db and 19 db rms tone-to-noise ratios are required in a 12-kc baseband in the up link and the down link, respectively. Required in the reverse direction of transmission are rms tone-to-noise ratios of 30 db and 20 db for the up and down links, respectively.

In the Section 4.2 it was indicated that frequency modulation is the currently-preferred modulation method for a multiple-access satellite communication system. Using this type of modulation and an FM feedback receiver, the required ratios of the received carrier power, C, to the noise in twice the baseband width, N_{2b}, at threshold are shown in Table 3 for the different links. These data are extrapolated from Reference 8. Included in Table 3 are the modulation indices, m, and the FM feedback factors, F, that correspond to these threshold values. Table 3 also shows the theoretical RF bandwidths and the IF noise bandwidths normalized with respect to the top baseband frequency, b, required for each link. The RF bandwidth, B_{RF}, is determined by Carson's rule:

$$B_{RF} = 2b(m + 1)$$

The IF noise bandwidth, B_{IF}, from reference 8, is given by

$$B_{IF} = 2b \times \frac{m}{F} \times \frac{\pi}{2}$$

TABLE 3

FM REQUIREMENTS OF APOLLO SATELLITE RELAY LINKS AT THRESHOLD

Link	Output T/N db	C/N_{2b} db	m	F, db	B_{RF}/b	B_{IF}/b
Shore to Satellite	32	12.0	6.0	13	14	4.2
Satellite to Ship	19	9.0	2.3	9.0	6.6	2.6
Ship to Satellite	30	11.5	5.0	12.5	12	3.7
Satellite to Shore	20	9.3	2.6	9.2	7.2	2.7

The satellite systems being considered in this report translate the frequency of the incoming frequency modulated signals at the satellite without any further modulation processing. Systems of this type have the same modulation index on both the up and down links. The parameters of Table 3, however, are for up and down links of different modulation indices. Therefore, the objectives of Table 3 must be restated in terms of tandem FM links having the same modulation index.

A possible approach would be to increase the modulation index that the down link is capable of supporting to that shown in Table 3 for the up link in the same direction of transmission. Increasing the modulation index requires an increase in the minimum permissible carrier power on the down link in order to stay above threshold.

Since transmission is already limited by the small power available at the satellite for the down link, it would not be wise to further increase the requirements of this link. Instead, a more realistic approach is to decrease the modulation indices shown in Table 3 for the up links to those which the down links are capable of supporting. In doing so, the carrier powers of the up links must be increased to maintain the same signal-to-noise ratios. Decreasing the modulation index of the shore-to-satellite link to 2.3 requires that the carrier-to-noise ratio, C/N_{2b}, be maintained at or above 22 db to realize the output T/N ratio of 32 db. Similarly, in order to maintain a 30 db T/N ratio in the ship-to-satellite link with a modulation index of 2.6, a 19.3 db carrier-to-noise ratio is required. Even with the increased requirements of the up link, it will be shown in the transmission calculations of Sections 7.2 and 8.2 that the down link limits the over-all circuit.

With the up and down links in one direction designed for the same modulation index, the RF carrier objectives that will be used for each satellite relay link are summarized in Table 4.

TABLE 4

FM REQUIREMENTS OF APOLLO SATELLITE LINKS
DESIGNED FOR COMPATIBILITY BETWEEN UP AND DOWN LINKS

Link	Output T/N, db	C/N_{2b} db	m	F, db	B_{RF}/b	B_{IF}/b
Shore to Satellite	32	22	2.3	9.0	7	2.6
Satellite to Ship	19	9.0*	2.3	9.0	7	2.6
Ship to Satellite	30	19.3	2.6	9.2	7.2	2.7
Satellite to Shore	20	9.3*	2.6	9.2	7.2	2.7

*A C/N_{2b} requirement of 10 db is used in the transmission calculations for the down links in Sections 7 and 8. The increase to 10 db from the values listed in this table is made to account for intermodulation noise in the RF spectrum generated within the satellite, as discussed at the end of Section 7.1.

6.0 ASSUMED SHIP AND LAND STATION PARAMETERS

In most radio transmission problems, it is possible to make tradeoffs between various system parameters. Relative costs and performance of transmitters, antennas, receiving systems, etc. can be assessed to arrive at a reasonably optimum over-all design.

In the problem at hand, an important degree of freedom has been eliminated by assuming that the technical characteristics of the satellite repeater are fixed, i.e., not subject to tradeoff. Given these characteristics, the problem is reduced to one of planning earth terminal facilities which will be compatible with the satellite repeater. Further, there is a forced imbalance between the designs of the ship and land terminals due to the restrictions on space for antennas aboard a ship.

The general approach adopted in Sections 7 and 8 is to calculate transmission performance given certain assumptions relative to the transmission parameters of the ship and land stations. These assumptions are stated in the following paragraphs.

6.1 Transmitter Power and Antenna Sizes

The choice of transmitter power for the ship and land stations is influenced primarily by two factors: (1) the objective of making the up-links enough better than the down-links, from a transmission viewpoint, so that their influence on the over-all circuit noise is negligible, and (2) the objective of having the carriers from all earth stations (assuming multiple users) arrive at the satellite at approximately equal power levels, thereby avoiding the signal-to-noise degradation that can result when signals of different levels pass through the repeater. The latter problem was discussed in Section 4.

The first objective presents no real problem; the state of the art permits much higher effective radiated power than is needed to assume that the up-link does not limit the circuit performance. The second objective says, in effect, that the radiated power of Apollo ship and land terminals should be commensurate with that of other earth stations which may use the satellite repeater; further, means should be provided to assure that carrier levels remain approximately equal at the satellite repeater despite variations in propagation conditions, path length, or other transmission parameters. There are at least two techniques that have been proposed to do this: (1) regulation of the power transmitted by each earth station in accordance with its own monitoring of the power radiated by the satellite; or (2) use of an RF carrier limiter at the input to the satellite. For present purposes, it is immaterial which method is used. We need only to assume a maximum power capability, to be employed under conditions of greatest transmission loss, and then assume further that the design of earth station facilities will include whatever is necessary to be compatible with the specific power control technique eventually adopted for the satellite system.

The earth station power specified by COMSAT Corporation to be assumed by contractors in preparing satellite design proposals earlier this year was 5 kw. Since an FM system was called for, this is implied as a CW, or average power capability. Also specified was an earth station antenna of 85-feet diameter. These same figures for power and antenna size will be assumed for the Apollo land station terminal in subsequent transmission calculations, so that the satellite input carrier level from this terminal will be commensurate with that from other land terminals.

The maximum antenna size practical for a shipboard satellite terminal installation is estimated to be of the order of 30 to 40 feet in diameter, depending on the size and type of ship and the demands for space of other radio and radar systems. To offset this reduction from the assumed 85-foot size of a land station antenna, 20 to 40 kw of transmitter power would be needed. Although this might be feasible, it poses a heavy demand on shipboard primary power capability and threatens a severe problem of interference with other shipboard electronic systems. Ten kw has appeared to be more nearly a practical upper limit, and will be assumed here. A 30-foot diameter antenna will be assumed, recognizing that another antenna of similar dimensions will also be needed on each ship for tracking and communication with the Apollo spacecraft. With these values of transmitter power and antenna gain, the carrier level at the satellite repeater during single-access operation would be about 6 db lower than the carrier from a land terminal using the 5 kw power - 85-foot antenna combination, other transmission factors being equal. Under these conditions, it is expected that the signal-to-noise ratio on the down link in the ship-to-shore direction will be degraded more than on the down link in the reverse direction, if both carriers pass through the same non-linear device in the satellite. In multiple-access operation, the degradation would be less if the power radiated by each ground station is reduced to keep the total power input to the satellite constant, since the powers radiated by land and ship stations would be more nearly equal. The amount of degradation is related to the satellite design, and appropriate values will be assumed in Sections 7 and 8.

6.2 Receiving System Noise Characteristics

To compensate for the fact that the effective radiated power from the satellite repeater will be very small, relative to that which can be radiated from an earth station, the earth station must employ not only high antenna gain but also a low-noise receiving system. The antenna gains at the land and ship terminals are set by the sizes of the antennas assumed in the previous paragraphs. Here we will discuss the noise characteristics assumed for these antennas and for other RF elements of receiving systems considered practical for the ship and land stations.

Figure 3 indicates the principal noise sources contributing to the total effective noise temperature of the receiving system. It is assumed that the antenna structure would be a paraboloid with a Cassegrainian feed system. Such a structure has inherently better noise-temperature properties than a conventional parabolic dish with a frontal feed system(9). Experience indicates that the noise contributions from side and back lobes of a well-designed Cassegrainian antenna can be held to the order of 20° to 30°K; the upper figure is assumed here.

If the main antenna beam is pointed no closer than 5° from the horizon, the effective sky temperature (ignoring "hot spots" such as the sun) will be no more than about 30°K at a frequency of 4 kmc (10). Thus, the total antenna temperature at the input to the antenna feed system, due to main beam, side and back lobes, can be taken as 30° + 30°, or 60°K.

If it is found necessary to enclose the antenna in a radome to protect it from weather, an additional noise contribution, as well as signal attenuation, must be expected. So long as the radome is dry, the net degradation to the received C/N is expected to be practically negligible (under 1 db). In the presence of moderate to heavy rain on the radome, however, Bell Laboratories' studies have indicated that the degradation of C/N may be of the order of 2 to 4 db greater than it would be in the absence of the radome. Snow, ice, or salt water spray can have similar effects in varying degrees. Since the added transmission loss due to these factors is so variable, no specific allowance is made for them. However, they account for the major portion of the 6 db transmission margin suggested in Sections 7 and 8 to account for miscellaneous losses.

Transmission lines, such as waveguide, diplexer, filters, etc. between the antenna feed and the input to the receiver, are further elements which not only attenuate the signal but also contribute to the receiving system noise. Their influence on effective antenna temperature as seen at the receiver is shown by:

$$T_{eff} = \frac{T_a}{L} + \left(1 - \frac{1}{L}\right) T_o$$

where T_a = antenna temperature, °K

T_o = transmission line temperature (generally assumed as 290°K)

L = transmission line loss ratio.

The effect of line losses on system noise temperature is illustrated in Figure 4. The moral is that the loss should be kept as small as possible, and one effective measure to accomplish this is to mount the receiver pre-amplifier very close to the antenna feed structure. This has become fairly common practice in designing low-noise receiving systems. Use of a Cassegrainian feed system, which is located at the center and behind the parabolic dish structure, facilities mounting the pre-amp near the feed.

If the receiver pre-amp is mounted as suggested, the principal loss elements between it and the antenna feed can probably be held to a few feet of transmission line and a diplexer.

In this event, a total loss of no more than 0.5 db seems possible. Referring to Figure 4, it is seen that the antenna temperature would be degraded from the assumed 60°K to about 85°K at the receiver input by the insertion of 0.5 db loss.

The principal remaining noise contributor is the receiver pre-amplifier. Conventional, non-cooled amplifiers would degrade the system temperature by many db to a probably-intolerable-and unnecessary-high level.

Cooled parametric amplifiers having effective noise temperatures (referred to their inputs) of a few tens of degrees Kelvin are now practical devices. One example is the two-stage parametric amplifier designed for the Telstar ground station receiving system [11]. The first stage is operated at liquid nitrogen temperature, the second at room temperature. The over-all input noise temperature of the amplifier is about 45°K. One version of the amplifier was specifically designed as a package to be mounted near the feed system of the Telstar ground station antenna at Andover, Maine. Another unit was used in conjunction with a smaller antenna during tests of a "mobile terminal" at Holmdel, N. J. While the specific design of these units probably would not be suitable for a shipboard environment, there is no reason to think that a suitable version of this or a similar parametric amplifier could not be developed for a shipbaord installation. On this assumption, the effective noise contribution of the pre-amplifier is indicated in Figure 3 as 45°K. This brings the total assumed effective noise temperature, referred to the input of the receiver, to 85° + 45°, or 130°K. This value will be used for the ship and the land stations.

Some reduction of the assumed total noise temperature might be realized by using a lower-noise, maser pre-amplifier and by very careful design and construction of the transmission elements between antenna and receiver. However, the improvement is limited by the antenna temperature, and it is very doubtful that an over-all system temperature less than 80°-90°K could be obtained without adopting a horn antenna configuration. A horn antenna structure of adequate size would be feasible at a land station, but appears rather impractical for ship applications.

6.3 Transmitting Line Losses

While it is practical to mount a receiving pre-amplifier near the antenna, it is generally less feasible to locate a transmitter power amplifier so conveniently due to its larger size and weight. As indicated on Figure 3, line losses in the transmitting path are assumed to total about 2 db. This allows for about 50 feet of waveguide between the transmitter output and the diplexer, in addition to the losses of the diplexer and the line from that unit to the antenna.

7.0 SYNCHRONOUS-ORBIT SATELLITE SYSTEM

The characteristics of the "Early-Bird" satellite currently being developed by Hughes Aircraft Co. for the Communication Satellite Corporation are to be used in this report as illustrative of a synchronous-orbit satellite system that may be operational within the next couple of years. Some of the operational and orbital parameters for this system were mentioned in the Introduction, Section 1. Transmission characteristics of the satellite repeater are reviewed in the following Section 7.1. These characteristics, along with the land and ship parameters assumed in Section 6, form the basis for the transmission calculations reported in Section 7.2. Section 7.3 discusses acquisition and tracking requirements for a ship installation.

7.1 Transmission Characteristics of "Early-Bird" Satellite

Figure 5 is a functional block diagram indicating our understanding of the general configuration of the proposed Early-Bird satellite repeater. It consists basically of two receivers and one common traveling-wave-tube (TWT) power amplifier. In each receiver a nominal 6 gc input signal is converted to IF, amplified, limited, and converted to a nominal 4 gc output frequency. Each IF amplifier has a bandwidth of about 25 mc. The spacing between the centers of the two bands is approximately 80 mc.

The receiving antenna gain is expected to be about 4 db at the 6 gc up-link frequency. Receiving line losses are estimated as 1.5 db, and the receiver noise figure as 9.5 db.

Transmitting antenna gain is quoted as 9 db relative to an isotropic antenna, and line loss between the TWT and the antenna is estimated as 2 db. The single-carrier power output of the TWT is about 4 watts maximum. However, tests performed on a laboratory version of a satellite repeater said to resemble closely the Early-Bird configuration indicate that better over-all multiple-access performance results if the repeater is modified in such a way that the single-carrier output is reduced to about 3 watts.(12) The latter figure will therefore be assumed here.

Single-access (two-way) operation of the satellite is as follows: Single 6 gc carriers from each of two ground stations arrive at the satellite with about 80 mc spacing. One carrier is received by each receiver. The design of the receivers is such that the outputs of the two limiters provide essentially equal drive to the TWT, even though the incoming carrier powers may be different by several db. Since the two inputs to the TWT are equal, the output power is also divided approximately equally. However, due to non-linearity of the TWT input-output characteristic, the two signals form intermodulation products which detract from the total power available, as discussed in Section 4.4.1. The BTL tests cited above showed that the TWT output power per carrier was about 3.7 db less than the single-carrier output, indicating that the useful power output was reduced about 0.7 db due to the intermodulation effects. It is worth adding here that the reduction of output power is the principal degrading effect in this single-access mode. The significant intermodulation products are odd-order products which fall largely outside the signal bands, hence do not contribute much noise at the output of the communication channels.

When more than one pair of stations use the satellite, there will be more than one carrier through each of the receivers. The tests of the Early-Bird laboratory model(12) employed various combinations of two and three carriers (total) among the two receivers. That is, some tests were made with only two carriers, both passing through the same receiver, while other tests employed two carriers through one receiver and a third carrier through the other. With these modes of operation, it was found that the non-linear characteristics of the limiters generated even stronger intermodulation products than were generated in the TWT. Again, so long as there are no more than two carriers per limiter, the intermodulation products reduce the useful TWT output signal power, although not much more than in the single-carrier-per-receiver case.

Another effect observed in the two-carrier-per-receiver tests was an added degradation of the weaker of two carriers which arrive at the receiver at unequal levels. For example, it was found that when the input levels were different by one db at the receiver input, the weaker carrier suffered an additional degradation of about 0.5 db at the TWT output. The added loss became progressively worse as the input level difference increased, reaching about two db when the inputs were different by 6 db. This suggests that regulation of carrier powers by ground stations to maintain closely equal levels at the satellite is a worthy goal. As brought out in the previous section, however, it is likely that a ship station may not be able to generate as much effective radiated power as a land station. Unfortunately from the standpoint of the Apollo ship-to-shore link, it is of little, if any, advantage to other users to reduce their radiated powers. This is because the limiter action in the satellite maintains a constant drive to the TWT over a wide range of input levels, with the result that the intermodulation noise due to the TWT is about the same whether or not the non-Apollo users reduce their carriers to be equal to the ship's carrier. Hence, it will be assumed here that ground stations using the Early-Bird satellite will not necessarily regulate their power according to the number of users, and a degradation of the Apollo ship-to-shore carrier may result.

Without dwelling further on the results of the laboratory tests reported in Reference 12, but nevertheless relying on them, the multiple-access characteristics for the Early-Bird satellite are summarized in Table 5. The data for three or more pairs of users are estimates extrapolated from the tests on the laboratory model, which did not go beyond two carriers per receiver.

Not included in Table 5 is the effect of intermodulation products on the noise performance of the down links. The laboratory tests showed that the total power of these products is only of the order of 8 to 10 db below the satellite output carrier levels (depending on the number of carriers) when the input carriers are approximately equal. These products are radiated from the satellite just as are the fundamental carriers, and they contribute to the total noise entering the ground receiver. Thus, they affect threshold performance of an FM receiver. The amount of the intermodulation noise entering a particular receiver will depend on the relative positioning and signal bandwidths of the several carriers passing through the satellite, which determine how the intermodulation products are distributed. The Apollo ship-shore link would be likely to occupy a considerably smaller band- sidth than the proportionate share indicated by the equal

Table 5

EARLY-BIRD SATELLITE MULTIPLE-ACCESS CHARACTERISTICS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pairs of Users	No. Carriers in TWT	TWT Output per carrier, ignoring IM	Power[a] Loss due to IM	Output[a] per carrier, incl. IM	Add'l Pw'r[b] Loss of weaker carrier	Output[c] Pw'r of weaker carrier	IF Band[d] per Carrier
1	2	+1.8 dbw	0.7 db	+1.1 dbw	Not Appl.	Not Appl.	25 mc
2	4	-1.2 "	1.0 "	-2.2 "	2 db	-10.2 dbw	11.25 mc
3	6	-3.0 "	1.3 "	-4.3 "	2 "	-12.3 "	6.67 "
4	8	-4.2 "	1.5 "	-5.7 "	2 "	-13.7 "	4.38 "
5	10	-5.2 "	1.6 "	-6.8 "	2 "	-14.8 "	3.00 "

Notes: (a) Assumes equal carrier levels at satellite receiver input.

(b) The additional power losses quoted apply to one carrier that is 6 db weaker than each of the other carriers.

(c) Composite of entries in Columns 3, 4, and 6, less the 6-db lower power assumed for the weaker carrier at the receiver input.

(d) Assumes 10% of the total IF band used as guard band between adjacent signal bands, and equal bandwidth allotments per carrier.

allotments listed in the last column of Table 5. Hence, a relatively small proportion of the intermodulation products would be expected to fall in the Apollo signal band. Assuming that the signal band would be no more than 1/10th of the allotment indicated in the table,* the intermodulation noise also would be reduced by a factor of 10 or more, and the carrier-to intermodulation ratio would be increased to about 20 db. Added to the threshold carrier-to-fluctuation noise ratios of about 9 db stated as objectives in Table 4 the resulting total carrier-to-noise ratios would be degraded to about 8.5 db. To compensate for the added effect of intermodulation noise, therefore, the carrier-to-fluctuation noise objective for the down links will be assumed increased to 10 db for the following transmission calculations. Then, so long as the carrier-to-intermodulation ratio does not fall much below 20 db, the total noise will not exceed the threshold value.

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*The RF band indicated in Table 4, corresponding to the minimum required baseband of 12 kc, is about 85 kc. With two pairs of users, which is the minimum number of users for which there could be significant intermodulation noise _in the signal bands_, later calculations indicate a maximum ship-to-shore baseband of about 38.8 kc, requiring an RF band of about 280 kc. This is much less than 1/10th of the allotment of 11.25 mc indicated in Table 5 for the case of two pairs of users.

7.2 Transmission Calculations

Using the transmission characteristics of the Early-Bird satellite along with the assumed characteristics of the ship and land terminals, the available transmission margins of the shore-to-ship links are calculated in Section 7.2.1. Calculations are performed for various numbers of ground stations. Throughout Section 7.2.1 it is assumed that a multiplexed baseband of 12 kc will be used in the shore-to-ship direction of transmission. In the reverse direction of transmission, a minimum baseband of 12 kc is also needed. However, a larger bandwidth for increased data transmission could be used if available. In Section 7.2.2 are found the calculations of the maximum capacity of transmission from ship-to-shore.

The calculations of Sections 7.2.1 and 7.2.2 are broken into two parts: up-link and down-link. Both of these links must meet the carrier-to-noise requirements set forth in Table 4. Since the Early-Bird satellite uses a limiter in each receiver, a further constraint is imposed on the up-link: the carrier-to-noise ratio measured in the IF noise band must be at least 10 db to maintain threshold. That is, the carrier-to-noise ratio at the satellite limiter output should not reach the point where it decreases faster than the carrier-to-noise ratio at the input.

7.2.1 Shore-to-Ship

7.2.1a Up-Link

The estimate of the satellite receiver noise bandwidth is 31 mc. To avoid breaking the limiter threshold, the required carrier power C_B at the satellite receiver input is

$$C_B = 10 + F + 10 \log kTW_N \text{ dbw}$$

where

F = satellite receiver noise figure = 9.5 db

k = Boltzmann's constant = 1.38×10^{-23} joules/°K

T = 290°K

W_N = satellite noise bandwidth = 31 mc

The carrier power required at the satellite receiver input to avoid breaking the limiter threshold is then

$$C_B = -109.6 \text{ dbw}$$

In addition to the up-link meeting this requirement, it was established in Section 5.0 that the satellite carrier-to-noise level, measured at the input to the satellite receiver in a band equal to twice the baseband width, must be at least 22 db. With a 12-kc baseband, a 290°K antenna temperature, and a 9.5 db noise figure, this corresponds to a required carrier power C_N of

$$C_N = 22 + 10 \log (1.38\text{x}10^{-23})(290)(24\text{x}10^3) + 9.5 \text{ dbw}$$

$$C_N = -128.7 \text{ dbw}$$

Since C_B is greater than C_N, the requirement of a 22 db carrier-to-noise ratio in twice the baseband is automatically met if the carrier power is sufficiently large to avoid breaking the threshold of the satellite limiter. Thus, a carrier power of -109.6 dbw at the satellite receiver satisfies all requirements.

The actual carrier power C at the satellite receiver will now be calculated.

<u>Ground Station</u>

Transmitted power(5 KW)	+37 dbw
Antenna gain (85 ft parabolic dish, 53% efficient at 6 kmc)	+61.6 db
Transmission line loss	-2.0 db
ERP	+96.6 dbw
Path loss at 6 kmc, and at 22,500 nm maximum slant range	200.5 db

Satellite

Receiving antenna gain	+4 db
Line loss	-1.5 db
Net receiving gain	+2.5 db

The carrier power at the satellite receiver is

$$C = 96.6 - 200.5 + 2.5 \text{ dbw}$$

$$C = -101.4 \text{ dbw}$$

The carrier power of the up-link is greater than required by

$$-101.4 - (-109.6) = 8.2 \text{ db.}$$

7.2.1b Down-Link

As the number of users of the satellite increases, the output power per carrier decreases. Consequently, the transmission margin of the down-link also decreases. This section calculates the transmission margin above threshold of the down-link for various numbers of satellite users.

Assuming the satellite input carrier level from the Apollo land terminal to be commensurate with that from other land terminals, it will not suffer the power loss that a weaker carrier would suffer when passing through the satellite. With this in mind, the satellite TWT output power used in the calculations for the Apollo shore-to-ship down-link is obtained from column 5 of Table 5. Using these powers along with other characteristics which have been stated for the satellite and ship terminals, the transmission margins above threshold will now be calculated for the down-link. Calculations will first be performed for one pair of users (2 carriers) of the satellite.

Satellite

Transmitted power	+1.1 dbw
Antenna gain	+9.0 db
Line loss	-2.0 db
ERP	+8.1 dbw

Path loss at 4 kmc, and at 22,500 nm maximum slant range	197.0 db
Ship	
Receiving antenna gain (30 ft parabolic dish, 53% efficient at 4 kmc)	+49.0 db
Line loss	-0.5 db
Net receiving gain	+48.5 db

The carrier power into the ship receiver is

$$C = 8.1 - 197.0 + 48.5 \text{ dbw}$$

$$C = -140.4 \text{ dbw}$$

With a shipboard receiving temperature of 130°K, the thermal noise in a band equal to twice the 12-kc baseband is

$$N_{2b} = -163.7 \text{ dbw.}$$

For one pair of users of the satellite, the carrier-to-noise ratio in twice the baseband at the ship receiver is

$$\frac{C}{N_{2b}} = -140.4 - (-163.7)$$

$$\frac{C}{N_{2b}} = 23.3 \text{ db.}$$

Since a 10-db carrier-to-noise ratio in twice the baseband is required at threshold, the transmission margin above threshold is 13.3 db. Similar calculations have been performed for 2, 3, and 4 pairs of users of the satellite and have been summarized in Table 6.

Table 6

Transmission Margin of Satellite-to-Ship Link for Various Pairs of Users of Early-Bird Satellite

Pairs of Users	$\frac{C}{N_{2b}}$ (1) db	Margin Above Threshold (2) db
1	23.3	13.3
2	20.0	10.0
3	17.9	7.9
4	16.5	6.5
5	15.4	5.4

(1) b = 12 kc baseband

(2) Threshold is $\frac{C}{N_{2b}}$ = 10.0 db

A margin is required to allow for variations of noise and attenuation which are experienced from rain, water vapor, equipment degradation, radome losses (if a radome is used), etc. In the 4 kmc to 6 kmc frequency range, it is estimated that the variation may be as much as 4 to 9 db. 6 db will be assumed here as the margin necessary to compensate for such increased system losses. With a 6-db margin, it is seen that transmission of a 12-kc baseband in the shore-to-ship direction is feasible with 4 or fewer pairs of users of the Early-Bird satellite.

7.2.2 Ship-to-Shore

7.2.2a Up-Link

The up-link must satisfy two criteria in order to be considered acceptable:

1. The carrier power at the satellite receiver input must be 10 db above the noise in the satellite noise bandwidth. This requirement is the same as is necessary in the reverse direction of transmission and is satisfied if the receiver input power to the receiver is greater than -109.6 dbw.

2. From Table 4, the carrier-to-noise ratio in twice the baseband must be at least 19.3 db. This is equivalent to saying that the carrier power at the satellite input must be

$$C \geq 19.3 + 10 \log 2kTb + F \text{ dbw}$$

or

$$C \geq -172.2 + 10 \log b \text{ dbw}$$

where

$k = 1.38 \cdot 10^{-23}$ joules/°K.

$T = 290°K$

b = top baseband frequency, cps

F = satellite receiver noise figure = 9.5 db

For all basebands less than 1.82 mc, criterion (1) is the more difficult to satisfy. Thus, provided that the baseband is less than 1.82 mc, the up-link objectives will be met if the satellite receiver input carrier power exceeds -109.6 dbw.

The actual satellite receiver input power C from the ship terminal will now be calculated.

<u>Ship Terminal</u>

Transmitted power (10 KW)	+40 dbw
Antenna gain (30 ft parabolic dish, 53% efficient at 6 kmc)	+52.6 db
Transmission line loss	-2.0 db
ERP	+90.6 dbw

Path loss at 6 kmc, and at 22,500 nm maximum slant range	200.5 db
Satellite	
Receiving antenna gain	+4 db
Line loss	-1.5 db
Net receiving gain	+2.5 db

The carrier power at the satellite receiver is

$$C = 90.6 - 200.5 + 2.5 \text{ dbw}$$

$$C = -107.4 \text{ dbw}$$

The up-link carrier power is greater than required by

$$-107.4 - (-109.6) = 2.2 \text{ db.}$$

The performance of the limiters when more than one carrier passes through each receiver is not clearly understood, but there is some evidence(12) that the margin will be no better than in the case of single-access operation. In fact, it appears that it might even be worse. In single-access operation, a 6-db margin could be realized by some combination of increased antenna size and transmitter power. For instance, 20 KW of transmitter power and a 33-foot parabolic antenna would provide the desired margin. If it is not possible to increase the shipboard capabilities it may simply be necessary to tolerate a lower margin.

7.2.2b Down-Link

The input carrier level to the satellite from the ship assumed in the calculations above is 6 db below that from ground stations. With the satellite operating in the single-access mode, the carrier outputs would be equal by virtue of the action of the limiters, although the incoming carrier powers are different. With more than one pair of stations using the satellite, but assuming that each station transmits with the same ERP as it would in single-access operation, the weaker carrier of the ship-to-shore circuit suffers the 6-db loss and is further degraded by nonlinearity. Since bandwidth and carrier power are directly related, it is to be expected that the available bandwidth is more restricted than in the shore-to-ship direction when the satellite is operating with more than one pair of users. This is borne out in the following calculations which determine the baseband that an Apollo ship-to-shore link can support. Calculations are first performed for one pair of stations using the satellite.

Satellite	
Transmitted power	+1.1 dbw
Antenna gain	+9.0 db
Line loss	-2.0 db
ERP	+8.1 dbw
Path loss at 4 kmc, and at 22,500 nm maximum slant range	197.0 db
Land Terminal	
Receiving antenna gain (85-ft parabolic dish, 53% efficient at 4 kmc)	+58.1 db
Line loss	-0.5 db
Net receiving gain	+57.6 db

The carrier power into the land station receiver when one pair of stations use the satellite is

$$C = 8.1 - 197.0 + 57.6 \text{ dbw}$$

$$C = -131.3 \text{ dbw}$$

When two pairs of stations use the satellite, the Apollo carrier's output power in the satellite-to-shore direction is -10.2 dbw (from Table 5, Column 7). Since this is 11.3 db below the output power of the satellite when operating in the single access mode, the carrier power into the land station receiver is -142.6 dbw. These results for one and two pairs, as well as for three and four pairs of users of the satellite, are summarized in Table 7.

Table 7

Received Carrier Power at Land Station

From Early-Bird Satellite

Pairs of Users	Received Carrier Power C in dbw
1	-131.3
2	-142.6
3	-144.7
4	-146.1

Since the satellite-to-shore link breaks at a carrier-to-noise ratio of 10 db as measured in twice the baseband width, the margin above threshold M as a function of the baseband b is

$$M = C - 10 \log 2kTb - 10 \text{ db}$$

From this equation, the margin above threshold is plotted in Figure 6 for one, two, three and four pairs of satellite users.

With a 6-db margin and only the Apollo pair of stations using the satellite, the ship-to-shore link would be capable of supporting a 525-kc baseband. Approximately 440 kilobits per second of data could be transmitted from the ship and all transmission requirements would be met. With two pairs of users and a 6-db margin, the permissible baseband drops to 38.8 kc which corresponds to data transmitted at approximately 32 kilobits per second.

With four pairs of users and a 6-db margin, the ship-to-shore link is limited to only 17 kc - little more than the minimum necessary baseband of 12 kc. No more than four pairs of carriers can pass through the satellite and still transmit 12 kc of information in each direction. Thus, for the assumed characteristics of each transmission terminal, no more than four pairs of stations can simultaneously use the satellite and still meet the minimum requirements.

7.3 Shipboard Acquisition and Tracking Requirements

The antenna mount and drive mechanism for the shipboard communication terminal of a synchronous satellite system must inevitably be more complex than that of a land station terminal. This is due primarily to the need to compensate for roll and pitch motion of the ship. A land terminal can get by with an azimuth-elevation mount, and if it communicates exclusively with one satellite, a few degrees of angular movement is all that is necessary to keep the antenna beam pointed at the satellite during the normal diurnal drift that the satellite may have. A ship antenna mount must also be able to follow the satellite drift, and in addition must be able to scan through 360° in azimuth relative to the ship's heading, and through many degrees in elevation, as the ship rolls and pitches. If the ship had an azimuth-elevation mount and was located at a point such that the satellite was nearly overhead, the antenna could undergo violent azimuth motion as it attempted to point through the zenith to compensate for ship motion. Thus, one of the first requirements for a satellite communications terminal aboard ship is the need for a 3-axis antenna mount. A mount of this type, supporting a 30-foot diameter antenna, is used aboard the USNS Kingsport satellite communication ship.[(13)]

The motion of the satellite over the surface of the earth is expected to be no more than 10 to 20 degrees of latitude on either side of the equator. Hence, the area of visibility of the satellite will be essentially constant and an earth terminal - including a ship terminal - will require only one antenna to maintain constant contact with the satellite.

A 30-foot diameter antenna has about a 0.4 degree beamwidth at 6 kmc. In order to acquire the satellite with a beam of this dimension in a reasonable time, pointing data must be supplied to the ship. Presumably, emphemeris data will be computed initially from tracking data generated by one or more precision land-based trackers. The ephemeris data consist of a table of satellite positions as a function of time, referenced to the center of the earth. From these basic data, coordinate transformations are required to obtain the x-y-z pointing data for a 3-axis shipboard mount. An initial transformation from ephemerides to azimuth and elevation pointing instructions at the location of the ship might be done by a land-based computer, assuming the ship's position is accurately known and available to be included in the computation. The subsequent transformation to coordinates with respect to the ship's heading and attitude must be done on the ship, since these must be handled on a real-time basis. Since computing facilities must be supplied for the latter transformation in any event, it seems reasonable that the entire transformation from ephemerides to 3-axis pointing data should be done on the ship. It is perhaps pointing out the obvious to note that the ship's antenna must be accurately boresighted, and that appropriate angle-reference measurements (ship's heading, roll, pitch) must be made on a real-time basis in order to use the pointing data effectively.

Theoretically, the procedures outlined for initial acquisition could continue to be used to track the satellite after acquisition. However, if there is appreciable ship motion, a safer approach to assure communication continuity would be to employ a real-time tracking technique. The Early-Bird satellite - and very likely subsequent satellites also - will radiate a CW beacon signal for tracking purposes. A conical-scan tracking system, or some variation of a monopulse system, could be employed with the ship's communication antenna to track this beacon.

8.0 6000-NM ALTITUDE, RANDOM-ORBIT SYSTEM

The performance of a medium-altitude system of the type proposed jointly by AT&T and RCA to the Comsat Corp.[4] will be considered here. The first two sections review the transmission characteristics of the satellites and the results of transmission calculations, in parallel with the treatment of the synchronous-orbit case. Shipboard acquisition and tracking requirements are discussed in Section 8.3, with emphasis given to the differences between the requirements for a medium-altitude system and those for a synchronous-orbit system. An analysis of visibility statistics for a medium altitude satellite system and selected pairs of ship and land stations is given in the Appendix.

8.1 Transmission Characteristics of Medium-Altitude Satellite

A functional block diagram of the satellite repeater is given in Figure 7. There are two basic differences between this configuration and that of the synchronous-orbit system in Figure 5:

1. A traveling-wave tube power amplifier is associated with each receiver, thereby creating, in effect, two separate and complete repeaters;

2. The limiters between the IF amplifiers and the up-converters in the Early-Bird design are eliminated in the BTL-RCA plan.

Values of parameters needed for transmission calculations in Section 8.2 are listed on Figure 7. Assuming spin stabilization of the satellite, with the spin axis normal to the orbit plane, the receiving and transmitting antenna patterns will be toroidal around the spin axis. A gain of about 1 db relative to an isotropic radiator is expected. Line losses have not been quoted, but are estimated here as 2 db at either the receiving or transmitting ends of the repeater. These are approximately the losses in the Telstar satellite, on which much of the design of the proposed operational system is based. The receiver noise figure is assumed as 9.5 db, the same as that of the Early-Bird satellite.

The single-carrier effective radiated power from each repeater is quoted in Reference 4 as 4.2 or 5 watts, depending on the specific satellite configuration decided upon. 4 watts (6 dbw) will be assumed here. Giving allowance for the 2-db line loss and 1-db antenna gain stated above, this implies a TWT output power of 5 watts, or 7 dbw.

In the Early-Bird satellite, intermodulation of the various carriers during multiple-access operation is expected to arise in the IF limiters as well as in the TWT. In contrast, the TWT is the principal source of intermodulation in the repeater discussed here. Reference 7 reports the results of theoretical and experimental studies of multiple-carrier intermodulation effects in a traveling-wave tube of the type used in the Telstar satellite. These studies indicate that in order to hold intermodulation noise to a level compatible with CCIR noise objectives in a telephone channel, the power levels of carriers into the TWT must be reduced so that the total input power is less than that of the single-carrier saturation input power. The amount of the total <u>output</u> power reduction corresponding to the required input power reduction is termed the "back-off factor." Its magnitude is a function of the TWT input-output characteristic and of the noise objectives for the circuits through the satellite, the number of simultaneous radio carriers, the total bandwidth of the satellite repeater, and a number of less important factors. Section 4.4 has discussed this problem at more length.

The specific back-off factors given in Reference 7 have been revised somewhat by subsequent studies reported in an internal Bell Telephone Laboratories memorandum. Using these later data, the back-off factors for 2 to 4 carriers per repeater are approximately as given in Column 2 of Table 8. The computation of these back-off factors, as reported in Reference 7, employed an ideal-limiter approximation of the TWT input-output characteristic reproduced here as Figure 8.

Also listed in Table 8 are the required reduction of effective radiated power (ERP) from ship and land stations (and hence also the carrier reductions at the input to the satellite) and the resultant TWT output powers. The single-carrier-per-repeater case is used as a reference.

Consistent with the assumption in Section 6.1 that the maximum ERP from a ship would be about 6 db less than that from a land station, the single-carrier TWT output on the satellite-to-land-station link is reduced from 7 to 3 dbw as indicated by the input-output characteristic, Figure 8.

In the cases of 2 or more carriers per repeater, the output power back-off factors require that the earth station ERP's be reduced from their single-access values by the amounts shown in Columns 4 and 5. The required reduction of the ship's ERP is less than that of a land station simply because its single-access ERP was already assumed 6 db lower. The relative satellite input differences from land and ship stations (not shown in the table) is responsible for the apparent discrepancy in Column 6 in going from 2 to 3-carrier operation.

TABLE 8

OUTPUT POWER OF TWT IN 6,000-NM ALTITUDE REPEATER

(1) No. of Carriers Per Repeater[a]	(2) Output Power Back-off Factor	(3) Total Divisible TWT Output Power	(4) Required Reduction of Ship's ERP	(5) Required Reduction of Land Station's ERP	(6) TWT Output Power, Satellite to Land Station Link	(7) TWT Output Power, Satellite to Ship Link
1	0 db	7 dbw	0 db	0 db	3 dbw[b]	7 dbw
2	1.0	6	0	3.0	0	3
3	1.2	5.8	0	5.8	0.8	1.0
4	1.5	5.5	1.5	7.5	-0.5	-0.5

Notes: [a] Number of carriers per repeater = number of pairs of users. It is assumed that the carriers in opposite directions between any two stations communicating together pass through separate repeaters in the satellite.

[b] Since the ship's maximum single-carrier ERP is assumed 6 db less than a land station's ERP (see Section 6), the TWT associated with the ship's carrier will be operated at a lower point on the input-output characteristic. Hence the reduction of single-carrier output from 7 to 3 dbw on the satellite-to-land link.

8.2 Transmission Calculations

Transmission calculations for the medium-altitude system parallel those of the synchronous-orbit system. With a 12-kc baseband, the transmission margins of the shore-to-ship links are calculated in Section 8.2.1 for as many as four pairs of satellite users. In the reverse direction of transmission, a larger bandwidth is desirable. In Section 8.2.2, the bandwidth capacity is calculated as a function of the number of stations using the satellite.

8.2.1 Shore-to-Ship

8.2.1a Up-Link

A major difference between the Early-Bird satellite and the proposed BTL-RCA satellite is that the latter is not expected to incorporate limiters between the IF amplifiers and the up-converters. Without any limiting in the receiver, it will not be necessary to meet a threshold requirement. The up-link requirements are established by the tolerable noise in the over-all circuit and are satisfied if the carrier-to-noise ratio in twice the baseband at the satellite receiver exceeds 22 db. With a 12-kc baseband, a 290°K antenna temperature, and a 9.5 db noise figure, the carrier power necessary at the satellite receiver is

$$C_N = -128.7 \text{ dbw}$$

With the satellite operating in the single-access mode, the carrier power into the receiver from an Apollo land station is calculated below.

Ground Station

ERP (5 kw transmitter, 85 ft. antenna 53% efficient, 2 db line loss)	+96.6 dbw
Path loss at 6 kmc, and at 8780 nm maximum slant range	192.2 db

Satellite

Receiving Antenna gain	+1.0 db
Line losses	-2.0 db
Net receiving gain	-1.0 db

The carrier power at the satellite receiver is

$$C = 96.6 - 192.2 - 1.0$$

$$C = -96.6 \text{ dbw}$$

The carrier power of the up-link is greater than required by

$$-96.6 - (-128.7) = 32.1 \text{ db}$$

As more carriers enter each satellite receiver, the input carrier powers must be reduced by the amounts shown in column (5) of Table 8 to hold the down-link noise level constant. The margin of the up-link is reduced to the values shown in Table 9.

TABLE 9

Transmission Margin of 12-kc Shore-to-Satellite Link

6000-nm Altitude Satellite

Pairs of Users	Margin db
1	32.1
2	29.1
3	26.3
4	24.6

8.2.1b Down-Link

In this section, the transmission margin above threshold of the down link is calculated for various numbers of satellite users. The computational procedures are similar to those performed for the shore-to-ship down link of the Early-Bird satellite; only the satellite characteristics and path loss are different. Calculations are first performed for one carrier per satellite repeater, corresponding to one pair of stations using the satellite.

Satellite	
Transmitted power	+7.0 dbw
Antenna gain	+1.0 db
Line losses	-2.0 db
ERP	+6.0 dbw
Path loss at 4 kmc, and at 8780 nm maximum slant range	188.7 db
Ship	
Net receiving gain (30 ft. antenna 53% efficient, 0.5 db line loss)	+48.5 db

With the satellite limited to one carrier per repeater, the carrier power at the ship receiver is

$$C = 6.0 - 188.7 + 48.5 \text{ dbw}$$

$$C = -134.2 \text{ dbw}$$

Thermal noise at the ship in twice the 12-kc baseband is

$$N_{2b} = -163.7 \text{ dbw}$$

Thus, the carrier-to-noise ratio in twice the baseband is

$$\frac{C}{N_{2b}} = -134.2 - (-163.7) \text{ db}$$

$$\frac{C}{N_{2b}} = 29.5 \text{ db}$$

Since a 10-db ratio is required to maintain threshold, the transmission margin above threshold is 19.5 db. As more stations use the satellite the TWT power is apportioned among the users, resulting in a lower output power per carrier, and also a lower transmission margin. Using the values of the satellite output power given in column 7 of Table 8, the transmission margins have been calculated and are given in Table 10. Comparing Table 10 with Table 9, it is seen that the down link is the weaker link and the overall margin is therefore that of the down link.

TABLE 10

Transmission Margin of 12-kc Satellite-to-Ship Link

6000 nm Altitude Satellite

Pairs of Users (1)	C/N_{2b} (2) db	Margin Above Threshold (3)
1	29.5	19.5
2	25.5	15.5
3	23.5	13.5
4	22.0	12.0

(1) Number of pairs of users = Number of carriers per repeater

(2) b = 12-kc baseband

(3) Threshold is $\frac{C}{N_{2b}} = 10$ db

Allowing for a 6 db margin, transmission of a 12-kc baseband from the shore-to-ship station is feasible with at least four pairs of stations using the medium-altitude satellite.

8.2.2 Ship-to-Shore

8.2.2a Up-Link

The maximum effective radiated power of the ship terminal has been assumed 6 db below that of a land station. Therefore, the maximum input carrier power C to the satellite receiver from the ship is 6 db less than from a land station, or

$$C = -102.6 \text{ dbw}$$

This represents the input power to the satellite receiver in the single-access mode.

To satisfy the Apollo requirements, it was established in Section 5.0 that C/N_{2b} must be at least 19.3 db. Allowing a 6 db margin to account for the variable effects of rain, water vapor, equipment performance, etc., the up-link can support a baseband determined by

$$C = 19.3 + 6.0 + F + 10 \log 2kTb$$

where

C = input carrier power to satellite receiver from ship, in dbw

F = satellite noise figure = 9.5 db

k = 1.38×10^{-23} joules/°K

T = 290°k

b = top baseband frequency, in cps.

When no more than three pairs of stations use the satellite, the ship is not required to reduce its ERP. Under this condition, C is -102.6 dbw and the corresponding capability of the ship-to-satellite link is 2.29 mc. With four pairs of users, the ship's ERP must be reduced by 1.5 db as indicated in column 4 of Table 8 to hold intermodulation noise at a level tolerable to the other users. The up-link capability is then lowered to 1.62 mc. The up-link capacity is summarized in Table 11.

TABLE 11

Capacity of Ship-to-Satellite Link With a 6 db Margin

Pairs of Users	Received Carrier Power C at Satellite, dbw	Baseband Capacity, mc
1	-102.6	2.29
2	-102.6	2.29
3	-102.6	2.29
4	-104.1	1.62

8.2.2b Down-Link

From Table 8 the TWT output power in the satellite-to-shore link is 3 dbw when the satellite is operating with one carrier per receiver. Based on this value, the carrier power into an Apollo land station receiver is

$$C = -129.1 \text{ dbw}$$

As more carriers enter each satellite repeater, the satellite output power is reduced as indicated in column 6 of Table 8 so that the power into an Apollo land station receiver is lowered to the values shown in Table 12.

TABLE 12

Received Carrier Power at Apollo Land Station from Medium-Altitude Satellite

Pairs of Users	Received Carrier Power C in dbw
1	-129.1
2	-132.1
3	-131.3
4	-132.6

Allowing a 6 db margin above threshold, where threshold is taken as C/N_{2b} = 10 db, the down link can support a baseband determined by

$$C = 10.0 + 6.0 + 10 \log 2kTb \text{ dbw}$$

where

C = input carrier power to land station receiver, dbw

$k = 1.38 \times 10^{-23}$ joules/°K

T = land station noise temperature = 130°K

b = top baseband frequency, cps

Using this equation, the baseband capacity in the satellite-to-land direction has been calculated and summarized in Table 13. For comparison, the capacity of the up link has been included in this table. Since over-all transmission is limited by the weaker link, the maximum capacity of the medium altitude satellite is that of the down link.

TABLE 13

Transmission Capacity of Ship-to-Shore Links with 6 db Margin on Each Link

Pairs of Users	Up-Link Baseband	Down-Link Baseband
1	2.29 mc	870 kc
2	2.29 mc	435 kc
3	2.29 mc	525 kc
4	1.62 mc	390 kc

In summary, it has been shown that in both directions of transmission, the down link limits the over-all circuit performance. The transmission capabilities have been recapitulated in Table 14.

TABLE 14

Transmission Capabilities of Medium Altitude Satellite With 30-foot Shipboard Antenna

Pairs of Users	Transmission Margin in Shore-to-Ship Direction with a 12 kc Baseband, db	Baseband Capacity in Ship-to-Shore Direction with a 6.0 db Margin, kc
1	19.5	870
2	15.5	435
3	13.5	525
4	12.0	390

Since transmission in both directions exceeds the performance assumed necessary, it is reasonable to ask how much the shipboard equipment requirements could be relaxed. In all likelihood, the antenna structure size would be the first shipboard capability that would be lessened. If the margin in the shore-to-ship direction of transmission were reduced to 6 db for four pairs of users, a 15-foot shipboard antenna would suffice instead of 30 feet. Assuming the same antenna would be used for transmitting and receiving, the radiated power from the ship with a 15-foot antenna would be 6 db less than previously calculated. In general, it would not automatically follow that the satellite output power on the satellite-to-land link would also be 6 db lower, since the relative ERP's from the ship and the other users must be taken into account. However, with less than four pairs of users, the reduction of carrier power in the Apollo satellite-to-land link would be very close to 6 db. This is the case since the TWT would be operated in a linear region and the ship's carrier level at the satellite would be far below that of the other ground stations. With four pairs of users, the difference in input carrier levels would be smaller and calculations show the output power to be only 4.5 db below that previously calculated. The reduced satellite output power to an Apollo land station can be converted directly to a reduced bandwidth; this has been done in Table 15. Included in this table are the transmission margins in the shore-to-ship direction of transmission. The apparent discrepancy in Table 15 indicating that performance in the ship-to-shore direction of transmission improves with an increase in the number of pairs of users from 2 to 4 can be attributed to unequal carrier levels at the satellite input.

TABLE 15

Transmission Capabilities of Medium Altitude Satellite

With 15-foot Shipboard Antenna

Pairs of Users	Transmission Margin in Shore-to-Ship Direction with a 12-kc Baseband	Baseband Capacity in Ship-to-Shore Direction with a 6.0 db Margin
1	13.5 db	218 kc
2	9.5	109
3	7.5	131
4	6	138

8.3 Shipboard Acquisition and Tracking Requirements

The requirements of a shipboard acquisition and tracking system for a medium-altitude satellite system are basically the same as those stated in Section 7.3 for a synchronous-orbit system. These include three-axis antenna mounts, computation facilities for converting ephemeris data to three-axis pointing data, and facilities for measuring accurately the ship's roll, pitch, and heading angles and combining these with antenna pointing data.

The principal difference between shipboard requirements for a synchronous-orbit system and those for a lower-orbit system stem from the basically different visibility characteristics of the two systems. For planning purposes, the visibility of a synchronous-orbit satellite from a pair of Earth stations can be considered constant. Thus, only one antenna is needed at each station. With a lower-orbit system - either random or phased orbits - the visibility pattern for a pair of stations is continually changing. If the communication needs of these stations demand continuous contact, each must be equipped with at least two antennas. As the satellite being tracked by one antenna at each station approaches the limit of visibility, the second antenna must acquire another satellite and be prepared to continue the communication path without noticeable disruption when a switch is thrown. Assuming no loss of time in switching, the communication intervals and outage times are governed entirely by the visibility statistics discussed in the Appendix.

There are two alternatives to an installation of two satellite terminal antennas aboard an Apollo C&T ship:

1. Since satellite visibility between two stations is accurately predictable and the time for switching from one satellite to another can be determined well in advance, launch and subsequent events in an Apollo mission might be planned with this as an added constraint;

2. The time involved in transferring an antenna from one satellite to another might simply be accepted as additional outage time.

In view of the many constraints already placed on the Apollo mission, the first alternative is not likely to be acceptable. Whether or not the second is acceptable depends on how fast an antenna can be transferred. Experience with the Telstar ground station antenna has been that if the antenna initially is pointed in the general direction of the satellite, solid tracking can be accomplished in a very few seconds after an acquisition order (based on ephemeris data) is given. The major portion of the time required to transfer from one satellite to another is likely to be the time required to slew the antenna. The total azimuthal slew angle could be as much as 180 degrees. At a slew rate of 20 degrees per second, considered a reasonable rate for an antenna and mount of the size visualized for the shipboard system*, the

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*The azimuthal tracking rate of the AN/FPQ-6 radar is quoted as 28 degrees per second (presumably a maximum rate). This radar employs a 30-foot antenna, the same size as assumed for the satellite communications antenna here. Many large shipboard search radars are capable of azimuthal-turning rates well above the 20 degrees per second figure assumed here.

slew time could be as much as 9 seconds. The total transfer time might therefore be as much as 12 to 15 seconds. Whether or not this is acceptable is an operational question. It should be noted that the probability of a transfer being required during the few minutes when the Apollo spacecraft would be in view is rather small, based on the statistics presented in the Appendix. Further, if it is assumed that the total time that the spacecraft is in view will total at least as much as three minutes, the indicated outage time for an antenna transfer is less than 10% of the available time. These factors would seem to suggest that a second antenna is not warranted.

9.0 POTENTIAL IMPROVEMENTS IN SATELLITE SYSTEM PERFORMANCE

The discussion of satellites thus far has dealt solely with the characteristics of systems expected to be operational sometime within the next two or three years. Looking beyond these "first-generation" operational systems, we can foresee new technology which should allow significant increases in communication capacity. Alternatively, improvements in satellite characteristics could relax requirements on earth station equipment. It is assumed that only relatively small improvements in the transmission characteristics of ship terminal equipment - antennas and receiving systems, particularly - are possible. Thus, most of the improvement must be sought in the satellite.

To avoid giving this discussion too much of the flavor of crystal-ball-gazing, we will restrict attention numerically to advances which might reasonably be expected within about the next five years. Only qualitative mention will be made of factors which might influence subsequent system performance.

In most satellite system plans that have been proposed, transmission performance of the up link is better than that of the down link. The parameter that is primarily responsible for the difference between the two links is transmitter power. The satellite power outputs quoted in Sections 7 and 8, for example, are 30 to 40 db lower than that generally discussed for an earth station. All experimental communication satellites thus far launched, as well as "first-generation" operational satellites in various stages of planning, employ solar cells as primary power sources. The amount of power finally deliverable to a transmitting antenna is a function of the total area of solar cells that can be designed around a particular satellite configuration, and of the efficiencies of these cells and the other electronic components in the repeater.

To a first approximation, the area devoted to solar cells is a function of the over-all size of the satellite, which in turn is a function of launch booster capability. Thus, some increase in power output capability can be expected if larger boosters are used. This must be termed a brute-force approach, however, and like so much of the history of brute-force approaches in communication systems engineering, the improvement is not likely to be dramatic (e.g., not order-of-magnitude) without entailing a disproportionately high cost. Assuming the area might be increased by 50% through some reasonable increase in size of the satellite or more effective techniques of cell arrangement, an improvement in primary power availability of about 2 db would be possible.

Efficiencies of solar cells and other electronic devices in a satellite can be expected to increase gradually, but again the improvement is not likely to be dramatic. For example, over-all efficiency from solar cell input to transmitter output could hardly be expected to double during the next five years. An increase of 25%, or about 1 db in transmitter output, is more probable. Thus, the total potential improvement in transmitter power during this period due to increased solar cell area and higher-efficiency components adds up to about 3 db.

In the more distant future, one can visualize significantly greater increases in satellite power capability through the use of new primary power sources, such as nuclear power supplies.[14] There is much research being done on such devices. Eventually, one or more order-of-magnitude improvements over the capabilities of systems using solar cells are probable, but they are not likely to be seen in communication satellites within the next five years.

The second major area of transmission improvement involves satellite antenna gain. Here, potential improvements could affect both up links and down links, although the need clearly is greatest for down links.

Assuming that a satellite system is intended to be used by several stations spread over a large area of the earth, it is reasonable to expect that antenna beamwidth would not be reduced much beyond the point where it just subtends the Earth (at whatever altitude the satellite is flown). For a synchronous satellite system, this angle is about 18 degrees, and the corresponding conical-beam antenna gain would be about 22 db. The subtended angle and related conical-beam gain for a satellite in a 6000-mile altitude orbit are about 43 degrees and 14 db, respectively. In both cases, the gains cited are theoretical; a practical system would have to allow for some earth-pointing inaccuracy and an antenna of less than 100% efficiency.

A breadboard model of an antenna system proposed by Hughes Aircraft Company for the Advanced Syncom satellite is reported to have achieved approximately 17 db gain. The Hughes approach employed phased-array techniques coupled with the spin-stabilization system of the satellite.[15]

Another technique which conceivably could provide equivalent gain with simpler implementation would include a combination of a fixed antenna structure and gravity-gradient stabilization. The latter technique will be tested in both synchronous and lower-orbit systems in NASA's planned series of Advanced Technology satellites.(16) It seems quite probable that one or the other technique eventually can be implemented in an operational synchronous-orbit system to realize about 17 db gain, about 5 db less than the theoretical amount for a beamwidth that just subtends the Earth, but still about 8 db more than was assumed in the calculations for the Early-Bird satellite in Section 7. Similarly, if it is assumed that a practical gain for the antenna in a 6000-mile orbit system would be about 5 db less than the theoretical value corresponding to the Earth-subtended angle at that altitude, the gain would be about 9 db. Again, this is about 8 db more than was assumed in the calculations for the lower-orbit system, Section 8. Unless unforeseen problems arise during the development and experimental testing of spin stabilization and/or gravity-gradient stabilization techniques, these gains should be realizeable within 5 years.

The potential improvements in transmitter power and antenna gain by 1969-1970 add up to about 11 db for either the synchronous-orbit or lower-orbit system. The only other conceivable sources of improvement in the down link to a ship terminal are slight reductions in RF line losses in the satellite and similarly slight reductions in receiving system noise temperature. (We have already assumed the receiving antenna to be about as large as is thought feasible for a ship installation.) Optimistically, a total improvement of about 12 db from all sources might be expected, while 10 db should be a rather safe estimate. To a first approximation, these numbers can be converted directly to comparable db increases in bandwidth. This would indicate an order-of-magnitude improvement in communication capacity within the next five years. Alternatively, if the additional capacity is not needed, some or all of the improvement in satellite performance might be devoted to reducing the size of a ship's antenna. A 10 db improvement, for example, could be used to reduce the antenna diameter from 30 feet to about 10 feet.

It is worth noting that if the performance of a satellite down-link alone is increased by 10 db or more, it will no longer be so much better than the up link that the latter's contribution to total noise performance can be ignored. Probably all this means is that somewhere along the line of evolution it may become necessary or desirable to increase the satellite's receiving antenna gain as well as the transmitting antenna gain, and perhaps also call for designs of lower-noise receiving systems for satellites.

APPENDIX

VISIBILITY STATISTICS OF 6000-NM ALTITUDE COMMUNICATION SATELLITE SYSTEMS

Introduction

This appendix reports the results of a study of visibility characteristics of several medium altitude satellite systems. The objective of this effort is to develop an over-all feeling for the kind of visibility pattern that representative satellite configurations can be expected to provide at several likely Apollo communications terminals, and to assess the adequacy of the resulting coverage. It is assumed that if a satellite is visible, it can serve as a communications link.

Over the past few years there have appeared many analyses of random orbit satellite system visibility characteristics. Most of these are necessarily statistical in nature, and derive expressions for the probability of mutual visibility at two terminals. For this current evaluation, a simulation approach due to Rinehart and Robbins(17) has been selected instead. Their method uses a computer to model a worldwide satellite system having specified parameters, and deduces the associated visibility pattern for given pairs of ground terminals. The reasons for preferring this approach are the following:

a) The availability and flexibility of their computer program giving the coverage pattern in terms of outage plots for a wide variety of satellite systems and ground station pairs.

b) The more illuminating, physical view of coverage inherent in the outage plot presentation, as compared with bare numbers expressing a probability of visibility.

c) Recognition of the tentative nature of both the satellite configuration and terminal locations. Because of this, it is reasonable to seek at this time only a qualitative determination of the possible usefulness of proposed satellite systems with Apollo terminals. It is felt such a judgement can be more readily made using this system model and simulation technique.

d) The sensitivity of the coverage pattern to changes in system parameters is readily revealed by this program.

The main body of this appendix discusses first the assumptions involved in the simulation, next develops visibility criteria, and then presents the outage plots and their evaluation with respect to coverage adequacy. No extended description of the logic or details of the simulation is given; these may be found in the referenced article of the authors. Finally, some general conclusions are stated regarding the applicability of typical systems to the intended Apollo mission use.

Assumptions in Simulation Model

The model used in this study makes use of certain assumptions which are certainly not precisely true of a real satellite system, but which are convenient, and result in simplifications. These are indicated below according to the characteristic affected.

a) Satellite Orbits - All orbits are assumed perfectly circular at a single nominal altitude. No precession occurs; i.e., the ascending node remains fixed in inertial space. The period is computed independently as a function of altitude, and read into the visibility program independently. (Where small variations in period are permitted among the satellites of a random system, no corresponding change in altitude or coverage is introduced, the effect being regarded as negligible.)

b) Coverage - The coverage associated with a ground terminal is taken to be a small circle on the earth, whose radius is a function of the altitude and antenna masking angle. The latter, which is the minimum elevation angle at which communications may take place, is assumed to be 7.5°* for all azimuths at all stations.

c) Handover - Handover is assumed to be no problem. The program examines only whether at least one satellite is within the zone of mutual visibility at a given time, and if this condition exists, coverage is asserted. This is equivalent to assuming instantaneous acquisition and tracking on entering the zone, and instantaneous handover where necessary.

d) Access - Access is assumed to be no problem; i.e., sufficient capacity is available so that other terminals which may have existing contact will not preclude communications by the Apollo terminals. Moreover, no preempting of access is permitted by higher priority stations. (The program of Rinehart and Robbins does have an option which recognizes priority assignments, but this feature was not utilized here.)

e) Solar Battery Operation - No restriction on communications is assumed as a result of the satellites' being in darkness (earth shadow). This is an optimistic assumption, but the simulation program is not presently capable of introducing the decreased coverage pattern due to nonfunctioning of solar cells in shadow.

Terminal Locations

There are at least three critical phases of the mission in which real time monitoring of S/C status and position by ships has been suggested. These are the insertion phase

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*This value, which was carried over from the earlier work of Rinehart and Robbins, is inconsistent with the value of 5° used in the transmission calculations of this report. It is one of the few conservative assumptions of this study, which helps offset some of the other more optimistic assumptions, but in any case introduces no serious error. It merely decreases the mutual visibility lune by a few per cent, with a corresponding decrease in indicated quality of service relative to the case when a 5° masking angle is assumed.

(into earth parking orbit), the translunar post-injection phase, and the reentry phase. Each ship in the system under investigation, would serve as one terminal in the satellite communications link to the MSCC. The other terminal is chosen on land, somewhat arbitrarily, but so as to provide a reliable, conventional link to MSCC. The terminals selected for this study are shown on the map, Figure A-1, and are also listed in Table A-1. It should be recognized that in many cases the specific coordinates selected for land terminals have no absolute validity in terms of existing facilities, but are merely representative of terminals that suggest themselves to complete the given link. Similarly, the ship terminals are in nominal positions, and in any mission would be shifted to optimize communications with the S/C. Accordingly, the resulting coverage pattern, which is dependent upon the terminal locations, can be considered only representative. The combinations of various ship and land terminals constitute links whose outage patterns were studied.

Satellite Orbit Configurations

Three basic satellite orbit configurations were studied. All had eighteen satellites in the system. The first was an ideally phased configuration of three polar orbit planes with six satellites per plane. The ascending nodes of the planes were spaced 120° apart, and the satellites equally spaced in each plane. This was a reference system designed to serve as a comparison standard for the others. The second system was a more realistic configuration in which inclination, phase, and period were permitted to assume small random variations about nominal values. However, three equi-spaced orbit planes were retained with six satellites per plane. This situation corresponds to a package-launch system. The final basic configurations corresponds to a system having a single satellite per launch, and therefore consists of eighteen orbit planes with one satellite in each plane. Random values (about nominal) of inclination, phase, period and ascending node are introduced. Other systems similar to the last two, but with different parameters, were also studied. Their results did not differ in character from the systems defined above, and hence they are not reported on here. The characteristics of the basic configurations studied are listed in Table A-2.

Development of Usability Criteria

In order to evaluate the adequacy of the various links for the intended Apollo application, it is necessary to establish criteria of usability which we express in terms of the outage plots. We assume first that for any real satellite system with parameters similar to those in the model, the outage statistics will be similar; i.e., the outage plot, which is completely defined for any real system in orbit, closely resembles our plot in distribution and length of outages. We then, somewhat arbitrarily, define the characteristics of an adequate outage plot: In general functional terms, an outage plot will be taken to imply a usable Apollo link coverage pattern if there is a high probability that the duration and spacing of outages will cause only non-critical delays in the scheduling of mission events, or negligible gaps in real time transmission of data.

Before assigning numbers to these outage parameters, this criterion must be considered in relation to the three critical phases during which communications is desired.

a) Insertion Into Earth Parking Orbit

Here real time communications with MSCC is highly desirable. (Some sources consider it a firm requirement.) In evaluating the coverage for insertion, we observe that only a short, clear interval is required in the vicinity of insertion time. This interval should extend from launch to about 30 minutes after launch. We would demand, then, of our outage statistics that at any arbitrary time, the probability of an outage exceeding, say, 20 minutes be very low (so as to impose, at most, a minor delay in launching), and also that at an arbitrary time the probability of a clear period ("innage") exceeding 30 minutes (to provide a clear channel from launch through insertion and to insure real time transmission of the tracking data) be very high.

Since these two probabilities will be used to evaluate the links in all phases, the method of calculating them from the outage plots will now be derived.

1) Probability of Outage (O) Occurring at Arbitrary Time Which Exceeds X Minutes, pr(O>X).

The program provides a value for P, the quality of coverage, defined as

$$P = \frac{\text{Total Clear Time ("Innage" Time)}}{\text{Total Sample Time (30 days in this program)}}$$

Then the probability that any outage exists at an arbitrary time is pr(O) = 1-P.

The program also provides a table giving the distribution of outages in terms of length of outage, X, vs. per cent of outages longer than X; i.e., we are given the probability of an outage exceeding X minutes duration, knowing that an outage exists. This is a conditional probability, denoted by

$$pr(O>X/O \text{ occurs})$$

By elementary probability theory

$$pr(O>X/O \text{ occurs}) = \frac{pr(O>X)}{pr(O)}$$

or $pr\,(O>X) = pr(O>X/O \text{ occurs}) \cdot pr(O)$

For the insertion phase, it has been stated that 20 minutes is a reasonable value for X, and hence we compute pr(O>20) by the above formula, hoping for an "acceptably" low value. (We note at once that $pr(O>X) \leq pr(O) = 1-P$. Hence if P is sufficiently high, our criterion is satisfied.) A value for $pr(O>20) < .05$, will be assumed here as satisfactory.

2) Probability of Innage (I) Existing at Arbitrary Time Which Exceeds Y Minutes, pr(I>Y).

To compute this probability, we use the following device: we augment each outage by Y minutes and then compute the resulting new quality of service P':

$$P' = pr(I>Y) = \frac{\text{Total (Old) Clear Time} - nY}{\text{Total Sample Time}}$$

$$= P - \frac{nY}{\text{Total Sample Time}}$$

where n is the number of outages in the 30-day plot.

We assert P' is the desired probability because it is the fraction of time in which an arbitrarily selected interval of Y minutes can never intersect an outage period.

Both n and P are given in the computer printout, and taking 30 days as the sample length, P' is readily computed for a given Y. In accordance with the "reasonable" criterion at the beginning of this discussion, Y is taken as 30 minutes, and a satisfactory value for $pr(I>30)$ is taken as .90.

In both these calculations, the random nature of outage occurrences is implicitly assumed, i.e., an outage is equally likely to occur at any instant. These criteria cannot, of course, be applied in the case of a phased-orbit system.

b) Translunar Post-Injection

The requirements of this phase seek transmittal of roughly 10 minutes of post-injection communications and tracking data by no later than 20 minutes after the end of the injection burn. In attempting to prescribe the outage statistics compatible with this phase, we note first that, unlike insertion, once the mission is underway, it is not feasible to delay injection to accommodate an outage pattern. Therefore, such an outage could occur throughout this entire critical post-injection tracking interval. However, we ask that in the final few minutes of this 10-minute period during which data is being acquired, there be a high probability of a clear period to permit transmission to MSCC. Assuming a communication interval of about 4 minutes is desirable, then, in terms of our earlier criterion, $pr(O>4 \text{ min.})$ should be low. A value of .01 seems reasonable.

c) Reentry

Knowledge of the outage pattern is of little use in insuring usability of the satellite link for reentry coverage in advance of a mission because the exact time of reentry is not determined until trans-earth injection. Moreover, there is no stated requirement for real time reentry communication with the S/C. What is highly desirable is expeditious transmittal of whatever tracking data is obtainable (plasma sheath, skin, or direction-finding) to assist redeployment and search action of recovery forces. Relaying of such reentry tracking and/or communications by the ships is desired even if delayed by a nominal amount. Therefore, the characteristics of the satellite link for reentry support are similar to, but somewhat less stringent than those for either insertion or injection. An acceptable criterion for this link would be a low probability (say, 0.1) of a moderate outage of perhaps 20 minutes duration.

It follows that the links should be evaluated separately according to function, the criteria applicable to different phases being sufficiently dissimilar so that a common performance yardstick is not suitable.

These criteria, as suggested by the arguments of this section, are summarized as follows:

Insertion into EPO:	$pr(O>20) < .05$
and	$pr(I>30) > .90$
Translunar Post-Injection:	$pr(O>4) < .01$
Reentry:	$pr(O>20) < .10$

<u>Results</u> Table A-3 presents a summary of the outage characteristics for all links in both random satellite systems. The columns for $pr(O>20)$, $pr(O>4)$, and $pr(I>30)$ do not appear for the phased system since the assumption of randomness necessary to valid computation of these probabilities cannot apply.

Figures A-2 through A-7 are selected outage plots to illustrate the characteristics of representative links in each mission phase for the random satellite systems. Figure A-8 is the only plot shown for the phased system, most of the others having complete coverage with no outages. Each line on the plots represents the visibility pattern during one 24-hour period, and each page covers a span of 30 days. The annotation on the bottom of each plot includes a reference to the system configuration. Random 3 refers to the third system studied, in this case the three-orbit plane system. Random 5 refers to the eighteen-orbit plane system. The station pair identification legend is given in Table A-1 and on the map, Figure A-1. The figures appearing next to the station pair are the colatitude,* west longitude coordinates of the ship and land terminal comprising the link, in that order.

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*Latitude = 90° - colatitude

The outage statistics indicate the superiority of the hypothetical phased system over the others. The three-orbit plane random system is seen to provide better coverage than the eighteen-orbit plane system.

In terms of the stated criteria, insertion is covered by either system on the link to Rosman, but only the three-orbit system satisfies the criteria on the longer link to Corpus Christi.

The post-injection criterion is satisfied only in one case, that of the three-orbit system link from the Indian Ocean ship to Carnarvon.

For the reentry phase, the coverage criterion is met by the three-orbit system in all cases except one very long link to Goldstone. The eighteen-orbit system also fails on the same link, and one other as well, from a ship off Australia to Hawaii.

These results indicate that an 18 satellite random-orbit system can meet the suggested criteria for the insertion and reentry phases. It does the first at the expense of a possible short hold at launch, and the second by not being constrained to real time transmission. In the case of post-injection coverage, the random system does not meet the stated criterion. In such a case, a synchronous system is the indicated solution if, indeed, the coverage must be had.

Because the quality of coverage exhibited by the satellite systems is critically dependent on terminal location, significant improvement can be obtained by a judicious choice of station location, within the constraints of the mission. In this connection, it should be noted that quality of coverage is not determined solely by station separation. For the case of a polar orbit system, the terminals should both be situated at latitudes near 30° (both north or south) to insure that their common visibility zone extends near a polar region where the converging polar orbits can provide coverage throughout a large part of the day. With this qualification, a link of better than 90% quality occurs when station separation is less than 65°, though this quality alone does not assure meeting the added criteria suggested earlier. One other point in regard to station location: Since the access problem, which has been bypassed in this visibility study, will arise in the real system, it will be well to select land stations in the southern hemisphere insofar as possible, to reduce competition with commercial traffic demands of the more numerous northern hemisphere cities.

Two other facts should be noted in mitigation of the implied inadequacy of the systems studied here.

a) It is possible that more than 18 satellites will be launched initially in an operational system. The coverage afforded by a larger number of satellites will be correspondingly better.

b) There may be deliberate attempts to launch later satellites so as to fill gaps noted in coverage of commercial station patterns. These would certainly improve Apollo terminal patterns as well.

Conclusions On the basis of certain reasonable, if arbitrary, criteria developed for satellite link performance, the insertion and reentry phases can be supported by an eighteen-satellite, random, polar orbit system.

A three-orbit-plane system with six satellites per orbit performs better in these two phases than an eighteen-orbit-plane system with one satellite per plane.

Neither system can give the desired assurance of coverage (at least in advance of insertion) of the uncertain times at which injection may occur, and consequently they cannot assure meeting a requirement for transmittal of 10 minutes of tracking data prior to 20 minutes after injection. While subsequent communications satellite launches and closer spacing of stations can improve the probability of such coverage, they can never make it certain; therefore, a synchronous system is indicated if this coverage is regarded as vital.

Station Pair/ Mission Phase	Ship Terminal Name	Ship Terminal Colat.	Ship Terminal W.Long	Land Terminal Name	Land Terminal Colat.	Land Terminal W.Long	Separation (Great Circle Degrees)
1/Insertion	Atlantic Ocean	65	45	Corpus Christi	63	97	46
2/Insertion	Atlantic Ocean	65	45	Rosman	55	82	34
3/Post-Injection	S. E. Africa	118	328	Antigua	73	62	102
4/Post-Injection	S. E. Africa	118	328	Rio de Janeiro	113	43	67
5/Post-Injection	S. E. Africa	118	328	Carnarvon	115	246	70
6/Post-Injection	Indian Ocean	110	272	Carnarvon	115	246	25
7/Post-Injection	Indian Ocean	110	272	Guam	77	216	66
8/Post-Injection	Indian Ocean	110	272	Canberra	126	211	55
9/Reentry	Samoa Landing	115	200	Canberra	126	211	14
10/Reentry	Samoa Landing	115	200	Hawaii	68	158	62
11/Reentry	Hawaii Landing (Equatorial)	90	190	Hawaii	68	158	39
12/Reentry	Hawaii Landing (Equatorial)	90	190	Goldstone	54	117	75
13/Reentry	Hawaii Landing (N. Pacific)	65	190	Hawaii	68	158	30
14/Reentry	Hawaii Landing (N. Pacific)	65	190	Goldstone	54	117	62

TABLE A-1

Ship-Land Communications Links

Configuration	Orbital Plane/ Satellite	W. Long. of Asc. Node at t = 0	Inclin. (degrees)	Initial Phase Single (degrees)	Period (Minutes)
3 Orbit, Phased	1/1	0	90	0	360
	1/2	0	90	60	360
	1/3	0	90	120	360
	1/4	0	90	180	360
	1/5	0	90	240	360
	1/6	0	90	300	360
	2/1	120	90	20	360
	2/2	120	90	80	360
	2/3	120	90	140	360
	2/4	120	90	200	360
	2/5	120	90	260	360
	2/6	120	90	320	360
	3/1	240	90	40	360
	3/2	240	90	100	360
	3/3	240	90	160	360
	3/4	240	90	220	360
	3/5	240	90	280	360
	3/6	240	90	340	360
3 Orbit Random (R-3)	1/1	0	88.5	54.0	384.0
	1/2	0	88.7	43.2	383.3
	1/3	0	88.6	154.8	383.8
	1/4	0	88.8	356.4	384.1
	1/5	0	88.6	185.2	383.1
	1/6	0	88.7	266.6	382.4
	2/1	120	89.2	277.2	382.9
	2/2	120	89.3	82.8	383.2
	2/3	120	89.4	68.4	381.7
	2/4	120	89.3	280.8	380.9
	2/5	120	89.5	26.5	381.5
	2/6	120	89.4	157.1	381.8
	3/1	240	90.5	5.0	382.9
	3/2	240	90.4	213.4	382.2
	3/3	240	90.6	343.5	382.7
	3/4	240	90.5	137.3	383.0
	3/5	240	90.5	176.4	388.9
	3/6	240	90.7	115.2	381.2

TABLE A-2

Satellite System Parameters

Configuration	Orbital Plane/ Satellite	W. Long. of Hse. Node at t = 0	Inclin. (degrees)	Initial Phase Single (degrees)	Period (Minutes)
18 Orbit, Random (R-5)	1/1	6.8	88.5	54.0	384.0
	2/2	28.3	88.7	43.2	383.3
	3/3	88.4	88.6	154.8	383.8
	4/4	220.3	88.8	356.4	384.1
	5/5	160.5	88.6	185.2	383.1
	6/6	5.6	88.7	266.6	382.4
	7/7	212.8	89.2	277.2	382.9
	8/8	320.7	89.3	82.8	383.2
	9/9	280.9	89.4	68.4	381.7
	10/10	340.7	89.3	280.8	380.9
	11/11	310.0	89.5	26.5	381.5
	12/12	65.9	89.4	157.1	381.8
	13/13	190.6	90.5	5.0	382.9
	14/14	110.2	90.4	213.4	382.2
	15/15	260.4	90.6	343.5	382.7
	16/16	18.7	90.5	137.3	383.0
	17/17	76.3	90.5	176.4	388.9
	18/18	135.8	90.7	115.2	381.2

TABLE A-2 (continued)

Satellite System Parameters

Configuration	Station Pair/ Mission Phase	Avg. Outage (Min.)	No. of Out. in 30 Days	P, Qual. of Serv.	pr(O) = 1-P	pr (O>20)	pr (O>4)	pr (I>30)	Meets Crit.
3 Orbit, Random (R-3)	1/Insertion	16.2	43	.984	.016	.003	.014	.954	√
	2/Insertion	10.8	24	.994	.006	.001	.004	.977	√
	3/Post-Injec.	88.5	347	.285	.715	.596	.696		X
	4/Post-Injec.	20.9	158	.923	.077	.032	.065		X
	5/Post-Injec.	23.0	180	.903	.097	.044	.086		X
	6/Post-Injec.	14.3	22	.992	.008	.002	.007		√
	7/Post-Injec.	26.8	274	.830	.170	.092	.152		X
	8/Post-Injec.	16.0	136	.949	.051	.014	.045		X
	9/Reentry	5.0	3	.99	.001	.000	.001		√
	10/Reentry	26.1	300	.818	.182	.092	.167		√
	11/Reentry	18.7	95	.986	.014	.005	.011		√
	12/Reentry	30.5	372	.736	.264	.153	.241		X
	13/Reentry	9.2	23	.995	.005	.001	.003		√
	14/Reentry	15.8	128	.953	.047	.013	.039		√
18 Orbit, Random (R-5)	1/Insertion	34.4	91	.927	.073	.046	.067	.864	X
	2/Insertion	18.5	73	.968	.032	.011	.025	.917	√
	3/Post-Injec.	88.8	339	.299	.701	.588	.672		X
	4/Post-Injec.	41.8	178	.827	.173	.110	.156		X
	5/Post-Injec.	41.4	187	.820	.180	.114	.158		X
	6/Post-Injec.	31.6	66	.951	.049	.026	.043		X
	7/Post-Injec.	46.3	212	.771	.229	.160	.219		X
	8/Post-Injec.	31.4	158	.884	.116	.061	.102		X
	9/Reentry	24.2	31	.982	.018	.009	.014		√
	10/Reentry	40.0	246	.772	.228	.135	.212		X
	11/Reentry	36.7	115	.902	.098	.060	.091		√
	12/Reentry	48.6	300	.661	.339	.231	.312		X
	13/Reentry	30.7	73	.948	.052	.028	.049		√
	14/Reentry	27.8	166	.893	.107	.057	.095		√

TABLE A-3

Summary of Outage Statistics

Configuration	Station Pair/ Mission Phase	Avg. Outage (Min.)	n, No. of Out. in 30 Days	P, Qual. of Serv.	pr(Ω) = 1-P	pr (O>20)	pr (O>4)	pr (I>30)	Meets Crit.
Phased	1/Insertion	0	0	1.00	0				✓
	2/Insertion	0	0	1.00	0				✓
	3/Post-Injec.	50.2	551	.357	.643				X
	4/Post-Injec.	5.0	5	.999	.001				✓
	5/Post-Injec.	0	0	1.00	0				✓
	6/Post-Injec.	0	0	1.00	0				✓
	7/Post-Injec.	5.0	5	.999	.001				✓
	8/Post-Injec.	0	0	1.00	0				✓
	9/Reentry	0	0	1.00	0				✓
	10/Reentry	3.0	11	.999	.001				✓
	11/Reentry	0	0	1.00	0				✓
	12/Reentry	10.7	233	.942	.058				✓
	13/Reentry	0	0	1.00	0				✓
	14/Reentry	0	0	1.00	0				✓

TABLE A-3 (Continued)

Summary of Outage Statistics

REFERENCES

1. "Transmission Techniques for Apollo Ship-Shore Communications," Bell Telephone Laboratories, Inc., September 1, 1963.

2. C. E. Clutts, "Project Apollo - Engineering Requirements for Ship-Shore Airborne Radio Relay System," Bell Telephone Laboratories, Inc., March 27, 1964.

3. "Early Bird Filing Opens New Comsat Phase," Aviation Week and Space Technology, March 16, 1964, p. 227.

4. "Commercial Communications Satellite," proposal by AT&T and RCA to Comsat Corp., February 10, 1964.

5. "Second Interim Report on Apollo Modulation Techniques Study," North American Aviation, Inc., September 3, 1964.

6. C. E. Clutts, "Reduction in Multi-Channel Peak Load Requirements by Speech Processing," internal BTL memorandum, January 30, 1963.

7. "A System of Multiple Access for Satellite Communications," Bell Telephone Laboratories, Inc., December 4, 1963.

8. L. H. Enloe, "The Synthesis of Frequency Feedback Demodulators," Proceedings of the National Electronics Conference, Chicago, 1962.

9. A. V. Balakrishnan, et al, Space Communications. New York: McGraw-Hill Book Company, Inc., 1963, Chapter 9.

10. D. C. Hogg, "Effective Antenna Temperatures Due to Oxygen and Water Vapor in the Atmosphere," Journal of Applied Physics, 1959, Vol. 30, p. 1417.

11. M. Uenohara, et al, "4-Gc Parametric Amplifier for Satellite Communication Ground Station Receiver," Bell System Technical Journal, July, 1963, Vol. XLII, No. 4, p. 1887.

12. "Communication Satellite Tests Pertaining to Multiple Access," Bell Telephone Laboratories, Inc., June 10, 1964.

13. D. J. Woodard and J. F. DeBold, "USNS Kingsport - Satellite Communications Ship," paper presented at 1st AIAA Annual Meeting, Washington, D. C., June 29-July 2, 1964.

14. N. I. Korman, "The 1970 Communication Satellite - A High-Power Satellite," paper presented at the XIIIth International Astronautical Congress, Varna, Bulgaria, September 23-29, 1962.

15. "Advanced Syncom," Space Aeronautics, September, 1963, p. 86.

16. L. Jaffe, "Present and Future Communication Satellite Programs of NASA," paper presented at 1st AIAA Annual Meeting, Washington, D. C., June 29-July 2, 1964.

17. J. D. Rinehart and M. F. Robbins, "Characteristics of the Service Provided by Communications Satellites in Uncontrolled Orbits, "Bell System Technical Journal, September 1962, Vol. XLI, No. 5, pp. 1621-1670.

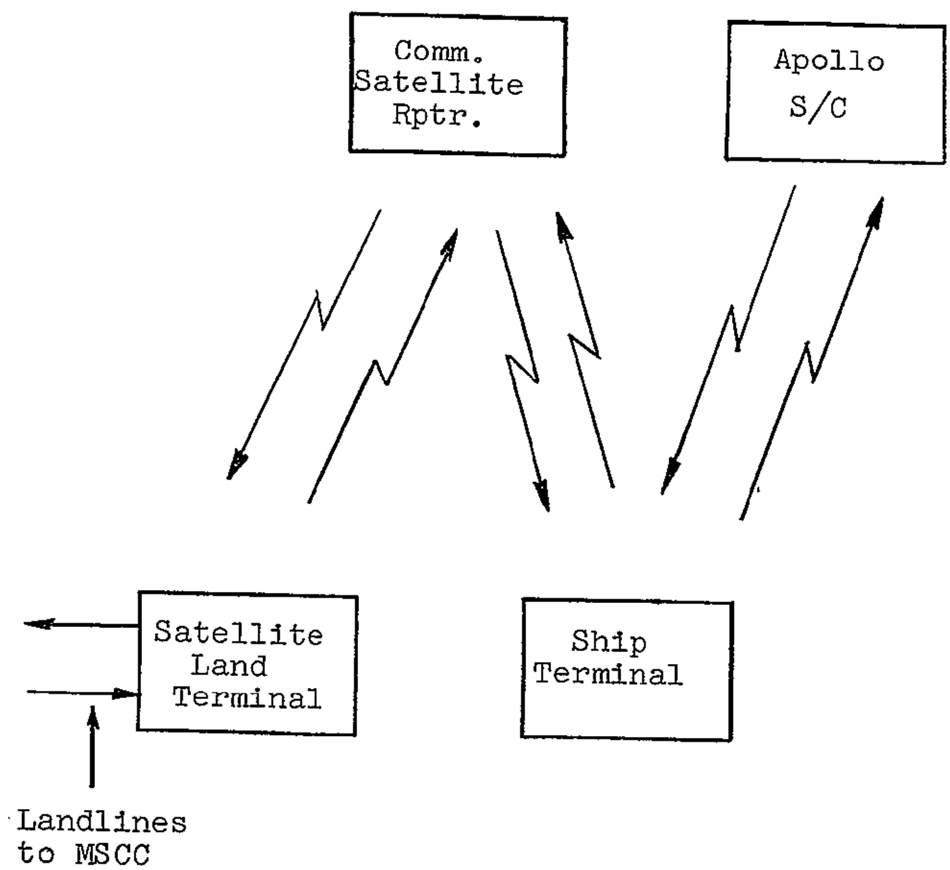
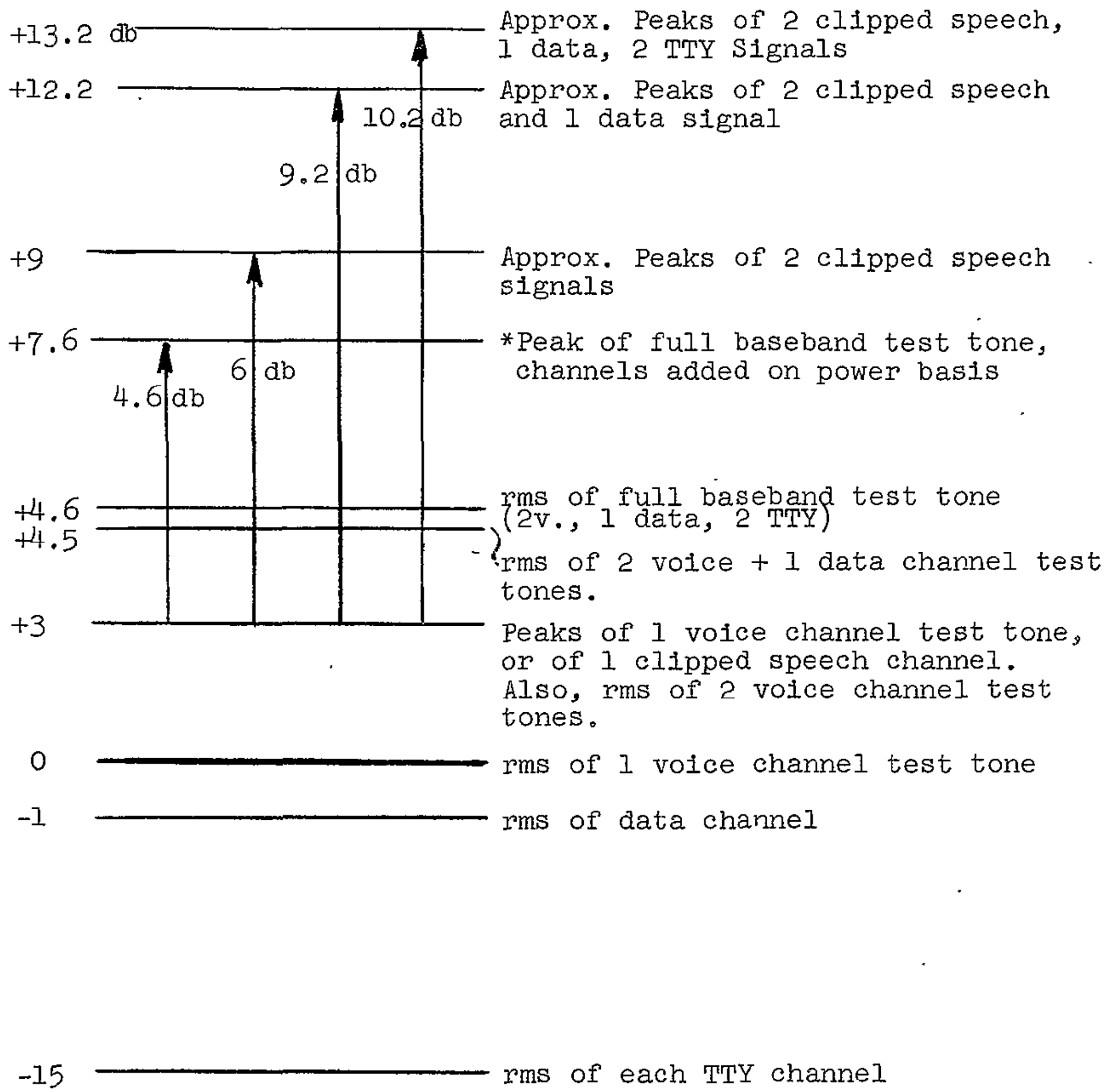


FIG. 1 - Major Links in Circuit From MSCC to Spacecraft



*Instantaneous combined voltages of 2 clipped speech channels alone would exceed this value (4.6 db above peaks of 1 channel) about 0.85% of the time.

FIG. 2 - Relative Levels of rms and Peak Values of Various Signals and Test Tone Combinations

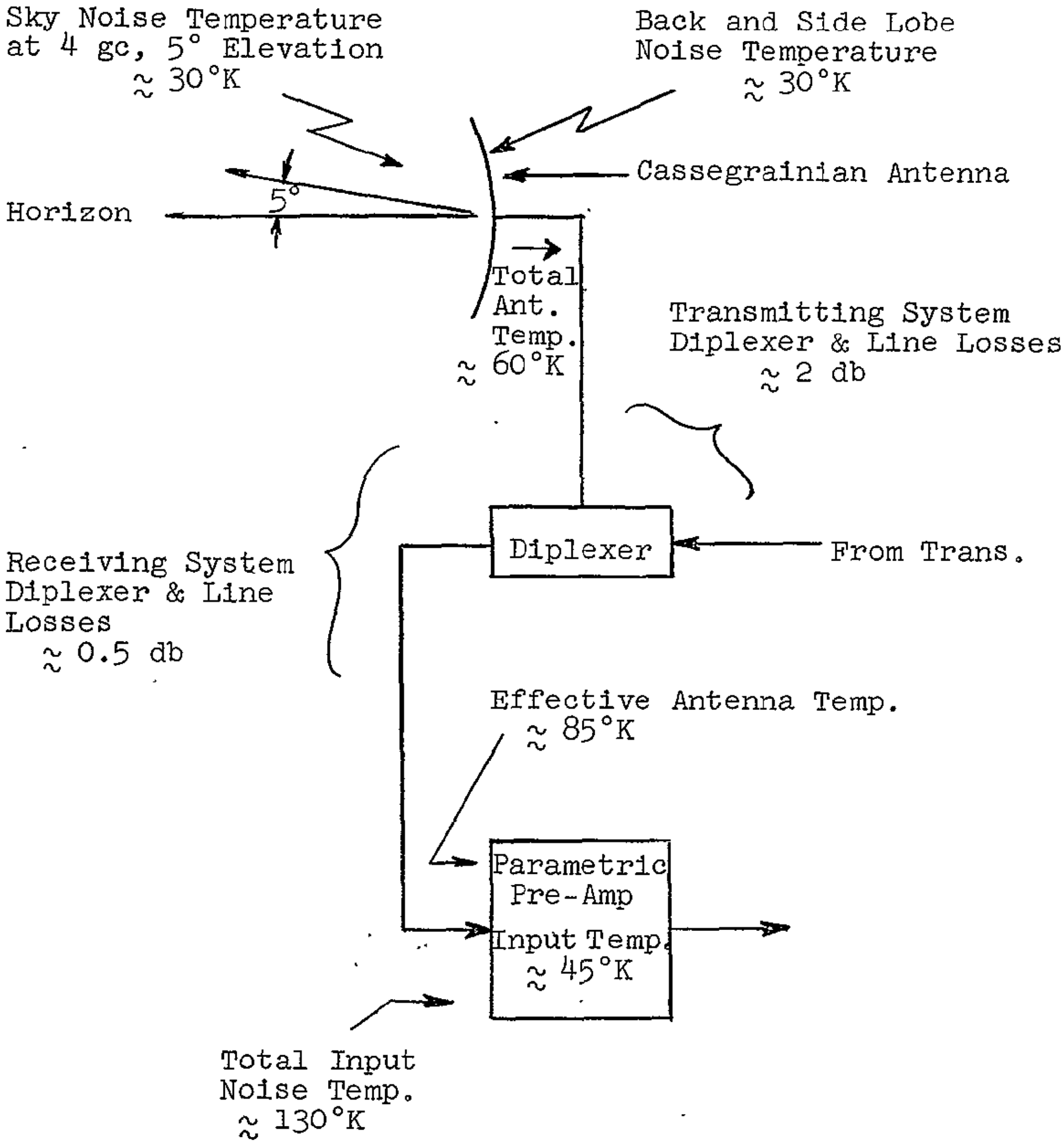


FIG. 3 - Ship or Land Station Receiving System Noise Sources

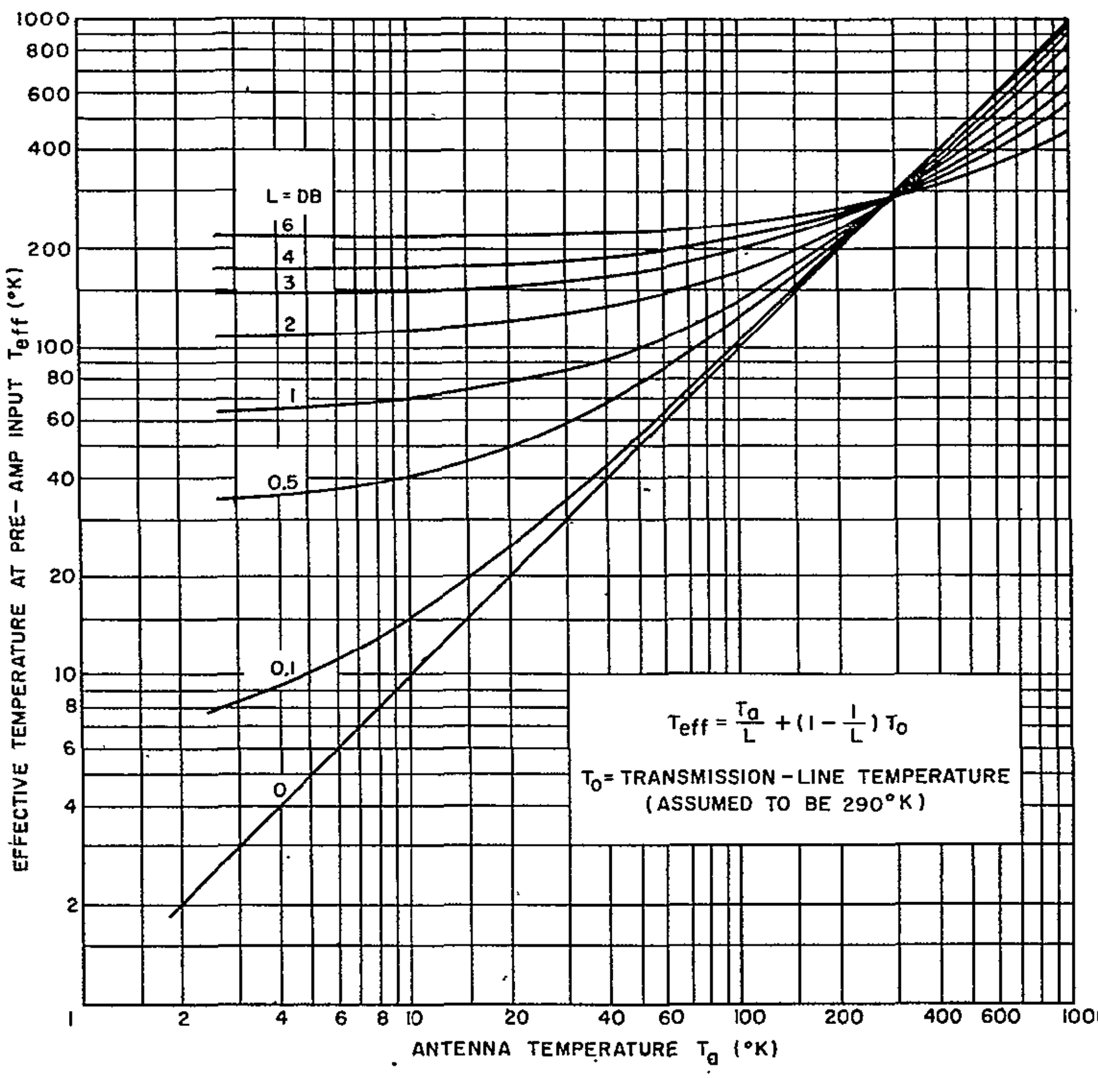
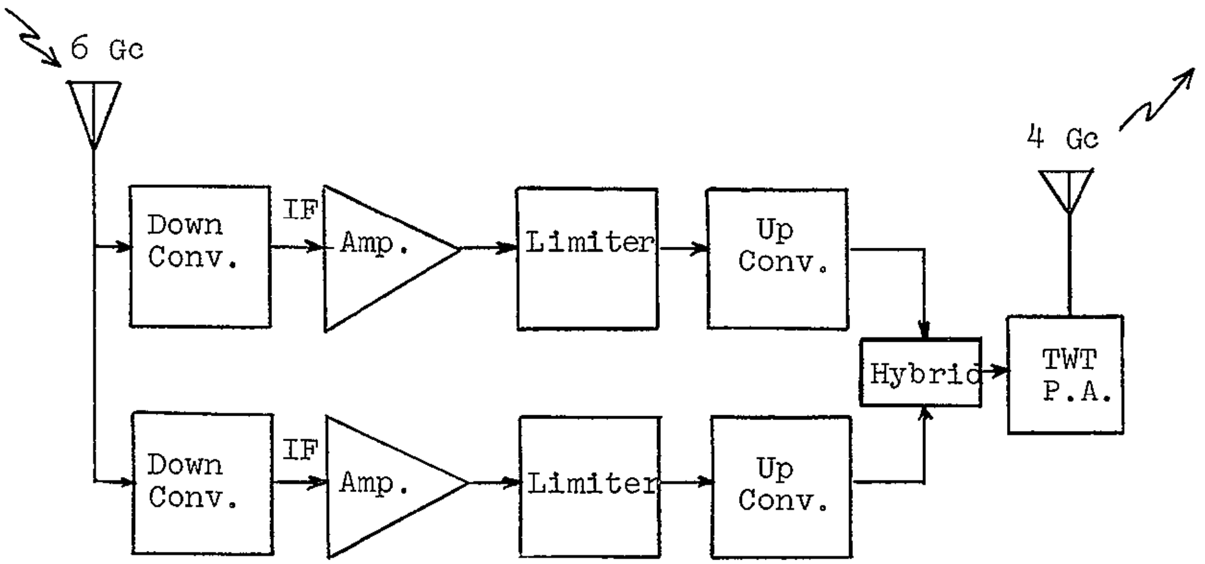


Figure 4. Effective Temperature of Pre-amplifier Input as a Function of Antenna Temperature and Transmission-Line Loss



Receiving Characteristics:

Antenna Gain	= 4 db
Line Losses	= 1.5 db
Rec. Noise Fig.	= 9.5 db
IF Bandwidth	= 25 Mc (each receiver) (31 Mc Noise Band)

Transmitting Characteristics:

Antenna Gain	= 9 db
Line Losses	= 2 db
TWT Power Output	= 3 watts single-carrier output when repeater is modified for optimum multiple-carrier transmission. See text, p. 38 .

FIG. 5 - Early-Bird Synchronous Satellite Functional Block Diagram

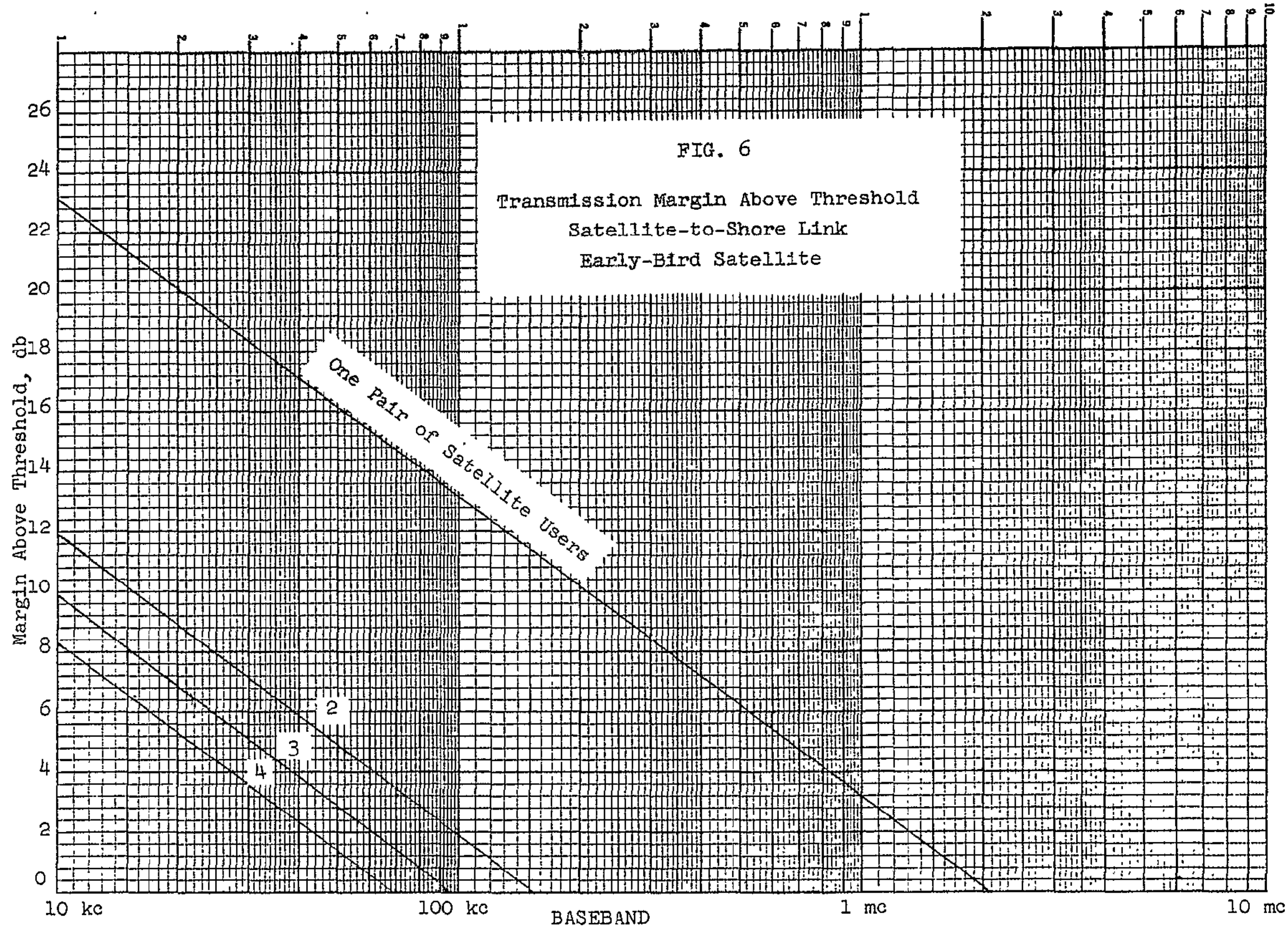
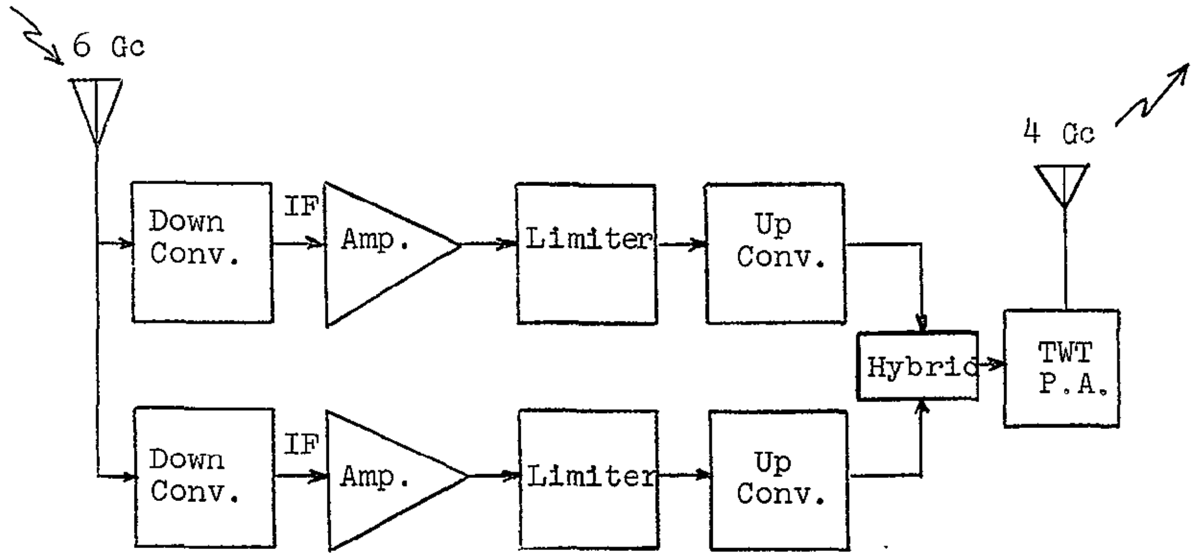


FIG. 6

Transmission Margin Above Threshold
Satellite-to-Shore Link
Early-Bird Satellite



Receiving Characteristics:

Antenna Gain	=	4 db
Line Losses	=	1.5 db
Rec. Noise Fig.	=	9.5 db
IF Bandwidth	=	25 Mc (each receiver) (31 Mc Noise Band)

Transmitting Characteristics:

Antenna Gain	=	9 db
Line Losses	=	2 db
TWT Power Output	=	3 watts single-carrier output when repeater is modified for optimum multiple-carrier transmission. See text, p. 33.

FIG. 5 - Early-Bird Synchronous Satellite Functional Block Diagram

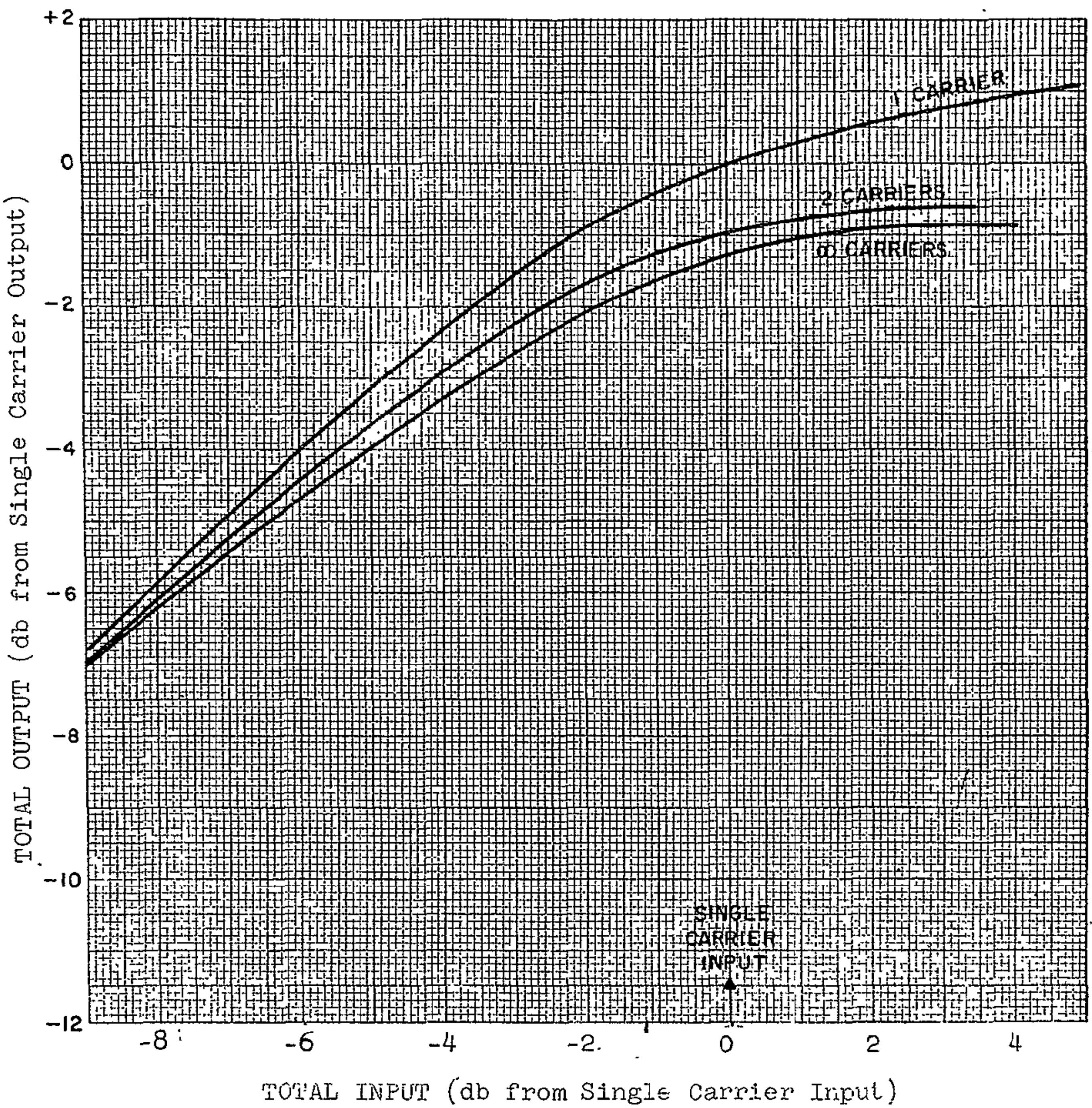


FIG. 8 - TWT Input-Output Characteristics (Taken from Reference 7)

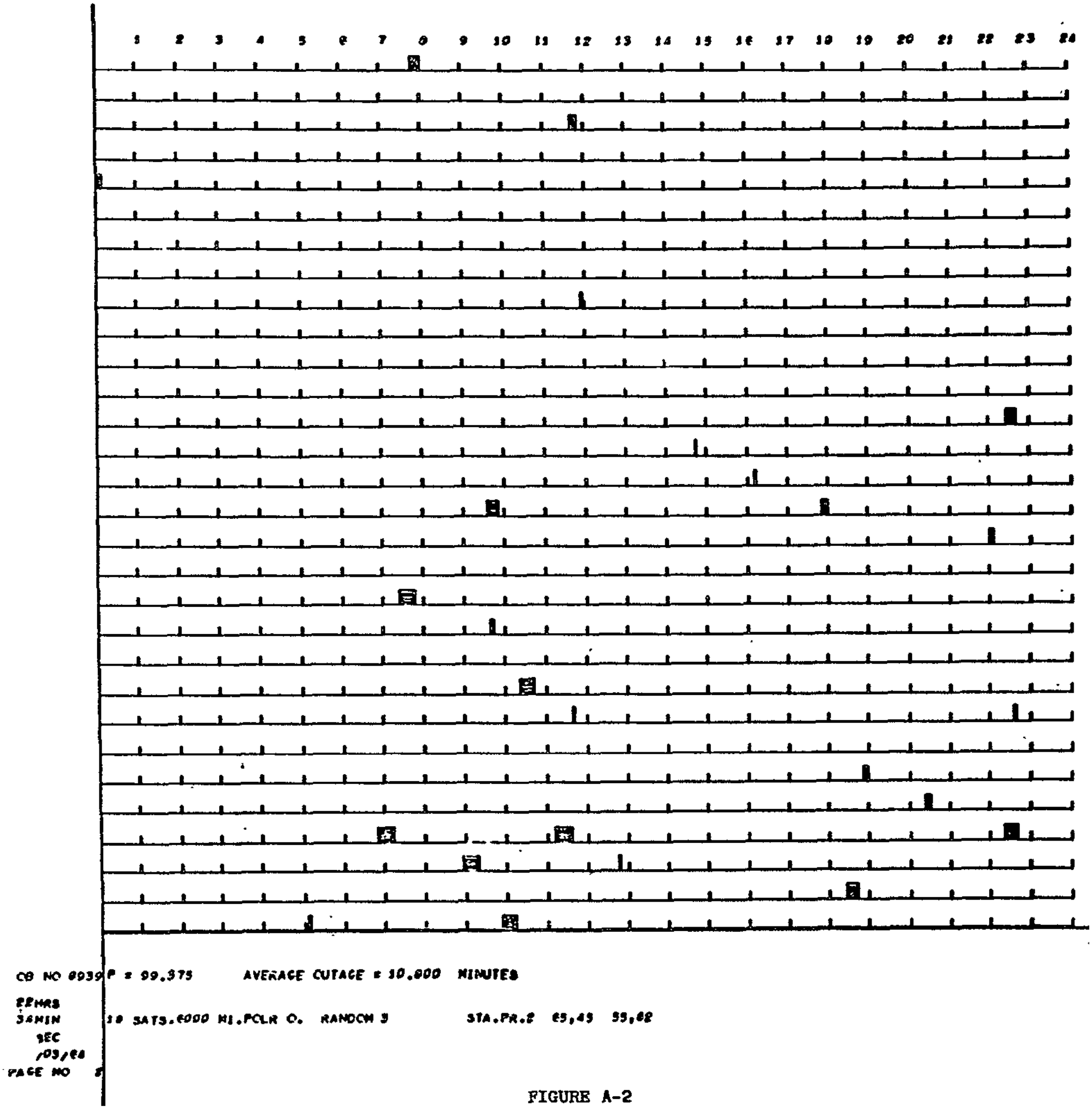
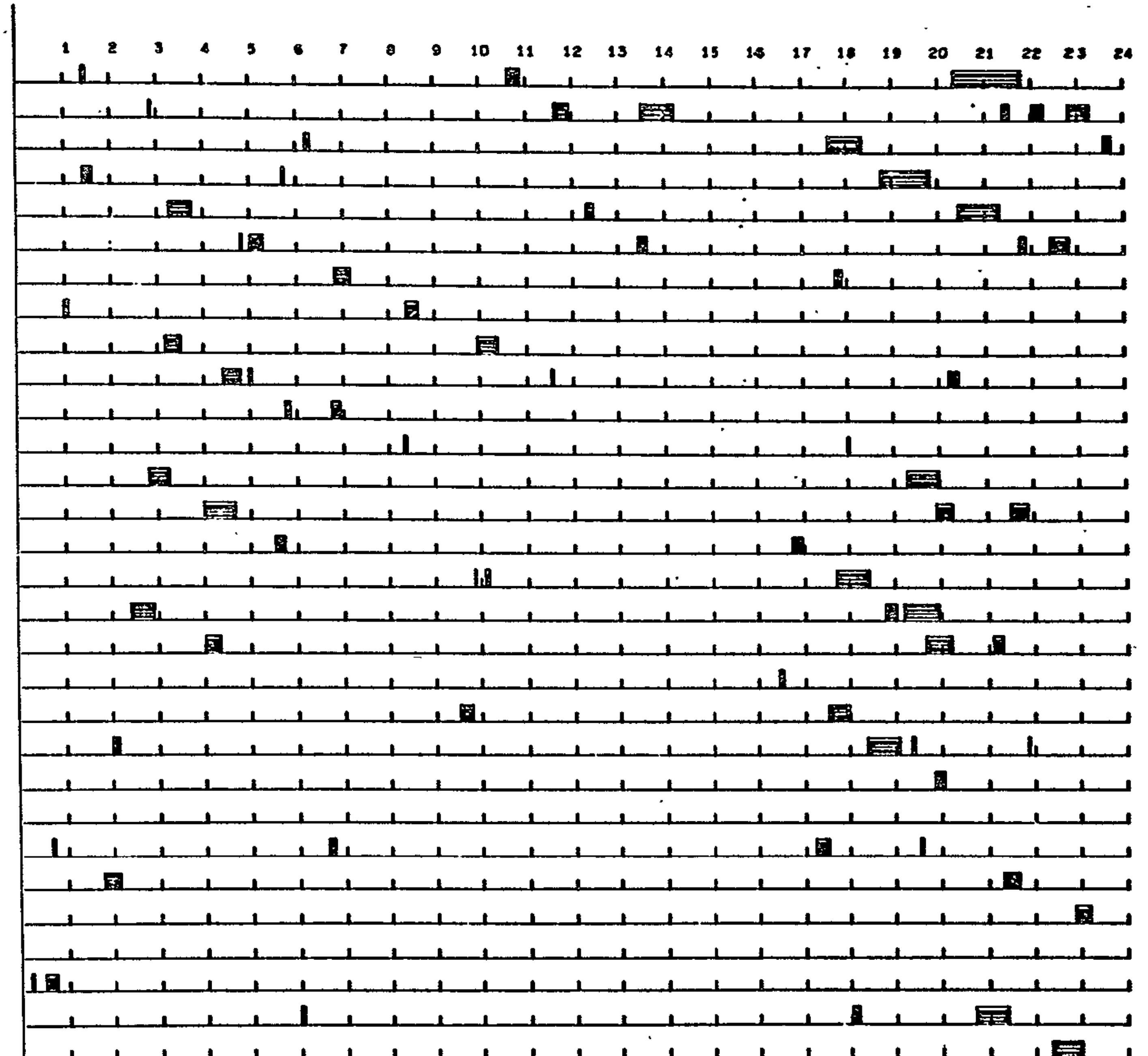


FIGURE A-2

Visibility Between Insertion Ship and Rosman, N. C.

18 Random-orbit Satellites in 3 Planes



JOB NO 8939 P = 96.833 AVERAGE OUTAGE = 18.486 MINUTES
HRS
MIN
C
06/08/64
PAGE NO 8
18 SATS.6000 MI.POLR O. RANDOM 5 STA.PR.2 65,45 55,82

FIGURE A-3

Visibility Between Insertion Ship and Rosman, N. C.

18 Satellites in Random Orbits

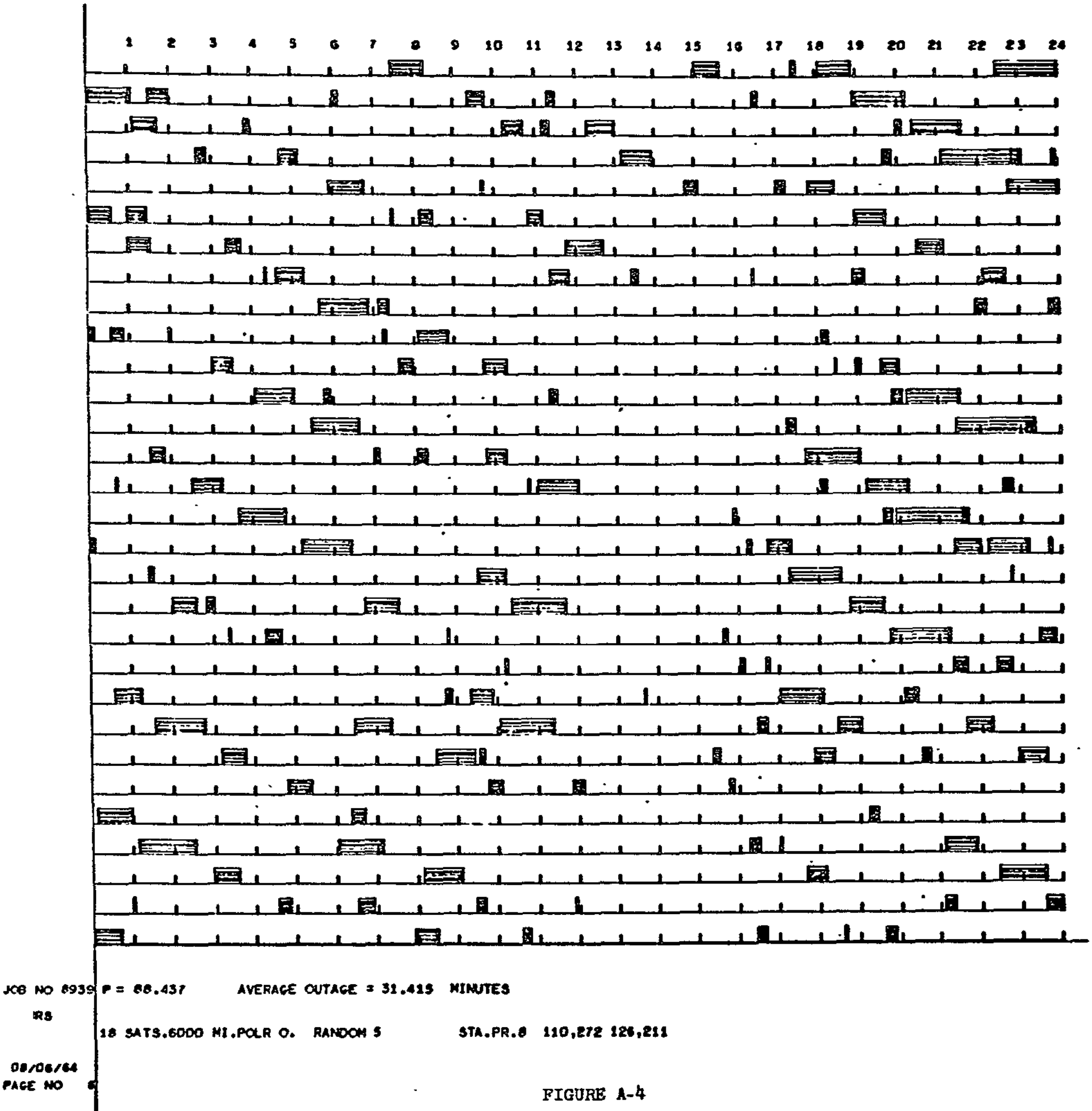


FIGURE A-4

Visibility Between Indian Ocean Injection Ship and Canberra

18 Random-orbit Satellites in 3 Planes

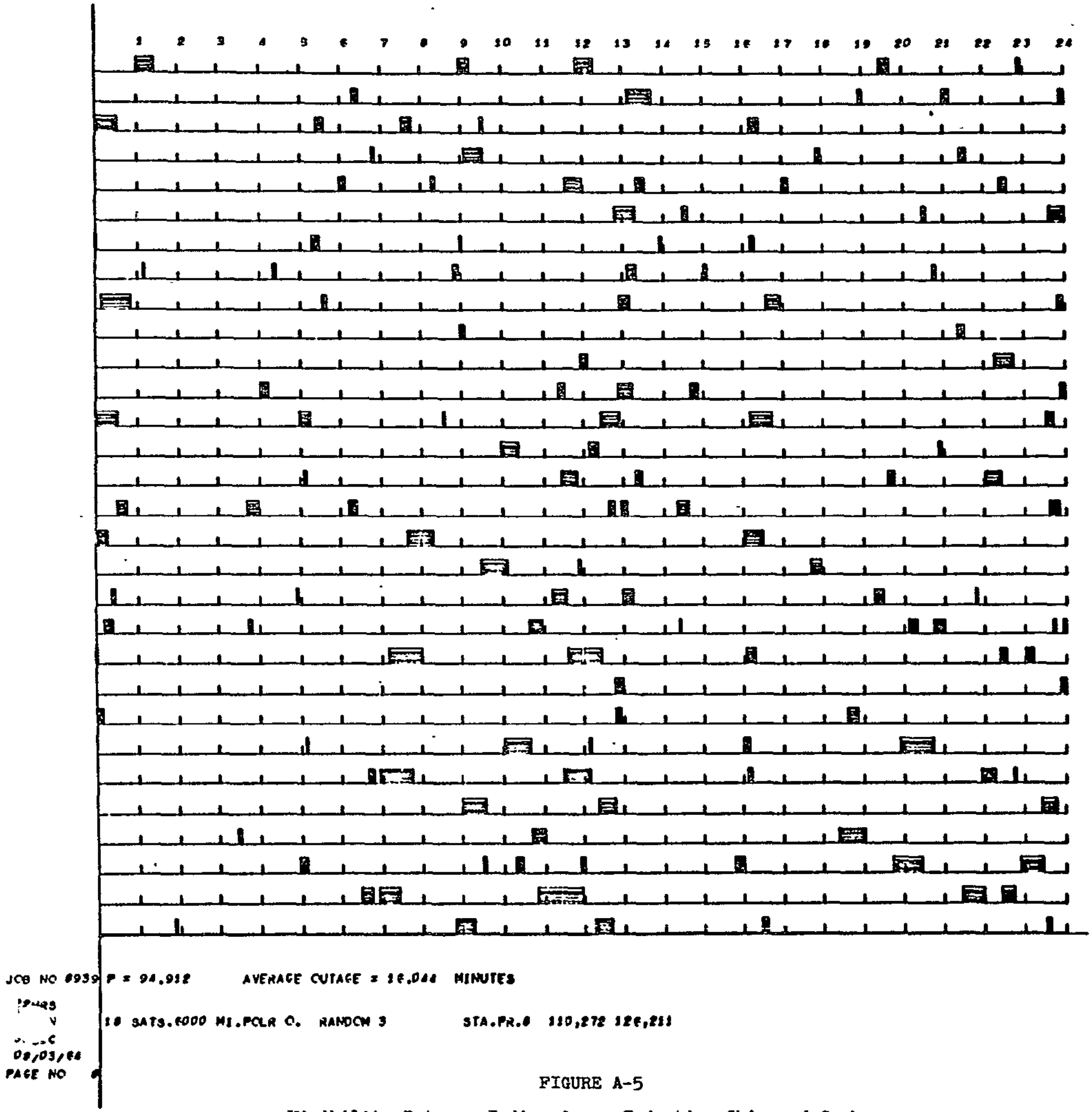
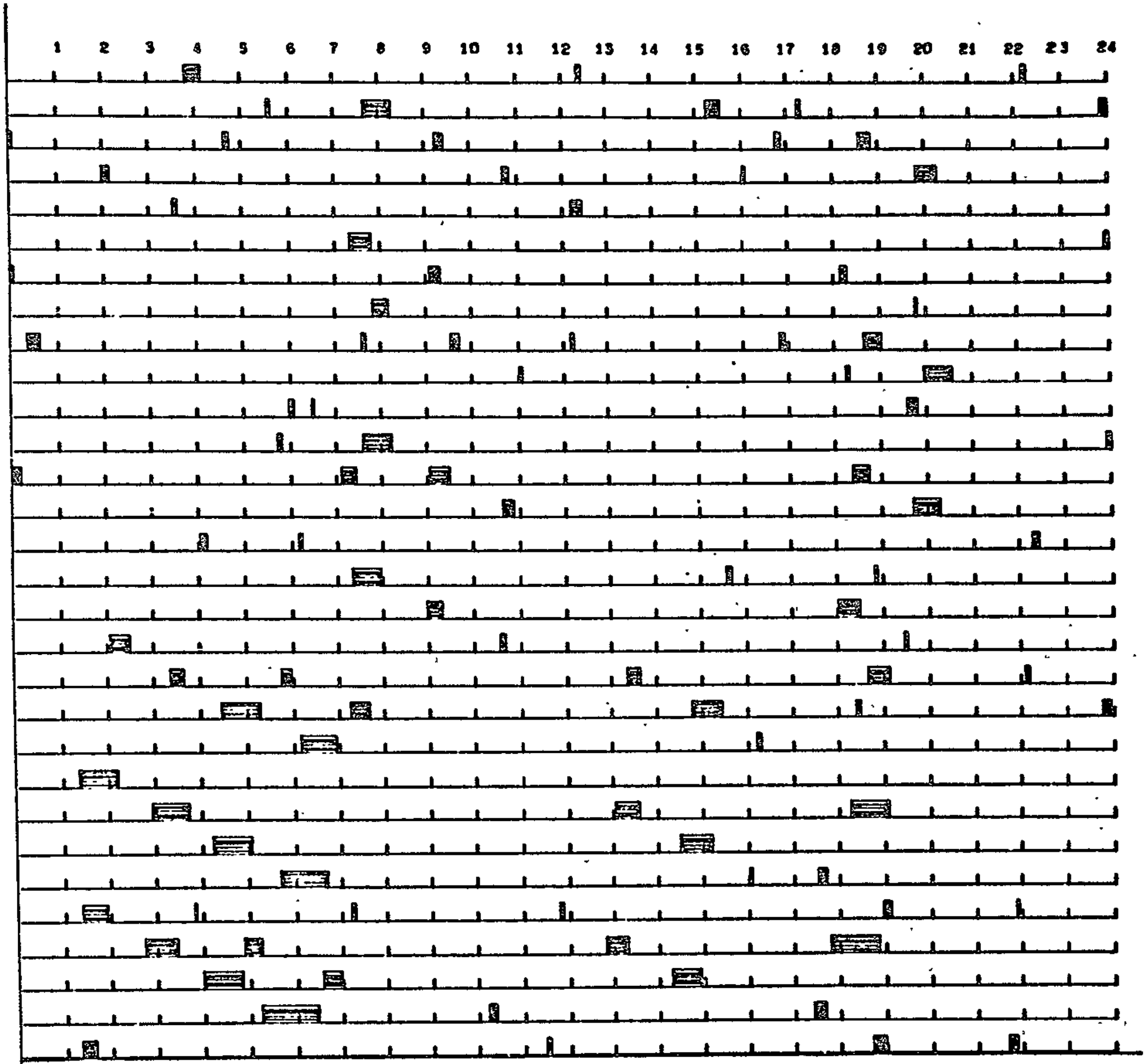


FIGURE A-5

Visibility Between Indian Ocean Injection Ship and Canberra

18 Satellites in Random Orbits



JOB NO 6939 P = 95.650 AVERAGE OUTAGE = 18.677 MINUTES

RS

IN 18 SATS.6000 MI.POLR O. RANDOM 3 STA.PR. 11 90,190 68,158

51SEC

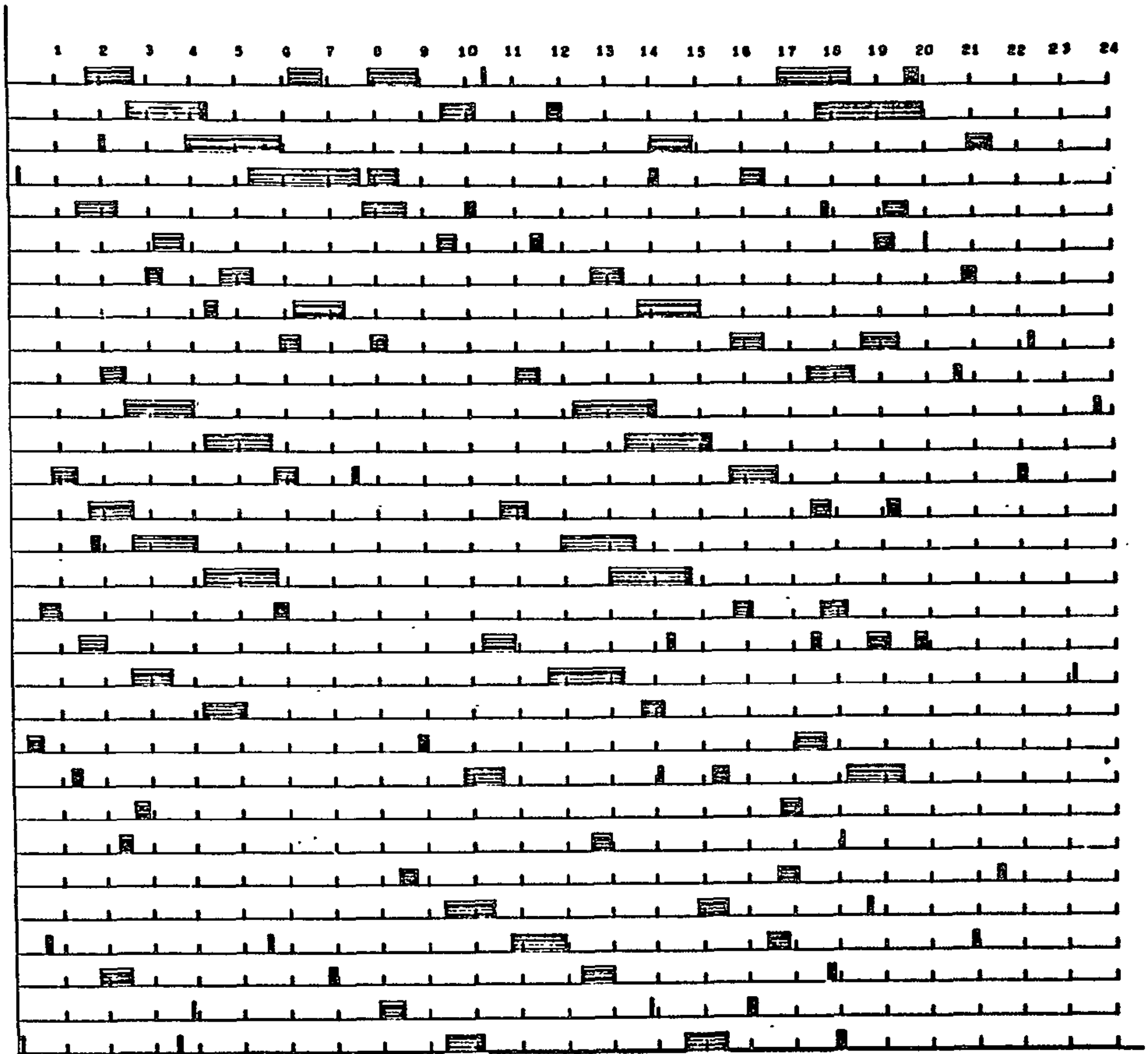
08/12/64

PAGE NO 3

FIGURE A-6

Visibility Between Hawaii Reentry Ship and Hawaii

18 Random-orbit Satellites in 3 Planes

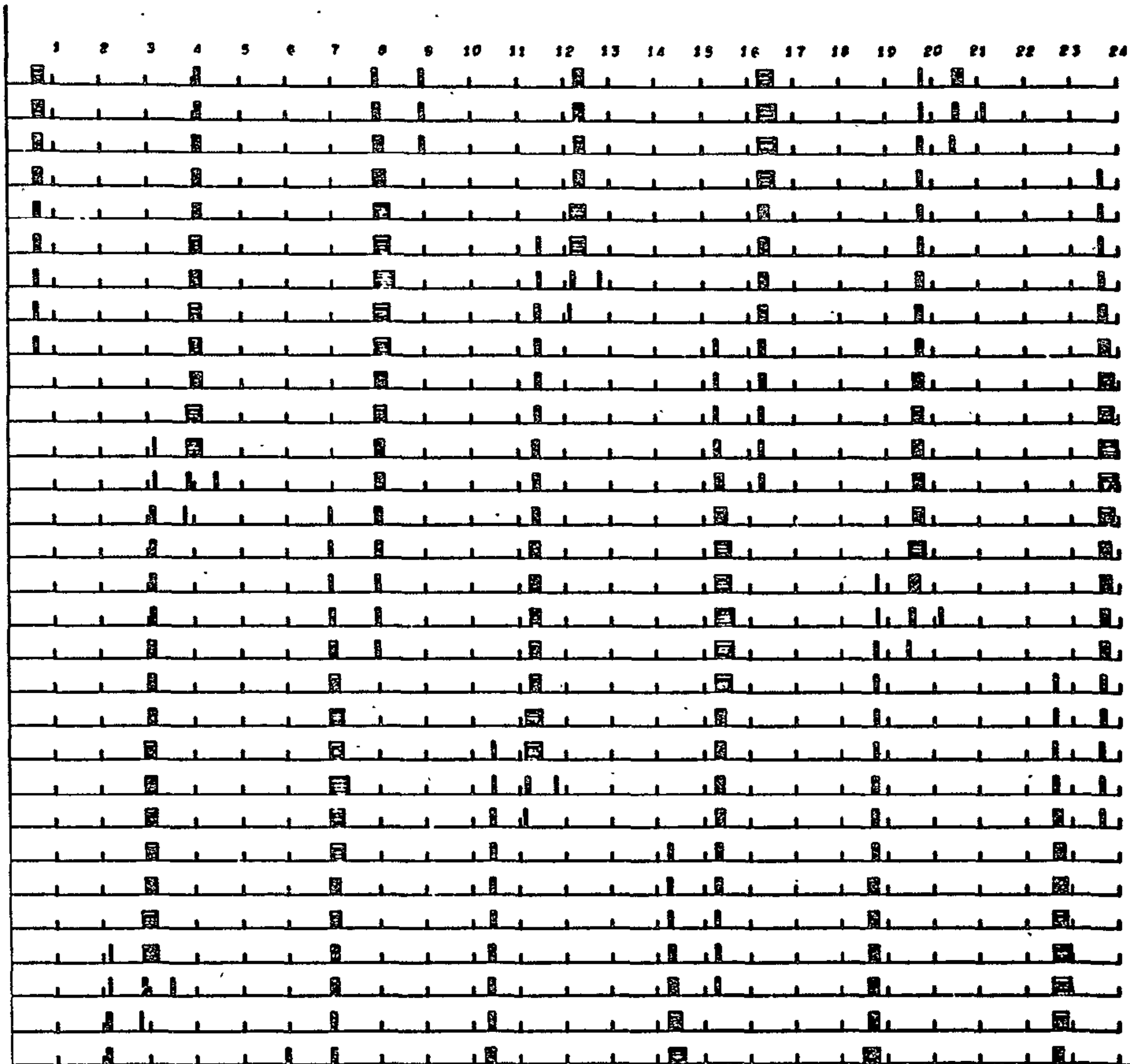


JOB NO 8939 P = 90.134 AVERAGE OUTAGE = 36.741 MINUTES
2HRS
48MIN 18 SATS.6000 MI.POLR O. RANDOM 5 STA.PR. 11 90,190 68,158
46SEC
08/10/64
PAGE NO 3

FIGURE A-7

Visibility Between Hawaii Reentry Ship and Hawaii

18 Satellites in Random Orbits



B NO 8939 P = 94.229 AVERAGE OUTAGE = 10.654 MINUTES

22HRS
40MIN
17SEC
08/03/64
PAGE NO 4

18 SATS.6000 MI.POLR O. PHASED STA.PR. 12 90,190 54,117

FIGURE A-8

Visibility Between Equatorial Site at 190° W. Long. and Goldstone

Phased-orbit System

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