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COVER SHEET FOR TECHNICAL MEMORANDUM

TITLE- The Use of Intelsat Satellites for Direct Voice Communications with Manned Space Vehicles

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DATE- September 30, 1968

FILING CASE NO(S)- 900

AUTHOR(S)- R. K. Chen

FILING SUBJECT(S)- Intelsat Satellites, Direct
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ABSTRACT

The practicability of using present and anticipated Intelsat satellites for direct voice communications relay between an orbiting manned spacecraft and a ground station for the post-Apollo period is examined. It is concluded that this could be done with reasonable modifications and additions to the manned spacecraft. A major consideration is the possible interference with terrestrial microwave relay systems; the analysis in this memorandum addresses this problem in some detail and the resulting system parameters are based on the interference limit established by CCIR. Although the principal emphasis of this memorandum is directed at the relay of voice, the analytical methods and tools provided are applicable to the direct two-way relay of any desired communications functions.

A typical system for a two-way voice link using Intelsat III satellites would require either an 11 ft. or 5.5 ft. diameter antenna on the manned spacecraft with corresponding transmitter power of 1.4 watts or 9.1 watts. The up-link (earth to manned spacecraft via Intelsat satellite) voice transmission would use frequency modulation with a frequency modulation with feedback receiver (FMFB) on the manned spacecraft; the down-link (manned spacecraft to earth via Intelsat satellite) would use a vocoder and digital transmission with a spread spectrum technique. The cost (in terms of equivalent voice channels that would need to be purchased) is primarily established by the up-link requirements. It is estimated that the cost for a manned spacecraft equipped with 11 ft. or 5.5 ft. antenna would be 156 or 588 equivalent voice channels, respectively. The same cost would be reduced to 24 or 60 equivalent voice channels if and when Intelsat IV satellites, which are still in the planning stage, are deployed.

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ABSTRACT (Cont'd)

The link capacity can be expanded with very little effort; for instance, the addition of 1.6 kbps telemetry to the down-link is free of additional channel cost and requires doubling the RF transmitter power on the manned spacecraft, which, in the worst case, is still less than 100 watts.

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FROM: R. K. Chen

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TECHNICAL MEMORANDUM

I. INTRODUCTION

Commercial communications satellites are being used for manned space flight operations. Intelsat II's, which were deployed by the Communications Satellite Corp. (Comsat), with NASA as a prime customer, are providing point-to-point voice and data circuits between the Mission Control Center (MCC) and several Manned Space Flight Network (MSFN) land stations and ships. In this memorandum, the results of a study are presented that indicate the practicability of using present and anticipated Intelsat satellites as a direct voice communications relay between an orbiting manned space vehicle and MCC during the post-Apollo period. The analysis is necessarily gross because it deals with anticipated future programs of both NASA and Comsat; it is also restricted to the technical aspects of a possible implementation on the manned space vehicle which would work with the Intelsat satellites as they are now, or will be.

The characteristics of the Intelsat satellites are described and summarized in Section II; the factors and ground rules assumed in the utilization of these satellites are given in Section III. Section IV provides the performance calculation and also discusses the criteria for the desired voice quality and suggests several modulation techniques. The detailed formulation of the equations for calculating RF performance of relay links is given in Appendix B. Section V establishes the communication system parameters in order to operate within the CCIR interference limit. The costs of utilizing the Intelsat satellites are reviewed in Section VI; these estimates are presented in terms of equivalent voice channels rather than dollars. The procedure and rationale used in making the cost estimates are outlined in Appendix D. The conclusions are given in Section VII.

One of the major concerns of satellite communications is the RF interference with existing terrestrial microwave radio-relay systems. The established CCIR interference limit and its impact on manned spaceflight applications is discussed in Appendix A. A short discussion of spread spectrum techniques that can be used to reduce radio interference of satellites to terrestrial systems is given in Appendix C.

II. INTELSAT SYSTEMS

Intelsat is an acronym for International Telecommunications Satellite Consortium for which the Comsat Corporation is the U.S. representative as well as the manager for the consortium. Five different Intelsat satellites are either in existence or being planned; these are known as Intelsat I, II, III, III 1/2, and IV. The first two are in service. Intelsat III, the first satellite to be used for worldwide communications service, is scheduled to be deployed during the second half of 1968. The Intelsat III 1/2 and IV satellites are in the planning stages. The requests for proposals for these spacecraft have been issued by Comsat.[1,2] The deployment of the Intelsat IV system is planned for 1971, and the Intelsat III 1/2 satellites may be deployed in the time period between the III and IV series to supplement, if required, the Intelsat III.

The characteristics of these satellites and their planned usage can be found in References 1, 2, 3, and 4. A summary of their characteristics are taken from these references and presented in Table I. It is noted that Intelsat III 1/2 and IV satellites are equipped with antennas for both earth-coverage and spot coverage. The two spot beams on each satellite are for transmitting only; they are not steerable but pointed permanently in the direction of North America and Europe.

The Intelsat I satellite, which is located over the Atlantic Ocean, will not be considered further in the analysis as its antenna does not provide full earth coverage and it is permanently offset to favor the northern hemisphere. The RF power sensitivities of the remaining satellites are given in Figure 1. Several assumptions should be considered in using the data in Figure 1, as follows:

1. The entire satellite is treated as a black box.

2. All satellites are equipped with quasi-linear repeaters; their effective isotopic radiated power (EIRP)* vs input power characteristics are approximated by two line segments. During normal

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*EIRP is the product of antenna gain, transmitter power and RF losses.

TABLE I - MAJOR PARAMETERS OF INTELSAT SATELLITES

ITEM	INTELSAT I	INTELSAT II	INTELSAT III	INTELSAT III½ [a]	INTELSAT IV [a]
REPEATERS	2	1	2	2	12
BANDWIDTH PER REPEATER, MHz	25	130	225	ONE EA. 200 ONE EA. 225	35-40
ANTENNA BEAM	11 x 360 DEG CENTERED AT + 7 DEG	12 x 360 DEG CENTERED AT EQUATOR	20 x 20 DEG	ONE EA. 20 x 20 DEG. TWO EA. 6 x 6 DEG	ONE EA. 20 x 20 DEG [b] TWO EA. 4.5 x 4.5 DEG
EFFECTIVE RADIATED POWER PER REPEATER, WATTS	10	35	150	200 WITH 20-DEG BEAM; 1600 WITH 6-DEG BEAM	200 WITH 20-DEG BEAM; 4000 WITH 4.5-DEG BEAM
TOTAL EFFECTIVE RADIATED POWER (ALL REPEATERS), w	20	35	300	1800	2400 (ALL 20-DEG BEAM); 25,200 (6 EA. 20-DEG BEAM + 6 EA. 4.5-DEG BEAM)
TOTAL TWO-WAY TELEPHONE CIRCUITS [c]	240	240	1200	1900	3600 TO 8000, DEPENDING ON TYPE OF MODULATION, NUMBER OF CARRIERS PER REPEATER, AND ANTENNA BEAMWIDTHS USED

a - PARAMETERS ESTIMATED.

b - SIX REPEATERS ARE PERMANENTLY CONNECTED TO THE 20-DEG BEAM ANTENNA, WHILE THE OTHER SIX MAY BE SWITCHED BETWEEN THE 20- AND 4.5-DEG BEAM ANTENNAS.

c - WHEN USED WITH STANDARD EARTH STATIONS HAVING 85- TO 97-FT-DIAM ANTENNAS.

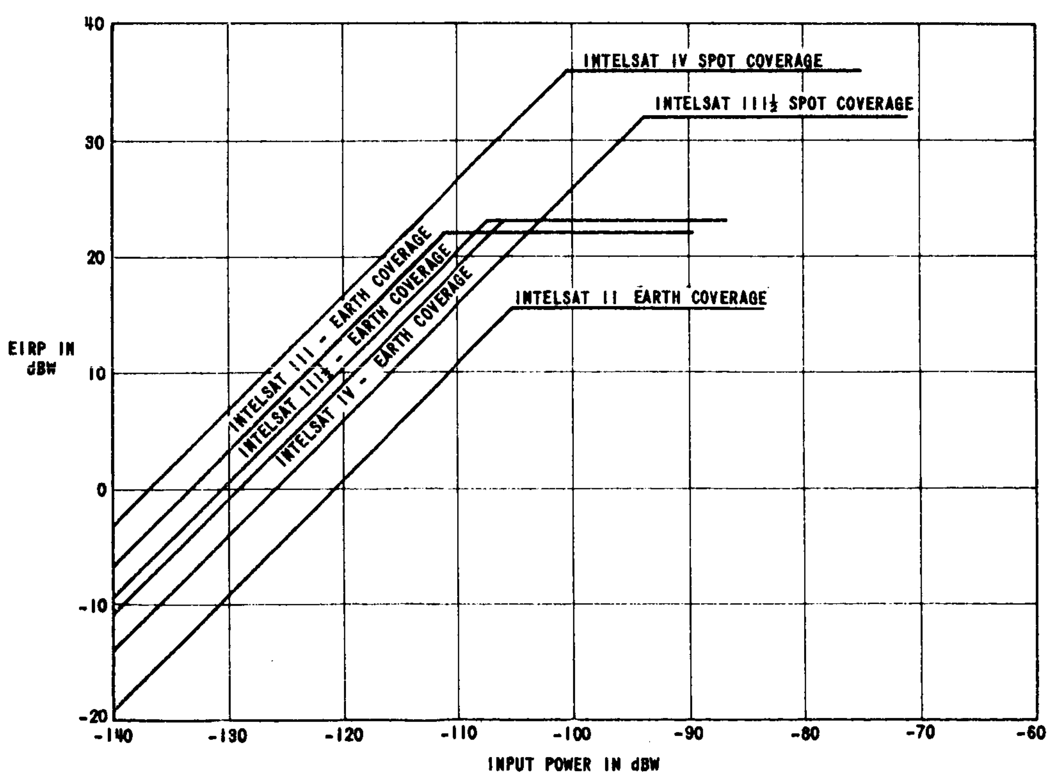

FIGURE I - ASSUMED INTELSAT CHARACTERISTICS RF POWER OUTPUT VS. RF POWER INPUT PER TRANSPONDER SINGLE CARRIER OR TWO CARRIER OPERATION commercial operations, the repeaters are operated below the knee of the curves so that their traveling wave tube power amplifiers are not operated in the saturated region. In reality the knees, or the transition region between the two line segments, of these curves do not occur abruptly as indicated in Figure 1.

3. Two sets of curves are given for Intelsat III 1/2 and IV satellites; one for earth coverage and the other for spot coverage antennas. The operational aspects of using these antennas will be discussed further.

4. The characteristics for the Intelsat III 1/2 and IV satellites are estimates at present, however, the gross capabilities of these satellites should be realizable.

The highest capacity ground station being planned by Intelsat will have an antenna gain to system noise temperature ratio (G/T) of 40.7 dB(5); in terms of physical parameters, this represents an 85 ft. antenna system with a receiving system noise temperature of 50°K at 4 GHz.

III. UTILIZATION OF INTELSAT SYSTEMS

For the purpose of this analysis, the utilization of the present Intelsat satellites for manned space flight operations will adhere to the present Intelsat practices as much as possible. Some of the major practices are:

1. The use of frequency division multiplex technique for multiple access operation of the satellites.

2. The use of common carrier frequencies, 6 GHz to the satellite and 4 GHz from the satellite.

3. Conformity with the maximum satellite radiated power bounded by the CCIR Recommendation 358-1 (Oslo, 1966).(6) This subject is discussed in more detail in Appendix A.

4. Conformity with the carrier group assignments planned by Comsat as follows:(5)

Bandwidth Units	Equivalent Voice Channels
5 MHz	24
10 MHz	60
20 MHz	132

The implication of the carrier group assignment is that the manned spacecraft will be treated as a terminal with a minimum assignment of 24 equivalent voice channels for its transmitting link; therefore, it could establish the minimum cost criterion for the link as well.

5. To avoid confusion, the following definitions will be used for the various RF links involved in a two-way relay communications link:

   a. To be consistent with the functional concept used in manned space flight operations, the "up-link" is defined as the MCC to manned spacecraft link (via Intelsat satellite), and the "down-link" is defined as the manned spacecraft to MCC link (via Intelsat satellite).

   b. Four sub-sets of the RF links which describe the physical concept are: "up-up-link" is defined as the ground station to Intelsat satellite link, "up-down-link" is defined as the Intelsat satellite to manned spacecraft link, "down-up-link" is defined as the manned spacecraft to Intelsat satellite link, and "down-down-link" is defined as the Intelsat satellite to ground station link.

For the cases of the Intelsat III 1/2 and IV satellites, there are two alternatives for operating the satellite on the down-down-link. This comes about because these satellites are equipped with two types of transmitting antennas; an earth coverage antenna with an on-axis gain of 19 dB and spot beam antennas with gain values of 28.5 dB (6° beamwidth) for Intelsat III 1/2 and 31 dB (4.5° beamwidth) for Intelsat IV. These spot beam antennas are to be directed continuously in the direction of the North American and European continents in anticipation that traffic demands for commercial communications will be the greatest between these areas. From Figure 1, it is seen that the use of the spot beam antenna on the Intelsat III 1/2 would provide higher transmitted RF power than the use of the earth coverage antenna, as expected, but the overall gain of the satellite is lower. Therefore, the use of the spot beam antenna on Intelsat III 1/2 will not be pursued further as subsequent analysis will show that the RF power availability from the satellites is not the limiting factor for the down-down-link. On the other hand, the use of the spot beam antenna on Intelsat IV does result in a higher overall gain repeater link which is advantageous. The spot beam antennas are not considered for the up-down-link application because of their lack of coverage. Therefore, the up-down-link transmission to the manned spacecraft will utilize the earth coverage antenna of the Intelsat satellites.

IV. PERFORMANCE CALCULATIONS

The criterion used for the minimum acceptable voice quality is 90% word intelligibility. Three voice transmission methods were investigated:

1. analog voice, 300-3,000 Hz, using frequency modulation with threshold extension receivers,

2. digital voice, 30 kbps, using a PCM/PM technique, and

3. digital voice with vocoder, 2.4 kbps, using a PCM/PM technique.

The RF performance requirements for these transmission methods are given in Table II.

Table II - Performance Criteria for Various Voice Modulation Method

Voice Modulation Method	S/N_{req}	Bandwidth	$C/N_{0_{req}}$	Reference
Vocoder, 2.4 kbps, PCM/PM	7 dB	3200 Hz	42 dB-Hz	7
Digital voice, 30 kbps, PCM/PM	8 dB	36 kHz	53.6 dB-Hz	7
FM with threshold extension receiver, m = 2	5.2 dB	18 kHz	47.8 dB-Hz	8

S/N_{req} = Signal-to-noise power ratio required in corresponding noise bandwidth.

BW = RF noise bandwidth.

$C/N_{0_{req}}$ = RF power-to-noise power spectral density ratio required = S/N_{req} x BW.

m = FM modulation index.

To make performance calculations, the communications parameters given in Table III are used. It should be noted that a figure of merit, G/T, is used for receiving systems and EIRP is used for transmitting systems. These parameters are used as the communication systems (Earth, Intelsat satellites, and manned spacecraft) are treated as black boxes with the interfaces at the antenna aperture.

Table III - Assumed Communications Parameters

Ground Terminal (GND)

G/T = 40.7 dB/°K

The ground system temperature, T, includes noise temperature of the receiver, RF losses, and antenna temperature.

Intelsat Satellite (IS)

Receiving System	G/T
Intelsat II	-32 dB/°K
Intelsat III	-20 dB/°K
Intelsat III 1/2	-20 dB/°K
Intelsat IV	-17.1 dB/°K

Transmitting System	k
Intelsat II	-120.8 dB
Intelsat III	-133.3 dB
Intelsat III 1/2	-130.5 dB
Intelsat IV	-129 dB Using earth coverage antenna -136.7 dB Using spot coverage antenna

k is the reciprocal of the gain of satellite repeaters (see Figure 1).

Manned Spacecraft (SC)

Receiving system noise temperature	1800°K
Receiver noise figure	5.5 dB
RF losses	3 dB
Antenna temperature	30°K

RF Frequencies

To Intelsat satellites	6 GHz
From Intelsat satellites	4 GHz

Free Space Losses (L_{fs})

To Intelsat satellites $(L_{fs})_6$	200.1 dB
From Intelsat satellites $(L_{fs})_4$	196.6 dB

The detailed formulation of the expressions needed for determining the RF performance of relayed links is provided in Appendix B. The numerical equations for each specific relay link involving different Intelsat satellites are obtained by using the estimated communication parameters of Intelsat satellites, ground terminal, and manned spacecraft given in Figure 1 and Table III. These are given as equations B-13 to B-22, and B-31; they are also plotted in parametric form in Appendix B as Figures (B-1) to (B-6). From these figures, the communications system requirements for various voice transmission modes as well as other desired communications functions can be determined when the performance criteria, in terms of $C/N_{0_{req}}$, of these communications functions are established. For the time being, we are assuming that the manned spacecraft carries a one degree beamwidth antenna, which corresponds to approximately an 11 ft. diameter parabolic antenna with 44 dB gain at the RF frequency of 6 GHz. It is also assumed that the RF loss of its transmitting system is 3 dB. The RF transmitter power required from the manned spacecraft for the down-up-link using various Intelsat satellites are shown in Table IV:

Intelsat Satellite	Vocoder	FMFB	Digital
II	9 watt	35 watt	150 watt
III	0.5	2.1	7.5
III 1/2	0.8	3.4	11.5
IV (earth coverage)	1	4	14.5
IV (earth coverage)	0.25	1	3.4

Table IV - RF Transmitter Power Required in Manned Spacecraft for the Down-up-Link

The EIRP required from the Intelsat satellites for various voice transmission modes for the up-down-link are:

Vocoder	1.6 watt
FMFB	6 watt
Digital	22 watt

It should be noted that when one applies the CCIR interference limits to these links, it becomes apparent that the limit of -13dBW/4kHz is exceeded by the emission from the manned spacecraft.* A suggested solution to this problem is discussed in the next section.

V. EFFECTS OF CCIR INTERFERENCE LIMIT

The RF frequency bands presently used by the commercial communications satellites are the same as those used by the common carriers for microwave radio-relay systems on earth. In order to allow frequency sharing of these systems, various criteria are established by the International Radio Consultative Committee (CCIR) of the International Telecommunication Union to prevent mutual interference. A more detailed discussion of this topic is given in Appendix A. In Appendix A, the CCIR interference limit is translated into the system parameter of maximum allowable EIRP/Hz from the Intelsat satellite and the manned spacecraft as follows:

from Intelsat satellite	-24.6 dBW/Hz
from manned spacecraft	-49 dBW/Hz .

The maximum EIRP allowed from the manned spacecraft is sensitive to its orbit; the number provided is based on a 260n.m. circular orbit.

A quick look at the results of Section IV shows that the EIRP required for voice transmission from the Intelsat satellites can be made to stay below the CCIR interference criterion; this is not the case for voice transmission from the manned spacecraft. In order to operate the manned spacecraft within the CCIR interference limit, a combination of two techniques is proposed:

1. Apply operational constraints so that only the low level side-lobe of the RF emission from the manned spacecraft illuminates the earth at any time.

2. Spreading the RF spectrum intentionally for the down-up-link by some modulation or coding technique.

*See Appendix A.

A. Side-Lobe Level of Manned Spacecraft Antenna

This item has been briefly discussed in Appendix A. From Figure A-3, it is seen that, in order to assure continuous global coverage of the voice links with an equally spaced three satellite system, the antenna side-lobe of the manned spacecraft should be sufficiently low at 43° off its boresight axis. However, it is doubtful whether any Intelsat system would be equally spaced over the equator; therefore further allowance should be made in the practical case. One obvious conclusion is to use an antenna with very low side-lobe level at a given angle off the boresight axis on the manned spacecraft. This could be accomplished in two ways, one is to use an antenna with very narrow beamwidth, the other is to have an antenna design with inherently low side-lobe level.

There is a practical limit to using very narrow beamwidth antennas on a spacecraft because of the size of the antenna and the increasingly difficult pointing problem associated with a large antenna. To obtain an antenna with low side-lobe level is a difficult problem especially for a spaceborne antenna system. It would require either a horn type antenna or a dish antenna with a carefully controlled illumination function. In addition, Hogg[9] has pointed out that the side-lobe level of a dish antenna is highly influenced by the surface accuracy of the reflector. He has determined both theoretically and experimentally that if a reflector has a surface accuracy of ($\lambda/25$),* the envelope of the side-lobe maxima reaches and maintains essentially an isotropic level at about eight beamwidths** beyond the antenna boresight axis.

Both factors suggest that it is desirable to use an antenna on the manned spacecraft with as high a gain as practicable. For the purpose of this analysis, an arbitrary but practical limit of one degree maximum antenna beamwidth is applied. In particular, simple parabolic dish antennas of 1° and 2° beamwidths are used to size other system parameters. These antennas would be about 11 ft. and 5.5 ft. in diameter and their assumed maximum side-lobe envelope patterns are shown in Figures 2 and 3.

B. Spread Spectrum Techniques

A brief discussion of spread spectrum techniques is presented in Appendix C. The term, spread spectrum, is used in various well known applications such as anti-jam or multipath situations. Under such circumstances, the spread spectrum

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*λ is the wavelength of the RF frequency used.

**Approximately true for the antenna sizes considered here.

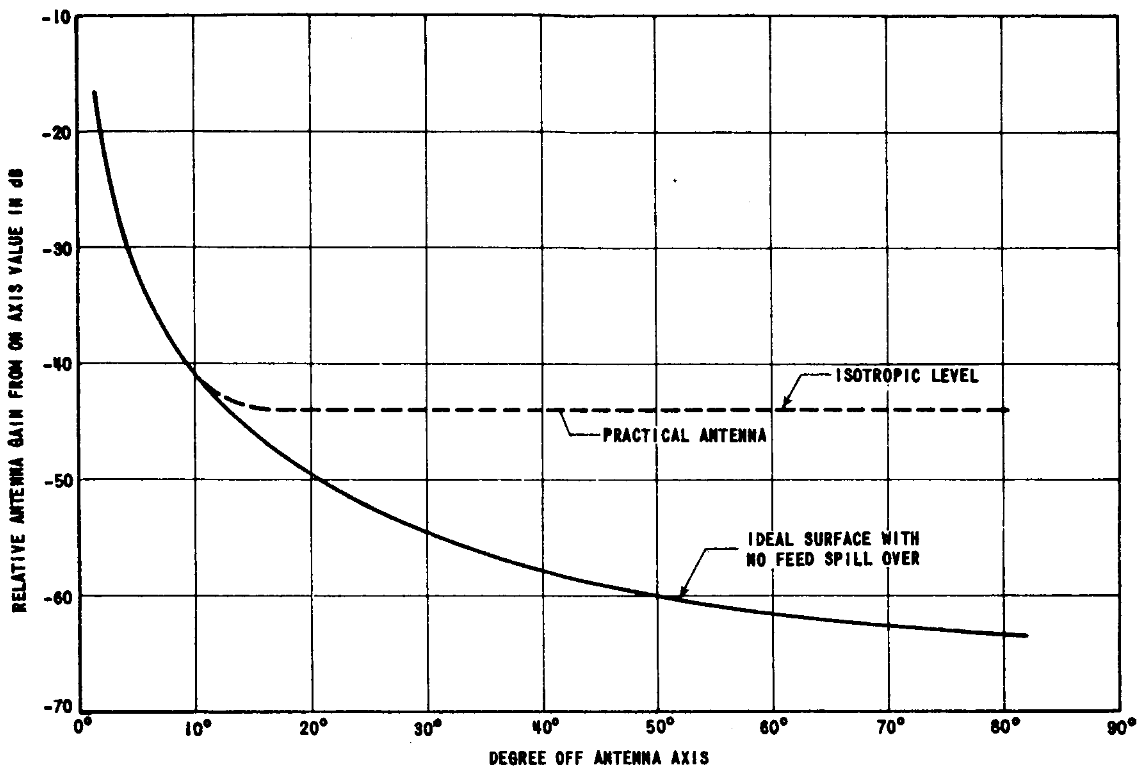


FIGURE 2 - ENVELOPE OF SIDELOBE MAXIMA FOR PARABOLIC ANTENNA WITH 1° BEAMWIDTH

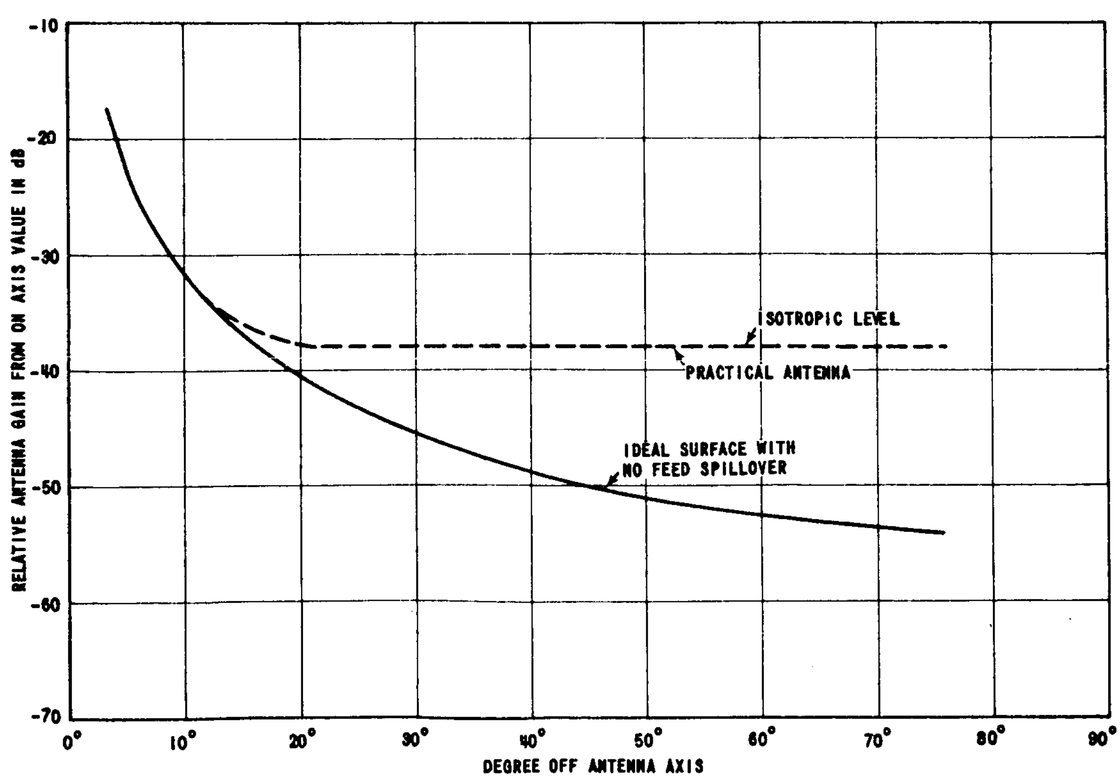


FIGURE 3 - ENVELOPE OF SIDELOBE MAXIMA FOR PARABOLIC ANTENNA WITH 2° BEAMWIDTH

techniques are used to overcome the adverse RF noise or fading environments; these are not the reasons for our application. Contrary to the more familiar design problem encountered with communication systems which are RF power and/or bandwidth limited, the problem here is that we are limited by the RF power spectrum density. Therefore, the purpose of using a spread spectrum technique here is to maintain a constant RF power spectrum density level and to permit increasing the total RF power, by increasing the RF bandwidth occupancy, until a minimum performance requirement of the needed communication function is satisfied. Technically, most of the spread spectrum techniques developed can be used for this application; but, for the sake of simple implementation, only two methods are considered: (a) wide deviation FM with a feedback receiver (FMFB) for analog voice transmission and (b) pseudo-noise (PN) code modulation for digital voice and vocoder voice transmissions. It is interesting to note that the use of a PN code for RF spectrum spreading also inherently fulfills the need of carrier energy dispersal under conditions of light loading from multichannel telephony discussed by CCIR.

The effects of the CCIR interference limit are shown in Figures 4 - 9. These figures are basically Figures B-1 to B-6 taken from Appendix B with the additions of:

1. Permissible operating regions based on the CCIR interference limit calculated for maximum side-lobe EIRP's when the manned spacecraft is using either a 1° beamwidth or 2° beamwidth parabolic dish antenna.

2. Performance requirements of various voice transmission modes using wideband FMFB or PN code spread spectrum techniques.

Several conclusions for the down-link can be drawn from Figures 4 - 8, namely:

1. Spread spectrum or RF bandwidth expansion techniques must be used for voice transmission in order to operate within the CCIR interference limit.

2. FMFB is the least efficient method when considering manned spacecraft transmitter power requirements.

3. The use of vocoders in conjunction with digital transmission is the most efficient method, from the standpoint of required manned spacecraft transmitter power.

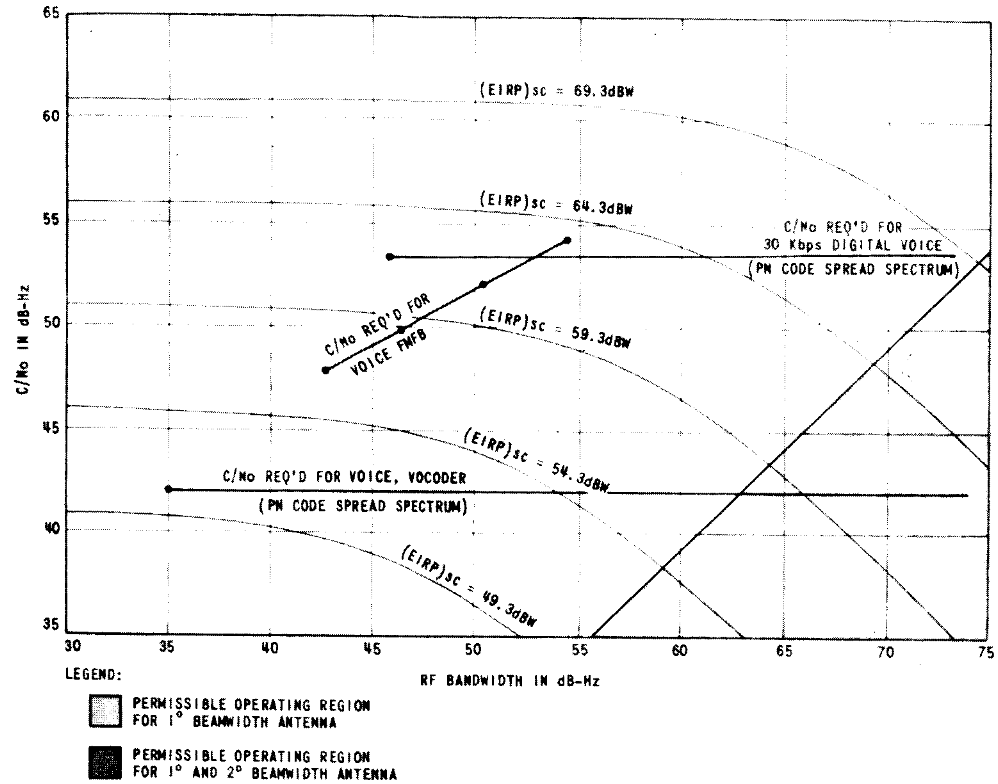


FIGURE 4 - INTELSAT II UTILIZATION REQUIREMENT SPACECRAFT TO GROUND LINK

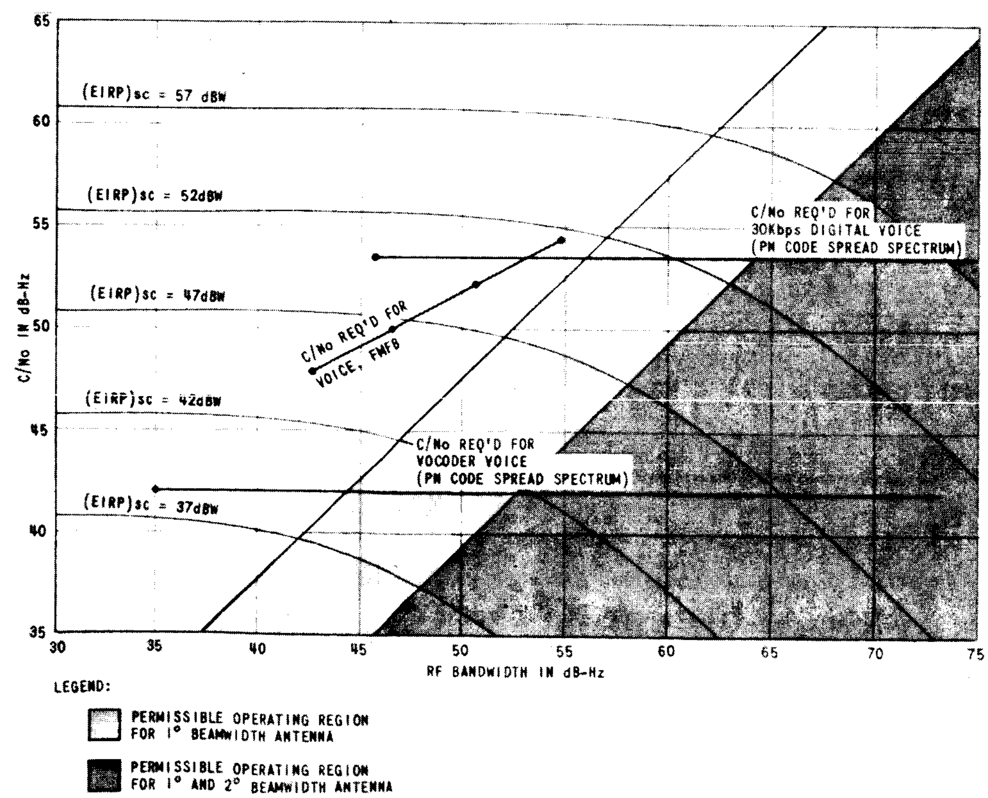


FIGURE 5 - INTELSAT III UTILIZATION REQUIREMENT SPACECRAFT TO GROUND LINK

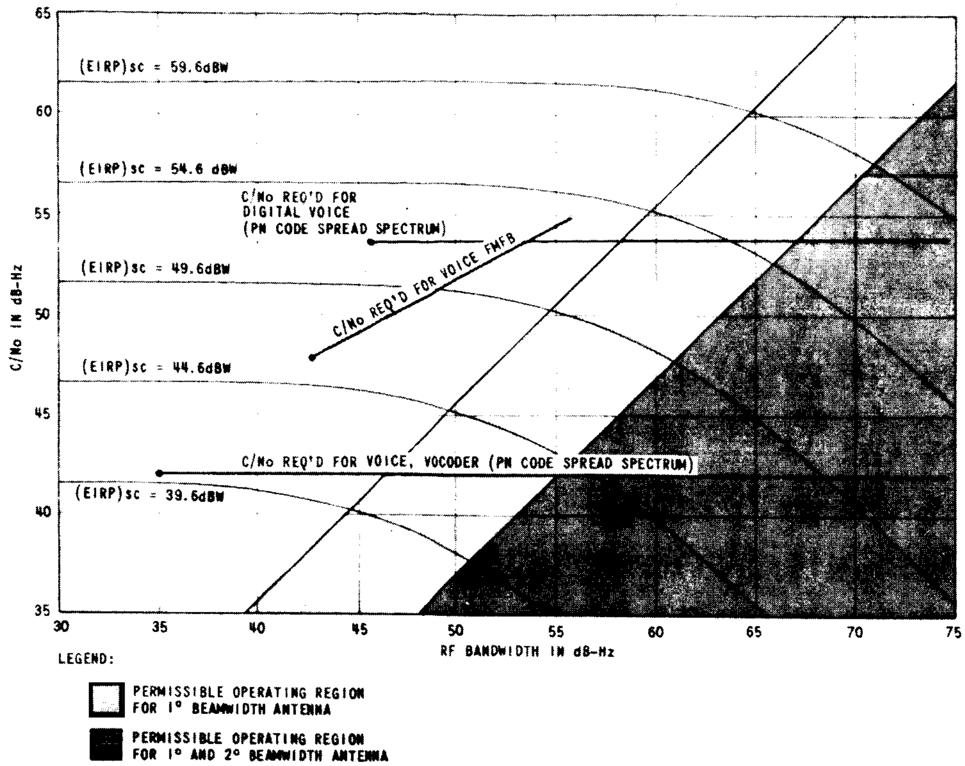


FIGURE 6 - INTELSAT III½ UTILIZATION REQUIREMENT SPACECRAFT TO GROUND LINK

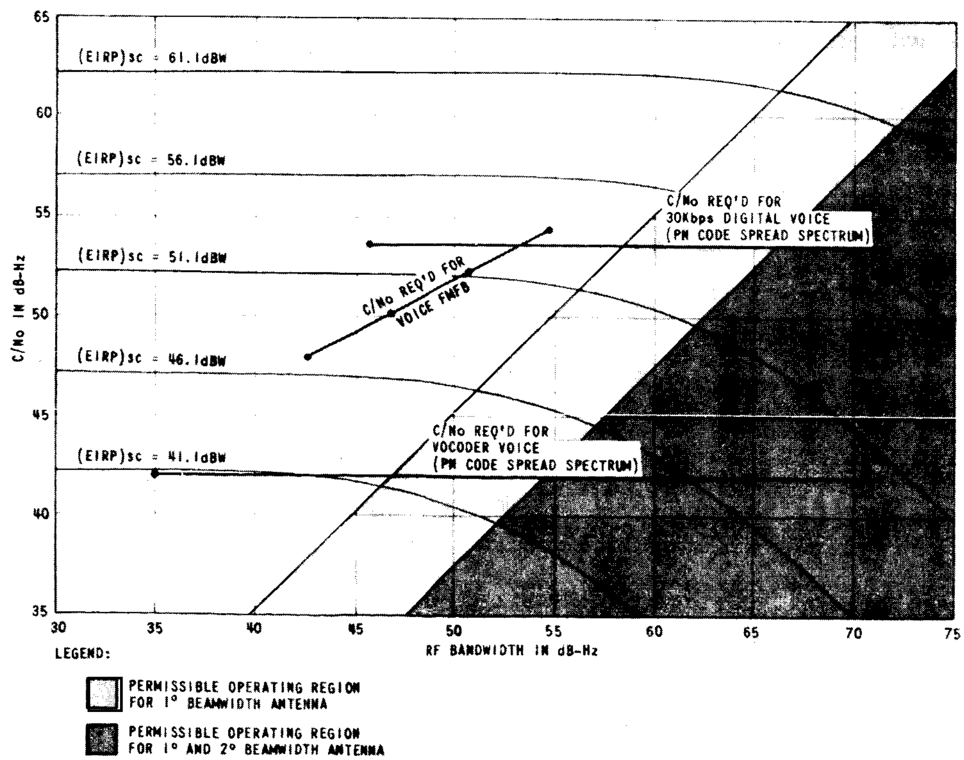
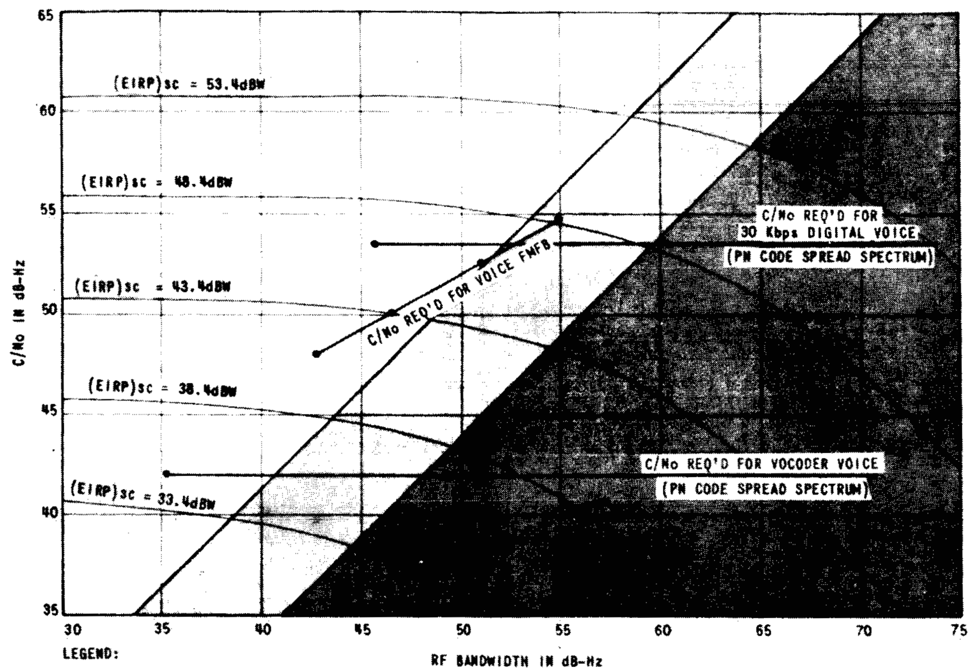


FIGURE 7 - INTELSAT IV UTILIZATION REQUIREMENT SPACECRAFT TO GROUND LINK
USING EARTH COVERAGE ANTENNA



LEGEND:

PERMISSIBLE OPERATING REGION FOR 1° BEAMWIDTH ANTENNA

PERMISSIBLE OPERATING REGION FOR 1° AND 2° BEAMWIDTH ANTENNA

FIGURE 8 - INTELSAT IV UTILIZATION SPACECRAFT TO GROUND LINK USING SPOT COVERAGE ANTENNA

Table V summarizes the manned spacecraft transmitte. power requirements, the RF bandwidth requirements and the EIRP requirements for various Intelsat satellites for the transmission of voice from a manned spacecraft to ground station link. A 3 dB margin is added to compensate the uncertainties of the assumed parameters used for the calculations. It is noted that FMFB method is not included in this table, as its usage would require unreasonably high RF power when compared with the other digital methods.

Figure 9 is the same as Figure B-6 from Appendix B, with the addition of an indication of the permissible operating regions for the Intelsat satellite based on the CCIR interference limit. Since the calculations indicate the up-down-link, which is part of the ground station to manned spacecraft link, can be operated within the CCIR interference

Intelsat Satellite	Manned Spacecraft Antenna Size	$(EIRP)^{*}_{IS}$		$(EISP)^{*}_{SC}$		SC Transmitter** Power		RF Bandwidth*	
		Vocoder	Digital	Vocoder	Digital	Vocoder	Digital	Vocoder	Digital
II	11 ft	-18.3dBW	---	61 dBW	---	100Watt	---	4 MHz	---
	5.5ft	---	---	---	---	---	---	---	---
III	11 ft	-24.6	-13 dBW	42.3	53.9dBW	1.4	20	56 kHz	800 kHz
	5.5ft	-22.3	-10.7	44.6	56.2	9.1	132	360 kHz	5.6 MHz
III 1/2	11 ft	-25.2	-13.6	44.4	56	2.3	32	85 kHz	1.35MHz
	5.5ft	-22.6	-10.6	47	59	16	250	640 kHz	10MHz
IV (earth coverage antenna)	11 ft	-26.3	-14.7	44.8	56.4	2.4	35	100 kHz	1.4 MHz
	5.5ft	-24.6	-13	46.5	58.1	14	200	560 kHz	8 MHz
IV (spot coverage antenna)	11 ft	-24.8	-13.4	38.6	50	0.6	8	24 kHz	350 kHz
	5.5ft	-23.2	-11.7	40.2	51.7	3.3	47	125 kHz	1.8 MHz

*Taken from Figures 4 - 8, with 3 dB added margin

**Includes 3 dB RF losses and 3 dB added margin

Table V - Down-Link Voice Transmission Parameters for Manned Spacecraft and Intelsat Satellites

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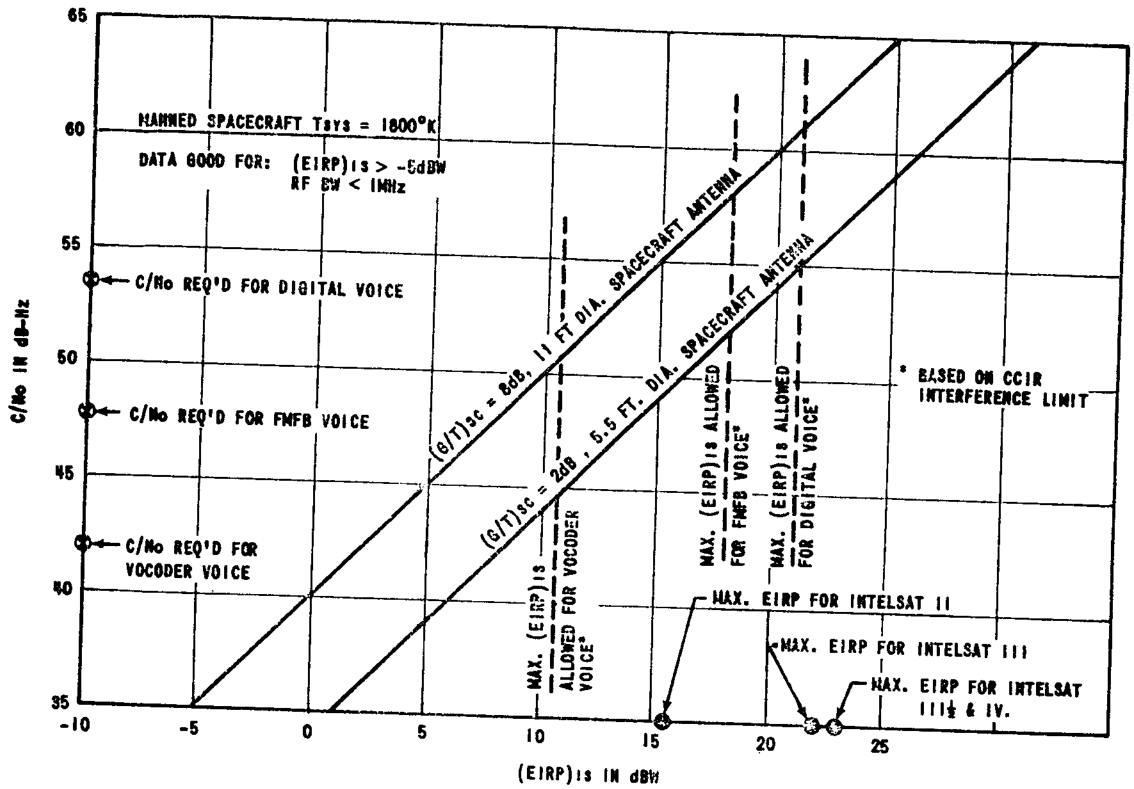

FIGURE 9 - INTELSAT UTILIZATION REQUIREMENTS - UP-LINK

Manned Spacecraft Antenna Size	Intelsat Satellite EIRP*			RF Bandwidth		
	Vocoder	FMFB	Digital	Vocoder	FMFB	Digital
11 ft dia.	5 dBW	10.8 dBW	16.5 dBW**	3.2 kHz	18 kHz	36 kHz
5.5 ft dia.	11 dBW****	16.8 dBW**	22.5 dBW***			

* Includes 3 DB added margin

** Exceeded the maximum EIRP capability of Intelsat II

*** Exceeded maximum EIRP capabilities of Intelsat II and III also exceeded the CCIR interference limit by 1.5 dB when 3 dB margin is added

**** Exceeded the CCIR interference limit by 0.5 dB when 3 dB margin is added

Table VI Parameters for Manned Spacecraft and Intelsat Satellites for Voice Transmission from Ground Station to Manned Spacecraft limit without resorting to any spread spectrum techniques* only the basic voice transmission modes discussed in Section IV are considered. It is also noted that this link is only affected by the G/T characteristics of the manned spacecraft, that is, the noise power contributed by the Intelsat satellite is negligible when compared to the noise power contributed by the receiving system of the manned spacecraft; therefore, Figure 9 can be used for all the Intelsat satellites considered. Table VI is a summary of the EIRP requirements for the Intelsat satellites, and the RF bandwidth requirements for various modes of voice transmission. Again, a 3 dB margin is added to compensate for the uncertainties in the assumed parameters used for the calculations. It is obvious that the transmission method using straight digitized voice is not desirable for several reasons: (1) it requires the highest EIRP from the Intelsat satellites, (2) the CCIR interference limit is exceeded when margin is added to the link, (3) it has the highest RF bandwidth occupancy, and (4) its EIRP requirements exceeded those available from Intelsat II and III. It is also seen from Table VI that if the manned spacecraft were equipped with a 5.5 ft. diameter antenna, three restrictions result:

1. The use of vocoder voice for the up-link is marginal because CCIR interference limit is exceeded by 0.5 dB.

2. Digital voice cannot be used for the up-link because the CCIR interference limit is exceeded by 3 dB.

3. FMFB voice cannot be relayed through the Intelsat II satellite as the EIRP required exceeds that available from the satellite.

VII. COST ESTIMATE OF INTELSAT UTILIZATION

The cost of utilizing the Intelsat Satellites is estimated not on the dollar cost but rather the number of equivalent voice channels required**. The assumptions and procedures used for making the cost estimates are outlined in Appendix D. Two factors determine the equivalent voice

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*The statement applies when the receiving antenna on the manned spacecraft is larger than 5.5 ft. which is being considered in this memorandum.

**A voice channel is a one-way voice link, while a voice circuit is a two-way voice link.

channel requirement, the bandwidth occupancy and the amount of EIRP needed from the Intelsat satellite. However, the assumption is made that the manned spacecraft is treated as an independent user terminal; therefore, it is required to purchase, or use, an integral assigned carrier group and its associated EIRP allotment of the Intelsat satellite. In most cases, the cost would be higher than that required for the transmission of a two-way voice circuit. In such cases, the excess capabilities purchased in satellite bandwidth and/or EIRP may be used for other communications functions, such as spacecraft telemetry on the down-link and up-data on the up-link, at no additional channel cost.

The cost of using the Intelsat satellites for the up and down-links are summarized separately in Tables VII and VIII. It is noted that the up-link cost is predominated by the satellite EIRP used and the down-link cost is predominated by the satellite bandwidth utilization. It is further noted that, indeed, in most cases, large amounts of excess capabilities in both satellite bandwidth and EIRP are used in order to satisfy the assumption of purchasing an integral carrier group assignment.

Table IX summarizes the combined cost of a two-way voice circuit using Intelsat satellites. For all cases except when the down-down-link uses the spot coverage antenna of Intelsat IV, the up and down-links are combined into one carrier group. The implication is that if the up-link cost is primarily due to the utilization of the satellite EIRP and the down-link cost is primarily due to the satellite bandwidth used, then the combined cost is the larger of the two provided that the same carrier group has sufficient capacities in both bandwidth and EIRP to accommodate the two-way voice circuit. In Table IX, not only the equivalent voice channel cost of the satellite utilization is included but also the manned spacecraft RF transmitter power requirements for the different combinations of up and down-link voice transmission modes. Whenever the RF transmitter requirement exceeds 100 watts, it is considered impracticable and that particular mode is deleted from the table.

From Table IX, several facts emerge:

1. In order to utilize Intelsat II, the manned spacecraft must be equipped with an 11 ft. diameter antenna and a 100 watt RF transmitter. Furthermore, it requires a vocoder on the manned spacecraft.

2. The manned spacecraft power requirements are dictated by the down-link, and the channel cost is dictated by the up-link.

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Voice Mode	Manned Spacecraft Antenna Size	Intelsat II				Intelsat III				Intelsat III-1/2				Intelsat IV			
		EIRP		BW	Net	EIRP		BW	Net	EIRP		BW	Net	EIRP		BW	Net
		need	used	used	cost	need	used	used	cost	need	used	used	cost	need	used	used	cost
Vocoder	11 ft	68	132	24	132	39	60	24	60	12	24	24	24	4	24	24	24
	5.5 ft*	270	288	24	288	152	156	24	156	43	60	24	60	13	24	24	24
FMFB	11 ft	260	264	24	264	144	156	24	156	40	60	24	60	13	24	24	24
	5.5 ft	--	--	--	--	575	588	24	588	164	192	24	192	48	60	24	60

All cost are in Equivalent Voice Channel Unit

Table VII Up-Link Cost Estimates

*The data is presented, although the link does exceed CCIR interference limit by 0.5 dB.

Voice Mode	Manned Spacecraft Antenna Size	Intelsat II		Intelsat III		Intelsat III-1/2		Intelsat IV earth coverage		Intelsat IV spot coverage	
		BW needed	Net cost	BW needed	Net cost	BW needed	Net cost	BW needed	Net cost	BW needed	Net cost
Vocoder	11 ft	4 MHz	24	56 kHz	24	85 kHz	24	100 kHz	24	24 kHz	24
	5.5 ft	--	--	360 kHz	24	640 kHz	24	560 kHz	24	125 kHz	24
Digital	11 ft	--	--	800 kHz	24	1.35 MHz	24	1.4 MHz	24	350 kHz	24
	5.5 ft	--	--	5.6 MHz	60	10 MHz	60	8 MHz	60	1.8 MHz	24

All cost are in Equivalent Voice Channel unit.

Table VIII Down-Link Cost Estimates

Voice Modes	Manned Spacecraft Antenna Size	Intelsat II		Intelsat III		Intelsat III 1/2		Intelsat IV Earth Coverage		Intelsat IV Spot Coverage	
		Channel Cost	SC RF Power	Channel Cost	SC RF Power	Channel Cost	SC RF Power	Channel Cost	SC RF Power	Channel Cost	SC RF Power
Vocoder both links	11 ft	132	100 w	60	1.4 w	24	2.3 w	24	2.4 w	48	0.6 w
	5.5ft*	--	--	156	9.1	60	16	24	14	48	3.3
FMFB up-link, Vocoder down-link	11 ft	264	100 w	156	1.4	60	2.3	24	2.4	48	0.6
	5.5ft	--	--	588	9.1	192	16	60	14	84	3.3
Vocoder up-link, Digital down-link	11 ft	--	--	60	20	24	32	24	35	48	8
	5.5ft	--	--	--	--	--	--	--	--	48	47
FMFB up-link, Digital down-link	11 ft	--	--	156	20	60	32	24	35	48	8
	5.5ft	--	--	--	--	--	--	--	--	84	47

Table IX - Cost Summary for Two-Way Voice Relay Using Intelsat Satellites

Channel Cost is in Equivalent Voice Channel Units

SC RF POWER is the RF transmitter power required from manned spacecraft, including 3 dB added margin

*The data is presented, although vocoder up-link does exceed CCIR interference limit by 0.5 dB.

3. The use of digital voice for down-link would require the use of an 11 ft. diameter antenna on the manned spacecraft for most cases.

4. There is no overriding advantages in using the spot coverage antenna on Intelsat IV for the down-down-link except in the case when digital voice is used. In this case, one may consider the use of a 5.5 ft. antenna on the manned spacecraft.

5. It is reasonable to use Intelsat III, III 1/2, and IV satellites. Among the three, Intelsat III has the highest channels cost (588 channels) but requires the least RF transmitter power from the manned spacecraft (20 watt max.). Intelsat IV is the least costly in equivalent voice channels used (60 channels max.) but requires the most RF transmitter power from the manned spacecraft (35 watt max.).

VIII. CONCLUSIONS

A two-way voice channel between an orbiting manned spacecraft and a ground station can be established with the use of a commercial type Intelsat satellite. The more desirable satellite types are Intelsat III and the projected Intelsat III 1/2 and Intelsat IV. The CCIR interference limit has a large effect on the system design of the down-link (manned spacecraft to Intelsat satellite to ground). In order to stay within the interference limit, the down-link transmission of voice requires:

1. spread spectrum techniques and digital transmission,

2. an operational constraint on the manned spacecraft transmission, and

3. the use of a high gain, narrow beam antenna on the manned spacecraft.

When the system design has satisfied the interference limit on the down-link, the up-link (ground to Intelsat satellite to manned spacecraft) system design is not affected by the CCIR interference limit.

A typical communication terminal on the manned spacecraft could be implemented as follows:

1. Antenna - 11 ft. (1° beamwidth)* or 5.5 ft. (2° beamwidth)* diameter parabolic dish. The antenna should have automatic pointing capability.

2. Transmitter Power - 47 watts maximum when used with a 5.5 ft. antenna and digitized voice. The minimum power required is 0.6 watt when used with an 11 ft. antenna and a vocoder.

3. Modulation and Baseband Processing - Digital voice transmission is recommended either with or without a vocoder. The advantage of using a vocoder results in a more efficient system in power utilization as can be seen in (2) above. Spread spectrum techniques are needed for the down-link. One way this could be accomplished is by combining the digitized voice signal with a PN code which is clocked at a high bit rate. The technique is believed to be practicable and not overly complicated in its implementation.

The cost of using these satellites in terms of equivalent voice channels that have to be purchased is dictated by the up-link requirements. That is, the EIRP that needs to be radiated from the Intelsat satellite to the manned spacecraft. The maximum estimated cost is 588 channels using FM voice on the up-link in conjunction with a 5.5 ft. receiving antenna on the manned spacecraft. The minimum cost is 24 channels using vocoder voice on the up-link in conjunction with an 11 ft. receiving antenna on the manned spacecraft.

The use of vocoders for both up and down-links results in the most efficient usage for both channel cost and manned spacecraft RF power. The maximum channel cost is 60 channels when using Intelsat III and the maximum RF transmitter power required is 2.4 watts using Intelsat IV, when an 11 ft. antenna is available on the manned spacecraft. The corresponding numbers using a 5.5 ft. antenna on the manned spacecraft are 156 channels and 16 watts. If the use of a vocoder proved to be undesirable because of the possible weight penalty, FMFB can be used for the up-link and straight digital voice for the down-link. However, it would require the use of an 11 ft. antenna on the manned spacecraft unless the restriction of using Intelsat IV with its spot coverage antenna only is acceptable. Under this restriction, a 5.5 ft. antenna and 47 watt transmitter on the manned spacecraft is sufficient, and the cost is 84 equivalent voice channels.

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*These beamwidths are for down-link transmission from manned spacecraft at 6 GHz frequency.

Several additional observations should also be mentioned:

1. Even if the CCIR interference limits are disregarded, the use of Intelsat satellites, as presently anticipated, would not be capable of providing the necessary voice links under certain emergency conditions. It can be shown that both the up and down voice links require a high gain antenna on the manned spacecraft. Therefore, if the attitude control system of the manned spacecraft failed as experienced during the Gemini GT-8 mission, the voice links would also fail.

2. Because of the excess capability that needs to be purchased from Intelsat, the capacity of the RF links can be expanded with very little additional effort. For instance, the addition of 1.6 kbps telemetry on the down-link is free of additional channel cost and only requires doubling the RF transmitting power on the manned spacecraft, which, in the worst case, is still less than 100 watts.*

3. The most direct impact of the CCIR interference limit is in the requirement for a high gain antenna on the manned spacecraft. Therefore, disregarding the CCIR interference limit could result in using lower gain antennas. The advantages that could be derived is in the size and weight of the antenna system and the less stringent antenna pointing and acquisition problems. However, the reduction of antenna gain must be matched directly by an increase in the EIRP from the Intelsat satellites, which is not unlimited, and means higher channel cost as well.

ACKNOWLEDGEMENT

The author wishes to thank his colleague, Mr. L. Schuchman, for his helpful and stimulating discussions on digital spread spectrum techniques. He also contributed Figure C-3 of Appendix C.

2034-RKC-dlb R. K. Chen

Attachment
(Appendices A through D)

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*The exact amount of additional telemetry and its associated spacecraft RF power requirement varies. They depend on the type of Intelsat satellite used.

Bellcomm, Inc.

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APPENDIX A

CCIR Interference Limit

The RF frequency bands presently used by the commercial communications satellites are the same as those used by the common carriers for microwave radio-relay systems on earth. In order to allow frequency sharing of these systems, various criteria are established by the International Radio Consultative Committee (CCIR) of the International Telecommunication Union (ITU) to prevent mutual interference. Many studies were made by international experts on the subject and resulted in several recommendations. One particular recommendation, No. 358-1, specifies the maximum allowable values of power flux density at the surface of the earth produced by communication satellites, which is:*

$$(-152 + \frac{\theta}{15})\text{dBW/m}^2 \text{ in any 4kHz band} \quad ,$$

where θ is the angle of arrival of the wave in degrees above the horizon. This limit specifically applies for a communication satellite system and line-of-sight radio-relay systems that share frequency bands in the range of 1 to 10 GHz. It is also stated that for communication satellite system using frequency modulation, a method of carrier energy dispersal could be employed to reduce the radio-frequency power flux-density in any 4 kHz band, under conditions of light loading from multi-channel telephony, or from television signals.

For the application considered here, there are two potential interference conditions to the terrestrial systems as shown in Figures A-1 and A-2. Figure A-1 is the familiar situation where the Intelsat satellite is in a geostationary orbit; in this case the interference limit at a frequency of 4 GHz can be translated to an allowable effective isotropic radiated power (EIRP) at the satellite.

The maximum flux-density on earth for a minimum angle of arrival of 5° above horizon would be (-152 + 5/15)= -151.7 dBW/4kHz/m^2. The effective area of an isotropic antenna

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*CCIR Document of the XI Plenary Assembly, Vol. IV, Part 2, Oslo, 1966.

Appendix A (Cont'd)

is $\lambda^2/4\pi$, where λ is the wavelength. The flux received by an isotropic antenna at 4 GHz on the earth surface is:

$$\text{Maximum flux on earth} = -151.7 + 10 \log \frac{\lambda^2}{4\pi}$$

$$= -185.2 \text{ dBW/4kHz} \quad .$$

The free space loss at this frequency and a distance of approximately 22,000 n.m. is 196.6 dB. Therefore, the maximum allowable EIRP from Intelsat satellites is 11.4 dBW/4kHz, or -24.6 dBW/Hz.

Figure A-2 depicts the case where the interference to the terrestrial systems is caused by the manned spacecraft at the RF frequency of 6 GHz. The geometry in this case becomes more involved and a realistic interference limit is yet to be established as can be seen in the following excerpts from a report* submitted to CCIR:

> "The continuous full in-beam condition is not typical of interference from systems of non-stationary satellites and, in these cases, the aforementioned power flux-density limits** would ensure a substantial margin for the protection of radio-relay systems."
>
> "In considering the limits of mean hourly interference, the worst conditions may arise when the two signals are relatively stable. It is necessary to make this assumption at the present time, but more experimental information on the fading of satellite signals arriving at very low elevation angles is desirable."

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*"Power Flux-Density at the Surface of the Earth from Communication Satellites", Report No. 387, CCIR Documents of the XI Plenary Assembly, Vol. IV, Part 2, Oslo, 1966.

**The limit referred in the report is -151 dBW/4kHz/m^2.

For the time being, the same interference limit used for stationary satellites is also applied to the down-up-link condition considered here. However, from the excerpts above, the limit may prove to be too severe.

Instead of calculating the maximum EIRP that can be allowed from the manned spacecraft, a maximum side-lobe EIRP is calculated. This implies that operational restrictions may be imposed on the transmission of the manned spacecraft so that its antenna's main beam would not illuminate the earth at any time. Using the geometry of Figure A-2, the relation between the side-lobe location of the antenna on the manned spacecraft and the spacecraft location with respect to the sub-satellite point of the communication satellite can be determined; this is shown in Figure A-3. For a typical case of a manned spacecraft in a 260 n.m. circular orbit, the maximum side-lobe EIRP that can be allowed from the manned spacecraft can be shown to be -13 dBW/4kHz or -49 dBW/Hz.

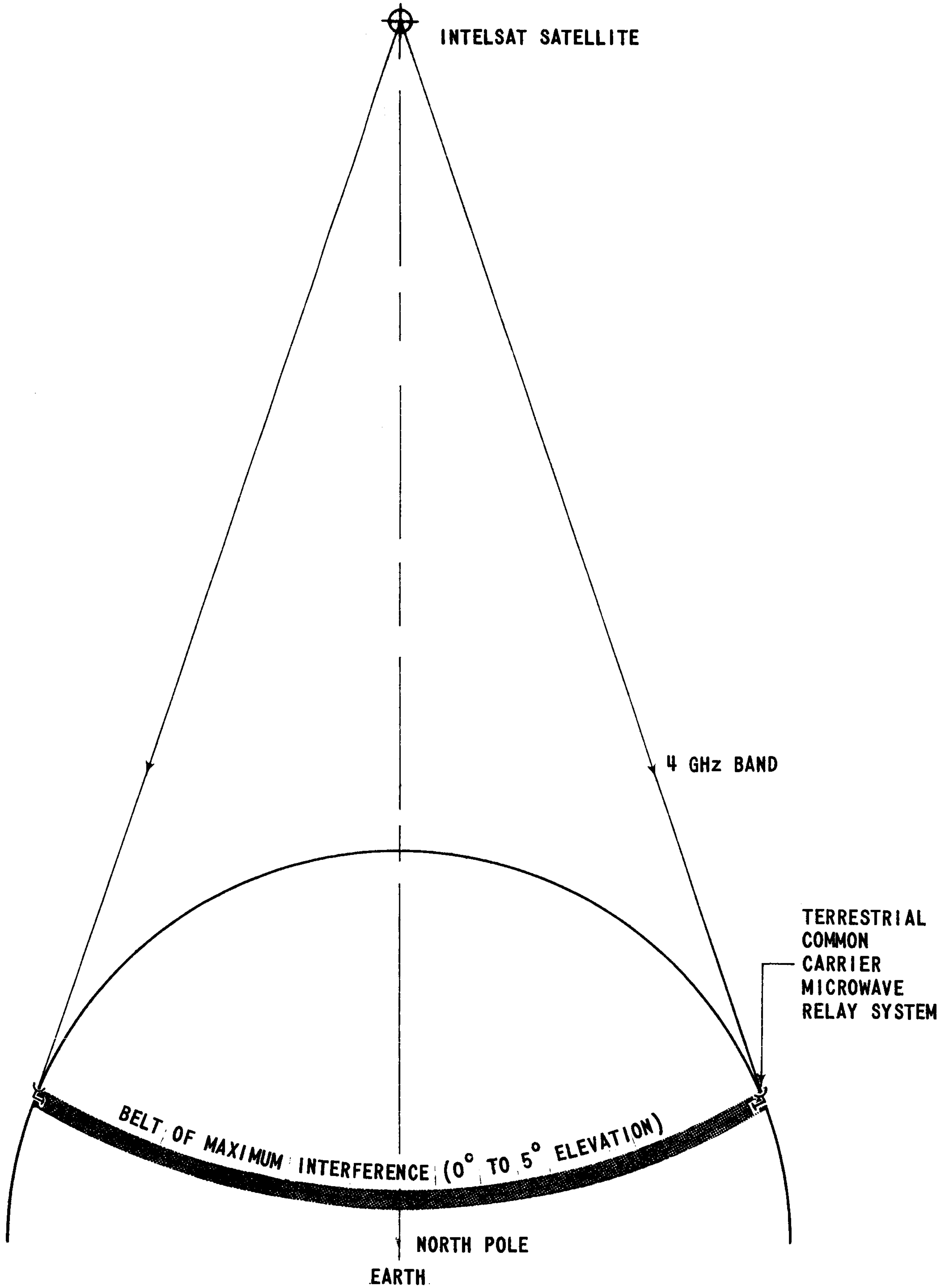


FIGURE A-1 - PICTORIAL VIEW OF TERRESTRIAL USERS BEING INTERFERED WITH BY INTELSAT SATELLITE

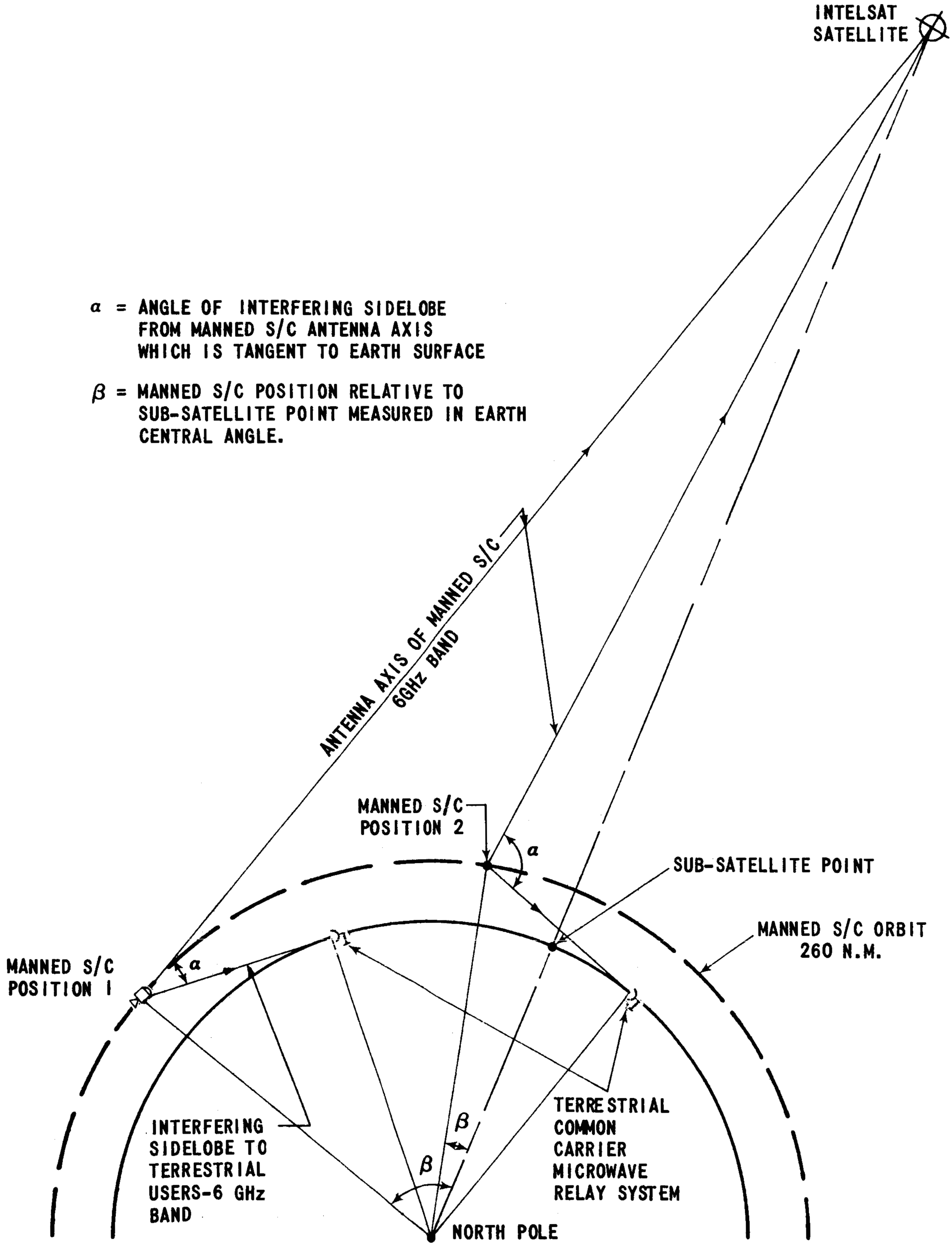


FIGURE A-2 - PICTORIAL VIEW OF TERRESTRIAL USERS BEING INTERFERED BY MANNED SPACECRAFT

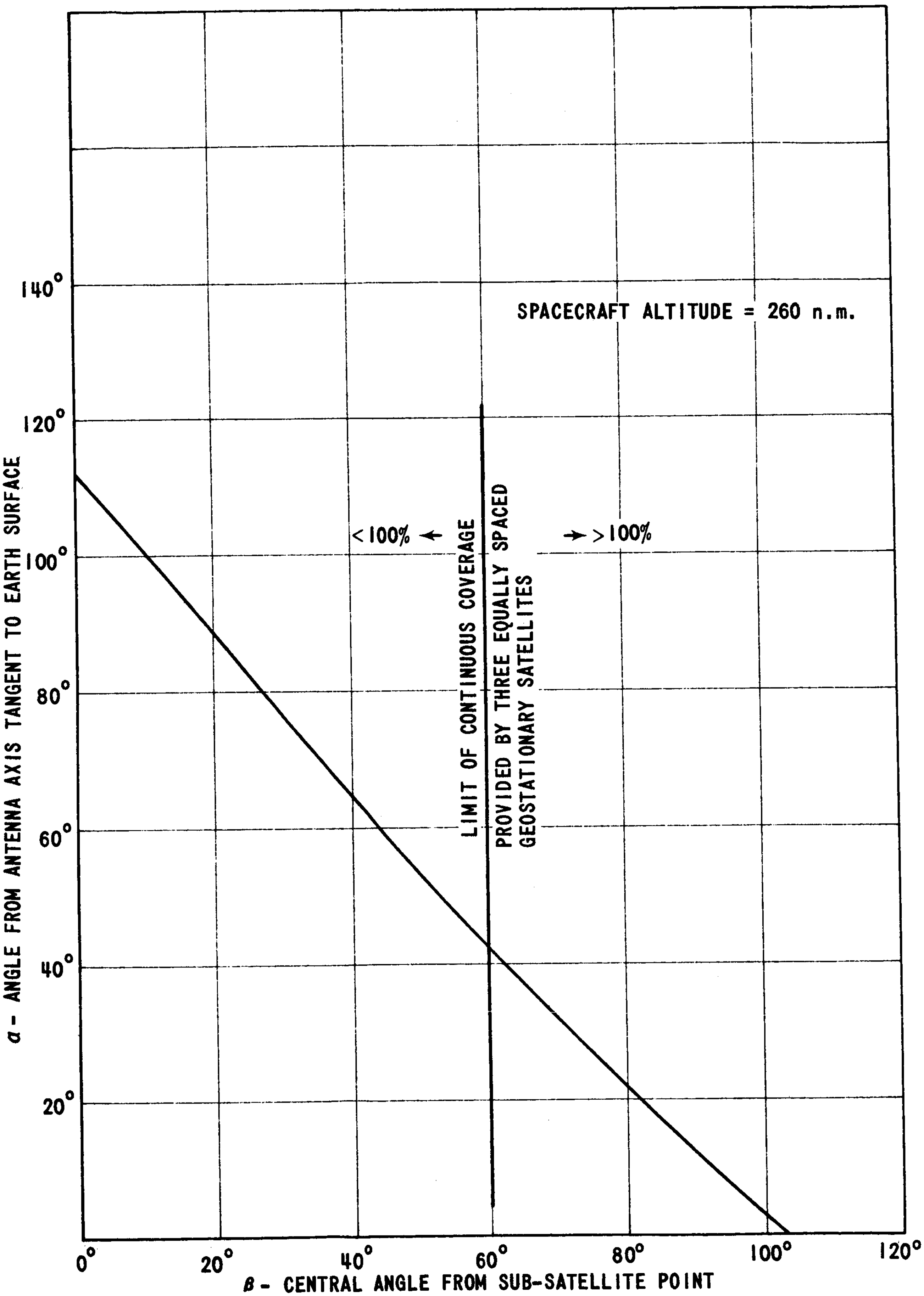


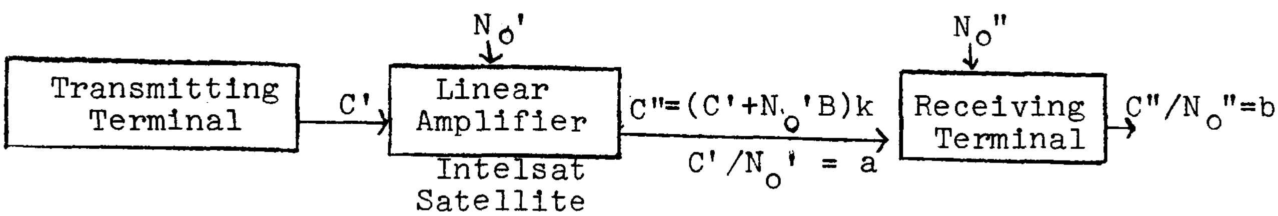
FIGURE A-3 - SPACECRAFT ANTENNA INTERFERENCE ANGLE TO TERRESTRIAL USERS

APPENDIX B

Derivation of RF Performance for Intelsat Satellite Relay Links

The RF performance of a relay link, using carrier power-to-noise power spectral density ratio (C/N_o) as the parameter, is derived in this Appendix. The expected performances of various Intelsat Satellites are then determined by inserting the estimated characteristics of these satellites and the terminals (Intelsat ground station and Manned Spacecraft).

The derivations are based on the following model.



The symbols used in this model are:

C'	=	carrier power received by the Satellite
N_o'	=	noise power spectral density of the Satellite
C'/N_o'	=	a = the value of C/N_o at the satellite output
B	=	RF bandwidth needed for the communication function.
C''	=	$(C' + N_o'B)k$ is the carrier power at the receiving terminal.
k	=	link constant includes total system gain and free space loss.
N_o''	=	noise power spectral density of the receiving terminal.
C''/N_o''	=	b = the value of C/N_o at the receiving terminal output for satellite to receiver link.

Assuming N_o' and N_o'' are Gaussian and White noises, plus the fact that they are independent of each other, the overall C/N_o of the entire relay link at the output of receiving terminal is:

$$C/N_o = \frac{kC'}{kN_o' + N_o''} \qquad \text{(B-1)}$$

Using the relationships indicated in the model:

$$N_o'' = \frac{C''}{b} = \frac{(C' + N_o'B)k}{b} \qquad \text{(B-2)}$$

and:

$$N_o' = \frac{C'}{a} \qquad \text{(B-3)}$$

Substituting: (B-2) and (B-3) into (B-1):

$$C/N_o = \frac{kC'}{kN_o' + \frac{(C' + N_o'B)k}{b}} = \frac{kbC'}{kC' + N_o'(B+b)k}$$

$$= \frac{bC'}{C' + \frac{C'}{a}(B + b)} = \frac{ab}{a + b + B} \qquad \text{(B-4)}$$

The parameters a and b are obtained by using the familiar formula for one way RF links:

$$C/N = \frac{P_t \quad G_t \quad G_r}{K\ T_{eff}\ B\ L_{fs}\ L_t} \qquad \text{(B-5)}$$

with slight modification

$$C/N = \frac{(P_t G_t / L_t)\ (G_r / T_{eff})}{K\ L_{fs}}$$

$$= \frac{(EIRP)\,(G/T)_r}{K\ L_{fs}} \qquad \text{(B-6)}$$

where:

C/N = Carrier-to-noise ratio

P_t = Transmitter power in watts

G_t = Transmitting antenna gain

G_r = Receiving antenna gain

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

T_{eff} = Receiving system noise temperature in °K

B = Noise bandwidth

L_{fs} = Free space loss

L_t = RF losses of transmitting system

EIRP = $(P_t\ G_t)/L_t$ is the effective isotropic radiated power in watts.

$(G/T)_r = G_r/(T_{eff})$ is the figure of merit of the receiving system in $°K^{-1}$.

Combining (B-6) and (B-4), the expression for C/N_o of the overall relay links are:

(A) <u>For Manned Space (SC) to Intelsat Satellite (IS) to Ground Station (GND) Link</u>

$$a = \frac{(EIRP)_{sc}\ (G/T)_{IS}}{K(L_{fs})_6} \qquad (B-7)$$

$$b = \frac{(EIRP)_{IS}\ (G/T)_{GND}}{K\ (L_{fs})_4} \qquad (B-8)$$

The subscripts denote the parameters associated with manned spacecraft (SC). Intelsat Satellite (IS), and ground station (GND). Other subscripts, 6 and 4, associated with L_{fs} indicate the free space loss evaluated at RF frequencies of 6 GHz and 4 GHz, respectively.

Since the Intelsat Satellites are essentially linear amplifiers when operated below the saturated region of their power amplifiers, $(EIRP)_{SC}$ and $(EIRP)_{IS}$ can be related as:

$$(EIRP)_{SC} = (EIRP)_{IS}\ (L_{fs})_6\ k_{IS} \qquad (B-9)$$

The parameter k_{IS} is the reciprocal of the power gain of various Intelsat Satellites (see Figure 1).

Combine (B-4), (B-7), (B-8), and (B-9):

$$C/N_o = \frac{k_{IS}\ (EIRP)^2_{IS}(G/T)_{IS}\ (G/T)_{GND}}{K(EIRP)_{IS}\ [k_{IS}(G/T)_{IS}(L_{fs})_4 + (G/T)_{GND}] + BK^2(L_{fs})_4} \qquad (B-10)$$

(B) <u>For Ground Station to Intelsat Satellite to Manned Spacecraft Link</u>

Using similar method as part (A):

$$C/N_o = \frac{k_{IS}\,(EIRP)^2_{IS}\,(G/T)_{IS}\,(G/T)_{SC}}{K(EIRP)_{IS}\,[k_{IS}\,(G/T)_{IS}(L_{fs})_4 + (G/T)_{SC}] + BK^2\,(L_{fs})_4} \qquad \text{(B-11)}$$

and (B-12)

$$(EIRP)_{GND} = (EIRP)_{IS}\,(L_{fs})_6\,k_{IS}$$

Using the estimated parameters in Table III, equations (B-10) and (B-11) in numerical forms for various Intelsat Satellites are:

(A) <u>Manned Spacecraft to Intelsat Satellite to Ground Station Link</u>

(1) <u>Intelsat II</u>

$$C/N_o = \frac{(EIRP)^2_{IS}}{8 \times 10^{-8}\,(EIRP)_{IS} + 1.4 \times 10^{-15}B} \qquad \text{(B-13)}$$

$$(EIRP)_{SC} \text{ in dBW} = 79.3 \text{ dB} + (EIRP)_{IS} \text{ in dBW} \qquad \text{(B-14)}$$

(2) <u>Intelsat III</u>

$$C/N_o = \frac{(EIRP)^2_{IS}}{8.32 \times 10^{-8}\,(EIRP)_{IS} + 1.54 \times 10^{-15}B} \qquad \text{(B-15)}$$

$$(EIRP)_{SC} \text{ in dBW} = 66.9 \text{ dB} + (EIRP)_{IS} \text{ in dBW} \qquad \text{(B-16)}$$

(3) <u>Intelsat III 1/2</u>

$$C/N_o = \frac{(EIRP)^2_{IS}}{6.9 \times 10^{-8}\,(EIRP)_{IS} + 8.17 \times 10^{-16}B} \qquad \text{(B-17)}$$

$$(EIRP)_{SC} \text{ in dBW} = 69.6 \text{ dB} + (EIRP)_{IS} \text{ in dBW} \qquad \text{(B-18)}$$

(4) <u>Intelsat IV Using Earth Coverage Antenna</u>

$$C/N_o = \frac{(EIRP)^2_{IS}}{6 \times 10^{-8}\,(EIRP)_{IS} + 2.93 \times 10^{-16}B} \qquad \text{(B-19)}$$

$$(EIRP)_{SC} \text{ in dBW} = 71.1 \text{ dB} + (EIRP)_{IS} \text{ in dBW} \qquad \text{(B-20)}$$

(5) Intelsat IV Using Spot Coverage Antenna

$$C/N_o = \frac{(EIRP)^2_{IS}}{8.65 \times 10^{-8} (EIRP)_{IS} + 1.73 \times 10^{-15} B} \qquad (B-21)$$

$$(EIRP)_{SC} \text{ in dBW} = 63.4 \text{ dB} + (EIRP)_{IS} \text{ in dBW} \qquad (B-22)$$

(B) Ground Station to Intelsat Satellite to Manned Spacecraft Link

(1) Intelsat II

$$C/N_o = \frac{(EIRP)^2_{IS} (G/T)_{SC}}{6.33 \times 10^{-4} (EIRP)_{IS} + 1.67 \times 10^{-11} B} \qquad (B-23)$$

$$(EIRP)_{GND} \text{ in dBW} = 79.3 \text{ dB} + (EIRP)_{IS} \text{ in dBW} \qquad (B-24)$$

(2) Intelsat III

$$C/N_o = \frac{(EIRP)^2_{IS} (G/T)_{SC}}{6.33 \times 10^{-4} (EIRP)_{IS} + 1.83 \times 10^{-11} B} \qquad (B-25)$$

$$(EIRP)_{GND} \text{ in dBW} = 66.9 \text{ dB} + (EIRP)_{IS} \text{ in dBW} \qquad (B-26)$$

(3) Intelsat III 1/2

$$C/N_o = \frac{(EIRP)^2_{IS} (G/T)_{SC}}{6.33 \times 10^{-4} (EIRP)_{IS} + 9.65 \times 10^{-12} B} \qquad (B-27)$$

$$(EIRP)_{GND} \text{ in dBW} = 69.6 \text{ dB} + (EIRP)_{IS} \text{ in dBW} \qquad (B-28)$$

(4) Intelsat IV Using Earth Coverage Antenna

$$C/N_o = \frac{(EIRP)^2_{IS} (G/T)_{SC}}{6.33 \times 10^{-4} (EIRP)_{IS} + 3.5 \times 10^{-12} B} \qquad (B-29)$$

$$(EIRP)_{GND} \text{ in dBW} = 71.1 \text{ dB} + (EIRP)_{IS} \text{ in dBW} \qquad (B-30)$$

Equations (B-23), (B-25), (B-27), and (B-29) would be identical and simplified to:

$$C/N_o = 1.58 \times 10^3 \, (EIRP)_{IS} \, (G/T)_{SC}, \qquad (B\text{-}31)$$

under the following restrictions:

(a) $(EIRP)_{IS} > -5dBW$

(b) $B < 1.0$ MHz

Equations (B-13), (B-15), (B-17), (B-19), (B-21), and (B-31) are presented parametrically in Figures B-1 to B-6. From these figures, the intersection of C/N_o and RF bandwidth for certain known communication functions provide the information of EIRP requirements of the manned spacecraft, the Intelsat satellite, and the ground station.

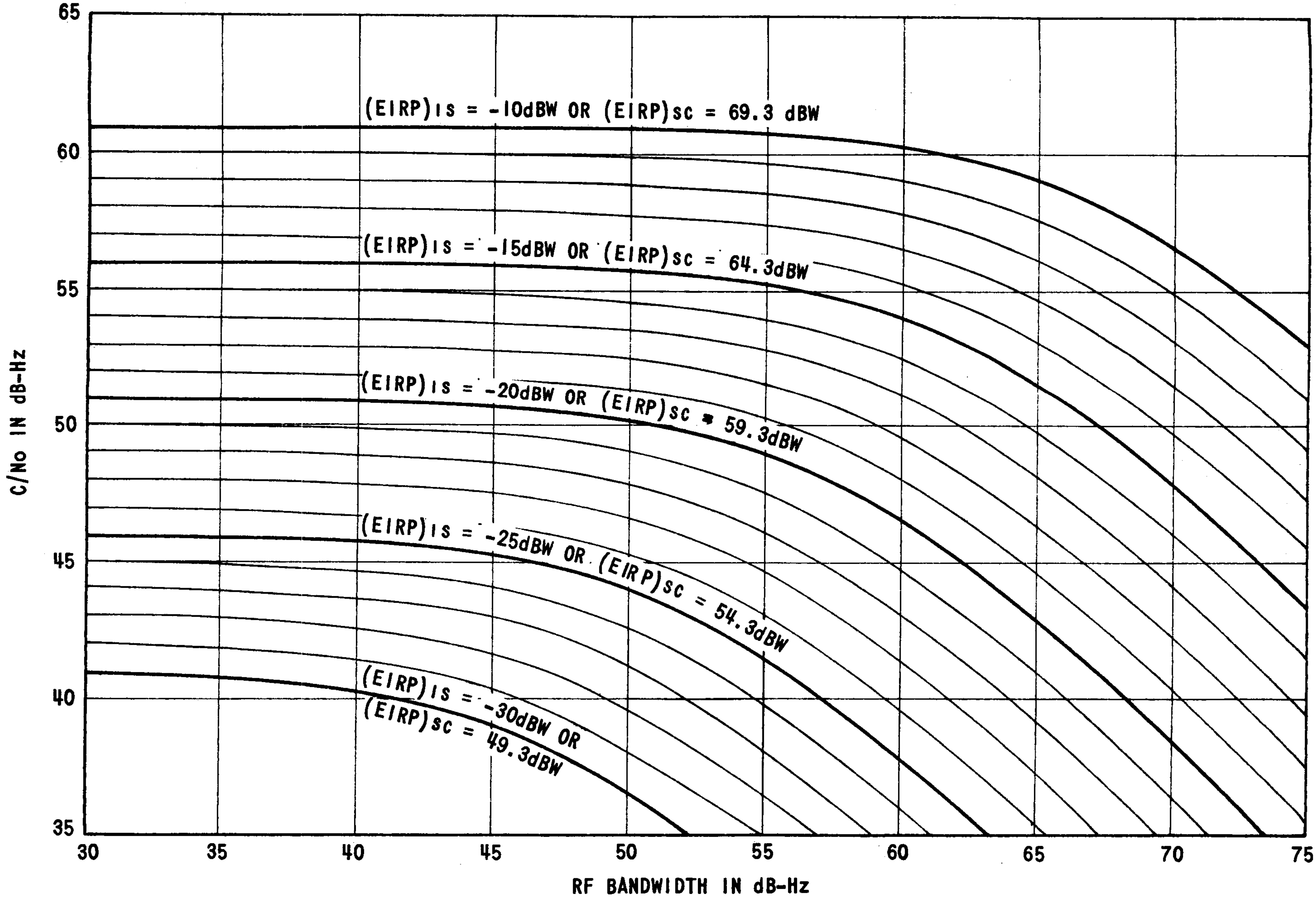


FIGURE B-1 - INTELSAT II UTILIZATION REQUIREMENT. SPACECRAFT TO GROUND LINK

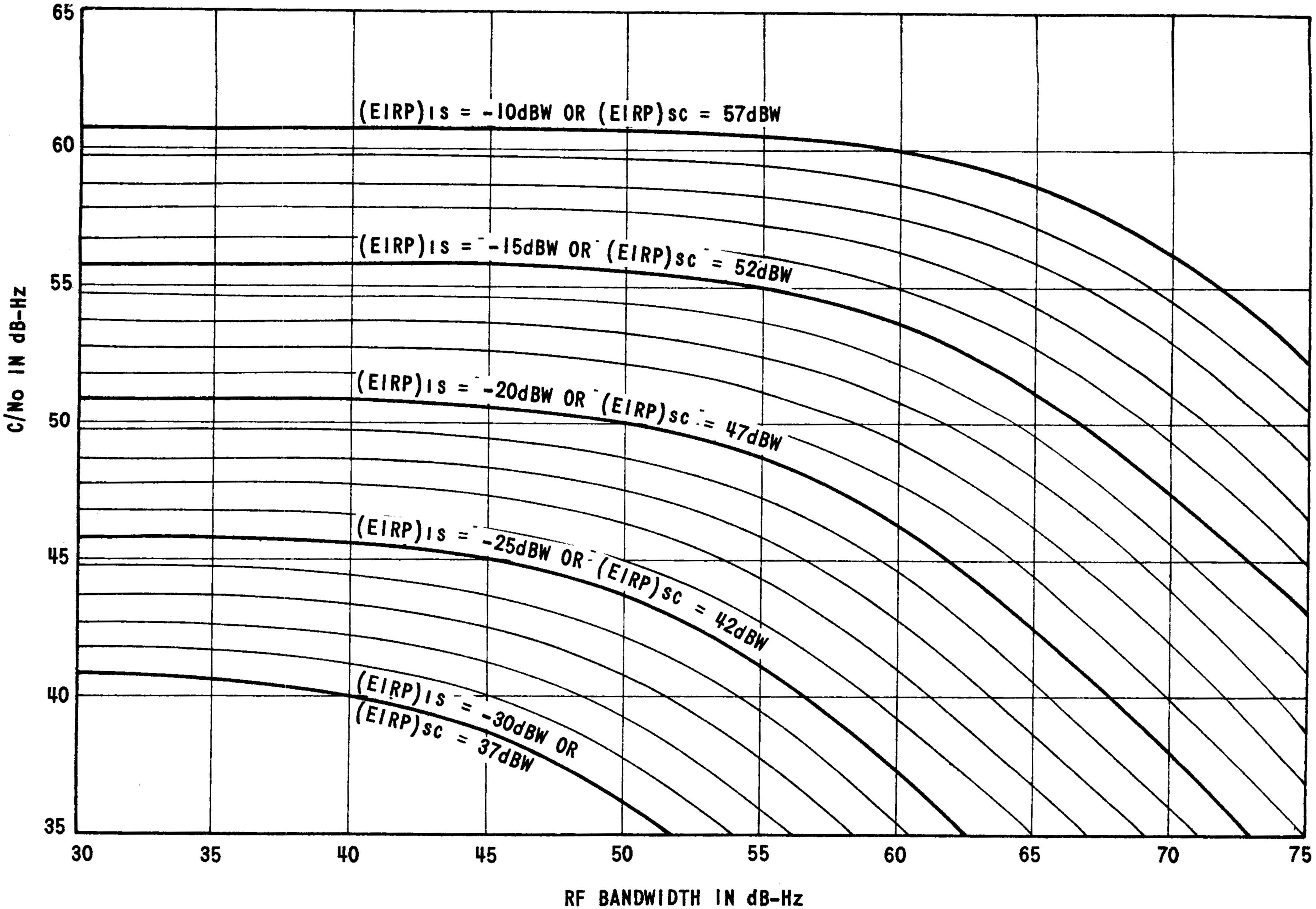


FIGURE B-2 - INTELSAT III UTILIZATION REQUIREMENT SPACECRAFT TO GROUND LINK

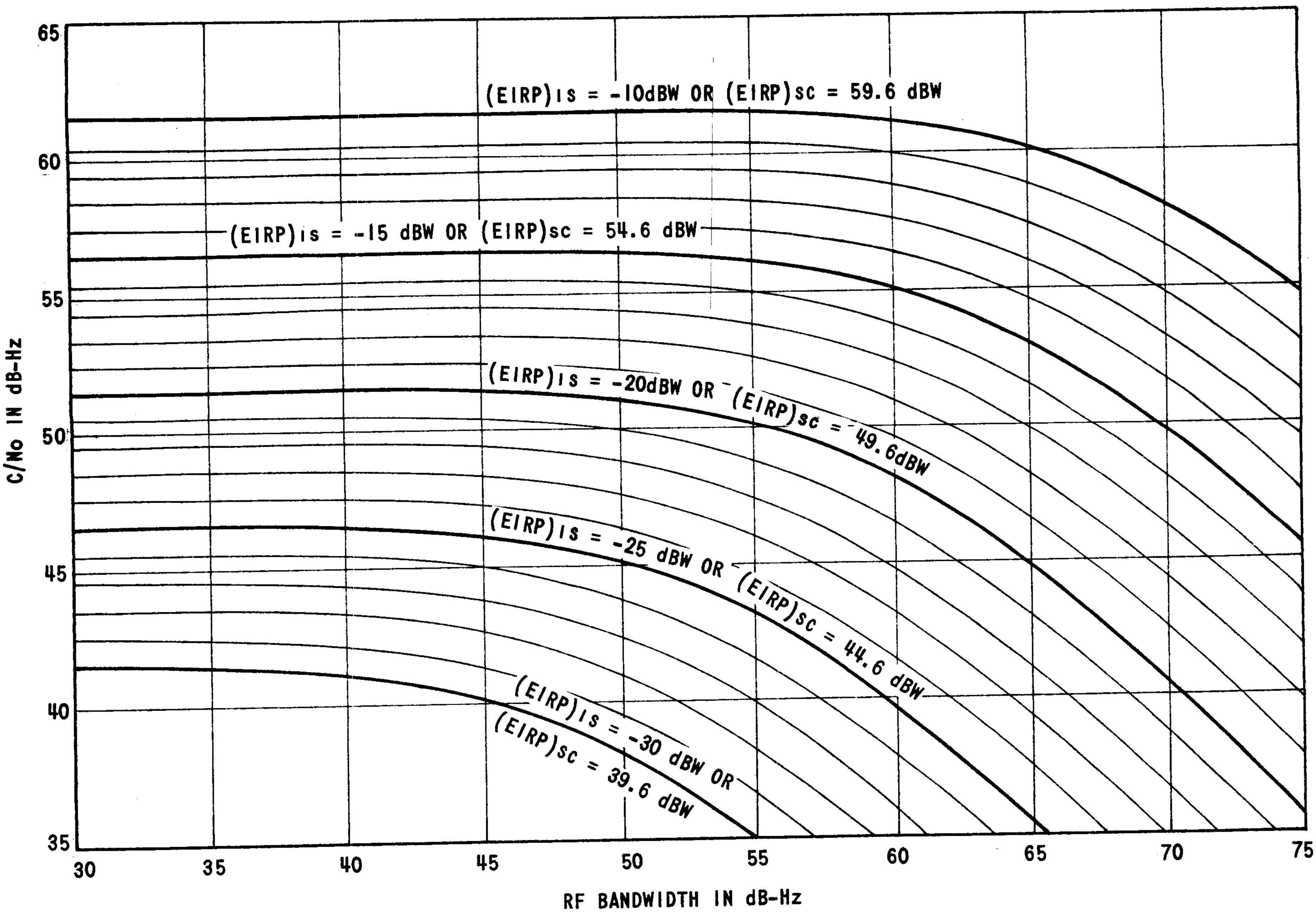


FIGURE B-3 - INTELSAT III$\frac{1}{2}$ UTILIZATION REQUIREMENT SPACECRAFT TO GROUND LINK

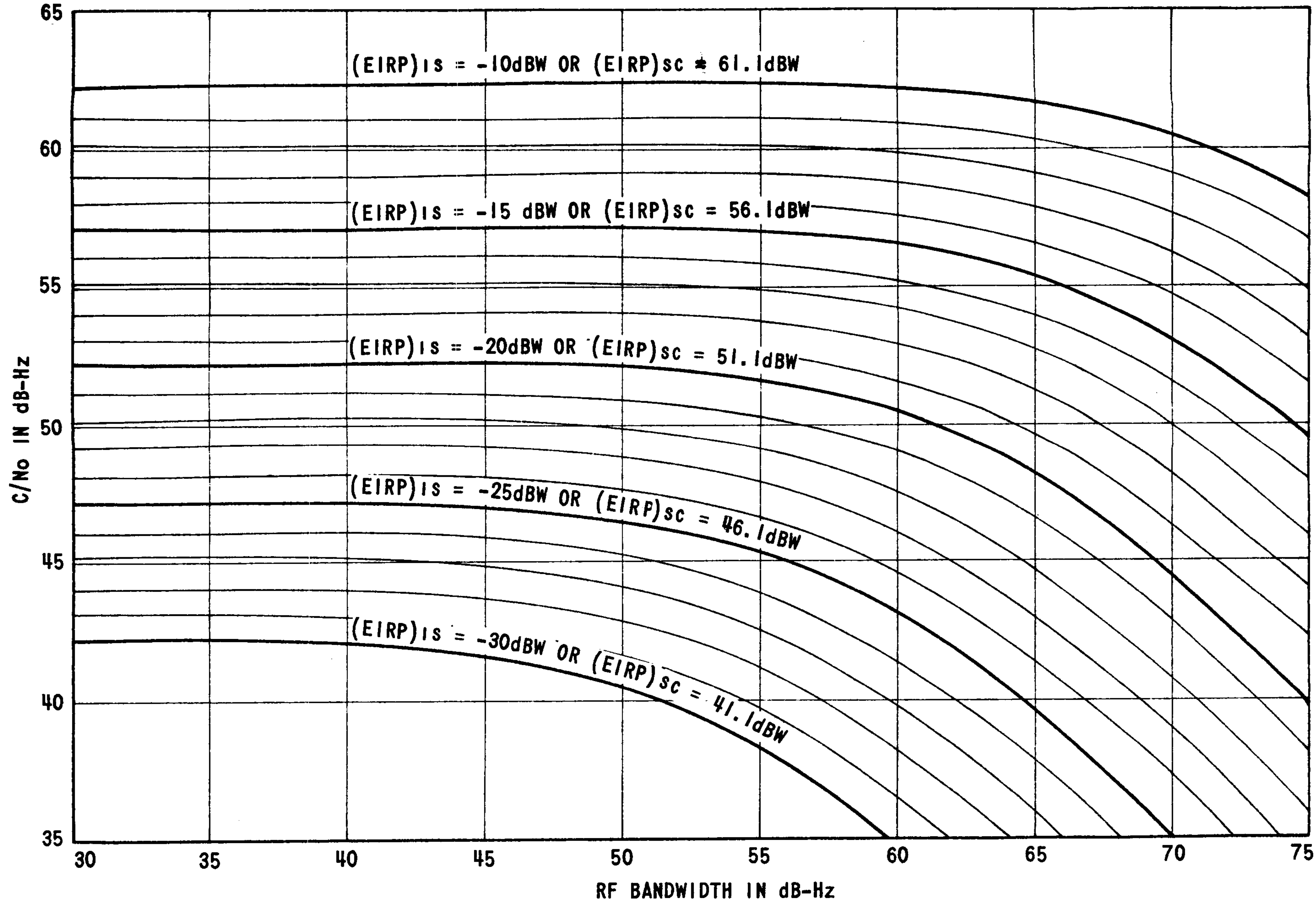


FIGURE B-4 - INTELSAT IV UTILIZATION REQUIREMENT. SPACECRAFT TO GROUND LINK USING EARTH COVERAGE ANTENNA

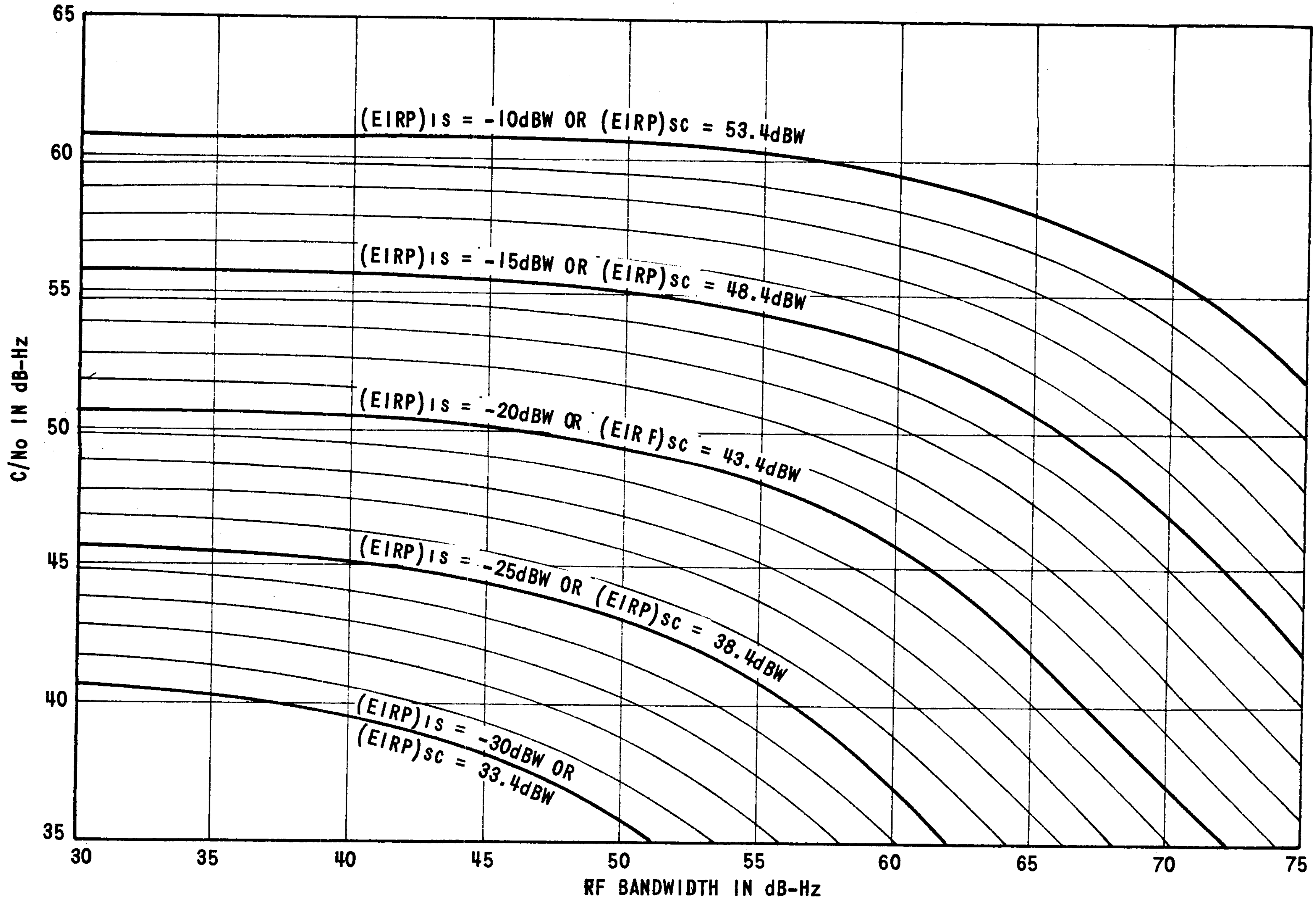


FIGURE B-5 - INTELSAT IV UTILIZATION SPACECRAFT TO GROUND LINK USING SPOT COVERAGE ANTENNA

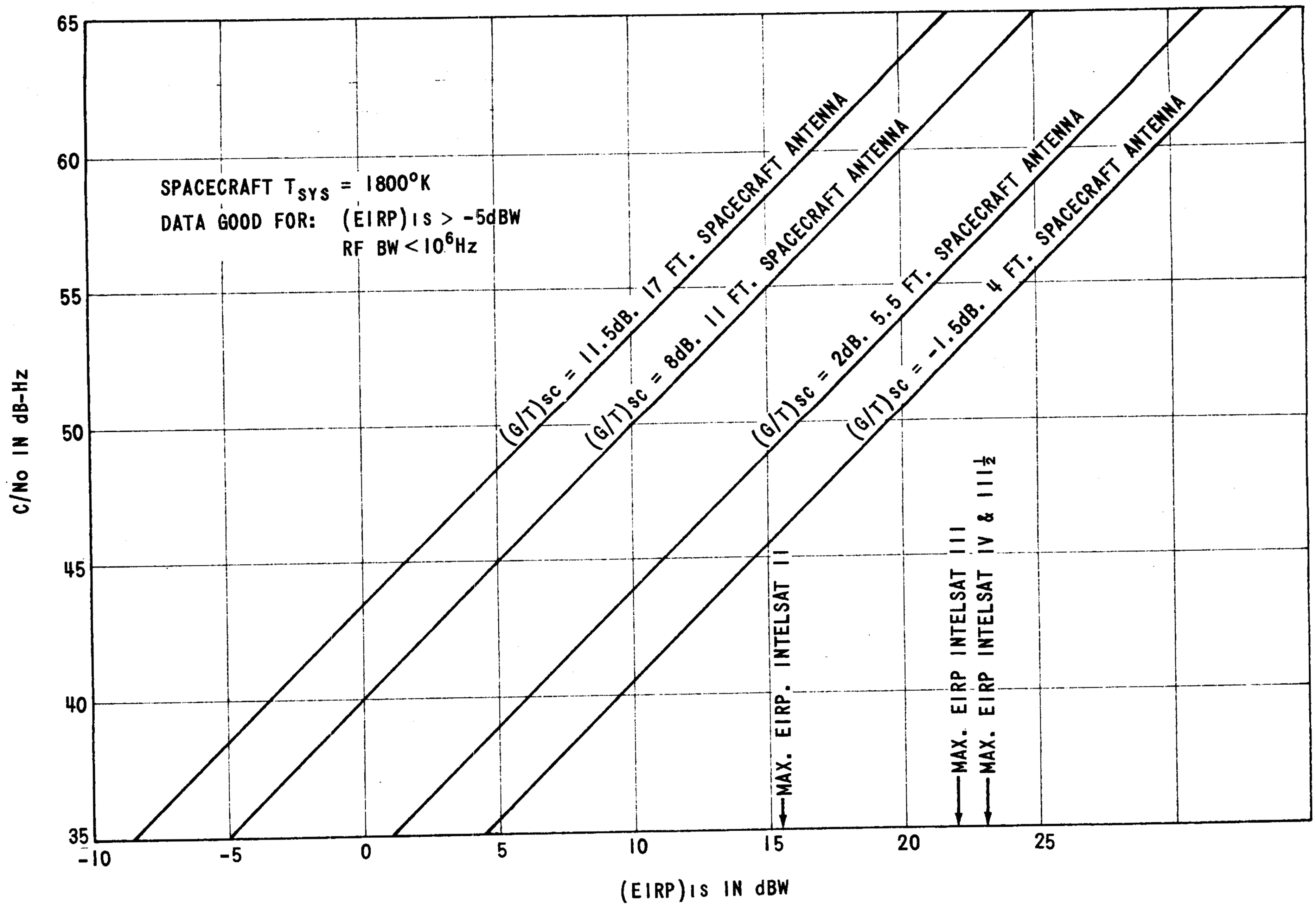


FIGURE B-6 - INTELSAT UTILIZATION REQUIREMENTS
GND——INTELSAT——SPACECRAFT LINK

APPENDIX C

Interference Limits and Spread Spectrum Techniques

From Appendix A, it is seen that a maximum allowable signal power spectral density exists for the Intelsat satellites and the manned spacecraft for the purpose of avoiding RF interference with the microwave radio relay systems on earth. For the particular application discussed in this memorandum, these limits are:

Intelsat satellites

$$\text{maximum EIRP}^* = -24.6 \text{ dBW/Hz} \tag{C-1}$$

Manned spacecraft

$$\text{maximum EIRP} = -49 \text{ dBW/Hz} \tag{C-2}$$

The restriction is particularly severe for the manned spacecraft when one uses the normal procedures to size a minimum system. To illustrate, we have been using the parameter carrier to noise spectral density ratio (C/N_0) to indicate the RF performance requirements of a particular communications functions. This quantity varies according to the modulation method chosen and consists of two basic parameters:

$$C/N_{0_{req}} = S/N_{req} \times B_{req} \tag{C-3}$$

Simply, for a given modulation method, a signal-to-noise ratio (S/N_{req}) must be maintained in a required bandwidth (B_{req}) when the quality of the communications function is specified. If our objective is to minimize the RF parameters of the system (e.g., antenna size and transmitter power), both S/N_{req} and B_{req} need to be optimized to arrive at a minimum $C/N_{0_{req}}$.

*Effective isotropic radiated power

The RF interference limit, effectively imposes a maximum EIRP that can be transmitted as a direct function of the RF bandwidth used. It can be shown that under certain conditions the performance requirement of the communications function cannot be fulfilled. To remedy this situation, one may choose a modulation method which would allow a large expansion of RF bandwidth, therefore, the allowable EIRP, but with proportionally less increase in $C/N_{0_{req}}$, that is:

$$\frac{\Delta B}{\Delta C/N_{0_{req}}} > 1 \qquad \text{(C-4)}$$

There are a number of techniques which satisfy (C-4). Several are discussed below.

A. Analog Transmission

The RF bandwidth of an analog signal, such as voice, can be expanded by using frequency modulation (FM). This is done by increasing the modulation index (m) while the baseband signal frequency remained fixed. Besides the increase in RF bandwidth, two other net effects result; one is the increase in the threshold C/N_0 requirement and the other is an improvement in baseband signal quality after demodulation $(S/N)_{out}$. Equation (C-4) is satisfied when a FM with feedback (FMFB) receiver is used. Figure C-1 is a plot of the increase in bandwidth vs the relative increase in RF power required. These data are taken from the analysis by Enloe* and Nelson.** The conventional FM receiver performance is also included for comparison to show that it fails the criterion of (C-4). Figure C-2 provides the net advantage of using a FMFB receiver. For instance, with m=20, the RF link performance can be improved by 4 dB over that of m=2. The attendant improvement in S/N_{out} is also given in the same figure.

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*L. H. Enloe, "The Synthesis of Frequency Feedback Demodulators", Proceedings of NEC, Oct., 1962.

**W. L. Nelson, "An Evaluation of Wide-Deviation FM Employing Frequency Feedback Demodulation", Memorandum for File, #MM-62-4213-5, Bell Telephone Laboratories, Inc., May 16, 1962.

App endix C (Contd.)

B. Digital Transmission

There are many techniques for digital transmission that would occupy an RF spectrum larger than required in order to improve system performance. Usually, under power limited conditions, for a given information bit error rate and data rate, the required C/N_0 decreases as the spectrum utilization is increased. Therefore, it is clear that, for the digital transmission case, a double advantage can be obtained by using a spread spectrum technique: (1) increase in the EIRP allowed, and (2) decrease in $C/N_{0_{req}}$. However, in order to derive the second advantage, it also incurs the disadvantage of system complexity at both the sending and the receiving terminals. Some of the typical systems that fall into this category are M'ary FSK, and numerous coding techniques (e.g., orthogonal and biorthogonal sequences). Figure C-3 provides a comparison of an M'ary FSK system with M=16 and a coherent binary PSK system. It is seen that the M'ary system would provide a net advantage of 8 dB (6 dB in bandwidth expansion and 2 dB in $C/N_{0_{req}}$) over uncoded PSK system for information bit error rate of 10^{-3}.

A simpler technique can be used which would forego the second advantage. It uses a binary psuedo-noise (PN) code which is clocked at a much higher rate than the data rate. If the data is logically combined with the PN code which in turn modulates the RF carrier, then by the use of a synchronous matched PN code, the combined signal can be compressed at the receiving terminal and yields the original data. In this case the performance requirement is identical to that required when no PN code is used. The net advantage in the link performance is directly proportional to the bandwidth expansion ratio (clock rate divided by the data rate).

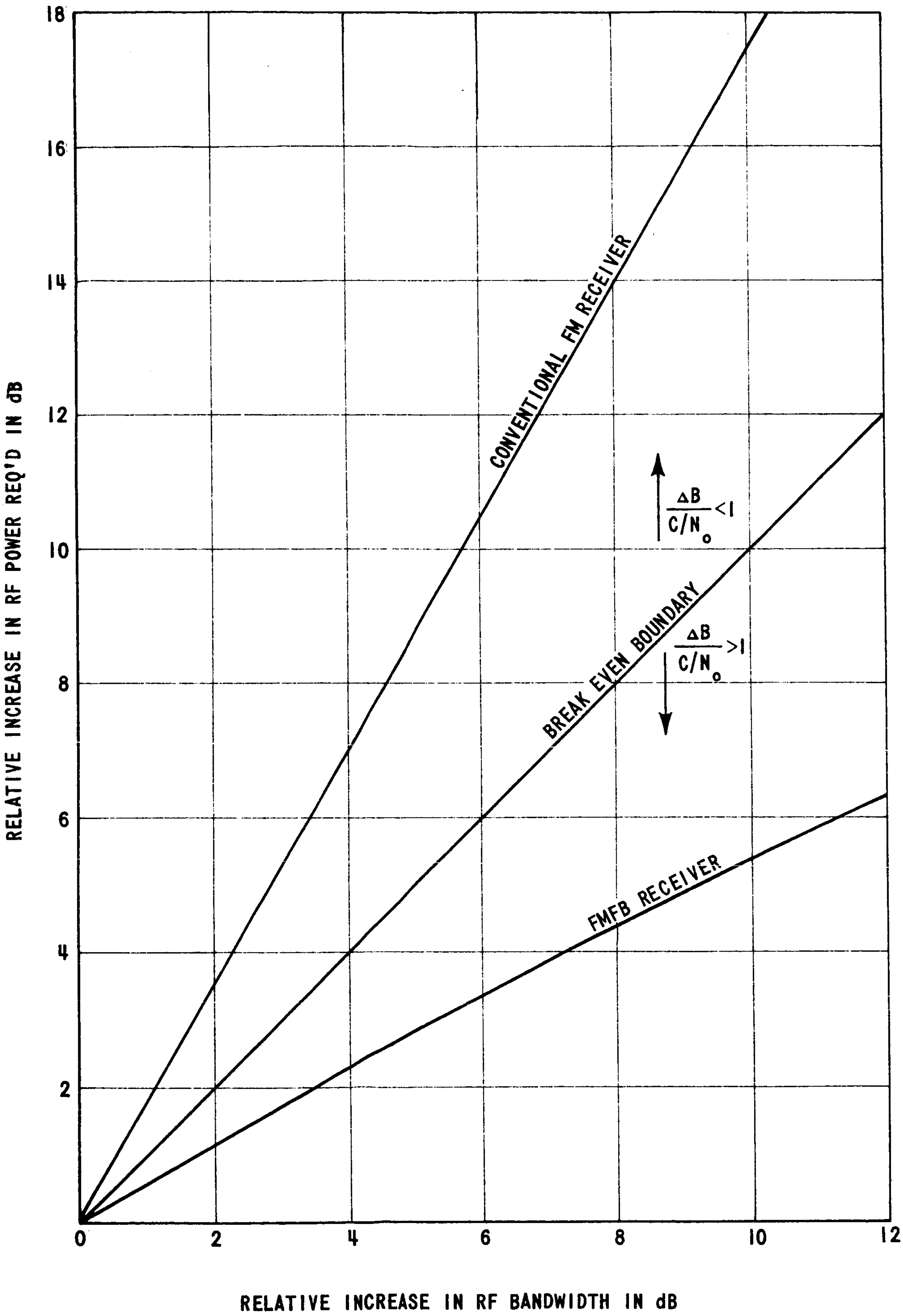

FIGURE C-1 - RELATIVE THRESHOLD PERFORMANCE REQUIREMENTS FOR FM RECEIVERS

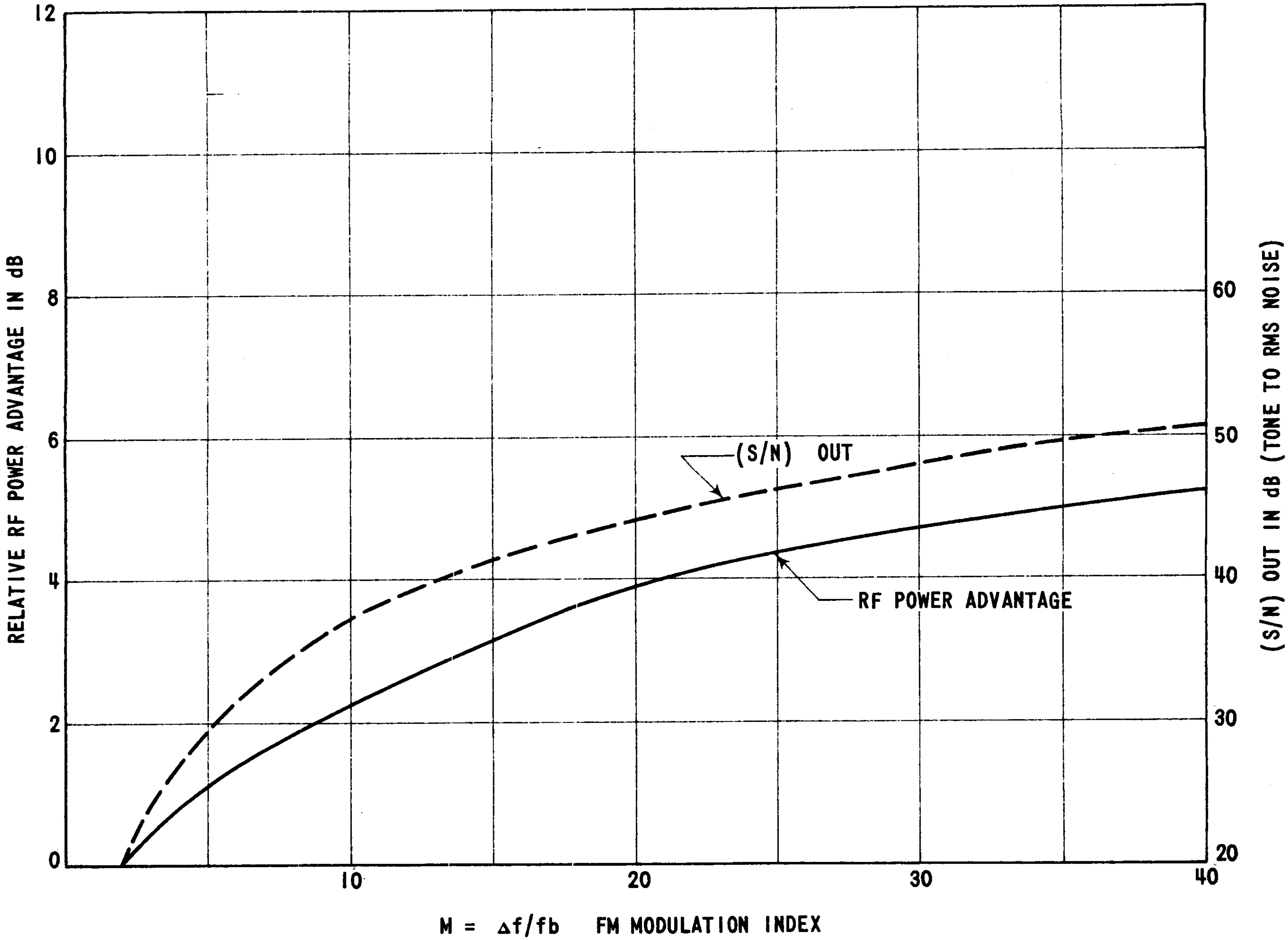

FIGURE C-2 - ADVANTAGES OF USING WIDE-BAND FM WITH FMFB RECEIVER FOR ANALOG VOICE UNDER INTERFERENCE LIMITED CONDITION

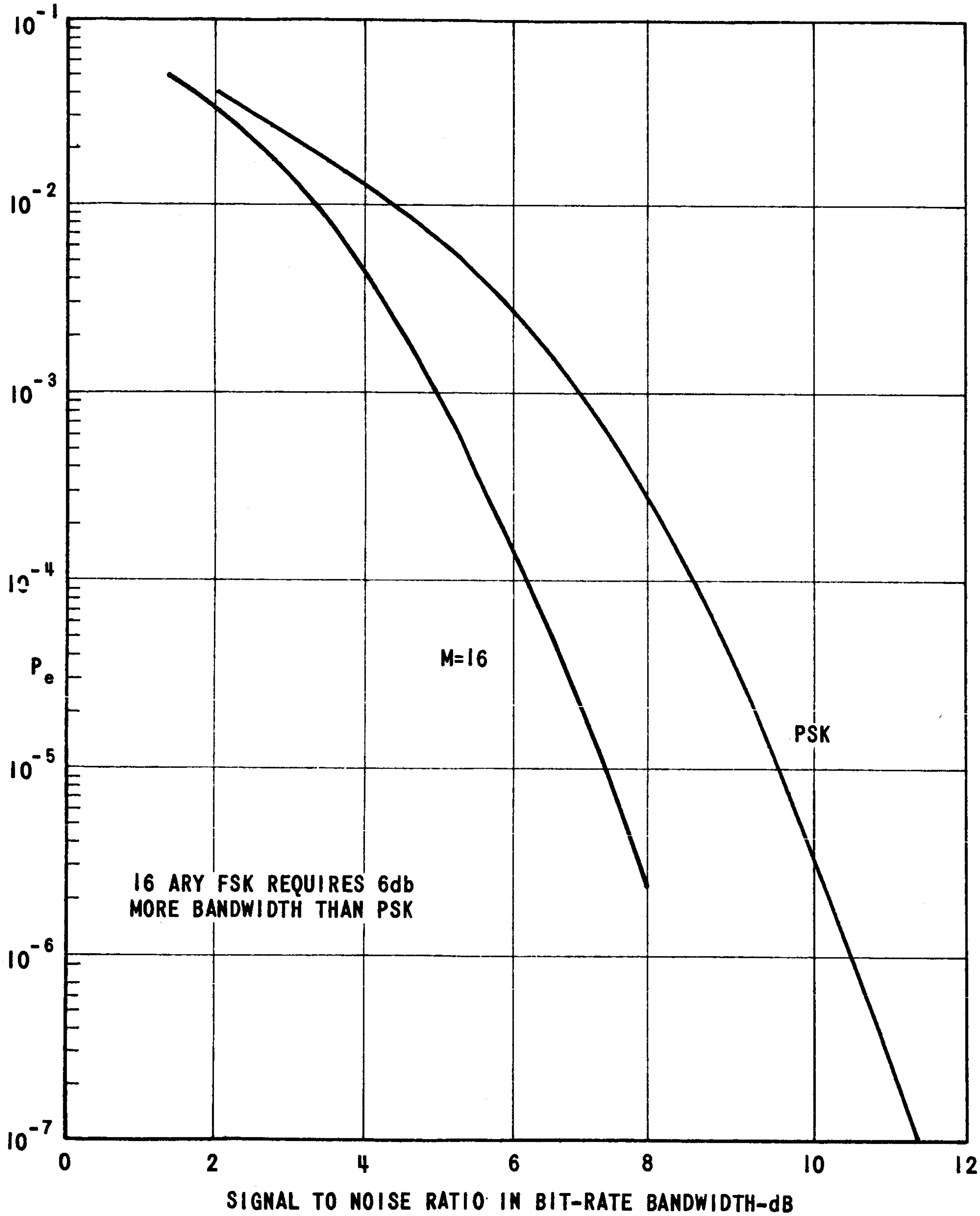

FIGURE C-3 - PROBABILITY OF A BIT ERROR AS A FUNCTION OF SIGNAL ENERGY PER BIT TO NOISE SPECTRAL DENSITY

APPENDIX D

Assumptions and Procedures of Cost Estimates for Utilizing Intelsat Satellites

The estimates of the cost of utilizing Intelsat satellites are based on several assumptions:

1. There is no cost differential among different types of Intelsat satellites at a given time.

2. The utilization of Intelsat satellites by manned space flight operations is a unique application, therefore, the orbiting manned spacecraft is treated as a distinct and independent user terminal.

3. Distinct carrier group assignments are dedicated to the two-way voice relay link for and during manned space flight operations.

4. The carrier groups assumed are those presently planned for Intelsat III as follows:*

   a. 5 MHz -- 24 equivalent voice channels

   b. 10 MHz -- 60 equivalent voice channels

   c. 20 MHz -- 132 equivalent voice channels

   d. any combinations of a, b, and c.

   The implication is that these are the integral carrier group and, therefore, represent the number of equivalent voice channels that must be purchased regardless of the actual RF bandwidth needed for a single two-way voice transmission by manned space flight operations.

5. Each equivalent voice channel represents a single unit cost in dollars regardless of their allocation in the carrier group assignment.

Two criteria are used for estimating the cost, the RF bandwidth used and the Intelsat satellite EIRP used. Both parameters have been calculated in Section V , they are compared and

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*R. Stamminger, " Transmission System Planning for Intelsat III", Presented at AIAA Second Communication Satellite Systems Conference, April, 1968. AIAA Paper No. 68-448.

determined as to which is the dominant parameter. For instance, for the up-link case very little bandwidth is needed but a large amount of satellite EIRP is used. The reverse is true for the down-link.

To translate the EIRP of the Intelsat satellite to equivalent voice channels, the following procedure is used:

1. Determine the required EIRP as a percentage of the total EIRP available from the Intelsat satellite. The available EIRP of the satellites are as follows:

Intelsat II	13.5 dBW
Intelsat III	23.0 dBW
Intelsat III 1/2	30.5 dBW
Intelsat IV	42.0 dBW

   These numbers are those presented in Table I less 2 dB. The 2 dB difference takes care of the "back-off" factor which is needed for avoiding excessive intermodulation distortion caused by the TWTA on the satellite operating near saturation under multiple carrier operations.

2. The number of equivalent voice channels needed is the product of percentage EIRP used and the total channel capacity of the satellite. The voice channel capacities of the various satellites are:

Intelsat II	480 equivalent voice channels
Intelsat III	2,400 equivalent voice channels
Intelsat III 1/2	3,800 equivalent voice channels
Intelsat IV	16,000 equivalent voice channels

3. The number of equivalent voice channels used (i.e., must be purchased) is the integral number of equivalent voice channels of a particular carrier group as indicated in 4a, b, c, and d as follows:

Appendix D (Contd.)

Number of Channels Needed	Number of Channels That Must be Leased
1 to 24	24
25 to 60	60
60 to 132	132
132 to 156	156
156 to 192	192
192 to 264	264

and so on.

The up and down-links will be combined into one carrier group for all cases except when the down-down-link uses the spot coverage antenna of Intelsat IV. For the latter case, an individual carrier group has to be used for each link. The implication is that if the up-link cost is primarily due to satellite EIRP used and the down-link cost is primarily due to the satellite bandwidth used, then the combined cost is the larger of the two.