A Reproduced Copy

OF

NASA CR- 167, 911

Reproduced for NASA

by the

NASA Scientific and Technical Information Facility

FFNo 672 Aug 65

NF02697

COMMUNICATIONS SATELLITE SYSTEMS CAPACITY ANALYSIS
Contract No. NAS3-22888

Final Report
NASA CR-167911

Prepared By:

Systematics General Corporation
1606 Old Ox Road
Sterling, VA 22170

Larry Browne, Taylor Hines, and Brian Tunstall

June, 1982

Prepared For:

NASA-Lewis Research Center
Cleveland, Ohio 44135

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. NASA CR-167911	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle COMMUNICATIONS SATELLITE SYSTEMS CAPACITY ANALYSIS	5. Report Date June, 1982
	6. Performing Organization Code

7. Author(s) Larry Browne, Taylor Hines and Brian Tunstall	8. Performing Organization Report No.

9. Performing Organization Name and Address Systematics General Corporation 1606 Old Ox Road Sterling, Virginia 22170	10. Work Unit No.
	11. Contract or Grant No. NAS3-22888
	13. Type of Report and Period Covered

12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	Contractor Report
	14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager, Dr. E. Miller, NASA Lewis Research Center, Cleveland, Ohio

16. Abstract

This study compares analog and digital modulation techniques with regard to efficient use of the geostationary orbit by communications satellites. Included is the definition of the baseline systems (both space and ground segments), determination of interference susceptibility, calculation of orbit spacing, and evaluation of relative costs. It is assumed that voice or TV is communicated at 14/11 GHz using either FM or QPSK modulation. Both the Fixed-Satellite Service and the Broadcasting-Satellite Service are considered. For most of the cases examined the digital approach requires a satellite spacing less than or equal to that required by the analog approach.

17. Key Words (Selected by Author(s)) communication satellites orbit spacing frequency modulation QPSK	18. Distribution Statement Unclassified - Unlimited

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 116	22. Price*

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Summary

The geostationary orbit is a valuable and limited resource for the positioning of communication satellites. The orbital slots in the sector of the orbit visible to the United States are being filled rapidly with satellites in the Fixed-Satellite Service (FSS) and soon they will start being filled with satellites in the Broadcasting-Satellite Service (BSS). This study treats one aspect of the attempt to increase orbit utilization efficiency, namely the impact of modulation choice upon satellite spacing. The types of modulation considered are FM, a traditional analog technique, and QPSK, a digital technique with good interference tolerance characteristics. This study considers systems which are in the FSS and BSS and which operate in the 14/11 GHz band. The service area is assumed to be the United States and the type of traffic considered includes voice and TV.

The study proceeds by carefully defining the system models. The bandwidth expansion factor for the systems is chosen subject to fidelity and signal to noise ratio considerations. Link budgets are prepared using standard techniques and the effect of rain on the system operating points is determined.

The satellite spacing is calculated by means of an expression which relates spacing to all of the link and geometrical parameters of the victim and interfering systems. Acceptable levels of performance are based on CCIR criteria.

To illustrate the cost penalties associated with efficient modulation, a satellite cost model developed by the U.S. Air Force was used to relate satellite cost to satellite power. Satellites representative of both the FSS and BSS are considered.

It is concluded that:

(1) In telephony systems, digital modulation reduces satellite spacing requirements by a factor of at least three relative to analog modulation systems unless uplink fading occurs, in which case the digital approach shows no advantage relative to the analog approach.

(2) In TV systems, digital modulation reduces satellite spacing requirements by a factor of from two to five relative to analog modulation.

1.0   Introduction

The geostationary orbit is a valuable and limited resource for the
positioning of communication satellites. The orbital slots in the sector of
the orbit visible to the United States are being filled rapidly with satellites
in the Fixed-Satellite Service (FSS) and soon they will start being filled with
satellites in the Broadcasting-Satellite Service (BSS). As of September 1981
approximately one half of the FSS slots in the 6/4 GHz band in the U.S.
visibility sector were filled and two satellites were operating in the 14/11
GHz band. By 1984 it is expected that the 6/4 GHz band will be full and the
14/11 GHz band about half full.

One approach to increase the efficiency with which this resource is
utilized is to space the satellites more closely. Indeed, the FCC has recently
proposed to decrease the 6/4 GHz band spacing from 4° to 2° and the 14/11 GHz
band spacing from 3° to 2°.

This study treats one aspect of the attempt to increase orbit utilization
efficiency, namely the impact of modulation choice upon satellite spacing. The
types of modulation considered are FM, a traditional analcg technique, and
QPSK, a digital technique with good interference tolerance characteristics.

The study considers systems which are in the FSS and BSS and which
operate in the 14/11 GHz band. The service area is assumed to be the United
States and the type of traffic considered includes voice and TV.

Chapter Two of this report establishes the models used in the subsequent
analysis: the bandwidth expansion used by both modulation formats is selected,
the baseline systems are described, and the effect of rain on communication

satellite operating point is reviewed. In Chapter Three the baseline system models are subjected to a detailed spacing and efficiency analysis: a general expression for spacing as a function of single entry and multiple entry interference levels is developed and the spacing requirements are calculated for both the FSS and BSS systems. In Chapter Four a cost analysis is performed which determines the relationship between satellite power and satellite cost; both recurring and non-recurring costs are considered. Overall conclusions of the study are contained in Chapter Five. Appendices A and B provide, as reference, the relevant ITU regulations and existing and planned systems, respectively.

2.0 Baseline Systems

The term baseline systems, as used here, refers to specified satellites and earth stations, either hypothetical or real, which function together in a manner representative of the fixed-satellite service (FSS), or of the broadcasting-satellite service (BSS), and which have technical parameters and operating characteristics chosen in a way that will permit valid comparisons of system capacity. System capacity has been analyzed in terms of the number of channels per unit of satellite spacing in the geostationary orbit per unit of spectrum. The comparisons of interest are between systems serving the same function but employing different modulation techniques (viz., analog and digital). Analog systems were assumed to use frequency modulation for television (TV/FM) and frequency modulation with frequency division multiplexing (FDM/FM) for voice. Digital systems were postulated using quadriphase shift keying (QPSK) for television and QPSK with time division multiplexing (TDM) for voice.

This chapter discusses the choice of RF bandwidths, the selection of baseline FSS and BSS systems, and the determination of system operating points.

2.1 Bandwidth Expansion Factor

The bandwidth expansion factor is defined:

$$BEF = \frac{\text{Bandwidth of modulated signal}}{\text{Bandwidth of the baseband signal (3.1 kHz-voice, 4.2 MHz-television)}}$$

The selection of bandwidth expansion factors for analog and digital systems took into account parameters representative of existing or planned systems. Furthermore, to fulfill the contract requirements the digital satellite system was constrained to:

(1) Utilize QPSK modulation

(2) Operate at a data rate for voice such that the bandwidth of the QPSK spectrum for digitized, coded, time multiplexed voice was the same, per channel, as the per channel bandwidth of FDM/FM voice channels.

(3) Operate at a data rate for video such that the bandwidth of the QPSK spectrum for digitized, coded video was the same as the bandwidth of an FM video channel.

2.1.1 Relation of Circuit Quality, C/N Ratio, and RF Bandwidth for Voice Systems

For FDM/FM voice systems, the circuit quality is dependent upon the post-detection signal-to-noise ratio (S/N). The S/N, the predetection carrier-to-noise ratio (C/N), and the RF bandwidth of the modulated signal are related as follows:[1], [2]

$$S/N = (C/N) \times \frac{3(F_{ch})^2}{f_2^3 - f_1^3} \times B_{RF} \times p \times W \qquad (2\text{-}1)$$

or

$$S/N = (C/N) \times \frac{(F_{ch})^2}{(f_m)^2 + \frac{b^2}{12}} \times (B_{RF}/b) \times p \times W \qquad (2\text{-}2)$$

where

> S/N = the ratio of test-tone power (1 mW at the point of zero relative level) to the psophometrically-weighted noise power in the highest telephone channel;
>
> C/N = the ratio of carrier power to noise power within the radio frequency bandwidth, B_{RF}.
>
> B_{RF} = the radio-frequency bandwidth (Hz).
>
> f_2 = the upper frequency bound of the passband of the highest baseband channel (Hz).
>
> f_1 = the lower frequency bound of the passband of the highest baseband channel (Hz).
>
> f_m = $(f_2 + f_1)/2$ = the mid-frequency (arithmetic mean) of the highest baseband channel (Hz).
>
> b = $(f_2 - f_1)$ = the bandwidth of the telephone channel (Hz).
>
> F_{ch} = the rms test-tone deviation per channel (Hz).
>
> p = the pre-emphasis improvement factor,
> = 4.0 dB
>
> W = the psophometric weighting factor.
> = 2.5 dB.

The preceding expression for the FM signal-to-noise ratio can be replaced with negligible error, by the approximation

$$S/N \cong (C/N) \times (F_{ch}/f_m)^2 \times (B_{RF}/b) \times p \times W \qquad (2-3)$$

provided that the value of f_m is greater than four times the value of b. This condition is usually met in multichannel systems; the value of b is typically 3100 Hz and the value of f_m is in hundreds of kilohertz[1], [2]. The ratio of the radio frequency bandwidth to the baseband width, B_{RF}/b, is the bandwidth expansion factor.

2-3

In planning an FDM-FM system, all the parameters in equation (2-3) are usually fixed by design goals except B_{RF} and F_{ch}. For example, the desired S/N is set by circuit quality criteria; the minimum carrier-to-noise ratio, C/N, must usually exceed some threshold determined by the FM demodulator; the telephone channel bandwidth, b, is an industry standard as are the factors p and W; f_m is usually taken to be 4.2 kHz times the number of voice channels[1], [2], [3].

To solve for F_{ch} and B_{RF}, one additional relationship between these two variables is required. This additional relationship is provided by Carson's rule, i.e.,

$$B_{RF} = 2(\Delta f + f_m) \qquad\qquad (2-4)$$

where

Δf = the multi-channel peak deviation = $F_{ch} \times g \times L$

g = peak to rms factor as a numerical ratio

$L = 10^{(-15 + 10 \log n)/20}$ $n \geq 240$ channels

    $= 10^{(-1 + 4 \log n)/20}$ $n < 240$ channels

n = number of telephone channels.

Early systems assumed a peak-to-rms factor of 4.47 while more recently a value of 3.16 has been used[1], [2], [3].

These relationships are used in subsequent sections to determine required carrier-to-noise ratios.

Circuit quality in digital systems generally depends upon the system bit-error-rate (BER), which depends on the predetection carrier-to-noise ratio C/N or E_b/N_0 ratio. In contrast to analog systems, this ratio is independent of the system bit rate or bandwidth expansion factor. For this report, the statement of work specified a 10^{-6} BER to define the circuit quality, corresponding to an E_b/N_0 of 10.5 dB. (This value corresponds to current CCIR criteria for digital voice circuits).

2.1.2 Choice of Bandwidth Expansion F·ctor For Voice Signal Systems

The bandwidth expansion factor for digital voice signals will depend upon the bit rate associated with a single voice channel. For FDM/FM, the dependence is more complex. In order to determine a single value of bandwidth expansion factor applicable to both FDM/FM and digital modulation it is useful to begin by surveying some existing and proposed digital systems.

The CCITT[4] specifies a particular pulse code modulation (PCM) format to be used in international connections of voice signals, resulting in a total bit rate of 64 kbit/s per speech channel.

Another PCM standard used in the INTELSAT single-channel-per carrier system also resulted in a gross bit rate of 64 kbit/s[1], [2]. The same reports also discuss adaptive differential pulse code modulation (ADPCM) that can be used for speech as well as for television signal coding. Extensive measurements have indicated using ADPCM a telephone signal can be transmitted at a rate of 32 kbit/s with the same subjective quality achieved by a standard PCM signal at the rate of 64 kbit/s.

2-5

Other schemes such as delta modulation and differential pulse code modulation allow bit rates in the range of 32 kbit/s to 64 kbit/s for toll or better quality. Bandwidth-per-voice channel and bandwidth expansion factors for this range of values are listed in Table 2-1.

For comparison, Table 2-2 lists published INTELSAT IV transmission parameters for FDM/FM systems for a wide range of number-of-voice channels-per-carrier. Occupied bandwidth-per-voice channel values were computed for each case and listed for comparison with digital values previously listed. Computed S/N ratios indicate that all FDM/FM cases meet current CCIR circuit quality criteria (51 dB).

The average of the occupied bandwidth-per-channel values computed from the INTELSAT data is about 29 kHz. From Table 2-1, the corresponding values in a digital system required a data rate of about 48 kbit/s per voice channel. The resultant bandwidth expansion factor would be 9.3.

Table 2-3 was prepared to examine the effect of bandwidth expansion factor upon predetection carrier-to-noise ratio for FDM/FM systems for comparison with digital requirements. It is evident that bandwidth expansion ratios less than about 10 require substantially higher C/N ratios.

The digital system must operate at an E_b/N_o value of about 10.5 dB for a bit error rate of 10^{-16}. The resultant value of C/N may then be determined as:

$$(C/N) = (E_b/N_o) + N + R - 10 \log \text{(noise bandwidth)} \qquad (2-5)$$

2-6

Table 2-1

Bandwidth Expansion Factor Computations

Bit Rate Per Channel (kbit/s)	Bandwidth Per Channel (kHz)	Bandwidth Expansion Factor
32	19.2	6.2
34	20.4	6.6
36	21.6	7.0
38	22.8	7.4
40	24.0	7.7
42	25.2	8.1
44	26.4	8.5
46	27.6	8.9
48	28.8	9.3
50	30.0	9.7
52	31.2	10.1
54	32.4	10.5
56	33.6	10.8
58	34.8	11.2
60	36.0	11.6
62	37.2	12.0
64	38.4	12.4

NOTE: Assumed bandwidth for QPSK = 1.2 (Bit Rate)/2
Bandwidth Expansion Factor = Bandwidth/(3.1 kHz)

Table 2-2

Spot-beam INTELSAT IV Transmission Parameters (8000 PWP) For Standard and Expanded Carriers From COMSAT Technical Review Volume 2, #2, Fall 1972

# of Channels	Top Baseband Frequency (kHz)	Occupied Bandwidth (MHz)	RMS Multi-Carrier Deviation (kHz)	C/N (dB)	Computed S/N (dB)	Occupied Bandwidth Per Channel (kHz)
60	252	2.25	276	21.1	50.9	37.5
72	300	2.25	261	23.4	50.9	31.3
132	552	4.40	529	20.7	50.7	33.3
192	804	4.50	459	25.8	50.9	23.4
192	804	6.40	758	19.9	50.9	33.3
252	1,052	6.75	733	23.2	51.0	26.8
252	1,052	8.50	1,009	19.4	50.9	33.7
312	1,300	9.00	1,005	22.0	51.0	28.8
432	1,796	13.00	1,479	21.2	50.9	30.1
612	2,540	17.80	1,996	21.9	51.1	29.1
792	3,284	18.00	1,784	26.2	51.2	22.7
792	3,284	22.40	2,494	22.3	51.0	28.3
972	4,028	22.50	2,274	25.7	51.0	23.1
1,872	8,120	36.00	3,181	29.5	50.6	19.2

Table 2-3

FDM/FM, C/N Required

Bandwidth Expansion Ratio	For 12 Channels (dB)	For 60 Channels (dB)	For 240 Channels (dB)
4.0	47.4	43.2	39.9
6.0	37.6	33.4	30.0
8.0	32.2	28.0	24.7
10.0	28.4	24.2	20.9
12.0	25.5	21.3	18.0
14.0	23.2	19.0	15.6
16.0	21.2	17.0	13.6
18.0	19.4	15.2	11.9
20.0	17.9	13.7	10.4

where: N = 10 log (number of channels)

R = 10 log (bit rate-per-channel)

Assuming the noise bandwidth to be equal to the occupied bandwidth and assuming that the occupied bandwidth of a QPSK signal is 1.2 times the numeric value of the symbol rate:

$$BN = 10 \log (1.2 \cdot N \cdot R/2) = -2.2 + N + R \tag{2-6}$$

and substituting Eq. (2-6) into Eq. (2-5):

$$(C/N) = (E_b/N_o) + N + R + 2.2 - N - R$$

$$(C/N) = (E_b/N_o) + 2.2 \tag{2-7}$$

Thus, for an E_b/N_o of 10.5 dB and an 0.8 dB implementation loss, the digital system will require a 13.5 dB C/N, independent of the bit rate per voice channel (and bandwidth expansion ratio) as well as the number of channels.   In contrast, from Table 2-3 for the FDM/FM system, the required C/N ratio is:

(1)   Dependent upon the bandwidth expansion factor (ratio),

(2)   For less than 240 channels-per-carrier, dependent upon the number of voice channels,

(3)   Only as small as the 13.5 dB value required by the digital system for greater than 240 voice channels and a bandwidth expansion factor in excess of about 16.

A bandwidth expansion factor of 16 would require that:

$$16(3.1 \times 10^3) = 1.2 \ (\text{Bit Rate})/2$$

and: Bit Rate = 82.7 kbit/s per voice channel

This is clearly an excessive value for voice transmission. It is now evident that practical analog and digital systems meeting current CCIR circuit quality criteria and exhibiting the same RF bandwidth per voice channel <u>cannot operate at identical C/N ratios.</u>

The analog system must operate at a higher value of C/N than the digital system, placing the analog system at a considerable disadvantage for inter-satellite spacing and capacity comparisons. With this observation in mind, and considering the data of Tables 2-1 through 2-3, four candidate cases were selected for further examination, and are presented in Table 2-4.

The 32 kbit/s case was rejected since the equivalent FDM/FM system requires a 30 dB C/N, some 20 dB greater than the digital system. The 64 kbit/s case was also rejected, since the C/N for the equivalent FDM/FM system (18 dB) is less than current FDM/FM practice.

The remaining cases differ little in the constraints placed upon the FDM/FM system. The 53.3 kbit/s system was finally chosen somewhat arbitrarily to result in a 32 kHz required bandwidth-per-channel.

Table 2-4

Candidate Cases Examined

Digital System Bit Rate/Channel (kbit/s)	Bandwidth Expansion Factor	Bandwidth Per Channel (kHz)	Approximate C/N Required for FDM/FM System (dB)
32	6.2	19.2	30
48	9.3	28.8	22
54	10.5	32.4	21
64	12.4	39.4	18

This implies a bandwidth expansion factor of 10.32; parameters for the resultant systems are then as follows:

Digital System -

Bit Rate/Voice Channel = 53.3 kbit/s

Occupied Bandwidth (QPSK) = 1.2 (Bit Rate)/2 = 32 kHz/channel

FDM/FM System -

Bandwidth Expansion Factor - 10.32

See Table 2-5 for computed parameters as a function of number of channels/carrier.

Table 2-5

FDM FM Parameters for BEF of 10.32

# of Channels	Top Baseband Frequency (kHz)	Computed Occupied Bandwidth (kHz)	Computed RMS Multi-Carrier Deviation (kHz)	Computed C/N (dB)
12	50	384	45	28
24	101	768	90	26
36	151	1,152	134	25
60	252	1,920	224	24
72	302	2,304	269	23
96	403	3,072	358	22
132	554	4,224	493	22
192	806	6,144	717	21
252	1,058	8,064	941	20
312	1,310	9,984	1,165	20
432	1,814	13,824	1,613	20
612	2,570	19,584	2,285	20
792	3,326	25,344	2,957	20
972	4,082	31,104	3,630	20
1,092	4,586	34,944	4,078	20
1,125	4,725	36,000	4,201	20
1,872	7,862	59,904	6,990	20

For S/N = 51 dB, occupied bandwidth/channel = 32 kHz

Peak-to-RMS factor = 10 dB

2.1.3 Choice of Bandwidth Expansion Factor For Television Signal Systems

The majority of FSS satellite television systems in use, proposed, or studied utilize a nominal 36 MHz wide frequency-modulated signal to transmit the video portion of the program. The provisions for transmission of the audio portion of the program, in comparison, occupy a negligible bandwidth and will not be considered further.

For an allocated bandwidth of 1.1 times the noise bandwidth and a top baseband frequency of 4.2 MHz, from Carson's Rule:

$$36/1.1 = d_{p-p} + 2 \times 4.2$$

A peak-to-peak deviation of 24.3 MHz would result.

For the FSS, a 53 dB post detection S/N (weighted) is required. Taking into account a 13.8 dB weighting factor and the 25.3 dB FM improvement factor resulting from a 24 MHz p-p deviation, a 13.4 dB predetection C/N would be required. This value is almost identical to the 13.5 dB value needed for a digital QPSK system (10^{-6} BER). The bandwidth expansion factor is then:

$$(24 + 2 \times 4.2)/4.2 = 7.71$$

and the required information bit rate, R, for an equivalent digital system:

$$24 + 2 \times 4.2 = 1.2 \ R/2$$
$$R = 54 \ Mbit/s$$

comfortably within the range of the present state-of-the-art.

Present BSS planning indicates TV/FM systems utilizing 12 MHz p-p deviation and requiring a 14 dB predetection C/N ratio. This value is also almost identical to the 13.5 dB value needed for digital QPSK system (10^{-6} BER).

The resulting bandwidth expansion factor is then:

$$(12 + 2 \times 4.2)/4.2 = 4.86$$

and the required information bit rate, R, for an equivalent digital system:

$$12 + 2 \times 4.2 = 1.2 \; R/2$$

$$R = 34 \; Mbit/s$$

2.2 System Descriptions

The purpose of this report is to determine the relative efficiencies of analog and digital modulation in utilizing orbit and spectrum space. The particular values obtained will depend to some extent upon the satellite link model employed for the analysis. This section will describe the satellite link models used for the analysis and list the signal characteristics that will be assumed.

The satellite link models are based upon available data for systems planned for the 12/14 GHz bands in the United States. The signal performance requirements are based upon applicable CCIR recommendations.

2.2.1 Link Model for the Fixed Satellite Service

The baseline link model for the fixed satellite service has been taken from characteristics for the Satellite Business Systems (SBS) USASAT 6A. The model

assumes 5 meter diameter earth stations for both the up and down paths and relatively broad satellite antenna beams. A sample link budget computation is shown on Table 2-6 to define the model parameters and to show power levels needed for a particular FDM/FM signal and its digital equivalent. This model sets the reciprocal of the link C/N equal to the sum of the reciprocals of the uplink C/N and the downlink C/N. Appropriate uplink and downlink margins will be inserted later in this report to account for rain attenuation.

2.2.1.1 Signal Characteristics for FSS Analog Voice

The FDM/FM signal characteristics to be used in this report have been listed on Table 2-5. They exhibit a constant bandwidth expansion factor (occupied bandwidth is 32 kHz times the number of voice channels.)

The performance criteria that will be employed are taken from CCIR Rec. 353-2. The noise power shall not exceed:

    10,000 pWOp for more than 20% of any month,

    50,000 pWOp for more than 0.3% of any month, or

    1,000,000 pWO (unweighted) for more than 0.01% of any month

    (562,300 PWOp, assuming a 2.5 dB weighting factor.)

2.2.1.2 Signal Characteristics for FSS Digital Voice

Digital voice signal characteristics assume QPSK modulation, occupying a bandwidth of 32 kHz times the number of voice channels. Time-division-multiplex at a nominal bit rate of 54 kbit/s times the number of voice channels will require a bandwidth equal to that an equivalent FDM/FM signal (digital overhead for multiplexing is assumed small enough to neglect).

2-16

Table 2-6

Link Budget for 972 Voice Channels

Uplink Computation @ 1.425×10^{10}	FDM/FM (8000 PWOP)	QPSK 10^{-6} BER
Transmitter power	22.3 dB (W)	15.7 dB (W)
Earth station antenna gain	55.5 dB (i)	55.5 dB (i)
Uplink margin	3.0 dB	3.0 dB
Basic transmission loss (35,858 km)	206.6 dB	206.6 dB
Spacecraft antenna gain	35.0 dB (i)	35.0 dB (i)
Signal power @ receiver	-96.8 dB (W)	-103.4 dB (W)
Effective noise temperature (1000 K)	30.0 dB (K)	30.0 dB (K)
Boltzmann's constant	-228.6 dB (J/K)	-228.6 dB (J/K)
Reference bandwidth (31.104×10^6 Hz)	74.9 dB (Hz)	74.9 dB (Hz)
Effective noise power @ receiver	-123.7 dB (W)	-123.7 dB (W)
Uplink C/N	26.9 dB	20.3 dB

Downlink Computation @ 1.200×10^{10} Hz		
Transmitter power	10.1 dB (W)	3.5 dB (W)
Space station antenna gain	35.0 dB (i)	35.0 dB (i)
Downlink margin	3.0 dB	3.0 dB
Basic transmission loss (35,858 km)	205.1 dB	205.1 dB
Earth station antenna gain	53.9 dB (i)	53.9 dB (i)
Signal power @ receiver	-109.2 dB (W)	-115.7 dB (W)
Effective noise temperature (225 K)	23.5 dB (K)	23.5 dB (K)
Boltzmann's constant	-228.6 dB (J/K)	-228.6 dB (J/K)
Reference bandwidth (31.104×10^6 Hz)	74.9 dB (Hz)	74.9 dB (Hz)
Effective receiver noise power	-139.2 dB (W)	-130.2 dB (W)
Downlink C/N	21.1 dB	14.5 dB
Link C/N	20.1 dB	13.5 dB

The performance criteria required are taken from CCIR Rec. 522. The BER shall not exceed:

10^{-6} for more than 20% of any month,

10^{-4} for more than 0.3% of any month, or

10^{-3} for more than 0.01% of any month.

2.2.1.3 Signal Characteristics for FSS Television

Frequency modulation from a system M (525 line, NTSC) baseband signal, 24 MHz peak-to-peak deviation, is assumed, using standard CCIR pre-emphasis and de-emphasis (13.8 dB weighting factor).

The performance criteria are taken from CCIR Rec. 567. The S/N shall not fall below:

53 dB (weighted) for more than 1% of any month, (corresponds to 39.2 dB unweighted), nor fall below

45 dB (weighted) for more than 0.1% of any month (corresponds to 31.2 dB unweighted).

An FM improvement factor of 25.8 dB (unweighted) results in required C/N ratios of 13.4 dB and 5.4 dB respectively. Since the latter is below a practical FM demodulator threshold, required C/N values of 13.4 dB and 10 dB will be assumed for the 1% and 0.1% time percentages respectively.

For digital television, QPSK modulation is assumed at a bit rate of 54 mbit/s, resulting in an occupied bandwidth identical to that of the analog frequency-modulated signal. The Statement of Work specified a 10^{-6} BER.

In order to make the analog vs. digital comparison as realistic as possible, the following performance criteria were assumed. The BER shall not exceed:

10^{-6} for more than 1% of any month
(corresponding to a C/N = 13.5 dB) nor exceed

10^{-5} for more than 0.1% of any month
(corresponding to a C/N = 12.8 dB).

2.2.2 Link Model for the Broadcasting Satellite Service

In selecting the link model for the broadcasting satellite service, applications recently received by the FCC were reviewed. These applications are summarized in Appendix B. The system proposed by the Satellite Television Corporation (STC) exhibited characteristics that generally fell within the mid-range of the 14 applications, as well as being in general accord with BSS planning criteria.

An 0.75 meter diameter receiving earth station antenna exhibiting a gain of 36.8 dB(i), a 546 K link noise temperature, and 1.8 degree 3 dB beamwidth are assumed.

2.2.2.1 Signal Characteristics for BS Analog Television

The STC system proposes a 10 MHz peak-to-peak FM deviation and occupies a bandwidth of 16 MHz (less than Carson's Rule value). A 14 dB C/N for 99% of the worst month is specified, along with a clear-air C/N value of 5.9 dB over a 10 dB demodulator threshold (15.9 dB total) to allow for down path rain fading.

It was decided to modify some of these characteristics to more closely reflect BSS planning criteria, but to maintain the fading margin to reflect a realistic case (BSS planning criteria specifies performance only for 99% of the time). Accordingly the following signal characteristics and performance criteria are assumed:

(a) 12 MHz p-p deviation

(b) 20.4 MHz Carson's Rule bandwidth

(c) C/N shall not fall below 14 dB for more than 1% of any month

(d) C/N shall not fall below 10 dB for more than 0.1% of any month. (5.9 dB fading margin assumed).

2.2.2.2 Signal Characteristics for BSS Digital Television

The highest baseband frequency for color TV signal is on the order of 5 MHz. If a digital system uses a 10 bit quantization the resulting bit rate is $5 \times 10^6 \times 2 \times 10 = 100$ MHz. Even with QPSK modulation the required RF bandwidth for such a system without the use of signal compression techniques, would be 50 MHz or more. There is a current research and development effort directed at techniques which can produce an appreciable reduction in the required bit rates by removing some of the redundant video information scan. Haskell and Steele have discussed a number of digital signal compression techniques, most of which have been successfully demonstrated. There is a tradeoff between receiver complexity (cost) and the required bit rate (bandwidth)[5]. If a digital broadcasting-satellite were to be proposed, the likelihood is high that some sort of compression technique would be employed. Consequently, for the purpose of this study is is necessary to make an estimate of the minimum bit rate sufficient to transmit quality video.

Burkhardt and Wasser, at Standard Elektrik Lorenz AG (SEL) in the Federal Republic of Germany, have demonstrated the feasibility of transmitting digitized still video frames with a bit rate of 34.368 Mbit/second using differential pulse code modulation[6]. This particular bit rate is of special interest since it is already a third order European standard for recording PCM. The necessary RF bandwidth for a 34 Mbit/s bit rate is approximately 21 to 22 MHz. This appears to be a reasonable bandwidth to assume for digital BSS use since the feasibility has been demonstrated by laboratory tests and it is consistent with existing standards and current analog TV planning, i.e., 16 to 20 MHz.

Therefore, a 34 Mbit/s QPSK signal occupying the same 20.4 MHz bandwidth as the analog TV/FM system is assumed.

The Statement of Work specified a 10^{-6} BER. In order to allow a realistic comparison of analog vs. digital modulation, the following performance criteria were assumed. The BER shall not exceed:

> 10^{-6} for more than 1% of any month
> (corresponding to a C/N = 13.5 dB) nor exceed
>
> 10^{-5} for more than 0.1% of any month
> (corresponding to a C/N = 12.8 dB).

2.3 Effect of Rain Attenuation on System Operating Points

Rain attenuation values in the 12/14 GHz bands are significant and could effect the baseline satellite system operating points to a degree that would influence the results of an analog vs. digital modulation comparison.

In this section, values of expected attenuation are listed for those time percentages pertinent to signals in the fixed satellite service and in the broadcasting satellite service. Then, using the satellite link models of the previous section, the degradation in link C/N caused by rain attenuation is computed. Finally, the performance of voice and television signals is examined in the presence of rain fading to determine whether rain attenuation is a significant factor in judging the analog vs. digital modulation comparison.

Table 2-7 lists rain attenuation values and earth station noise temperature increases computed for a number of geographic areas within the continental United States (data from and methods of CCIR Reports 563-1 (MOD 1), 564-1, and 721 (MOD 1)). The two regions labled "D" and "E" in the Table represent areas comprising the majority of the land area in the U.S. and the area of highest rain attenuation, respectively.

Values from these two representative areas were then inserted into the satellite link model of Table 2-6 to determine the link C/N degradation that would result from either up-path or down-path fading. The resultant values are listed in Table 2-8. These values may now be used in conjunction with the appropriate performance criteria and detector transfer characteristics to evaluate rain fade effects upon satellite system operating points.

Figure 2-1 shows the theoretical FM detector transfer characteristics (S/N vs. C/N) for several types of analog voice signals. Required values of post detection S/N to meet CCIR performance criteria are also shown (Rec. 353-2 and assuming link thermal noise allowance = total allowance - 2000 pWOp). One may

2-22

TABLE 2-7

Values of Rain Attenuation and Earth Station
Noise Temperature Increase (15 Deg. Elev. Angle.)

% OF TIME	UPLINK (14 GHz) (dB)					DOWNLINK (12 GHz) (dB)					EARTH STATION NOISE TEMPERATURE INCREASE (K)				
	E	D	C	F	B	E	D	C	F	B	E	D	C	F	B
0.01	17.9	13.0	9.1	7.7	7.5	13.4	9.5	6.5	5.6	4.9	277	257	225	210	196
0.1	15.2	5.7	3.2	2.4	2.4	10.4	3.7	1.9	1.4	1.4	264	166	103	80	90
0.3	5.7	3.2	1.8	0.8	0.8	3.7	2.0	1.1	0.6	0.6	166	107	65	37	37
1.0	2.8	1.3	0.8	0.0	0.5	1.7	0.8	0.6	0.0	0.3	94	49	37	0	19

NOTE: E = FLORIDA & GULF COAST

D = EAST COAST & CENTRAL U.S.

C = PACIFIC NORTH WEST

F = PACIFIC SOUTH WEST

B = CENTRAL NORTH WEST

TABLE 2-8

Link C/N Values Relative to Clear Air C/N

| % OF TIME | FLORIDA & GULF COAST | | EAST COAST & CENTRAL US | |
	UPLINK	DOWNLINK	UPLINK	DOWNLINK
0.01	-17.9 dB	-15.9 dB	-13.0 dB	-11.9 dB
0.1	-15.2 dB	-12.8 dB	- 5.7 dB	- 5.4 dB
0.3	- 5.7 dB	- 5.4 dB	- 3.2 dB	- 3.1 dB
1.0	- 2.8 dB	- 2.7 dB	- 1.3 dB	- 1.4 dB
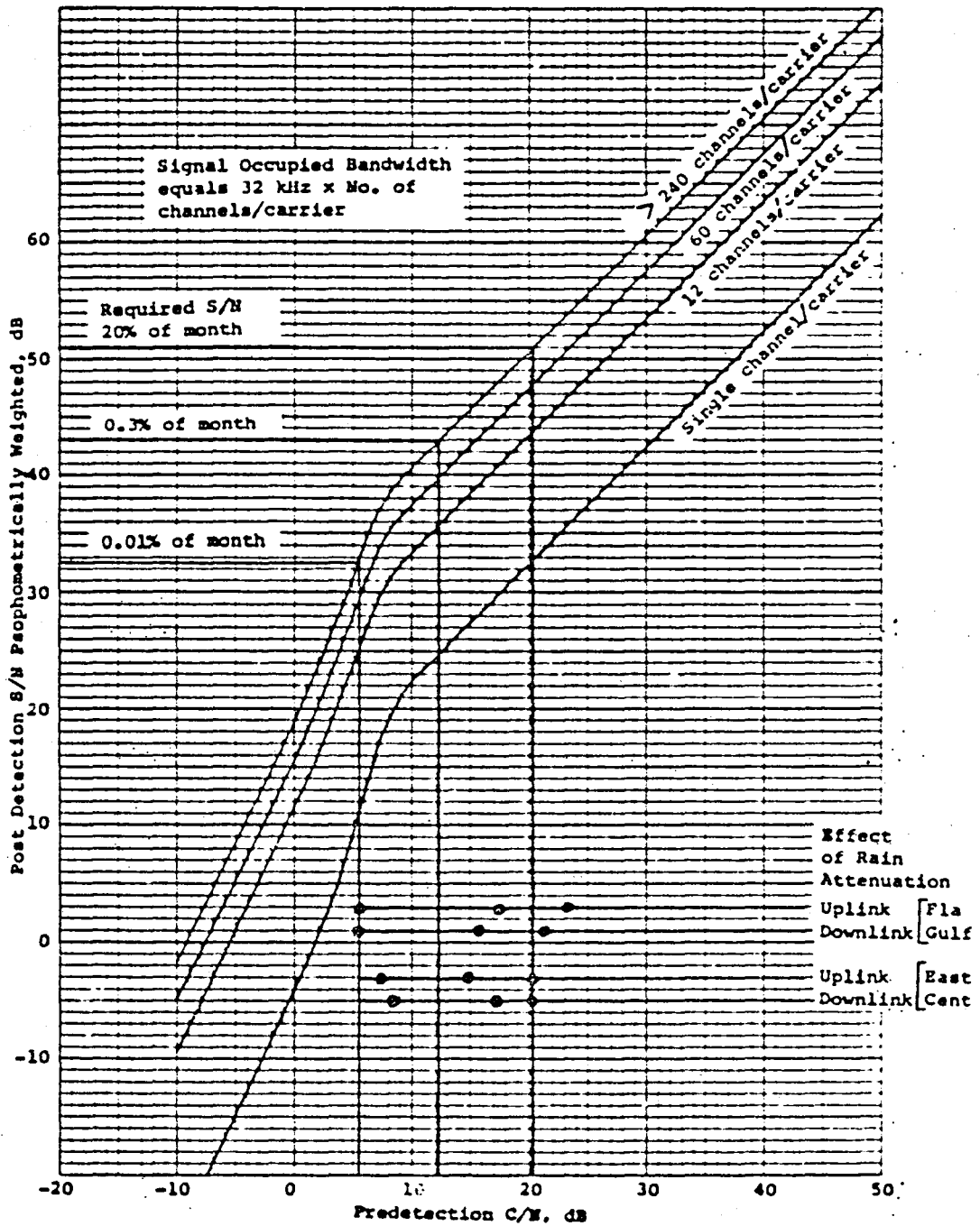
Figure 2-1. C/N Determination For More Than 240 Channels/Carrier.

determine the link C/N needed to satisfy each S/N requirement by extending each S/N value to the appropriate detector transfer curve, as shown. For example, the link C/N needed to satisfy the 0.01% performance criteria is about 5.5 dB. From Table 2-8, uplink rain attenuation in the Florida and Gulf Regions for this time percentage will reduce the link C/N by 17.9 dB. Therefore, the satellite system must be designed to provide a 5.5 + 17.9 = 23.4 dB C/N in clear air in order to meet the 0.01% performance criteria.

Examining all three time percentages, the clear air C/N must be:

To meet 20% criteria, 20.1 + 0 = 20.1 dB

To meet 0.3% criteria, 12.2 + 5.7 = 17.9 dB

To meet 0.01% criteria, 5.5 + 17.9 = 23.4 dB

and the largest value is then controlling. The satellite system must operate at a clear air C/N value of 23.4 dB to guarantee that performance criteria will be met under all specified fading conditions. A fading margin of 23.4 − 20.1 = 3.3 dB is therefore required for this case.

The results of the process just described may be illustrated graphically as shown on Figure 2-1. The resulting values of C/N for the three time percentages are shown as black dots. A modest fading margin is required for the Florida and Gulf Coast Region. No fading margin is needed for the East Coast and central region of the U.S. for FDM/FM signals.

In contrast, Figure 2-2 indicates that a fading margin is always required for TV/FM using 24 MHz p-p deviation. Note, that the 0.1% S/N value intersects the detector transfer characteristic well below threshold. Below threshold, the output noise spectrum of an FM detector changes to effectively reduce the television noise weighting factor from about 13.8 dB to perhaps 2 dB. As a result, operation below detector threshold (about 10 dB C/N) is not feasible for TV/FM.

For example, should 12 MHz p-p deviation be used? The 0.1% horizontal line would intersect the detector characteristic well above the 10 dB C/N threshold. The 31 dB unweighted S/N would then result in a weighted S/N of 31 + 13.8 = 43.8 dB which would represent satisfactory picture quality for this time percentage. However, for 24 MHz p-p deviation case, operating below threshold, the weighted S/N would increase by only about 2 dB to a value of 33 dB, representing an unsatisfactory picture quality. This limited investigation into the effect of rain attenuation upon the required satellite system operating point has shown that these effects may well influence analog vs. digital modulation comparisons. These effects will therefore be considered in greater detail later in this report.

2-27
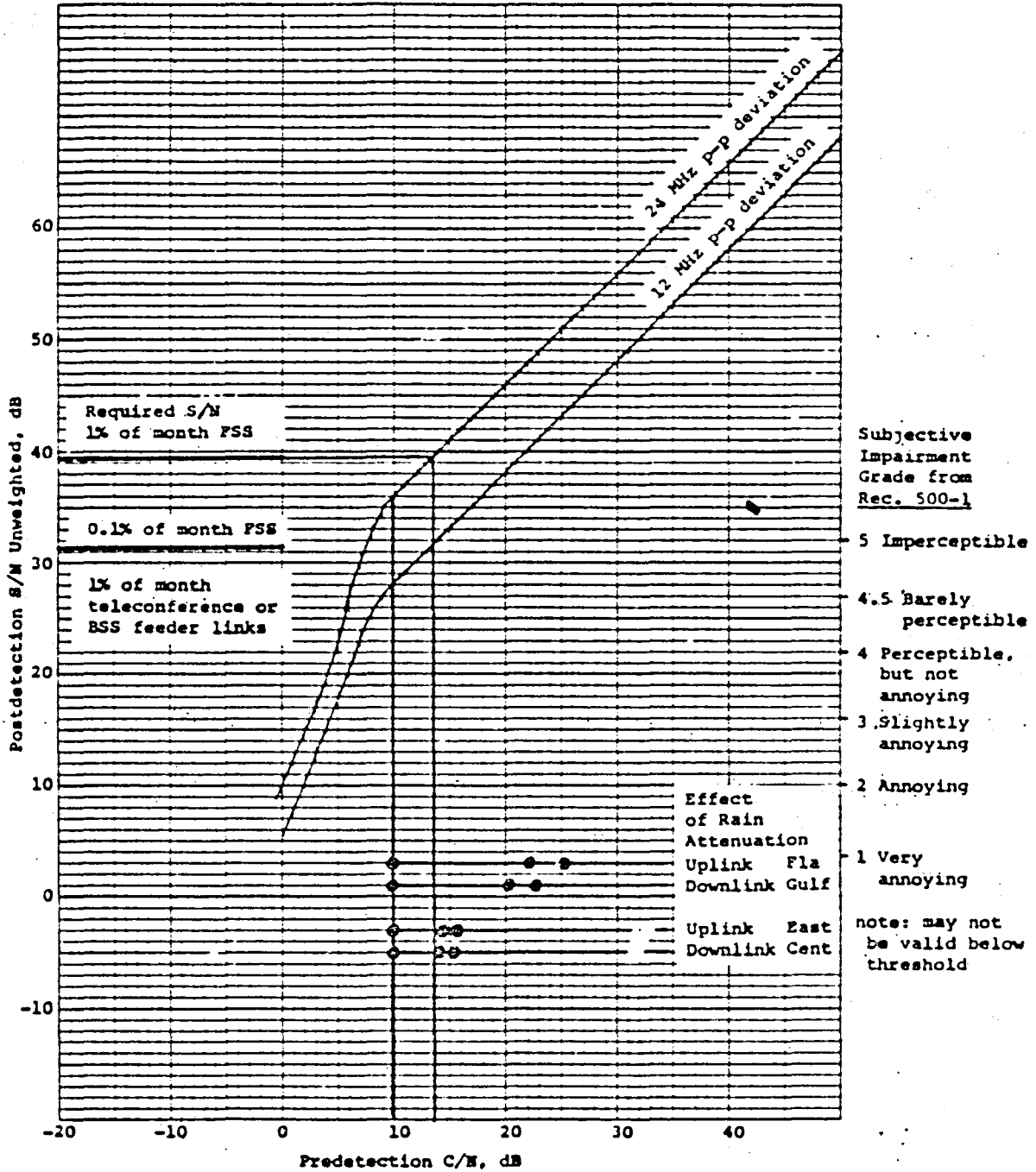
Figure 2-2.   C/N Determination For TV.

3.0 Spacing and Efficiency in the FSS and BSS

Based upon the bandwidth expansion factor selected and the baseline system descriptions presented in Chapter 2 the trade-off analysis of digital and analog modulation formats may be performed. In this chapter the relationship of multiple entry to single entry interference levels and the satellite spacings and efficiencies for the FSS and BSS baseline systems are derived and discussed.

3.1 Satellite Spacing as a Function of Interference Levels in Homogeneous Systems

The I/C ratio at a satellite earth station due to a single adjacent unwanted satellite system at an orbital spacing, θ, is given for homogeneous systems by:

$$\frac{i}{c} = \frac{p_1' \, g_1'(\theta) l_u \, g_2 \, a \, g_3 \, l_d \, g_4 + p_1' \, g_1' \, l_u \, g_2' \, a \, g_3' \, l_d \, g_4(\theta)}{p_1 \, g_1 \, l_u \, g_2 \, a \, g_3 \, l_d \, g_4} \qquad (3\text{-}1)$$

where: p_1 = earth station transmit power

$g_1(\theta)$ = earth station transmit antenna gain at angle θ from axis

$g_1 = g_1(0)$

l_u = uplink transmission path gain

g_2 = satellite receive antenna gain

a = satellite transponder power gain

g_3 = satellite transmit antenna gain

l_d = downlink transmission path gain

$g_4(\theta)$ = earth station receive antenna gain at angle θ from axis

$g_4 = g_r(0)$

primed quantities (') pertain the the unwanted signals, those not primed, to the wanted signals.

For homogeneous systems, the expression for i/c reduces to:

$$\frac{i}{c} = \frac{g_1(\theta)}{g_1} + \frac{g_4(\theta)}{g_4} \quad\quad\text{power ratio} \quad\quad\quad (3\text{-}2)$$

Given the standard CCIR sidelobe envelope of $32 - 25 \log(\theta)$ then:

$$g(\theta) = 1585\ \theta^{-2.5} \quad\quad\quad\quad \text{power ratio} \quad\quad\quad\quad (3\text{-}3)$$

and (3-2) may then be written:

$$\frac{i}{c} = 1585\ (1/g_1 + 1/g_4)\ \theta^{-2.5} \quad\quad \text{power ratio} \quad\quad\quad (3\text{-}4)$$

for a single interference entry.

Now, given the usual case where homogeneous satellite systems are equally spaced (see Figure 3-1), the sum of the multiple entries is:

$$\frac{i}{c} = 2 \times 1585\ (1/g_1 + 1/g_4)[(\theta)^{-2.5} + (2\theta)^{-2.5} + \ldots + [K\theta)^{-2.5}]$$

$$= 2 \times 1585\ (1/g_1 + 1/g_4)\ \theta^{-2.5}\ [1^{-2.5} + 2^{-2.5} + \ldots K^{-2.5}]$$

$$= 2 \times 1585\ (1/g_1 + 1/g_4)\ \theta^{-2.5}\ \sum_1^K p^{-2.5} \quad\quad\quad (3\text{-}5)$$

and:

$$\frac{i/c\ (\text{multiple entry})}{i/c\ (\text{single entry})} = 2 \sum_1^K p^{-2.5} = a(K) \quad\quad\quad (3\text{-}6)$$

Thus, for the case of equi-spaced homogeneous unwanted satellite systems, the total interference may be computed by:

1. Computing the largest single interference entry and,

2. Multiplying by the factor a(K) from Table 3-1.

3-2
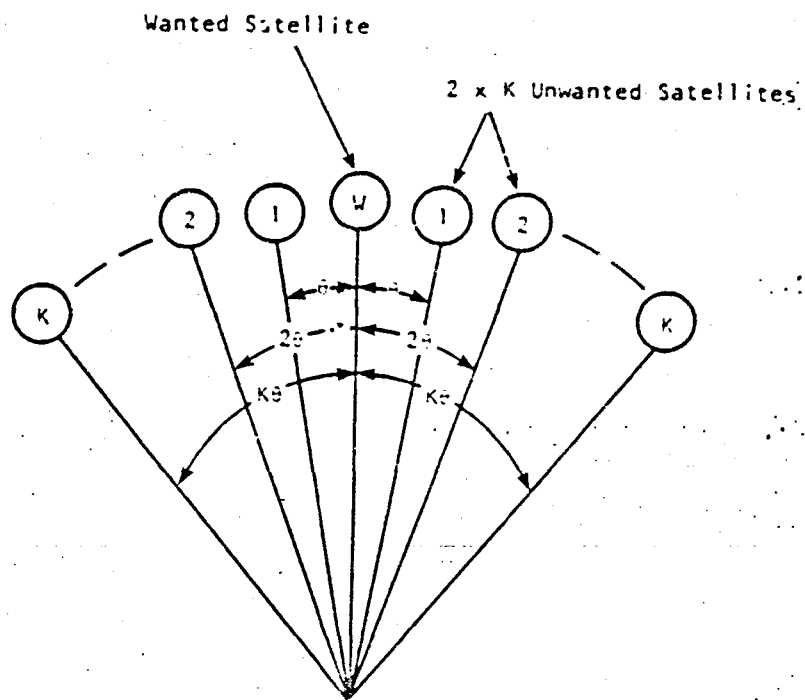
Figure 3-1.   Geometry, Homogeneous Equi-spaced Satellite Systems

Table 3-1

Ratio Of Aggregate Interference Power to the Largest Single Entry
(Equi-spaced, Homogeneous Systems)

Number of Unwanted Satellite Pairs K	Ratio of Total Interference Power To Largest Single Entry	
	a(K) Ratio	A(K) (dB)
1	2.00	3.0
2	2.35	3.7
3	2.48	4.0
4	2.54	4.1
5	2.58	4.1
10	2.64	4.2
100	2.68	4.3

Alternatively, from Eq. (3-5) and (3-6), the aggregate i/c ratio is then:

$$i/c = a(K) \ 1585 \ (1/g_1 + 1/g_4) \ \theta^{-2.5} \qquad \text{power ratio} \qquad (3-7)$$

Now, by solving (3-7) for the intersatellite spacing:

$$\theta = [(c/i) \ a(K) \ 1585 \ (1/g_1 + 1/g_4)]^{0.4} \quad \text{degrees} \qquad (3-8)$$

and the number of satellites that may occupy a given orbit arc is proportional to the allowed interference level raised to the 0.4 power (see Table 3-2). Thus, if the interference allowance can be increased by 3 dB, the number of satellites occupying a given orbit arc may be doubled.

Table 3-2

Orbit Utilization as Allowed Interference Level Increases

Allowed Increase in Interference Level	Relative Number of Satellite Systems That May Occupy a Given Orbit Arc
0 dB	1.00
1 dB	1.10
2 dB	1.20
3 dB	1.32
4 dB	1.45
5 dB	1.58
6 dB	1.74
7 dB	1.91
8 dB	2.09
9 dB	2.29
10 dB	2.51

3.2   Spacing and Efficiency in FSS Systems

If all other factors are held constant, the maximum orbit spectrum utilization efficiency is achieved by minimizing the intersatellite spacing.

This section develops the relation between C/I and C/N when the grade of service is held constant.   The resultant effect upon required intersatellite spacing is then investigated.   Systems transmitting telephony and television signals are evaluated to compare the efficiency of analog versus digital modulation methods in utilizing the orbit spectrum resource.

3.2.1   Link C/I vs. C/N Ratio for a Specified Grade of Service

For a specified grade of service, there may usually be a trade-off between link C/I and C/N.   In general, if one quantity is decreased, the other must be increased.   For many analog systems a linear relationship may be assumed.   For digital systems, the relation is generally non-linear.

3.2.1.1   C/I vs. C/N Ratio for FDM/FM Telephony

For the large post-detection signal-to-noise (S/N) ratios needed for FDM/FM systems[7, 8]:

(1)   The ratio of interference to noise is assumed to be the same before and after detection.

(2)   Interference is additive on a power basis.   The effective interference power due to multiple unwanted signals is the sum of the unwanted signal powers.

3-6

(3) The susceptibility of an FDM/FM signal to identical, FDM/FM, cochannel
      unwanted signals is about 3 dB worse than that due to an equal amount
      of thermal noise power. For the case considered in this report where
      the signal occupied bandwidth is 32 kHz per voice channel, the
      computed interference "peaking" factor is a power ratio of 2.19 or 3.4
      dB. (Method of CCIR Report 388-3, paragraph 2.1.2.4.)

The combined thermal and interference link noise values conforming to CCIR
Rec. 353-2 on voice channel noise performance will be allocated as follows:

A. For more than 20% of any month:

     9,000 pWCp thermal + interference noise

     1,000 pWOp earth station equipment noise

    10,000 pWOp total

    Post detection S/(N+I) = 50.46 dB

B. For more than 0.3% of any month:

    49,000 pWOp thermal + interference noise

     1,000 pWOp earth station equipment noise

    50,000 pWOp total

    Post detection S/(N+I) = 43.10 dB

C. For more than 0.01% of any month:

    561,000 pWOp thermal + interference noise

      1,000 pWOp earth station equipment noise

    562,000 pWOp total (1,000,000 PWO unweighted)

    Post detection S/(N+I) = 32.51 dB.

3-7

The required predetection C/(N+I) ratios corresponding to the above operating conditions may be determined from the FM detector transfer curves given in Section 2.2. For convenience, values are listed in Table 3-3 for the 20% time value.

Table 3-3

FM Improvement Factor Above Threshold and C/(N+I)

Number of Voice Channels per Carrier	Required S/(N+1)	FM Improvement Factor	Effective C/(N+I) Needed 20% of Month	
	(dB)	(dB)	(dB)	(Power Ratio)
240	50.46	30.85	19.61	91.41
60	50.46	27.52	22.94	196.8
12	50.46	23.33	27.13	516.4

Taking into account the "peaking" factor associated with unwanted FDM/FM signals, the aggregate interference power allowed for a specified grade of service (C/(N+I) may the be determined from:

$$2.19 \ i/c + n/c = (n+i)/c \quad \text{effective power ratio} \qquad (3-9)$$

and solving for the allowed aggregate interference-to-carrier ratio:

$$i/c = (1/2.19)[(n+i)/c - n/c] \quad \text{power ratio} \qquad (3-10)$$

In this section, lower case variables, such as i/c, represent numerical values; upper case, such as I/C, represent dB values.

3.2.1.2 C/I vs. C/N Ratio for Frequency-Modulated Television (TV/FM)

For the Fixed Satellite Service, where further distribution of the television signal would be required, CCIR Rec. 567 specifies the following peak-to-peak luminance to RMS noise S/N ratios:

A. For more than 1% of any month:

S/N = 53 dB (weighted); corresponds to 39.2 dB unweighted
(13.8 dB weighting factor)

B. For more than 0.1% of any month:

S/N = 45 dB (weighted); corresponds to 31.2 dB unweighted.

A 24 MHz peak-to-peak deviation will be assumed for the transmitted signal, resulting in an FM improvement factor of 25.8 dB and a 32.4 MHz occupied bandwidth. The required value of predetection C/N for more than 1% of any month will then be 13.4 dB.

For video teleconferencing, a high-quality service approximately equal to that provided by the broadcasting satellite service will be assumed (12 MHz P-P deviation and at least a 14 dB C/N ratio at the earth station receiver for 99% of the worst month, BSS planning values). Considering that the FM improvement factor for a 12 MHz deviation signal is about 17.7 dB, a post-detection S/N ratio of 31.7 dB (unweighted) results.

From the data of CCIR Rep. 634-1, subjective measurements indicate that the protection ratios (C/I) required for TV/FM appear to be independent of the system C/N ratio. A few observations even indicate that the effects of a given

3-9

level of interference may become more noticable as the C/N ratio is increased. Accordingly, it must be assumed that no trade—off between C/I and C/N is possible for TV/FM.

Allowed values for C/I assumed for this report are taken from BSS planning values given in Appendix 30 of the Radio Regulations for a P-P deviation of 12 MHz and adjusted according to the relation given there:

$$C/I = R - 20 \log (D/12) \, dB \hspace{4cm} (3-11)$$

where: R = protection ratio for a 12 MHz P-P deviation

D = deviation of the wanted signal in MHz

Planning values given in Appendix 30, Annex 9, (R.R.) allow the following values of C/I:

A.   For the Broadcasting Satellite Service (12 MHz P-P):

(Assume in this report for the FSS teleconferencing also)

35 dB for any single entry

30 dB aggregate

B.   For the Fixed Satellite Service (12 MHz P-P):

37 dB for any single entry (31 dB for 24 MHz P-P)

32 dB aggregate (26 dB for 24 MHz P-P)

3.2.1.3 C/I vs. C/N Ratio for Digital Signals

For the case of digital interference to a wanted digital signal[9, 10]:

(1) When the C/I ratio is large compared to the C/N ratio, the effect of interference is approximately the same as an equal level of thermal noise power.

(2) When the C/I ratio is in the order of (or smaller than) the C/N ratio, the effect of interference is less severe·than an equal level of thermal noise power.

(3) For a given total C/I ratio, the degradation increases with the number of unwanted signals.

As a result, a rather complex computer program is necessary to study the effect of interference for each specific case of interest. Intersatellite interference problems present a particular computational challenge. Given a constant intersatellite spacing, the spectrum of unwanted signals consists of equal amplitude pairs, decreasing in amplitude according to the earth station antenna sidelobe characteristics.

Reference 10 presents curves of error rate for 4-phase CPSK (QPSK) as a function of the link C/N ratio for a range of intersatellite spacings. The particular case treated considered 5 pairs of satellites flanking the wanted satellite system. Earth station antenna gains and assumed sidelobe character- istics were given. With this information, it was possible to compute the aggregate C/I ratio associated with each value of intersatellite spacing. Several values·of C/I versus C/N were then obtained for the·symbol error rates listed in Table 3-4.

Table 3-4

Values of C/N vs. C/I From Figure 3 of Reference 10

Values of C/N (dB) for the Listed Symbol Error Rate

Aggregate C/I (dB)	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}
22.7	15.1	14.2	13.3	12.2	10.5
20.7	15.5	14.5	13.7	12.3	10.7
18.3	16.1	15.1	14.1	12.8	11.2
15.2	17.9	16.8	15.6	14.0	12.0
13.2	20.1	18.7	17.1	15.4	13.0
11.8	—	21.8	19.5	17.1	14.0

Regression Coefficients

	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}
A =	0.0184264	0.0187101	0.020002	0.0210269	0.232826
B =	-1.95373	-1.78287	-1.73433	-1.55326	-1.36675
R^2 =	.999	.999	.998	.997	.994

For N > I:
C/(N+I) =   14.4 dB   13.5 dB   12.8 dB   11.7 dB   10.2 dB

3-12

In order to facilitate later computations, a regression analysis was performed on the listed data in an effort to obtain a mathematical expression describing the data with reasonable accuracy. An expression of the form:

$$(i/c)^{1.8} = A + B (N/C)^{1.8} \quad \text{dB ratios} \tag{3-12}$$

was success ul where the coefficients A and B are listed on Table 3-4 along with the computed coefficients of determination, R^2.

As noted at the beginning of this section, when the c/i ratio is large compared to the c/n ratio, the effect of interference is approximately the same as an equal level of thermal noise power. As a result, for large values of c/i, the relation of c/i and c/n are take. to be:

$$i/c = (n+i)/c - n/c \quad \text{power ratio} \tag{3-13}$$

where c/(n+i) is the c/n ratio needed to support a given symbol error rate in the absence of interference. c/(n+i) values adjusted to obtain a best fit between equations (3-12) and (3-13) are also listed at the bottom of Table 3-4.

Figure 3-2 shows C/I versus C/N curves computed from equation (3-12) for four values of constant symbol error rate (solid lines). Also shown are lines of constant N/I ratio.

The dotted lines plotted on Figure 3-2 show computed values from equation (3-13) which assume the effect of interference to be equal to that produced by the same level of thermal noise. Note that the thermal noise approximation is within 1 dB of the exact solution for n/i values greater than unity.

Figure 3-2. C/I vs C/N for Constant Values of Symbol Error Rate.
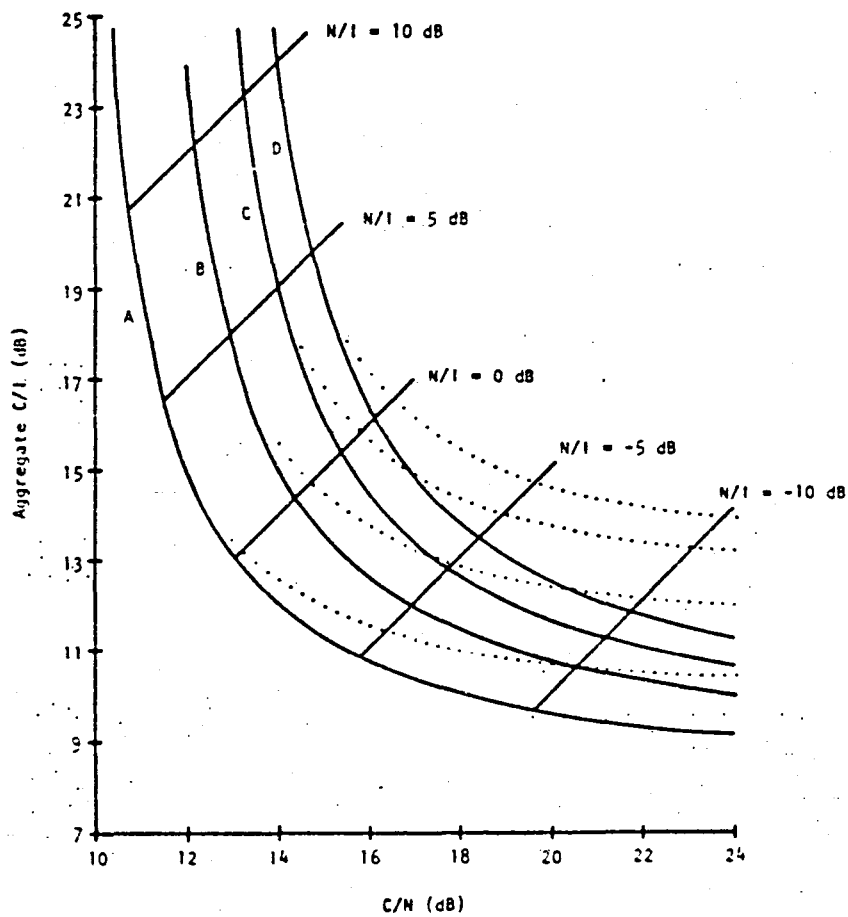
A 10^{-3} symbol error rate

B 10^{-4} symbol error rate

C 10^{-5} symbol error rate

D 10^{-6} symbol error rate

.... thermal noise approximation

3-14

Several sources in the literature have noted that, for a given C/I ratio, the symbol error rate may be reduced indefinitely by increasing the C/N ratio. This is true, provided that the C/I ratio exceeds a computable lower bound. For binary PSK, the sum of the magnitudes of the individual unwanted signal voltage vectors must not exceed the wanted carrier voltage. For the case of QPSK with 5 pairs of unwanted signals, the limiting value of C/I is 7.77 dB. As may be seen from Figure 3-2, astronomical values of C/N would be needed to allow required C/I values to approach this limit, making this property of academic interest only.

CCIR Rec. 522 specifies the following bit error rates for voice systems in the FSS:

A. For more than 20% of any month:

   10^{-6} BER

B. For more than 0.3% of any month:

   10^{-4} BER

C. For more than 0.1% of any month:

   10^{-3} BER

Also, the statement of work specifies that a bit error probability of 10^{-6} with QPSK modulation shall be assumed for the digital systems in this study. This requires a quaternary symbol error probability of approximately 2×10^{-6} since a quaternary symbol error typically results in one, rather than two, bit errors. However, the differential coding normally employed to resolve ambiguity in QPSK systems doubles the raw quaternary symbol error probability

3-15

before the conversion into binary symbols takes place. Therefore, a raw quaternary symbol error probability of 10^{-6} is assumed in this study corresponding to curve D in Figure 3-2.

Now that all the necessary relations between C/I, C/N, and intersatellite separation are complete, curves of separation versus C/N may be generated. The transmitting earth station antenna gain was set equal to 55.5 dB and receiving earth station antenna gains to 53.9 dB (corresponding to 5 meter antenna diameters).

For FDM/FM, equation (3-10) was used to compute allowed values of aggregate C/I versus C/N, assuming a total interference plus noise allowance of 9,000 pWOp in a baseband voice channel. Curves are plotted on Figure 3-3 for 12, 60, and 240 or more voice channels per carrier.

For digital signals, it was remembered that the C/I versus C/N relation is dependent upon the number of unwanted signals. Considering that both up and down path interference is considered in this study, there was some question at this point as to whether the interference spectrum model at the wanted system earth station receiver should consist of 5 pairs or 10 pairs of unwanted signals. However, since data given in Ref. 10 indicates a maximum difference in C/N for a given C/I of 0.1 dB for the two cases, 5 pairs were assumed. The up and down path contributions were added on a power basis. For a 10^{-6} symbol error rate, values of C/I were computed from equation (3-12) for substitution into equation (3-8). Values of required intersatellite separation thus obtained were plotted as the solid curve on Figure 3-3.
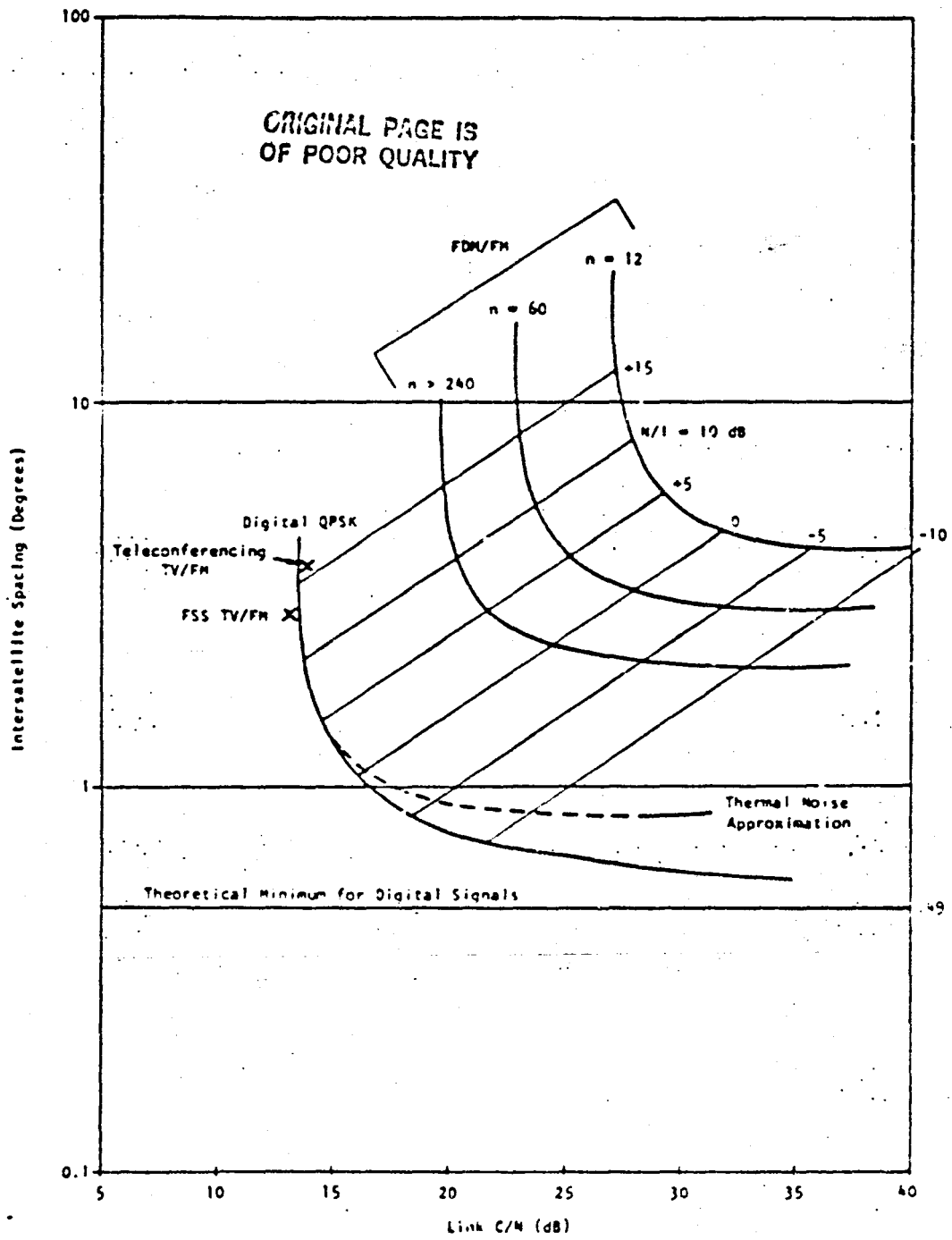
Figure 3-3. Satellite Spacing vs C/N in the FSS.

The dashed portion of the digital curve is the result of assuming digital interference to have the same effect as an equal level of thermal noise power. Values of C/I were computed using equation (3-13) and a 13.5 dB C/(N+I) ratio. Note that the error incurred by adopting the simplifying assumption that interference to a digital signal may be treated like thermal noise is small unless the aggregate interference power significantly exceeds the thermal noise power in the system.

As discussed above, the error rate for a digital signal may be reduced indefinitely by increasing the C/N, provided that the C/I ratio is above the minimum threshold (7.8 dB for the case here, corresponding to a lower bound on intersatellite separation of 0.49 degrees). The trend of the digital curve on Figure 3-3 toward this lower bound is evident.

The values for TV/FM in the FSS and for teleconferencing plotted on Figure 3-3 used the aggregate C/I planning values of 26 dB and 30 dB respectively and minimum recommended C/N values given in section 3.2.1.2. Note that the required C/I (and intersatellite separation) is independent of increased C/N as discussed in the same section. It is also noted that the two TV/FM points plotted on Figure 3-3 lie essentially on the QPSK digital curve. Thus, for the relatively high N/I ratios required for TV/FM, this method of modulation would appear to offer a spectrum utilization efficiency equal to that of digital transmission. Digital modulation for television, however, offers a C/I versus C/N trade off not available to TV/FM.

In order to aid comparisons, lines of constant N/I are also plotted on Figure 3-3. Common FDM/FM operating practice is to allocate 8,000 pWOp to link thermal noise and 1,000 pWOp to interference, corresponding to a post detection N/I ratio of 9 dB. Since the effect of FDM/FM interference is about 3.4 dB worse than an equal level of thermal noise power (see section 1.1), the predetection N/I operating point is then 12.4 dB. From Figure 3-3 for a 240 channel FDM/FM system, this condition requires an intersatellite spacing of about 4.5 degrees. Intersatellite spacing could be reduced by a factor of about 2 to 2.3 degrees by assigning equal noise and interference allowances (and 4.5 dB increase in carrier power).

A change from FDM/FM to digital modulation at a fixed I/N ratio affords a spacing reduction factor of at least 2 and a reduction in required carrier power of about 5 dB.

A digital system operating at the same carrier power as needed for current 240 channel or greater FDM/FM practice allows intersatellite spacing to be reduced from about 4.5 degrees to 0.75 degrees (a factor of 6). Note, also that unlike FDM/FM, the intersatellite spacing required for digital modulation is independent of the number of voice channels per carrier.

3.2.2 Orbit Spectrum Utilization Efficiency in FSS Systems

A figure of merit, the orbit/spectrum utilization efficiency is defined as:

$$UE = \frac{(\text{Number of channels})}{(\text{Degrees of orbit occupied})(\text{MHz of bandwidth occupied})} \quad (3-14)$$

For this report, signals carrying telephony have been designed to occupy a necessary bandwidth of 32 kHz for each voice channel. The total bandwidth occupied by a signal is assumed to be 1.1 times the necessary bandwidth to allow for guard bands between adjacent signals. Therefore (3-14) may be written:

$$UE = \frac{N}{\theta \times 1.1 \times 32 \times 10^{-3} \times N} = \frac{28.41}{\theta} \qquad (3-15)$$

where N is the number of channels.

For 24 MHz P-P deviation TV/FM or equivalent digital TV:

$$UE = \frac{1}{\theta \times 1.1 \times 32.4} = \frac{.028}{\theta} \qquad (3-16)$$

For 12 MHz P-P deviation TV/FM or equivalent digital TV:

$$UE = \frac{1}{\theta \times 1.1 \times 20.4} = \frac{.045}{\theta} \qquad (3-17)$$

The utilization efficiencies for the cases shown in Figure 3-3 are shown in Figures 3-4 and 3-5 for voice and TV systems, respectively.

3.2.3 Effect of Rain Fading Upon Spacing in FSS Systems

Up to this point, the effect of the C/N versus C/I tradeoff on intersatellite spacing has assumed ideal propagation conditions. Particularly in the higher frequency bands now being developed, rain fading can have a significant effect upon the results of a digital versus analog modulation comparison. Rain fade margins and their effect upon the required satellite system operating points are discussed in Section 2.3.
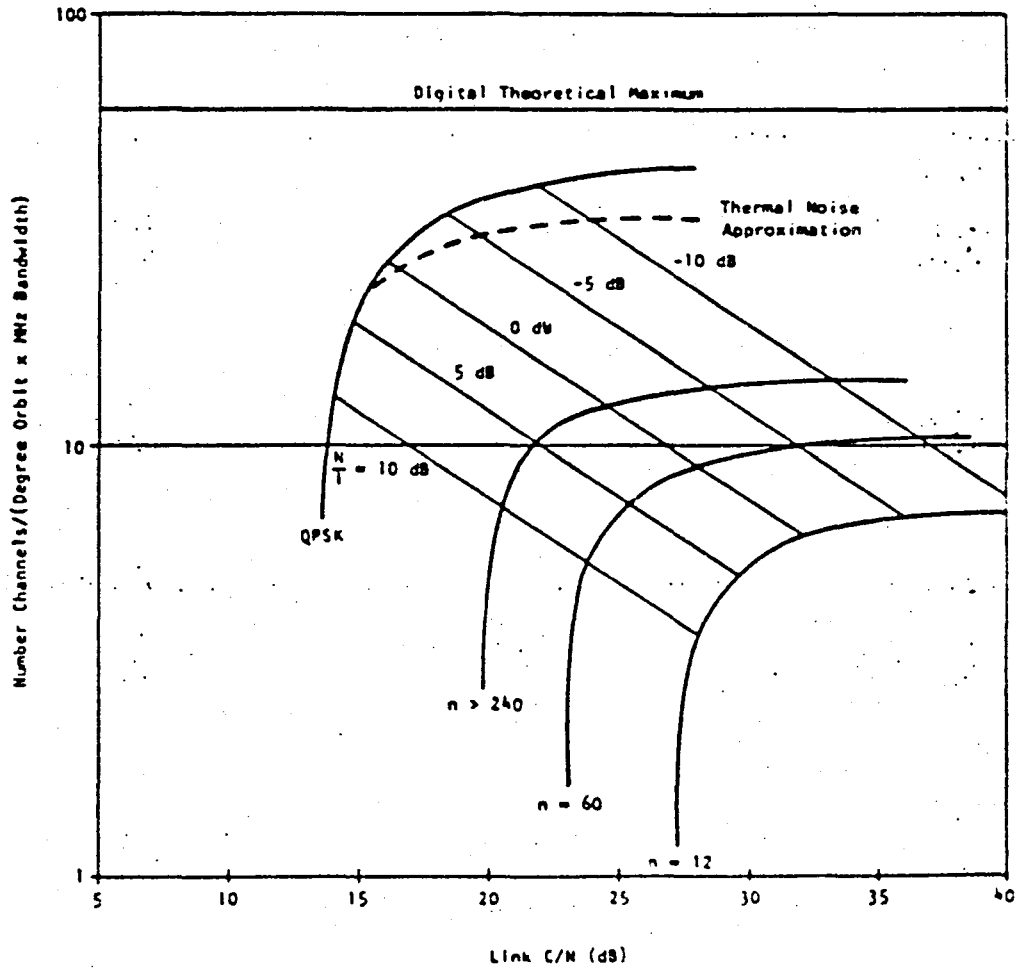
Figure 3-4.   Orbit/Spectrum Utilization Efficiency
               for Voice Systems in the FSS.

3-21
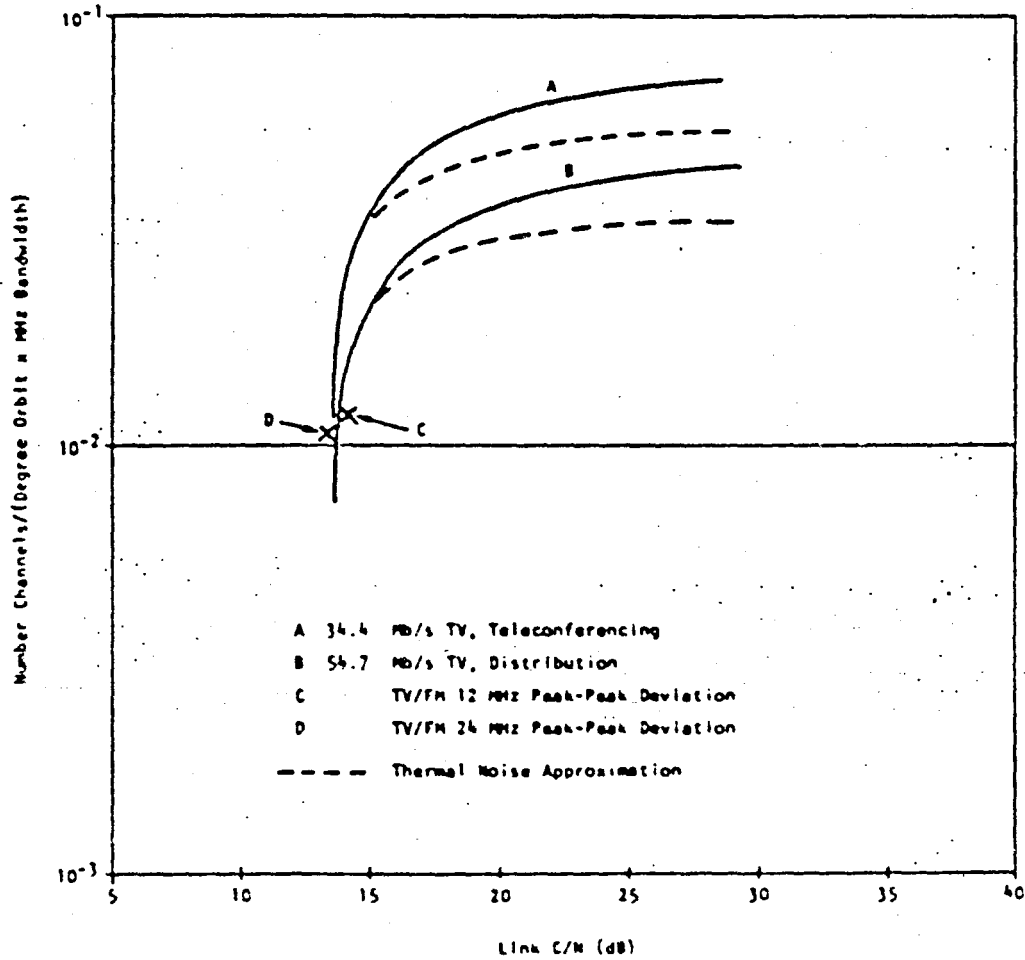
Figure 3-5. Orbit/Spectrum Utilization Efficiency
for TV Systems in the FSS.

3-22

Table 3-5 lists the rain fading considerations and performance criteria
needed to determine the effect of fading upon intersatellite spacing. For
voice, the performance criteria for FDM/FM and digital signals follow CCIR Rec.
353-3 and 522. Required values of C/N to meet the three performance criteria
are listed for FM and digital QPSK systems.

For TV/FM the required C/N value for 0.1% of the time was below the
demodulator threshold. Threshold operation at a 10 dB C/N was therefore
assumed. (Although the BSS CCIR planning criteria does not specify performance
requirements for time percentages less than 1%, systems planned for the United
States include a 5.9 dB fade margin. Since this value was close to the 5.4 dB
value computed for 0.1% of the time for East Coast and central U.S. locations,
a 0.1% criterion was added for BSS TV.) No performance criterion was found in
the literature for digital TV for time percentages less than 1%. For purposes
of this report, a 10^{-5} bit-error-rate was assigned.

Table 3-5 also lists the reduction in link C/N that may be expected in the
12/14 GHz bands due to rain fading for the three time percentages. Uppath and
downpath values of fading margin are listed separately. The required clear air
C/N for each condition is then the required C/N plus the magnitude of the
fading margin.

Consider, for example the right-hand column of Table 3-5. For digital QPSK
subject to downpath fading, a 13.5 dB C/N would meet performance criteria for
10% or more of the time. However, 0.3% of the time, downpath fading could be
expected to reduce the link C/N by 3.1 dB, leaving a link C/N of 13.5 - 3.1 =
10.4 dB; less that the required value of 11.7 dB. Thus, to insure that the

3-23

Table 3-5. Performance Criteria and Rain Fade Considerations.

TIME %	FM SYSTEM	PERFORMANCE CRITERIA DIGITAL QPSK BER	REQUIRED C/N (NO INTERFERENCE) FM SYS. (DB)	REQUIRED C/N (NO INTERFERENCE) DIGITAL QPSK (DB)	FAILED LINK C/N RE TO CLEAR AIR (EAST COAST & CENTRAL U.S.) UPPATH (DB)	FAILED LINK DOWNPATH (DB)	REQUIRED CLEAR AIR C/N (NO INTERFERENCE) FM UPPATH (DB)	FM DOWNPATH (DB)	DIGITAL QPSK UPPATH (DB)	DIGITAL QPSK DOWNPATH (DB)
VOICE, >240 CHANNELS										
90%	9000 PWOP (NOISE + INT)	1E-6	19.6	13.5	0	0	19.6*	19.6*	13.5	13.5
0.3%	49,000 PWOP (NOISE + INT)	1E-4	12.0	11.7	-3.2	-3.1	15.2	15.1	14.9	14.8
0.01%	561,000 PWOP (NOISE + INT)	1E-3	5.3	10.2	-13.0	-11.9	18.3	17.2	23.2*	22.1*
FSS TV (24 MHZ P-P)										
1%	26 DB C/I (AGGREGATE)	1E-6	13.4	13.5	-1.3	-1.4	14.7	14.8	14.8	14.9
0.1%	26 DB C/I (AGGREGATE)	1E-5	10.0	12.8	-5.7	-5.4	15.7*	15.4*	18.5*	18.2*
BSS TV (12 MHZ P-P)										
1%	35 DB C/I (SINGLE ENTRY)	1E-6	14.0	13.5		-1.4		15.4		14.9
0.1%	35 DB C/I (SINGLE ENTRY)	1E-5	10.0	12.6		-5.9		15.9*		18.7*

* CONTROLLING VALUES TO INSURE THAT PERFORMANCE CRITERIA ARE MET FOR ALL SPECIFIED TIME PERCENTAGES

specified performance criteria are met for both 20% and 0.3% of the time, the
required clear air C/N must be increased from 13.5 dB to the 14.8 dB value
listed in the right-hand column.

In the same manner, to insure that the specified performance criteria are
met for all three time percentages (20%, 0.3%, and 0.01%), the required clear
air C/N must be increased from 13.5 dB to 22.1 dB.

As a result, the largest of the values tabulated in a particular column
(marked ≈) is the controlling value needed to insure that performance criteria
are met for all specified time percentages.

An examination of the 4 right-most columns of Table 3-5 reveals that all
the signal types listed require a fading margin with the exception of FDM/FM
voice. Using the required clear air C/N values marked ≈, we may now
investigate the effects of fading upon spacing in the fixed satellite service
as well as the digital versus analog modulation comparison.

Figure 3-6 illustrates the results for voice signals. Since FDM/FM needs
no fading margin, the curves are identical to those shown previously on Figure
3-3. The digital QPSK curve marked "A" (no fade margin, no fading) is repeated
for comparison. The curve marked "B" shows the increased clear air C/N needed
to accommodate downpath fading. It is assumed that both the wanted and
unwanted signals are reduced equally by the fade.

The curve marked "C" shows the increased clear air C/N and increased
spacing values needed to accommodate an uppath fade. It is assumed that the
wanted signal only is reduced by the fade. A linear transponder is also

3-25
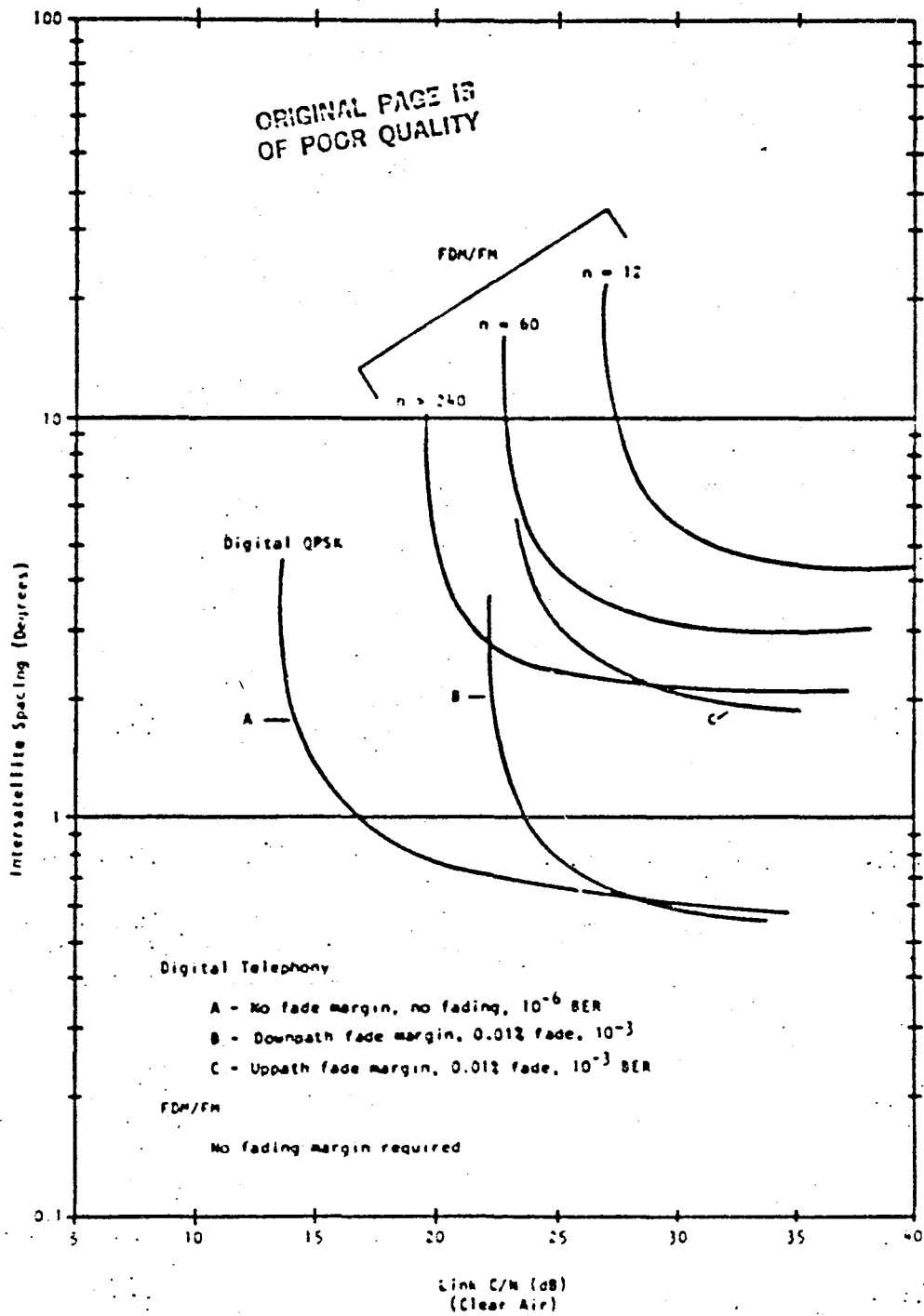
Figure 3-6. Effect of Rain Fading on FSS Voice Systems

assumed to illustrate the worst case. For a saturated transponder (where a reduction in uppath received signal level causes no reduction in downpath EIRP), the resultant performance curve on Figure 3-4 would be approximately midway between curves "B" and "C".

For voice signals then, a comparison of digital versus analog modulation from Figure 3-6 shows that:

(1) Considerable reductions in intersatellite spacing using either type of modulation may be obtained by increasing the link C/N (satellite power); a factor of about 2.

(2) For frequency bands or geographical areas where rain fading is not significant:

   a)   Digital systems require less satellite power.

   b)   Digital modulation allows the intersatellite spacing to be reduced by a factor of at least 3 compared to the equivalent FDM/FM system.

(3) For frequency bands and geographical areas where rain fading is significant:

   a)   For small C/N ratios (power limited satellite), FDM/FM can offer smaller intersatellite spacings than digital systems.

   b)   For downpath fading alone, digital systems with increased link C/N (satellite power) can operate with intersatellite spacings of about 1/3 those of a comparable FDM/FM system.

   c)   Where uppath fading must be considered, the performance of digital signals may offer no improvement over equivalent FDM/FM systems.

3-27

Figure 3-7 illustrates the effect of rain fading considerations upon television system performance in the fixed satellite service (12/14 GHz band). Curve "A" and the point marked "A'" are repeated from Figure 3-3 for comparison.

In order to accommodate downpath fading, the operating conditions must be moved to curve "B" and point "B'" for digital and FM signals respectively. To accommodate uppath fading, curve "C" and point "C'" apply. As can be seen, frequency modulation requires lower values of C/N than does digital modulation. However, for increasing values of link C/N (satellite power), the use of digital modulation offers a spacing reduction of about a factor of 2 or more, primarily due to the fact that the present form of TV/FM does not allow a C/N versus C/I trade off.

3.3 Spacing and Efficiency in BSS Systems

The minimum orbital separation angle required for satisfactory operation of homogeneous, co-channel broadcasting satellites can be estimated very simply as follows: It will be assumed that adjacent geostationary broadcasting satellites have the same service. An individual receiver would therefore have only its antenna sidelobe discrimination to reject unwanted signals.

For the BSS reference pattern given in the ITU Radio Regulations, Appendix 30, Annex 8, the sidelobe discrimination is given by:

3-28

Digital

    A - No fade margin, no fade, 10^{-6} BER

    B - Downpath fade margin, 0.1% fade, 10^{-5} BER

    C - Uppath fade margin, 0.1% fade, 10^{-5} BER

TV/FM

    A' - No fade margin, no fade

    B' - Downpath fade margin, 0.1% fade

    C' - Uppath fade margin, 0.1% fade
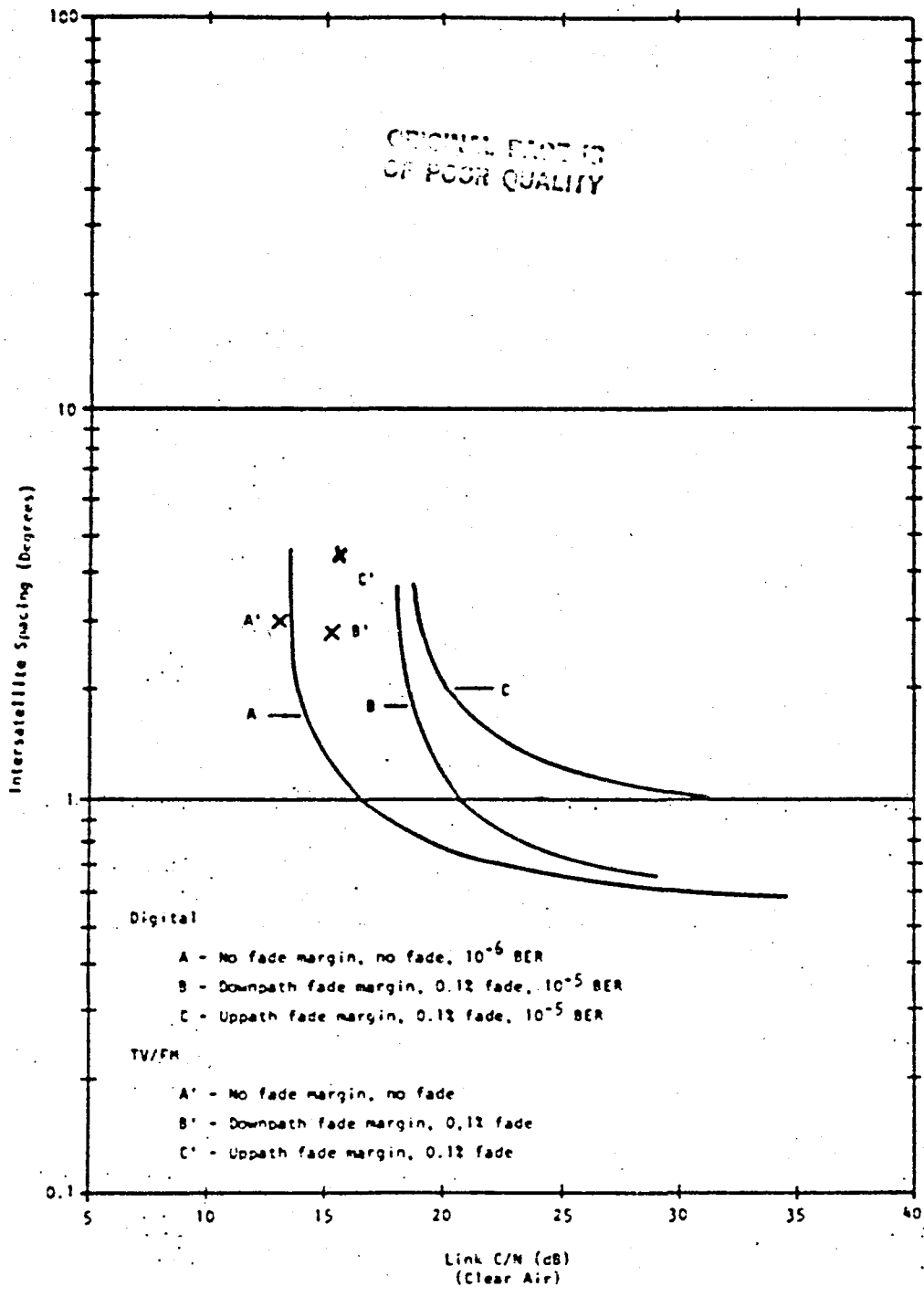
Figure 3-7. Effect of Rain Fading on FSS TV Systems

$$\Delta G_r = 0 \qquad\qquad 0 \leq \theta \leq 0.25\theta_0 \qquad\qquad (3\text{-}18)$$

$$\Delta G_r (\theta) = -12 \left(\frac{\theta}{\theta_0}\right)^2 \qquad\qquad 0.25\theta_0 < \theta \leq 0.707\theta_0$$

$$\Delta G_r (\theta) = -\left[9.0 + 20 \log \left(\frac{\theta}{\theta_0}\right)\right] \qquad .707\theta_0 < \theta \leq 1.26\theta_0$$

$$\Delta G_R (\theta) = -\left[8.5 + 25 \log \left(\frac{\theta}{\theta_0}\right)\right] \qquad 1.26\theta_0 < \theta \leq 15.14\theta_0$$

$$\Delta G_r (\theta) = -38 \text{ dB} \qquad\qquad \theta > 15.14\theta_0.$$

where

$\Delta G_r (\theta)$ = the relative antenna gain at angle θ off-axis, dBi

and

θ_0 = the half-power beamwidth, degrees.

Using Equation 3-18 with $\theta_0 = 1.8$ degrees (Section 2.2.2):

$$C/I = -\Delta G_r (\theta) = 8.5 + 25 \log (\theta/1.8) \qquad\qquad (3\text{-}19)$$

and the carrier to interference ratio is then:

$$C/I = 2.12 + 25 \log \theta \qquad\qquad (3\text{-}20)$$

for a single interference entry. The correction factor, $A(K)$, relating the aggregate interference from K pairs of unwanted satellites to the single-entry value was given previously in Table 3-1. The aggregate C/I ratio is then:

$$C/I = 2.12 - A(K) + 25 \log \theta \text{ dB} \qquad\qquad (3\text{-}21)$$

or:

$$c/i = 1.63 \, \theta^{2.5}/a(K) \qquad\qquad (3\text{-}22)$$

and solving for the intersatellite spacing:

$$\theta = [c/i \; a(K) \; 0.614]^{0.4} \text{ degrees} \qquad\qquad (3\text{-}23)$$

3-30

For TV/FM in the Broadcasting Satellite Service, the single-entry protection ratio of 35 dB is controlling (Radio Regulations, Appendix 30, Annex 9). This and other protection criteria are discussed in Appendix A of this report. Substituting the 35 dB C/I value into equation (3-20) results in a required separation of 20.7 degrees. This value is plotted on Figure 3-8, point "A'", at the 14 dB C/N value required should no downpath fading margin be required. The points marked "B'" and "C'" reflect the increased clear air C/N values required to accommodate downpath fading in the 12 GHz band (from Table 3-5).

Although the CCIR performance objectives require only that a 14 dB C/N ratio be maintained for at least 99% of the worst month, systems proposed for the United States propose a fading margin for 0.1% fading values. Thus, point "C'" on Figure 3-8 is probably representative of the typical operating point to be used.

For digital television, it was assumed that bit-error-rates of 10^{-6} and 10^{-5} must be maintained during 1% and 0.1% down path fades, respectively. Equation 3-12 was used to compute the C/N versus C/I trade off. Resultant C/I values were then substituted into Equation 3-23 to determine the separation values plotted on Figure 3-8. The correction factor a(K) was taken to be 2.58 (from Table 3-1), assuming 5 pairs of interfering satellites, since the C/N versus C/I relation of Equation 3-12 is valid only for this curve. From the resulting separation values plotted on Figure 3-8, the assumption of 5 pairs of unwanted satellites may be excessive for the larger separation values. However, both the change in correction factor, a(K), and the error incurred in Equation 3-12 is relatively small for lesser number of unwanted satellite pairs. The assumption is therefore valid for practical purposes.

3-31

TV/QPSK

    A - No fade margin, no fade, 10^{-6} BER

    B - 1.4 dB fade margin, 1% fade, 10^{-6} BER

    C - 5.9 dB fade margin, 0. fade, 10^{-5} BER

TV/FM

    A - No fade margin, no fade, C/I = 35 dB, C/N = 14 dB

    B - 1.4 dB fade margin, % fade, C/I = 35 dB, fade C/N = 14 dB

    C - 5.9 dB fade margin, 0.1% fade, C/I = 35 dB, fade C/N = 10 dB

Link C/N, dB
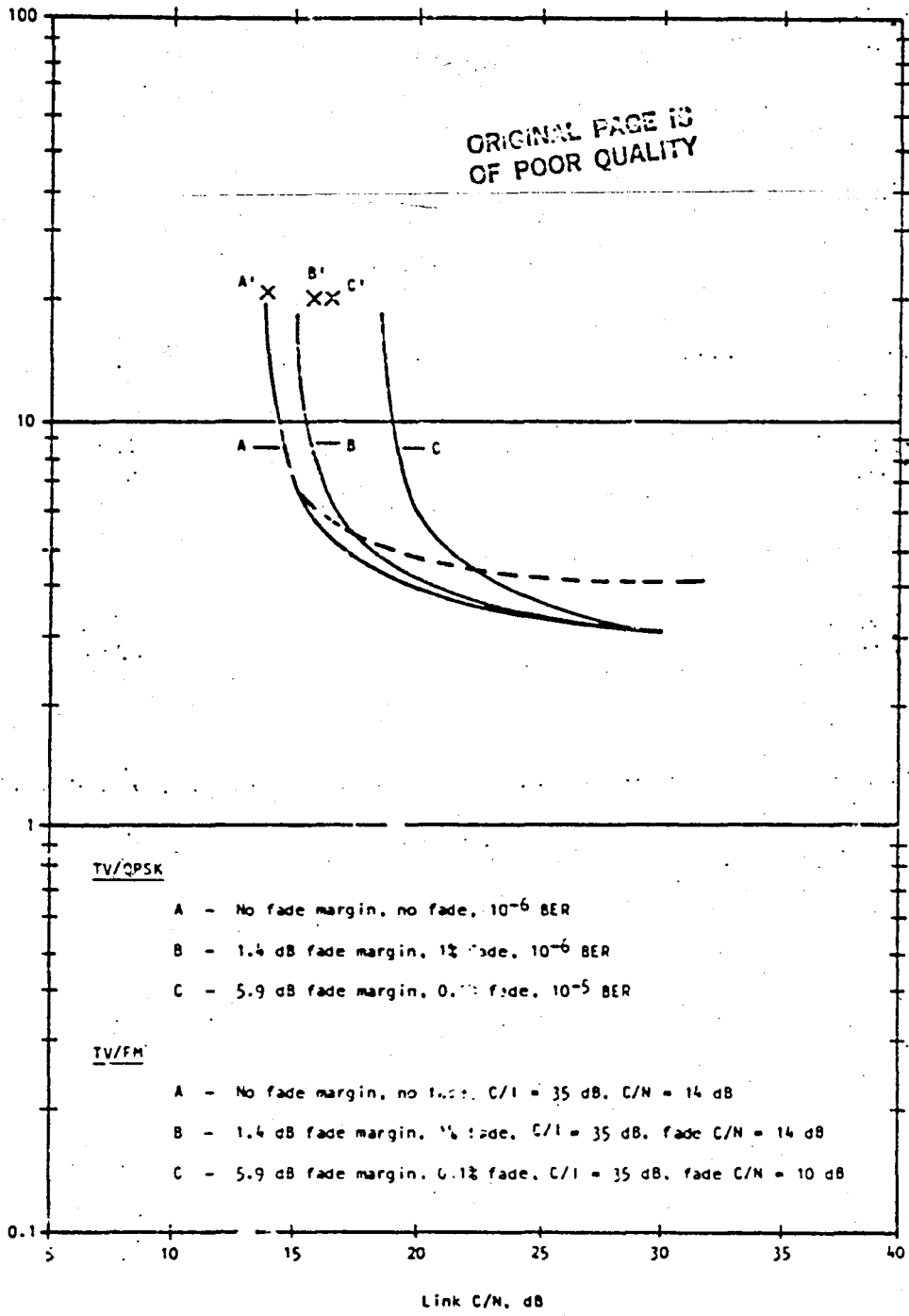
Figure 3-8.   Satellite Spacing vs C/N in the BSS;
Only Down-path Fading Considered.

3-32

An examination of Figure 3-8 points out that:

(1) The primary advantage of digital modulation over TV/FM is the fact that a C/N versus C/I trade-off is possible for digital TV but not TV/FM.

(2) For geographical areas where down path fading is not significant:

(a) For small values of C/N (satellite power limited), digital modulation offers no separation advantage over FM.

(b) Separation may be reduced from 20° to 4° or less by adopting digital modulation and increasing link C/N (satellite power) by 6 dB or more.

(3) For geographical areas where down-path fading is a significant factor:

As in case (2), intersatellite separation values may be reduced from 20° to 4° or less by adopting digital modulation and increasing the link C/N (satellite power) by 6 dB or more over values needed to support TV/FM.

It should be noted that any reduction in C/N values due to uppath fading will severely impact these reduced separation values (see Figure 3-7, FSS TV system performance).

3-33

4.0 Cost Analysis

4.1 Introduction

Chapter Three has presented the satellite spacings and efficiencies for FSS and BSS systems as functions of the carrier to noise ratio. These results indicate the proper choice of modulation type and power level to support a specified satellite spacing. Were efficiency the only criterion for system design these results would suffice for making the modulation and power level choices. However, power level has a significant impact on system cost and this is always a consideration in any practical system.

This Chapter presents the results of a cost analysis in which the costs associated with increasing or decreasing the satellite EIRP are examined. It is assumed that all changes in EIRP are accomplished by changing the satellite power only. The cost analyses treat all satellite subsystem costs plus the launch vehicle costs. These results are expressed in 1980 constant dollars.

4.2 Models and Assumptions

In support of this cost analysis numerous individuals and companies in the cost analysis and communication satellite business were contacted. The general consensus is that the SAMSO and RCA PRICE cost models are the best available models. However, in order to use the RCA PRICE model it is necessary to have considerable training and to understand very well the internal operation of the company which builds the hardware. Thus, the RCA PRICE model was not deemed appropriate for this contract. The SAMSO model was used; the Fifth Edition, dated June 1981, which is the latest available version was employed.

To use the SAMSO cost model it is necessary to have the weight and power requirements of each part of the spacecraft. Ford Aerospace and Communications Corporation has a computer program that calculates these based on various spacecraft parameters. The cost analysis uses a modified version of this program which estimates the weight and cost of 3-axis stabilized broadcasting satellites. It was prepared by NASA Headquarters for inclusion with the United States submission to Interim Working Party Plenary/3 of the ITU for publication in the Special Report on Possible Broadcasting Satellite Systems and their Relative Acceptibility.

When the Ford program was exercised the estimate of spacecraft structure weight seemed low. In order to be consistent with the structure weight estimated by COMSAT for its broadcasting satellite and with guidelines from other sources, the Ford estimates for structure weight were multiplied by the factor 2.5. As a result of this correction the estimates of structure weight ranged between 15% and 22% of total spacecraft weight.

Other assumptions which were made are:

(1) all spacecraft are 3-axis stabilized:

(2) four units of a given design will be developed and, therefore, the cost per unit can be expressed as the recurring cost plus one fourth of the non-recurring cost;

(3) there is no eclipse operation, i.e., there are no batteries;

(4) weights of the high powered TWT's and klystrons were extrapolated from known tube weights as a linear function of power;

4-2

(5) for total satellite powers in excess of 3250 Watts power system
complexity factors were extrapolated but recurring power system costs
were limited to 2/3 of non-recurring power system costs;

(6) program management costs of 36% were added to the basic costs of the
spacecraft and the apogee and perigee motors; a fee of 15% was added
to the cost estimates for the spacecraft bus and communications
payload.

Information concerning the apogee motor, perigee motor, and the Space
Transportation System (STS) parameters and costs were obtained from Thiokol
Corporation, McDonald Douglas Corporation, and NASA, respectively. Table 4-1
shows information concerning the STAR family of solid fuel rocket motors
m-nufactured by Thiokol. These are assumed in this study to serve as the
apogee kick motor to circularize the satellite orbit at geostationary altitude.
Table 4-1 lists the model, motor weight, maximum satellite weights, and
recurring costs (in 1980 dollars). Non-recurring costs are typically neglible,
according to Thiokol.

In Table 4-2 the parameters and costs associated with the PAM-D and PAM-A
perigee motors as determined from McDonald Douglas are shown.

In 1986 the user cost of STS launches is expected to increase. This study
assumes the pre-1986 STS prices apply and uses the following relationship to
calculate STS launch costs in 1980 constant dollars:

Table 4-1 Apogee Motor Parameters and Costs

STAR Model Designation	Maximum Satellite Weight, Pounds	Motor Weight, Pounds	Recurring Costs, 1980 $
26	600	580	265K
27	850	800	284K
30B	1450	1380	340K
37XF	2200	2106	473K
37X	2750	2520	510K

Table 4-2 Perigee Motor Parameters and Costs

Model	Maximum Weight of Satellite Plus Apogee Motor, Pounds	Weight of Perigee Motor Plus Cradle, Pounds	Recurring Costs, 1980 $	Non-Recurring Costs, 1980 $
PAM-D	2320	9,052	3639K	329K
PAM-D, Augmented	2750	10,068	3910K	329K
PAM-A	4400	17,396	5656K	829K

$$\text{User Cost} = \frac{W_S}{W_C L_F} [I_F (C_B + C_I) + C_U]$$

where,

W_S = total weight of satellite, apogee motor, perigee motor, and cradle, in pounds

W_C = payload capacity of STS

   = 65,000 pounds

L_F = loading factor

   = 0.75

I_F = inflation factor; converts 1975 dollars to 1980 dollars

   = 1.515

C_B = baseline cost for maximum payload

   = $18 M

C_I = reflight insurance

   = $0.271 M

C_U = use fee

   = $4.298 M (real year dollars)

Thus,

User Cost = (.6560) W_S, thousands of 1980 dollars

4.3 Effects of Power Levels on Costs

The costs for a series of identical satellites can be broken into non-recur-
ring and recurring costs. In this study it is assumed that a total of four
satellites of a given design will be purchased and that the non-recurring costs
will be divided equally among them. Five and ten tube satellites, represent-
ative of FSS applications, and three tube satellites, representative of BSS
applications, were analyzed. Program management costs of 36% were added to the
basic costs of the spacecraft and the apogee and perigee motors. In accordance
with the design of the SAMSO model, a fee of 15% was added to the cost esti-
mates for the spacecraft bus and communications payload. The composite (recur-
ring plus one fourth of the non-recurring) costs per satellite are shown in
Figure 4-1 for three, five, and ten tube satellites as functions of RF power
and the corresponding values of C/N (link parameters from Chapter Three are
used.)

The maximum values reached by the points in Figure 4-1 are governed by the
capacity of the PAM-A perigee motor. Larger spacecraft could be analyzed
assuming the use of the Inertial Upper Stage (IUS) but the power levels shown
in Figure 4-1 cover the ranges determined to be useful in Chapter Three. The
values shown in Figure 4-1 are tabulated in Table 4-3.

Each set of points in Figure 4-1 shows a pronounced jump in cost at power
levels corresponding to the transition from PAM-D to PAM-A perigee motor
assemblies. This transition occurs between the 20 Watt and 100 Watt levels for
the 10 tube case, between the 150 Watt and 200 Watt levels for the 5 tube case,
and between the 270 Watt and 450 Watt levels fo the three tube case.

An example of how the cost is calculated for one point on Figure 4-1, the
100 Watt, 10 tube point, is shown in Table 4-4.
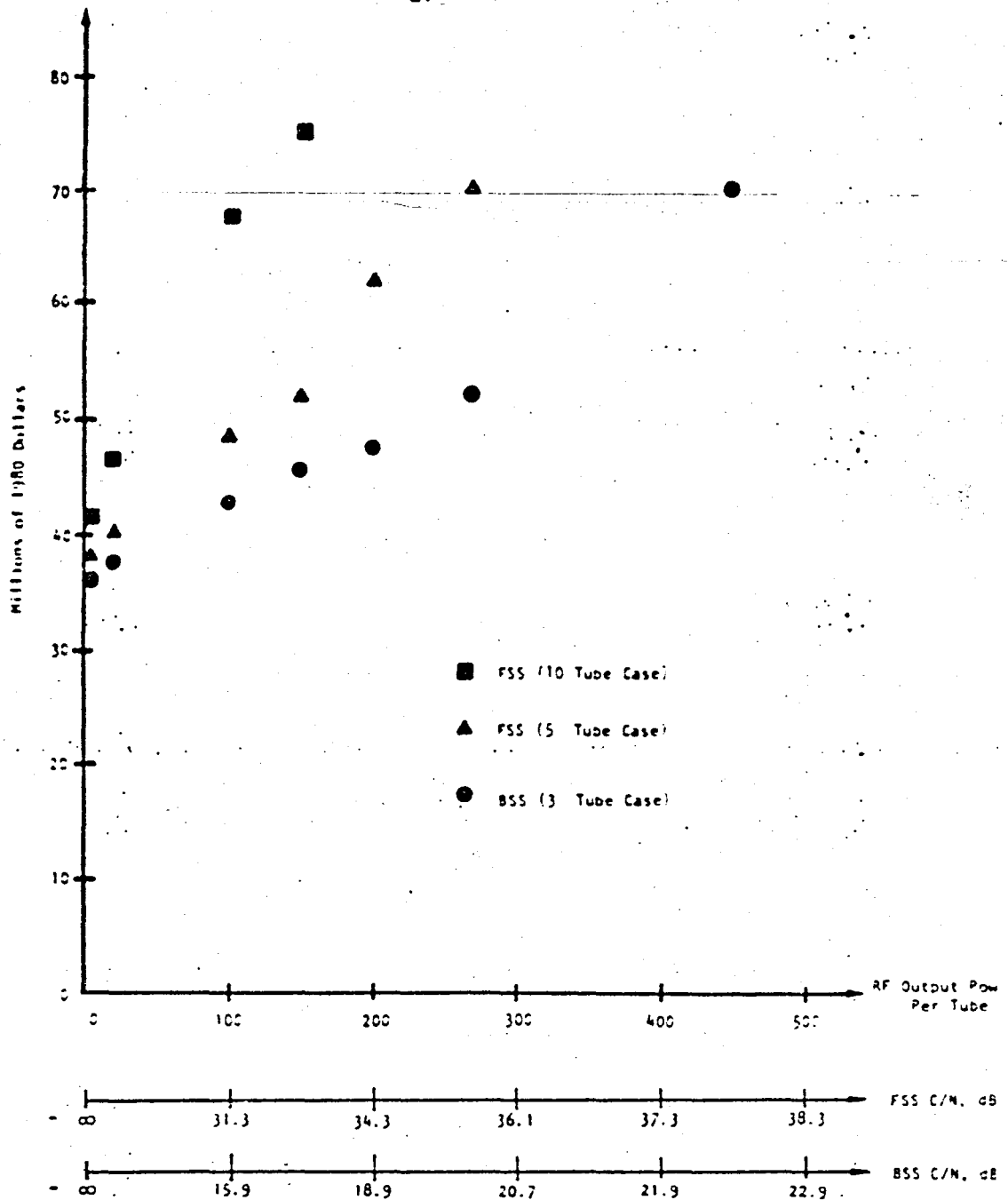
Figure 4-1   Recurring Costs Plus One Fourth of
             Non-Recurring Costs per Satellite,
             Including Launch Costs

Table 4-3. Recurring Costs Plus One Fourth of Non-Recurring Costs per Satellite, Including Launch Costs: Millions of 1980 Dollars

BSS C/N, dB	FSS C/N, dB	RF Output Power per Tube	BSS (3 Tube Case)	FSS (5 Tube Case)	FSS (10 tube case)
-1.8	13.6	1.7 Watts	36.0	37.8	41.1
8.9	24.3	20	37.4	40.0	46.7
15.9	31.3	100	42.5	48.4	67.5
17.7	33.1	150	45.9	52.1	74.9
18.9	34.3	200	47.4	62.1	**
20.2	35.6	270	52.1	70.3	
22.4	37.8	45C	70.0	**	

** Requires Inertial Upper Stage

4-9

Table 4-4 Sample Calculation of Cost
          for 100 Watt, 10 Tube Satellite

Weight per tube (not extrapolated): 15 pounds

Input power at 33% efficiency: 3000 watts

Power for receivers and drivers: 22 watts

Total power for communications system: 3022 watts

Weight of receivers, drivers, multiplexers, switches, filter, feeds, antenna,
    power splitter, isolator, test couplers, waveguides, and coax: 148 pounds

Total weight of communications system (no redundancy): 298 pounds

Solar array weight = contingency x BOL/EOL x 1/solar array mass density x
    (communications system power + other spacecraft power) = 1.05 x 1.37 x
    1/17.5 watts/pounds x (3022 + 380) = 280 pounds

Other spacecraft power = 0.2 x (RF Power - 200) + 220 = 0.2 x (1000-200) + 220
    = 380 watts

Weight of power processing equipment = 7.5/1000 x DC power required + 20.8 =
    7.5/1000 x 3402 + 20.8 = 46.3 pounds

Electrical power system weight = 280 + 46.3 = 326 pounds

Structure weight = 2.5 x larger of 0.367 x comm. sys. or 0.288 x elec. sys. =
    2.5 x 109 = 273 pounds

Thermal weight = 0.07 x (Comm. sys. + elec. sys.) = 0.07 x 624 = 44 pounds

TT&C weight = 50 pounds

Attitude control system weight = 187 pounds

Electrical integration weight = 0.136 x comm. sys. = 0.136 x 298 = 41 lbs.

Structural integration weight = 0.215 x structure = 0.215 x 273 = 59 lbs.

Sum of above weights: 1278 pounds

Fuel (hydrazine) required for 7-year station keeping: 0.212 x Weight = 0.212 x
    1278 = 271 pounds

Propulsion hardware = 0.1 x fuel = 27 pounds

Dry weight of spacecraft: 1305 pounds

Wet weight of spacecraft: 1576 pounds

Weight of spacecraft bus without payload = 1305 - 298 = 1007 pounds

4-10

Apogee motor required: STAR 37XF

Total weight into transfer orbit = 1576 + 2106
$$= 3682 \text{ pounds}$$

Perigee motor required: PAM-A

Weight of Perigee motor and cradle = 17.39u pounds

Total weight imposed on STS = 3682 + 17.396
$$= 21.078$$

Non-recurring spacecraft bus cost = 7414

+ 22.5 x [spacecraft bus weight]

= 7414 + 22.6 x 1007

= 30.172 k (1979 dollars)

= 1.094 x 1.15 x 30.172

= 37.959 k (1980 dollars, including fee)

Non-recurring communication subsystem cost

= 1.094 x 1.15 x 13.482

= 16.962 k (1980 dollars, including fee)

Non-recurring motor costs (Apogee and Perigee)

= 829 k (1980 dollars)

Non-recurring STS costs = 0

Total non-recurrring cost

= Program cost x (non-recurring spacecraft + non-recurring motor costs)
+ non-recurring STS costs

= 1.3568 x (37.959 + 16.962 + 329) + 0

= 75.642 K (1980 dollars)

Recurring spacecraft bus cost

 = 1.094 x 1.15 x 9510

 = 11.965 k (1980 dollars, including fee)

Recurring communication subsystem cost

 = 1.094 x 1.15 x 5993

 = 7540 k (1980 dollars, including fee)

Recurring motor costs = 5656 + 473

 = 6129 k (1980 dollars)

Recurring STS costs = .656 x 21.078

     = 13.827 k (1980 dollars)

Total recurring cost

 = Program costs x (recurring spacecraft + recurring motor costs)
  + recurring STS costs

 = 1.3568 (11.965 + 7540 + 6129) + 13.827

 48.607 k (1980 dollars)

Weighted total cost

 = Total recurring cost + 1/4 total non-recurring cost

 = 48.607 + 1/4 (75.642)

 = 67.513 (1980 dollars)

4.4 Impact of Cost on Modulation Choice and Operating Point

In order to apply the results of the cost analysis to the results of the
orbit/spectrum efficiency analysis it is necessary to express the relationship
between the link carrier to noise ratio, C/N, and the RF output power per tube.
Using the link parameters assumed in Chapter Three this relationship for the
FSS case is:

$$C/N = P_S + 11.3, \text{ dB}$$

and for the BSS case,

$$C/N = P_S - 4.1, \text{ dB}$$

where P_S is the satellite output power per tube.

Thus the 1.7 Watt to 270 Watt range of power for the FSS cases shown in
Figure 4-1 and Table 4-3 corresponds to a range from 13.6 dB to 35.6 dB in C/N
on Figures 3-6 and 3-7. The corresponding BSS range is from -1.8 dB to 22.4 dB
in Figure 3-8. Note that these ranges in C/N span the ranges of operating
points which are likely to be of interest.

Referring to the curves of satellite spacing in voice systems in Figure 3-6
labeled FDM/FM, n > 240, and Digital QPSK, "C", it can be seen that the digital
and analog approaches offer approximately the same minimum satellite spacing,
about 2°, and that this spacing is achieved at the same power level and cost.
For larger and less efficient spacing the analog approach requires approxi-
mately 3 dB less C/N. Specifically, for a 5° spacing, the analog and digital
approaches C/N values of 20 dB and 23 dB, respectively, corresponding
to power level 7.4 Watts and 14.8 Watts, respectively. Referring to the

cost analysis results in Figure 4-1 it can be seen that both approaches would require the use of a 20 Watt tube. Taking a more theoretical approach, assuming that the points in Figure 4-1 are samples of continuous relationship between cost and power, the reduction of power from 14.8 Watts to 7.4 Watts still represents a savings in cost of only about 4.4% for the 10 tube case or 1.5% for the 5 tube case.

The FSS-TV situation is slightly different as shown in Figure 3-7, point C' and curve C. For a satellite spacing of 4.5° the analog system requires 3 dB less power than does the digital. This, however, again represents a negligible cost savings.

The spacing results for BSS are shown in Figure 3-8, point C' and curve C. For a spacing of 20° the analog approach requires 2 dB less power than the digital approach resulting in an 8.7% cost savings.

A somewhat more interesting application of the cost analyses is to examine the cost impact of decreasing the satellite spacing when using digital modulation. The curves labelled "C" in Figures 3-6, 3-7, and 3-8 corresponding to the worst case fading will be used and interpolation is again applied to the cost results in Figure 4-1. Assuming a reference spacing of 3° for FSS (the spacing currently used by the FCC) and 20° for BSS the cost increase associated with decreases in the spacing are shown in Table 4-5. Costs are shown for decreases in satellite spacing from 3° to 2.5° or 2° for FSS-voice, from 3° to 2° or 1° for FSS-TV, and from 20° to 10° or 5° for BSS-TV. Note that due to the intially steep slope of the curves in Figures 3-6, 3-7, and 3-8 small decreases in satellite spacing are proportionately less   ...sive than larger decreases.

Table 4-5. Cost Impact of Decreased Satellite Spacing;
            Digital Modulation with Worst Case Fading

SERVICE	REFERENCE SPACING	REDUCED SPACING	COST INCREASE
FSS-Voice	3°	2.5°	3.5% (5 tube), 7.6 % (10 tube)
FSS-Voice	3°	2°	18.1% (5 tube), 38.2% (10 tube)
FSS-TV	3°	2°	0.5% (5 tube), 0.9% (10 tube)
FSS-TV	3°	1°	24.5% (5 tube), 55.2% (10 tube)
BSS-TV	20°	10°	1.3% (3 tube)
BSS-TV	20°	5°	52.7% (3 tube)

4-15

5.0 Conclusions

Conclusions based on the results of Chapter Three and Four can be summarized as follows:

For telephony systems in the FSS:

(1) Considerable reductions in intersatellite spacing using either type of modulation may be obtained by increasing the link C/N (satellite power).

(2) For frequency bands or geographic areas where rain fading is not significant:

   (a) Digital systems require less satellite power.

   (b) Digital modulation allows the intersatellite spacing to be reduced by a factor of at least three compared to the equivalent FDM/FM system.

(3) For frequency bands and geographical areas where rain fading is significant:

   (a) For small C/N ratios (power limited satellite), FDM/FM can offer smaller intersatellite spacings than digital systems.

   (b) For downpath fading alone, digital systems with link C/N greater than 25 dB can operate with intersatellite spacings of about 1/3 those of a comparable FDM/FM system.

5-1

(c) When uppath fading must be considered, the performance of digital systems offers little or no improvement over equivalent FDM/FM systems. The 3 dB reduction in C/N for FDM/FM relative to digital modulation under power limited conditions represents a less than 5% saving in satellite cost.

(d) If digital modulation is used when uppath fading must be considered, a reduction in satellite spacing from 3° to 2.5° increases power requirements by 2 dB and increases costs by as much as 3%; reduction from 3° to 2° increases power requirements by 6 dB and increases costs by as much as 38%. This is representative of the tendency of small spacing reductions to be proportionately less expensive than larger reductions.

For TV systems, present frequency modulation methods do not allow a C/N versus C/I trade-off to reduce satellite spacing. Changing to digital modulation offers significant reductions in intersatellite spacing.

For TV systems in the FSS:

(1) The FM system requires from 1 to 3 dB less power than the digital system for equivalent satellite spacing representing a cost saving of less than 5%.

(2) The use of digital modulation can reduce the spacing requirement by a factor of 2 or more. For example, if digital modulation is used when uppath fading must be considered, a decrease in satellite spacing from

3° to 2° will increase power requirements by 1 dB and increase

costs by as much as 1%; spacing reductions from 3° to 1° will

increase power requirements by 12 dB and increase costs by as much

as 55%.

For TV systems in the BSS:

(1)   For geographical areas where downpath fading is not significant:

   (a)   For small values of C/N, digital modulation offers no

         intersatellite separation advantage over FM.

   (b)   Intersatellite separation may be reduced from 20° to 4° or less by

         adopting digital modulation and increasing link C/N by 6 dB or

         more.

(2)   For geographical areas where downpath fading is significant digital

       modulation again allows a reduction in intersatellite spacing. For

       example, if spacing is reduced from 20° to 10° the power requirement

       increases by 0.5 dB and the cost is increased by about 1%; a reduction

       from 20° to 5° increases the power requirement by 4.5 dB and increases

       costs by about 53%.

APPENDIX A

ITU REGULATIONS AND PLANNING PARAMETERS

The amended Radio Regulations resulting from the 1979 General World Administrative Radio Conference (WARC) took effect internationally on January 1, 1982. WARC agreements, and thus the Radio Regulations, bear the status of an international treaty upon ratification by the U.S. Senate. In addition, amended U.S. national regulations corresponding to the international regulations are being developed by a joint effort of the National Telecommunications Information Administration (NTIA) and the Federal Communications Commission (FCC).

Specific ITU radio regulations which are pertinent to this study are the frequency allocations for the Broadcasting-Satellite Service (BSS), and for the Fixed-Satellite Services (FSS) near 12 GHz, space station power flux density restrictions on the surface of the earth, and BSS and FSS protection criteria. In addition, the criteria used as the basis for the planning of the BSS downlinks in Regions 1 and 3 provide baseline criteria for planning in Region 2.

This attachment discusses further the results of the 1979 WARC and provides information from CCIR Reports and Recommendations which is relevant to this study.

Allocations

The allocations for the Broadcasting Satellite Service and the Fixed-Satellite Service in and around K_u band are relatively complex. This has resulted from the numerous compromises required to satisfy the various conflicting interests already exploiting this segment of the spectrum.

In Region 2, the frequency band 12.7 - 13.25 GHz has been allocated to the Fixed-Satellite Service for Earth-to-space transmissions and the band 10.7 - 12.3 GHz has been allocated to the FSS for space-to-Earth transmissions. (The upper limit for the FSS space-to-Earth band, 12.3 GHz, may be moved between 12.1 and 12.3 GHz at the 1983 WARC-BS according to the footnote 3787B.

The Region 2 allocation for the Broadcasting-Satellite Service in the space-to-Earth direction is between 12.1 GHz and 12.7 GHz with the lower limit, 12.1 GHz, subject to change in 1983 according to footnote 3787B in the same manner as is the upper limit of the FSS band. Planning for the BSS in Region 2 is the subject of the 1983 Regional Administrative Radio Conference (RARC). The principle feeder links for the BSS in Region 2 are allocated within the band 17.3 - 18.1 GHz. The 14.0 - 14.8 GHz band is also available for BSS feeder links in Region 2. All allocations mentioned for both the BSS and FSS are on a primary basis and have priority over secondary services. Note that BSS feeder link allocations have been made by footnote within the FSS bands, since by ITU definition the FSS includes BSS feeder links.

The BSS may also broadcast (space-to-Earth) within the FSS band 11.7 - 12.1 GHz (see FN 3787A), provided that the effective isotropic radiated power (eirp) does not exceed 53dBW per TV channel and provided that the interference caused by, and the protection required for, the BSS satellite are no greater than that which would be required for a fixed satellite.

A-2

Power Flux Density Restrictions

In bands shared with terrestrial services, i.e. 10.7 to 11.7 GHz in all ITU Regions and 12.2 to 12.75 GHz in Regions 1 and 3, the International Telecommunications Union (ITU) has established power flux density (pfd) limits at the Earth's surface which are applicable to Fixed-Satellite emissions. From the ITU Radio Regulations (6067 through 6074.2), the pfd limits in the band 10.7 to 11.7 GHz in all ITU Regions are:

"−150 dB (W/m^2) in any 4 kHz band for angles of arrival between 0 and 5 degrees above the horizontal plane;

−150 + 0.5 (θ − 5) dB (W/m^2) in any 4 kHz band for angles of arrival θ (in degrees) between 5 and 25 degrees above the horizontal plane;

−140 dB (W/m^2) in any 4 kHz band for angles of arrival between 25 and 90 degrees above the horizontal plane".

Similarly, the pfd limits in the band 12.2 to 12.75 GHz (from ITU RR 6067 − 6074.2) in ITU Regions 1 and 3 are:

"−148 dB (W/m^2) in any 4 kHz band for angles of arrival between 0 and 5 degrees above the horizontal plane;

−148 + 0.5 (θ −5) dB (W/m^2) in any 4 kHz band for angles of arrival θ (in degrees) between 5 and 25 degrees above the horizontal plane;

−138 dB (W/m^2) in any 4 kHz band for angles of arrival between 25 and 90 degrees above the horizontal plane."

These limits apply for "all conditions and for all methods of modulation" to the earth exploration-satellite service (space-to-Earth), to the space research service (space-to-Earth), and to the fixed-satellite service (space-to-Earth).

A-3

In the band 11.7 to 12.2 GHz, pfd limits are specified in Article 9 and
Annex 5 of new Apppendix 30 (old Appendix 29A) of the ITU Radio Regulations to
protect terrestrial services in Regions 1 and 3 from interference from BSS
space stations in Region 2. Specifically, these limits are as follows:

"1) for all the territories of administrations in Regions 1 and 3:

       -125 dB (W/m^2/4 kHz)   for broadcasting-satellite

                                            space stations using circular

                                            polarization;

       -128 dB (W/m^2/4 kHz)   for broadcasting-satellite

                                            space stations using linear

                                            polarization;

   for all angles of arrival; and

2) for territories of administrations in Region 3 and those in the
western part of Region 1, west of longitude 30'E:

       -132 dB (W/m^2/5 MHz)   for angles of arrival between

                                            0° and 10° above the

                                            horizontal plane;

       $-132 + 4.2 (\gamma - 10)$ dB (W/m^2/5 MHz)   for angles of arrival γ (in

                                            degrees) between 10° and 15°

                                            above the horizontal plane;

       -111 dB (W/m^2/5 MHz)   for angles of arrival between

                                            15° and 90° above the

                                            horizontal plane."

In addition, Article 10 of Appendix 30 (old Appendix 29A) of the ITU Radio Regulations provides for the protection of space services in Region 2 from interference due to BSS space station transmitters in Regions 1 and 3, by requiring that power flux densities computed at a reference test point (longitude 35°W, latitude 3°S), by the method specified in Annex 11, Appendix 30, not exceed the values tabulated in Annex 11, and arranged according to orbital position, IFRB number and channel number. (see ITU Radio Regulations Appendix 30).

Furthermore, Article 7 and Annex 4 of Appendix 30, ITU Radio Regulations, require coordination of space stations in the FSS or the BSS of Region 2, in accordance with the procedures specified in Article 6, Appendix 30, whenever their transmitters produce a pfd on the territory of an administration in Region 1 or in Region 3 which exceeds the following values:

"-147 dB (W/m^2/27 MHz) for $0 \le \theta < 0.44°$

$-138 + 25 \log \theta$ dB (W/m^2/27 MHz) for $0.44° \le \theta < 19.1°$

-106 dB (W/m^2/27 MHz) for $19.1° \le \theta$ "

θ = the difference in degrees between the longitude of the interfering broadcasting-satellite or fixed-satellite space station in Region 2 and the longitude of the affected broadcasting-satellite space station in Regions 1 and 3.

Techniques for Efficient Use of Spectrum/Orbit Resource

Annex 7 of new appendix 30 (old appendix 29A) of the ITU Radio Regulations discusses ten techniques "...leading to a more efficient use of the spectrum/

orbit resource..." and recommends that they "...be applied to the maximum extent technically and economically practicable consistent with the capability of systems to fulfill the requirements for which they were designed."

1. Clustering
2. Cross-polarization
3. Crossed-beam geometry
4. Paired service areas
5. Frequency interleaving
6. Minimum space station spacings
7. Space station antenna discrimination
8. Earth station antenna discrimination
9. Minimizing eirp differences
10. Realistic quality and reliability objectives.

Protection Criteria

Protection criteria have been established for co-channel services sharing the 12 GHz band in Annex 9 of new Appendix 30 (old Appendix 29A) of the ITU Radio Regulations. Table A-1 was taken directly from Appendix 30 and lists the applicable protection requirements, for wanted services, from those co-channel services which could cause interference under specified reference conditions.

When the reference conditions, i.e.

a) 12 MHz peak-to-peak frequency deviation of wanted signal

b) grade 4.5 service quality

c) co-channel carriers,

are not fulfilled, the FM/TV protection ratio can be determined from (ITU RR AP30, Annex 9):

R = 12.5 - 20 log $(D_v/12)$ - Q + 1.1Q^2 (dB)

D_v = nominal peak-to-peak frequency deviation (MHz)

Q = impairment grade, concerning interference only.

A-6

Wanted Service[1]	Wanted Signal[1]	Interfering Service[1]	Interfering Signal[1]	Protection Requirements[2]	
				Total Acceptable[3]	Single Entry
BSS	TV/FM	BSS, FSS FS, BS	TV/FM	C/I = 30 dB[4,7]	C/I = 35 dB[4]
FSS	FDM/FM	FSS	TV/FM	N = 500 pW0p[3]	N = 300 pW0p
FSS	TV/FM	BSS, FSS	TV/FM	C/I = 32 dB[5]	C/I = 37 dB[5]
FSS	4 -PSK	BSS, FSS	TV/FM	C/I = 30 dB	C/I = 35 dB
FSS	FDM/FM	FSS	FDM/FM	N = 1000 pW0p	N = 400 pW0p
FS	FDM/FM	BSS	TV/FM	N = 1000 pW0p	-125 dB (W/m^2/4 kHz)[6]
BS	TV/VSB	BSS	TV/FM	C/I = 50 dB	not applicable

Notes: [1] BSS   = broadcasting-satellite service
        FSS   = fixed-satellite service
        BS   = broadcasting service
        FS   = fixed service
        TV   = television
        FM   = frequency modulation
        FDM   = frequency division multiplex
        4 -PSK = four-level phase shift keying
        VSB   = vestigial sideband

[2] These limits include both up-link and down-link contributions: They are expressed:

  - in dB for carrier-to-interference ratio;
  - in pW0p for noise;
  - in dB(W/m^2/4 kHz) for power flux-density in a 4 kHz band.

[3] Values in dB are protection ratios for the sum of interfering signals. Values in pW0p represent interference noise in the worst telephone channels caused by the sum of interfering signals.

[4] For BSS satellites located at the interfaces of Regions 1/3 and Region 2, the C/I ratios should be 1 dB higher.

[5] See CCIR Recommendation 483.

[6] This value may be suitably modified for tropical regions to take account of rain attenuation. Allowance may also be made for polarization discrimination.

[7] C/I = ratio of carrier-to-interfering signal

[8] N = noise power

BSS Constraints in Regions 1 and 3

The technical data used as a basis for developing the Broadcasting-
Satellite Service Plan for ITU Regions 1 and 3 are published in Annex 8 of the
new Appendix 30 (old Appendix 29A) of the Radio Regulations. Some of the
values assumed for critical or key parameters in Regions 1 and 3 may also be
applicable to Region 2. The BSS Plan for Region 2 will be developed at the
Region 2 Regional Administrative Radio Conference (RARC) in 1983. Constraining
values of technical parameters in Regions 1 and 3 are summarized as follows.

Propagation loss on the space-to-Earth link should be assumed to equal the
free space path loss plus the rainfall attenuation appropriate to the climatic
zone and the antenna elevation angle at the Earth's surface (see Section 2.,
An. 8, AP 30 ITU RR). The difference between clear weather attentuation and
the attenuation for 99% of the worst month should be limited to 2 dB or less by
choice of elevation angle.

The signal should consist of a video signal and audio sub-carrier, both
frequency-modulating an RF carrier in the 12 GHz band with pre-emphasis
characteristics as given in Section 3 (An. 8, AP 30, ITU RR). Other types of
modulation are permitted provided they do not cause greater interference than
the FM-TV system described in An. 8, AP30, ITU RR.

According to the ITU, circular polarization should be used in Regions 1, 2
and 3, although the U.S. Administration has objected since the FSS in the U.S.
may employ linear polarization, thereby precluding the use of crosspolarization
discrimination in BSS design if circular polarization is used.

A-8   C - 2

The carrier-to-noise ratio should be assumed to be 14 dB for 99% of the worst month. The reduction in downlink quality from uplink thermal noise is assumed to be equivalent to a degradation in downlink carrier-to-noise ratio not exceeding 0.5 dB for 99% of the worst month. The protection ratio for co-channel signals is taken to be -31 dB and for adjacent-channel signals is -15 dB.

The spacing between adjacent frequency channels is 19.18 MHz. In Region 1 the channel assignments were made by attempting to group all channels radiated within a single antenna beam, within a frequency range of 400 MHz. The spacing between two channels feeding a common antenna were assumed to be 40 MHz or more, to simplify satellite transmitter output circuits.

The assumed figure-of-merit (G/T) of a receiving installation was taken as 6 dB/K for individual reception and 14 dB/K for community reception. The minimum diameter of receiving antennas should be such that the half-power beam-width is 2° for individual reception in Regions 1 and 3, 1.8° for individual reception in Region 2 and 1° for community reception in all Regions. The receiving antenna reference radiation patterns should conform to the curves presented in Section 3.7, An. 8, AP30.

The necessary bandwidths are considered to be: 27 MHz for 625-line systems, 27 MHz for Region 3 525-line systems, and 19 and 23 MHz for 525-line systems in Region 2. Guardbands necessary to protect services in adjacent frequency bands are listed in the following table.

Region	Guardband at the lower edge of the band (11.7 GHz)	Guardband at the upper edge of the band (12.2/12.5 GHz)
1	14 MHz	11 MHz
2	12 MHz	9 MHz
3	14 MHz	11 MHz

These values assume a maximum beam center eirp of 67 dBW for Regions 1 and 3 and 63 dBW for Region 2, based on individual reoption. The filter rolloff is assumed to be 2 dB/MHz. The guardbands can be reduced 0.5 MHz per dB decrease in eirp.

The BSS plan for Regions 1 and 3 has generally assumed nominal orbital positions spaced uniformly at 6° intervals. These positions are required to be maintained with an accuracy of ± 0.1° in the N-S and E-W directions (maximum excursion of ± 0.14° from nominal position). Furthermore, the Regions 1 and 3 BSS plan has assumed a minimum receiving antenna elevation angle of 20° to minimuze the required satellite eirp, although elevations less than 20° will generally be required at latitudes above 60°. Minimum elevations of 30° were used to select orbit slots for some mountainous areas, and minimum elevations of 40° were used in high precipitation service areas (climatic zone 1).

Transmitting antennas have been assumed to have elliptical or circular cross-sections with:

$G_m = 27,843 /ab$

where:

G_m = numeric gain

a and b are the angles in degrees, subtended at the satellite by the major and minor axes of the beam cross-section

The transmitting antennas are assumed to have efficiencies of 55%. The minimum practicable half-power transmitting antenna beamwidth has been taken to be 0.6°. Transmitting antenna radiation diagrams must conform to the sidelobe envelopes specified in Section 3.13.3, An. 8, AP 30, ITU Radio Regulations. The satellite antenna axis must be capable of pointing in the intended direction within an accuracy of 0.1°. Angular rotation of the beam must not exceed ±2°, except in the case of circular beams using circular polarization.

The output power of a broadcasting satellite must not rise by more than 0.25 dB relative to its nominal value. The pfd at the edge of the coverage area for 99% of the worst month must be less than:

-103 dB (W/m^2) for individual reception in Regions 1 and 3

-105 dB (W/m^2) for individual reception in Region 2

-111 dB (W/m^2) for community reception in all Regions

The difference between the e.rp at the beam edge and at the beam axis is assumed to be 3 dB.

CCIR Reports and Recommendations

In the absence of specific ITU radio regulations, the CCIR literature provides valuable data pertinent to the efficient utilization of the orbit. Many of the Reports in Study Group 4 and Study Group 10/11 volumes (Fixed-Satellite Service and Broadcasting Services, respectively) provide general useful information. Of particular note, however, for this study is Report 559 (S.G. 4) on the effect of modulation characteristics on the efficient use of the geostationary orbit in the fixed-satellite service. This report discusses

the interference immunity of a signal as affected by the ratio of the frequency bandwidth to the information bandwidth for both digital and analogue transmissions. Another pertinent report in this regard is Study Group 4, 9 Report 388-3.

Sharing criteria for the K_u band between the FSS and the BSS is provided and discussed in Reports 560-1, 561-1, and 809. Report 455-2 on frequency sharing between networks of the Fixed-Satellite Service documents the relation between carrier-to-interference power ratio and satellite separation angle. Report 558-1 provides satellite antenna patterns in the Fixed-Satellite Service. A discussion of modulation utilized for Broadcasting-Satellite Service is contained in S.G. 11 Report 632-1. Report 633-1 supports and elaborates on the 1977 WARC BS plan parameters for Regions 1 and 3. Measured carrier-to-interference Protection Ratios for the BSS are contained in Report 634-1 and the BSS reference antenna patterns are presented in detail in Report 810.

APPENDIX B

EXISTING AND PLANNED
REGION 2 FSS AND BSS SYSTEMS

Fixed-Satellite Systems

At present there are only two 11/14 GHz domestic satellite systems in geostationary orbit within the U.S. visibility sector (see Figure B-1). Both of these are operated by Satellite Business Systems.

A substantial number of new domestic satellites are proposed for launch during the next 4 or 5 years. These satellites are intended to expand the capacity of systems now in operation, to replace earlier launched satellites on the approach of end of life and to provide new types of service in the 1980's. Table B-1 provides a brief summary of these satellites. It should be noted that this table provides a mix of FDMA and TDMA systems with most of the 12 GHz systems planning to employ TDMA techniques.

Western Union is in the process of developing two Advanced WESTAR satellites which will have the capability of supporting four 225 Mbps data streams in the 12/14 GHz bands using spot beams and cross polarization techniques.

Satellite Business Systems is now proposing to expand its system at 12/14 GHz by the launch of its "on-the-ground" spare satellite. GTE Satellite Company is proposing its own two in-orbit satellite systems with frequency reuse via cross polarization in the 12/14 GHz band. Southern Pacific Communications Company is proposing a four in-orbit satellite system with hybrid operations in both the 4/6 GHz and 12/14 GHz bands. Finally, Canada is presently operating ANIK B-1 in both the 4/6 and 12/14 GHz bands. Figure B-2 shows the systems planned to be in operation by 1984.
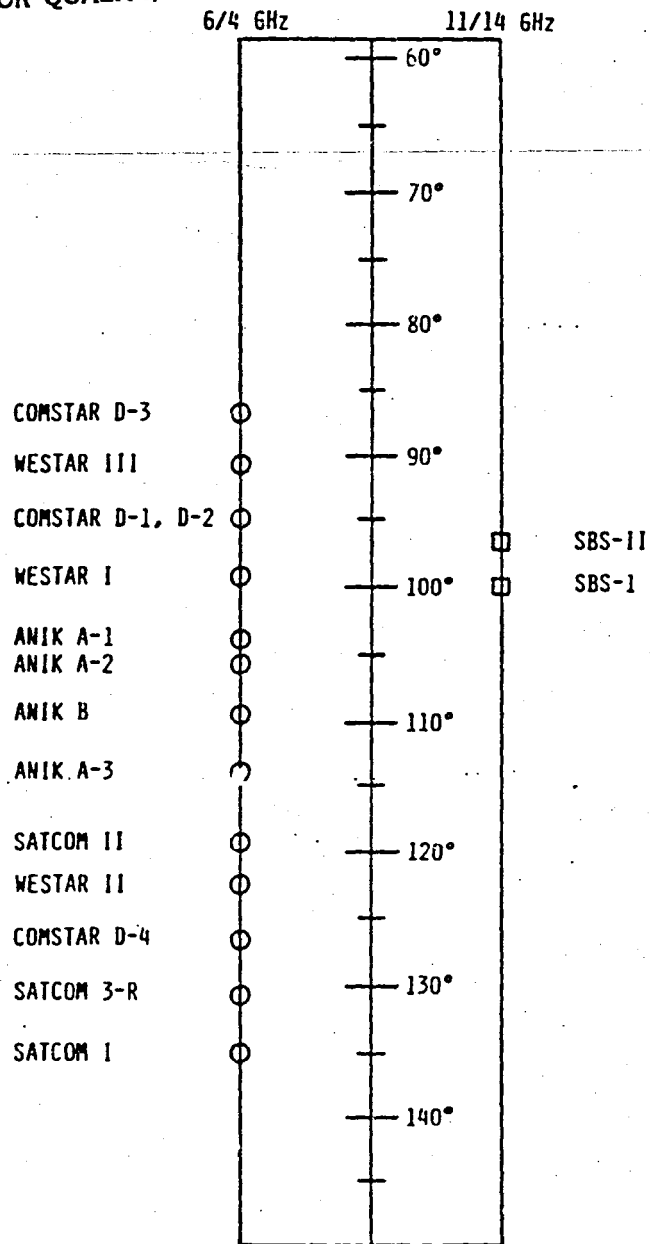
Figure B-1.   Orbital Slots in the U.S. Visibility Sector
As of September 1981

Table B-1

PROPOSED DOMESTIC SATELLITES

Transponders/Bandwidth

Satellite Network	Orbital Locations	4/6 GHz	12/14 GHz	Notes
Western Union				
WESTAR III	1	12-36MHz	-	Launched during 1979.
WESTAR IV, V	2	24-36MHz	-	
Advanced WESTAR	2	12-36 MHz	4-225MHz	Shares spacecraft structure with TDRSS.
RCA Americom				
SATCOM I-V	5	24-36MHz	-	Includes replacement of SATCOM I and II launched during 1975-1976.
AT&T	3	24-36MHz	-	Replacements for COMSTAR D-1 through D-4.
SBS	3	-	10-43MHz	Launch of on-the-ground spare now being proposed.
GTE Satellite	2	-	16-54MHz	New system.
Hughes	3	24-36MHz	-	New system.
Southern Pacific	4	12-72 MHz	12-72MHz	New system.

4/6 GHz   11/14 GHz

SBTS: BRAZIL ()

SBTS: BRAZIL ()

SPACENET II (10-84)   — 70   □   SPACENET II

GALAXY-B
SATCOL: COLUMBIA (84)

ADV. WESTAR (5-84)   — 80   □   ADV. WESTAR

SATCOM IV (12-81)

TELSTAR B (2-84)

ADV. WESTAR (1-84)   — 90   □   ADV. WESTAR

TELSTAR (7-83)   □   SBS III (11-82)
                                               ■   SBS II (6-81)
WESTAR IV (2-82)   100   ■   SBS I 11-80)

ANIK D-1 (4-83)   □   GSTAR I (3-84)
                                               □   GSTAR II (9-84)
ANIK D-2 (85)   — 110   □   ANIK C-3 (85)

ANIK D-3 (4-84)   □   ANIK C-1 (5-82)
                                               □   ANIK C-2 (8-82)
SPACENET I (2-84)   — 120   □   SPACENET I

WESTAR V (9-82)

COMSTAR D-4 (2-81)

SATCOM III-R (9-81)   — 130

GALAXY-A (6-83)   PLANNED:

SATCOM I-R (10-82)   — 140   □
                                                       ○
SATCOM II-R (3-83)

                                              RECENTLY LAUNCHED
                                                       ■
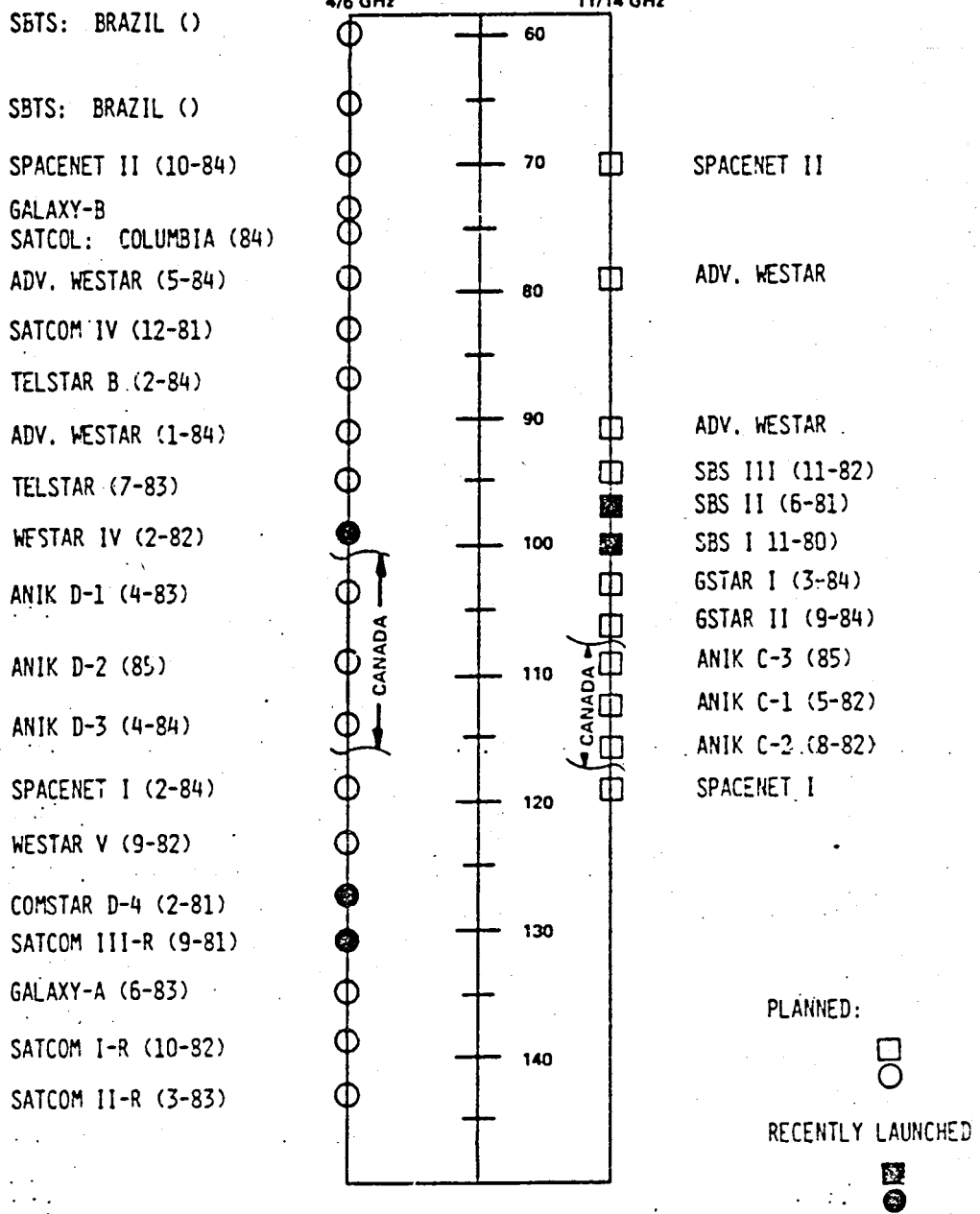   ●

Figure B-2. Orbital Slots in the U.S. Visibility Sector
                    (1984 Timeframe)

Broadcasting-Satellite Systems

The Broadcasting-Satellite Service (BSS) is, in reality, a new telecommunication service, even though it had been defined by the ITU at least as early as the second World Administrative Radio Conference for Space Telecommunications, held in Geneva in 1963[1]. Furthermore, there are presently no fully evolved broadcasting-satellites in service anywhere in the world, even though the technical parameters, frequency channels, and orbit slots were planned for Regions 1 and 3 at the World Administrative Radio Conference for broadcasting-satellites in 1977[2]. Systems have been studied and proposed, but only three experimental systems have resulted in hardware, and this has been developmental in nature. The U.S./Canadian Communication Technology Satellite (CTS) and the Japanese Broadcasting-Satellite Experiment (BSE) have tested BSS design concepts. Previously, the United States' Advanced Technology Satellite Program (ATS-F) had also demonstrated the feasibility of direct satellite television broadcasting, but not at K_u-band.

In ITU Region 2, numerous systems are being planned but designs cannot be finalized until after the 1983 Regional Administrative Radio Conference (RARC) to be held specifically for planning the Region 2 BSS.

In anticipation of the results of the 1983 RARC, the Satellite Television Corporation (STC), a division of Communications Satellite Corporation (COMSAT), filed an application to the Federal Communications Commission (FCC) to begin a

---

[1] 1976 Radio Regulations, ITU, Geneva 1976
[2] Final Acts of the WARC-BS, ITU, Geneva 1977

national satellite-to-home subscription television service, perhaps as early as

1985 in the eastern time zone of the United States. In responding to COMSAT's

petition, the FCC issued a Notice of Proposed Policy Statement and Rulemaking,

promulgating basic policies and procedures, and inviting comments and addi-

tional BSS proposals, for the United States, by July 16, 1981.

Thirteen additional proposals were received by the FCC, bringing the total

number to fourteen, including that of STC. Table B-2 summarizes the operating

characteristics, where they have been specified, for the fourteen proposed U.S.

systems, now being considered by the FCC. Several of the petitions did not

initially specify operating parameters but promised detailed specifications at

a later date.

Of the systems which have defined operating parameters, all specified

effective isotropically radiated powers (eirp) between 53.7 dBW and 65 dBW,

with most under 60 dBW. The transmitting antenna axial gains ranged between 29

and 39 dBi, with most between approximately 32 and 35 dBi. The major

differences between the systems described concerned numbers of satellites,

arrangment of service areas and type of service. Some of the more important

(and controversial) differences with respect to type of service were: pay or

free TV, direct broadcast to home or terrestrial retransmission, and ordinary

or high definition TV.

The controversy over subscription (pay) TV has to do with the method of

funding — i.e. by advertisers or by users. That controversy centering on

direct satellite broadcasting versus distribution to local stations and cable

systems is closely related to the question on subscription. Furthermore, the

Table B-2. Characteristics of Direct Broadcast Satellites [1]

Applicant	No. of Satellites (Spares)	No. of Channels per Satellite	Channel Bandwidth (MHz)	Downlink Power (W / dBW)	Antenna Axial Gain (dBi)	EIRP (dBW)	Total Satellite Power (Watts)	Weight Of Satellite In Orbit (lbs)	Satellite Design Life (Years)	Orbital Slot (Degrees West Longitude)	Type of Service
Advance, Inc.	-	-	-	-	-	-	-	-	-	-	1,2,3
CBS, Inc.	4(2)	3	27	400/26	34-39	.60-65	4000	2317	7	-	1,3,4,5,7,9,10
Direct Broadcast Satellite Corp.	3(1)	14	22.5	200/23	33	56	4600	2987	7	103,123,143	7,8,9,10
Focus Broadcast Satellite Corp.	3,4, or 5	-	-	.	.	.	-	.	-	-	1,2,3,4,5,6,7,9,10
Graffic Scanning Corp.	2(1)	2	18	300/24.7	29-32	53.7-56.7	2000+	-	-	143,115	1,2,7,10
Home Broadcast Television Partners	1	-	-	19.7/12.9	-	-	-	-	.	110	11
National Christian Network, Inc.	4	-	-	-	.	.	-	.	-	-	-
RCA American Communications	4(2)	6	24	230/23.6	34.4	58	4770	2415	7	-	8,9
Satellite Development Trust	4(2)	3	-	150-250/21.8-25	-	-	-	-	-	115,135,155,175	8
Satellite Television Corp.	4(2)	3	16	185/22.7	32.3-37.3	55-60	1700	1430	7	115,135,155,175	1,2,5,7,9,10
United States Satellite Broadcasting Co. (Hubbard Broadcasting, Inc.)	2(1)	6	16	230/23.6	33.4	57	4000	2300	7	115,135	1,3,4,6,9
Unitel Corp.	-	-	-	.	.	.	.	.	-	100	11
Video Satellite Systems, Inc.	2	2	18	150-190/21.8-22.8	32.2-35.2	54-59	1000	1201	8	115,135	1,3,4,5,8,9
Western Union Telegraph Co.	4(2)	4	16	100/20	35.5-38	55.5-58	-	1175	7	60,100	8

(1)
-1

Table B-2

(Continued)

Legend:

1 - Direct to home (or business)

2 - Pay Television

3 - Advertiser supported

4 - Terrestrial retransmission by broadcasters

5 - Terrestrial retransmission by cable systems

6 - Terrestrial retransmission by LPTV stations

7 - Electronic text services

8 - Leased-channel system

9 - High definition TV

10 - Additional audio services

11 - Unspecified

[1] Prepared from information contained in "Good News, Bad News in DBS Spacerush", Broadcasting July 20, 1981, Vol. 101, No. 3 and

"Fourteen Seek Direct Broadcast Rights", Aviation Week and Space Technology, August 10, 1981.

two uses also parallel the ITU's definitions of individual and community

reception. Probably both types of service will be required to satisfy all the

vested interests, local broadcast stations, cable TV services, associations of

broadcasters, etc.; as well as to serve those homes which have no TV service

(or only one channel).

Many of the applicants have proposed experiments with high definition TV,

(HDTV), offering higher quality pictures for very large screens. Probably some

type of HDTV will be provided even though the RF bandwidth required is

considerably higher. The optimum RF bandwidth for HDTV has not been determined

absolutely but could be as high as 72-100 MHz instead of the more normal 16

MHz.

REFERENCES

[1]   International Radio Consultative Committee, Recommendations and Reports of the CCIR, 1978, Vol. IV, Report 708, Geneva, 1978.

[2]   International Radio Consultative Committee, Conclusions of the Interim Meeting of Study Group 4, Report 708 (Mod 1), Geneva, 1980.

[3]   Van Trees, Harry L., editor, Satellite Communications, New York: IEEE Press, 1979, pp. 141-158.

[4]   International Telephone and Telegraph Consultative Committee, Recommendation G.711.

[5]   B. G. Haskell and R. Steele, "Audio and Video Bit-Rate Reduction", Proc. of IEEE, February, 1981.

[6]   R. Burkhardt and J. Wasser, "Digital Television Transmission with 34 Mbit/s", SMPTE Journal, April, 1980.

[7]   "A Survey of Interference Problems and Applications to Geostationary Satellite Networks", Jeruchim, Proc. IEEE, Vol. 65, March, 1977.

[8]   International Radio Consultative Committee, Recommendations and Reports of the CCIR, Report 388-3 (Mod 1).

[9]   "Binary PSK Error Probabilities with Multiple Cochannel Interferences", Rosenbaum, IEEE Trans. Comm. Tech., Vol. Com-18, June 1970.

[10] "Spacing Limitations of Geostationary Satellites Using Multilevel Coherent PSK Signals", Jeruchim and Lilley, IEEE Trans. Comm., Vol. Com-20, October 1972.

END

DATE

FILMED

SEP 9 1982

End of Document