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A Super-High-Frequency Satellite Communications System for Canada (1977-1985)

Volume 2

Report on a Study for
Department of Communications
Canada
September 1971

A Super-High-Frequency Satellite Communications System for Canada (1977-1985)

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Final Report

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1. INTRODUCTION

The subject of the report is introduced. Time scale of the consultation contract was six months, with a resource limitation of three people. The broad aims are stated and the depth of study commented on.

During March 1971 the Department of Communications, Government of Canada requisitioned consulting services from Bell-Northern Research, Ottawa. These consulting services were to be used to carry out a study. The major aim of the study was to evaluate the significance to Canada of satellite communications in the frequency range 12 GHz through 18 GHz in the time frame 1977 through 1985. The Director General, Communications Research Centre, Department of Communications, was designated the "Design Authority" for the administration and direction of the study.

In the context of the major aim it was considered appropriate

(i) to establish an informed first estimate of the order of investment necessary - and possible trade-offs - to best suit the probable needs of Canada in the time frame considered, if this frequency range was exploited for satellite communications; and

(ii) to survey the possibilities, such that the most applicable and promising approaches could be identified for consideration in the choice of possible future detailed planning, study, applied research and development.

The depth of the current study was confined, to a duration of approximately 6 months, with a resource allocation of three people. This limitation was considered to be not unreasonable on two counts, and was introduced intentionally in spite of the comparative complexity of the subject. Firstly, uncertainties are inherent in any forecasts of the future; and demand forecasts for individual services are no exception. Secondly, possible technical advances during the intervening years, especially in a rapidly advancing field, add another dimension of uncertainty. Thus, refinement of analysis beyond a certain depth of detail only detracts from the degree of credibility achieved. The intent was to establish the bounds for these uncertainties and to examine which of these uncertainties are likely to have significant effects in the context of developing technological and operational trends in satellite communications. In this respect, viz. of presenting a logical outline picture in spite of the uncertainties, the study was truly systems-oriented.

This task has been carried out, and is reported on in the subsequent chapters. The presentation of the report is in the well-known STOP format wherein the theme and any major conclusions of each section are outlined at its commencement.

1. Introduction

1.1 SPECIFIC OBJECTIVES OF STUDY

The major aim, which is to evaluate the significance to Canada of satellite communications systems operating in the frequency range 12 GHz through 18 GHz in the time frame 1977-1985 is to be attained by the fulfillment of seven specific objectives, agreed at the commencement of the study. These are listed and are an amalgamation from the "specifications" of the contract and its clarification.

An excerpt from the specifications for the study reads:

"The aim of the contract is to evaluate the significance to Canada of satellite communications systems operating in the frequency range 12 GHz to 18 GHz post 1977. In broad outline, the tasks to be performed in the study are as indicated below, with maximum allowances for flexibility, at the direction of the Design Authority, within the scope of the contracted effort. Tasks i) and ii) are to be carried out with frequent consultation with the Design Authority and are to be followed with a written interim report.

i) identify services which could be provided by satellite systems in the designated time frame

ii) identify those services for which a need is likely to exist in Canada in the time frame and which can feasibly be provided by satellite systems operating in the 12 GHz to 18 GHz range

iii) establish basic satellite requirements to provide the services and investigate the satellite technology which will be available in the time frame

iv) synthesize and model satellite systems to provide the required services in the frequency bands available and within the limitations of the available technology

v) develop system, subsystem and unit specifications for both the space and ground segments of the system modeled

vi) perform cost analyses for the system, including development, implementation, operating costs

vii) prepare final report."

The following clarifications were agreed in the discussions as reasonable and applicable.

1. Although the time frame to be considered is specified as "post 1977" in the Work Statement the actual period which will be considered will be 1977 through 1985.

2. As the contract is based on a specified amount of effort it is understood that the depth of detail in the study will be limited by that amount of effort. In this context the cost analyses will be first-estimate ones and the definitions of system, subsystem and unit specifications are as given below:

a) System Specifications - overall specifications of the system mainly consisting of quantitative information regarding the quality of the various types of service provided by the system models considered.

b) Subsystem Specifications - overall specifications of the ground segment and the space segment of the system.

c) Unit Specifications - block diagrams of the spacecraft communications subsystem and the various types of earth stations used in the system and a general description of the major units within these subsystems.

3. Direct-to-home television and sound broadcasting considerations of satellites are excluded from this study, but the study will concern itself with all the communications type services and satellite designs considered in the study will aim at meeting the needs of all the types of communications services.

1.2 STUDY METHODS

An overview of the methods employed in carrying out the tasks is presented, in the sequence in which they were carried out. Demand estimation, review of trends in satellite technology and investigation of propagation phenomenon was followed by "Systems mapping" for individual services based on transmission performance objectives agreed with the Design Authority. Reasoned boundaries were introduced on the maps to enable cost optimization in bounded ranges. First-estimate cost data gathered was used in service economic optimization. Two satellite and earth segment models were synthesized. Estimates of costs of models were obtained with emphasis on the one with greater standardization.

At the commencement of the study three tasks were started, viz. an estimation of the likely demand for satellite services in the 1977-1985 time frame, an investigation of the trends in satellite technology in the frequency range covered by the study, and the identification of particular bands of interest in this range together with a study of propagation data in the frequency range.

The method employed for demand estimation followed three sequential steps. Firstly, a listing was made of all the possible categories of communications services feasible in Canada during 1977 through 1985. From this a more limited list was made of those services for which any noticeable demand may reasonably be expected, and which are likely to benefit from the special attributes of satellite communications. The potential users of the services were identified. Seven different potential users were consulted by direct interviews. The possible demands of certain major users could only be indirectly obtained or deduced from published data. Duplications were eliminated, and from the consolidated list so obtained allowance was made for the capacity of satellite facilities shortly to be deployed in Canada. This yielded a forecast demand for new satellite facilities together with ranges and confidence limits, both for the earth and space segments.

An interim report was issued, as required, in May 1971 and was accepted by the Design Authority.

The investigation into trends in satellite communications technology was performed by literature survey, consultations with the Design Authority, and visits to certain organizations in the U.S. where advanced research is now in progress in this general field. Notable among the latter were visits to NASA, Bell Labs and COMSAT. These are reported on in Appendix D to this report. From these sources trends as well as practical technological limitations could be identified. Also, from these visits and an analysis of certain submissions recently made to the Federal Communications Commission of U.S.A. (FCC) for satellite systems, certain relationships between spacecraft physical parameters (such as weights, powers, launch vehicles) and costs were established. First estimates of costs were obtained in what were considered as areas of maximum variance by direct reference to established suppliers. Relationships between capital costs and anticipated annual costs which could be derived by assuming values of certain basic economic factors were confirmed by reference to similar figures quoted in the FCC submissions. This was done both for the earth segment and the space segment.

The most probable frequency band, within the frequency range, was identified in consultations with DOC and CRC. This was later confirmed by the allocations of the World Administrative Radio Conference at Geneva in June/July 1971, and note was taken of certain further allocations in the study. The study of propagation data was directly aimed at assessing the margins, for each of the services identified in the demand estimate, to overcome the effects of fading. Detailed consultations, not only with Canadian experts at CRC but also with the Bell Labs and COMSAT, together with a comprehensive survey of technical literature enabled estimates to be made with a reasonably high degree of confidence.

Next, the quality of transmission considered satisfactory for each of the services was established in quantitative terms. This was done by a brief survey of current North American Transmission standards, using reference to quality demanded in recent requests for proposals in Canada, qualitative reasoning, and reference to technical literature. These standards were then debated with the Design Authority and concurrence obtained.

Having gathered all the necessary tools, systems modeling could now commence in earnest. The strategy was, firstly, to take account of immutable laws of physics which express fundamental relationships between transmission parameters and the quality of transmission achieved for each of the two methods of modulation - analogue FM and digital CPSK - considered to be suitable for confident implementation during the time scale of the study. These were then divided into their well known subsets. These fundamental relationships were then graphically represented in "systems modeling maps" - one map corresponding to each subset. This method, which had been developed at BNR for general application, makes it possible to see at a glance how the variation of any one of the fundamental parameters would inexorably affect the others. On these systems modeling maps the technical and technological constraints appropriate to that subset could be drawn as boundary bands. Some of these constraints may be fundamental - like those of threshold - while others may be derived - like the median operating point, which resulted as a direct consequence of the system fading margin arrived at during the considerations of propagation. Each of these constraints was analyzed and justified before the boundary band was introduced. The bounded area enclosed by the bands then represented the limits of the interrelated, fundamental transmission parameters within which practical systems could exist. At this stage also, a gross analysis of the geographical distribution of anticipated demand for each of the services was performed to establish the area coverage required by each service. Narrative reasoning very quickly led to the most desirable arrangement of satellite beams.

At this stage the system cost optimization exercise could commence. The information being gathered, in parallel with the preparation of the systems modeling maps for each of the generic types of transmission considered therein, was analyzed to establish relationships between satellite transponder rf powers and the estimated weights of electronic hardware required to produce this power. A relationship also was established between the communications hardware weights and the total weights of non-communications type subsystems of typical and forecasted satellites. From these weights the corresponding costs could be calculated. Similar data of first estimates of costs was collected for major constituent components of earth stations, such that the earth station cost variance with the antenna diameter, transmitter power, type of low-noise amplifier, and other similar parameters could be estimated. From this data base, and the estimate of demands for each of the services, an optimization exercise was performed to choose the most efficient mode of transmission and the associated bandwidths. The choice of the most effective division between the earth segment and the space segment then commenced within the constraints of the systems modeling maps. This was performed by minimizing the annual charges that could be imputed to each service for each permissible combination of the earth and space segment arrangements which could still meet the quantity of the identified needs, and the quality of transmission required. Sensitivity analyses to parameter changes were also performed.

The sum total of these optimizations yielded a model, dubbed model 1. This model was examined from the point of view of weights and physical feasibility only, disregarding any considerations of engineering acceptability. It was called, truly, the minimum hardware cost model. It was accepted that development costs would most certainly be higher than if any degree of standardization was obtained. It straddled the available frequency bands but the frequency bandwidth could technically be provided. Alternatively, with only marginal increase in complexity, polarization diversity and frequency re-use methods could be employed to retain the emission in the more limited band. The model also called for some special extensions to the Thor-Delta launch vehicle which once again was considered entirely feasible by the suppliers.

The second model was set up to examine what degree of standardization could be achieved in the hardware, what were the penalties in terms of restriction of services if only the 500 MHz band were used, and what other limitations, if any, would become significant. This yielded a more hygenic and more technically acceptable model which was not only within the broad limitations of the total capital costs, but also had associated minimum annual charges for the services provided together with an acceptable degree of standardization.

In all of these analyses and stages of optimization extensive use of computer facilities at BNR was made.

In parallel with the optimization and modeling process, report outlines were prepared and the chapters corresponding to the work in the earlier phases of the study were prepared in the STOP format. The final chapters of the report were completed.

2. Estimates of Likely Service Demand for 1977 through 1985

2.1 GENERAL DISCUSSION

Estimates of the demand for transmission facilities by Canadian communications users during the time from 1977 through 1985 is vital to the intelligent design of a satellite system.

Prior to the design of any communications system it is imperative that services to be carried be identified and quantified. Only when the type and amount of information to be transferred is identified can an efficient and minimum cost communications system be devised. Task i) and ii) of the Work Statement[2.13]* reproduced below recognize this basic need.

" i) identify services which could be provided by satellite systems in the designated time frame,

ii) identify those services for which a need is likely to exist in Canada in the time frame and which can feasibly be provided by satellite systems operating in the 12 GHz to 18 GHz range. "

To ensure that sufficient data on the services to be carried was obtained the above tasks were expanded as below. (The three subtasks given below were referred to as Task A in the Interim Report.)

a) Identify all possible communications services which would be feasible during the time frame 1977-85. List those services which could be provided via satellite systems, including any new services which might arise because of the unique features of satellite systems.

b) Identify those services which could be feasibly provided by satellite systems operating at frequencies above 10 GHz during the time frame 1977-85.

c) Establish the requirements or needs in Canada for these services during the time frame 1977-85.

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* References are given in section 2.12.

Tables 2-1 and 2-2 of section 2.2 were generated in partial fulfillment of Tasks i) and ii). To quantify the service needs of each of the entries in Table 2-1 would have taken more time than was allocated. Thus the major needs were examined by reference to various documents and by interviews with certain potential users to whom access could be obtained. In the following sections of this chapter the services most likely to be using the satellite medium in the 1977-1985 time frame are identified and estimates of their needs are made.

2.2 POSSIBLE COMMUNICATION SERVICES, 1977-1985

Table 2.1 is a comprehensive listing of all the possible categories of communication services feasible in Canada during 1977-1985, independent of their volume, economics, or the medium of transmission. Table 2.2 is a listing of those of the above services which are more likely to exist and benefit from the unique area coverage and other technical attributes of satellites.

Any individual listing of electronic information transfer services is likely to be extensive. Fortunately many individual services have common features which enables them to be grouped, and categorized. A list of some 400 services was reduced to 28 demand groups in Ref 2.1 and 2.2 in which potential demands up to the year 1990 were estimated for the U.S. A list of 255 demand titles was grouped into 32 demand categories in Ref 2.3 and 2.4.

In the preparation of the list of the categories of possible communications services in Canada during 1975 through 1985 extensive use of the above references was made. The listing of data services applicable to Canadian computer utilities, as published by Telecommission Study 5[2.5] was examined. Additionally the possible need for video-telephone service was considered. Certain special services which may be unique to Canada, due to its geographical and demographic attributes like communication to remote communities and dissemination of provincial, educational TV, were added.

Of the services listed in Table 2-1, and using the above references, a selection of those services for which a demand may reasonably be expected, in Canada, in the time frame 1977-1985 was made. This eliminated some of the far-out categories like the 'chequeless society', 'automated library', etc. The next stage of filtering involved a consideration of the special attributes of satellite systems, particularly the ones of area coverage, long to medium distance point-to-point transmission and multi-point communications. This led to the more limited listing of those services for which any noticeable demand may reasonably be expected in Canada, during the period covered by this study, and which are likely to benefit from the use of a satellite system for transmission. The next stage was to attempt a quantification of the demand for the services identified.

Table 2-1 Possible Communications Services, 1977-1985

SERVICE	DESCRIPTION
Audio	Telephone - including service to remote areas Program channels - e.g., AM/FM radio "Talking" computers Digitizing analog (audio) signals Discussion "party lines"
Visual	Broadcast TV - network Local TV - closed circuit Educational TV Video telephone - PICTUREPHONE * - conference facilities Information display - e.g., newspaper, retrieval "Canned" programs upon request 3D TV Holographic transmission Direct satellite broadcasting to the home CATV network
Data	Low- to high-speed data rates Variable data rates upon request Computer dumping - computer data exchange Remote data collection and polling Computer controlled processing Data banks "Pure" data networks Computer networks - time sharing terminals Transaction-oriented networks (e.g. point of sale transactions)
Facsimile	Newspapers to the home Remote printing Mail Press services
Medical	Diagnostic services Remote monitoring of patients
Financial and Credit	"Chequeless" society Stock transfers Inventory control
Information Retrieval and Storage	Library browsing Searches Reservations Law-enforcement information systems "Automated" library "Instantaneous" access to reference material Centralized library services

(cont'd)

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Table 2-1 (continued)

SERVICE	DESCRIPTION
Computer Aided Instruction	Schools Industry

Table 2-2 Possible Communications Services Using a Satellite System (above 10 GHz), 1977-1985

SERVICE	DESCRIPTION
Audio	Point-to-point telephony Multi-destination telephony Telephony to remote and/or northern communities AM/FM program channels AM/FM news program distribution
Visual	Network TV distribution to major centers Network TV distribution to small and/or remote communities Educational and instructional TV Video-telephone network distribution
Data	Remote data collection and polling Variable data rates upon request Data networks using roof top-antennas Remote access to computer facilities Transaction-oriented networks
Facsimile	Electronic mail distribution network between major centers One-way electronic mail distribution to outlying areas Remote printing
Financial and Credit	Transaction-oriented data system
Information Retrieval and Storage	Reservations Law-enforcement information systems Centralized library services Computer-aided learning Instructional and entertainment programs (visual and audio) upon demand

* * *

2.3 COMMUNICATIONS USERS IDENTIFIED AND CONSULTED

The potential users of the communications services given in 2.2 were identified. As many of these users as possible were consulted to obtain their future communications needs. At the request of DOC, extensive use of already collected data about the requirements of several major users was made and these users were not consulted again for the purposes of this study.

From the services in Tables 2-1 and 2-2, it was possible to identify sources of information that could be used to obtain the needs and requirements of these services for the 1977-1985 time frame. The first source of information was the telecommission studies compiled by the Department of Communications over the last year and a half. (See "Instant World"[2.12] for a list of study areas.) From these studies it was possible to determine what other information was required for this study. Various organizations and agencies were then identified as being able to provide the necessary information. A list of questions for each of these organizations was prepared and distributed to the Department of Communications (DOC) and the Communications Research Center (CRC). Contacts were made with the agencies listed in Table 2-3 and information pertaining to the questions was obtained.

For a number of major users data had already been collected and estimates made for the purposes of the telecommission and other studies. As directed by DOC and CRC, these users (Trans Canada Telephone System, Canadian National/Canadian Pacific and Canadian Broadcasting Corporation) were not contacted again and hence are absent from the list of agencies in Table 2-3. Some of these estimates were checked against other previously published data and rates of growth anticipated. The estimates obtained in this manner reflect, in the circumstances, best estimates based on data available.

During discussions with each of the organizations directly consulted it became clear that estimates should be made of what future needs and requirements would be if the current thinking was continued into the time frame of this study. It is understood that if circumstances beyond the control of the organizations took effect, they could not be held to any of the estimates given. However, the results obtained from these meetings have proven to be very useful in defining the magnitude of the communications needs of Canada for the services listed.

Because of shortage of time, many organizations which could have provided a useful input to our study were not consulted, e.g. representatives of Canada's newspapers, RCMP, university library services, banks, medical institutions and computer companies. While it is anticipated that the needs of the above organizations will be small for the next few years, there may be some areas that can be expected to require an increasing amount of communications which would be amenable to satellites (for example, province-wide library services, computer networks). Not knowing what the possible demand from this sector of society might be in the years to come, it has not been included as a separate input to this study. Some of the above users, e.g. newspapers, RCMP, banks, etc., are served by the telephone companies, whose forecasts normally would take the future needs of their customers into account. Hence, for this study, it has been assumed that the growth of the telephone network will satisfy this demand.

Summaries of the meetings with each of the organizations listed in Table 2-3 are in Volume 3. These summaries are of a confidential nature and must be so treated. The questions that were used to generate comments for these meetings are in Volume 3. Conclusions drawn from these meetings are presented in the following sections. In most cases, the information obtained from the potential users of a satellite system has been tempered by the realization that any one transmission media will not be used exclusively for a given service. Also, where estimates of service demand in the 1977-1985 time frame are difficult to make, ranges are given.

The communications needs of each of the organizations contacted will be examined in the ensuing sections under the following headings:

MESSAGE SERVICES
    Interprovincial telephone
    Telephone to remote areas
    Audio program services

VISUAL SERVICES
    Video telephone - PICTUREPHONE
    Commercial TV
    Educational TV
    Television to remote areas

ELECTRONIC MAIL

DOMESTIC DIGITAL SERVICES
- Computer services
- Data services
- Facsimile services
- Postulated wideband satellite service

OTHER SERVICE NEEDS
- Department of National Defence
- Ministry of Transport
- Government Telecommunications Agency

Table 2-3 Organizations and Agencies Consulted

ORGANIZATION OR AGENCY	DATE OF MEETING	CONTACT	POSITION or DEPARTMENT	ADDRESS
Computer/ Communications Task Force	April 19 May 4	Dr. H. Von Bayer R.H. Taylor H.H. Brune	Director - General - -	100 Metcalfe St., Ottawa
Department of National Defence	April 20	J. Eaton Maj. T. Grinnell Col. G. Simpson	Communications Systems	'C' Building, Laurier at Elgin, Ottawa
Canada Post Office	April 23	J. Bromley J.D. Thomas	Chief, Mail Processing Div., Systems R&D Branch Analyst, Environmental Forecasting Div.	Confederation Heights, Ottawa
Ministry of Transport	April 26	R. Farrell J.A. Quigley	Engineer-in-charge, Communications Sys. Superintendent - Commercial and Leased Services	#3 Building, Wellington at Lyon, Ottawa
Government Telecommunications Agency	April 26	H. McLaughlan	Technical Assistant, Planning and Design Division	78 Albert St., Ottawa
Canadian Association of Broadcasters	May 4	T.J. Allard N. MacDonald	Executive Vice-Pres. Director of Member Services	85 Sparks St., Ottawa
Ontario Educational Communications Authority	May 6	J. Cook I. Waniewicz R.D. Tilroe	Executive Director Superintendent Development Officer	1670 Bayview Ave., Toronto

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2.4.1 DEMAND ESTIMATE FOR INTERPROVINCIAL TELEPHONE

An estimate of the interprovincial telephone traffic has been obtained from previously published information. Assuming that only 15 percent of all interprovincial telephone traffic will be routed by satellite, a demand for 2200 one-way voice channels will arise in 1977 increasing to 6600 in 1985.

Trans-Canada telephone service on a switched and leased basis is being provided by the Trans-Canada Telephone System (TCTS) and Canadian National/Canadian Pacific Telecommunications (CN/CPT). To obtain estimates of the interprovincial telephone traffic for the 1977 through 1985 time frame of this study, it is necessary that both the traffic being carried today and a growth rate be determined.

A detailed study of East-West telephone traffic forecasts was carried out in 1967 for the then Department of Transport by Northern Electric[2.10]. New forecasts have not been made for reasons already discussed. However, the forecasts given in Ref 2.10 are believed by the Design Authority to be still applicable, and it is proposed to use these forecasts.

An examination of Table 2-1 of Volume 1 (of Ref 2.10) indicates that if all East-West terrestrial circuits which cover more than 1000 miles were routed by a satellite system to central locations of eight provinces (New Brunswick and Nova Scotia considered as one and P.E.I. excluded) then approximately 14,400 one-way satellite voice channels would be needed. Table 2-4, which is taken from Ref 2.10, shows the distribution of total traffic between each of the eight centers in 1977. Note that no Toronto to Montreal traffic is shown. This information is not available at this time and hence no allowance has been made for it in the calculations. However, once there are satellite earth terminals at Toronto and Montreal, it can be expected that some of the Toronto to Montreal traffic may be routed by satellite. Growth rates for toll traffic of between 12 and 22 percent per year are being used in telephone planning for the next 15 years. Using an accepted growth rate of 15 percent per year for the 8 years from 1977 to 1985, the total potential satellite traffic in 1985 would thus be 44,000 one-way voice channels.

How much of this total traffic is likely to be routed via a satellite system? In order to answer this question it is necessary to examine how a satellite system will be integrated with terrestrial facilities. A satellite system can be used for telephony in any or all of the following ways:

a) trunk connections

b) peak traffic overflow

c) restoration of communications during catastrophic failure of alternate transmission facilities

d) alternate routing to ensure survivability

e) communications to remote and isolated areas.

Note that Table 2-4 was derived using only those circuits which span 1000 miles or more. Excluding e) above, it can be expected that at most 33 percent of the interprovincial telephone traffic given in Table 2-4 will be routed through a satellite. This upper limit is due to survivability conditions being designed into the total communications networks of Canada. Once a satellite system, including the ground segment, is available it is quite possible that trunk connections between locations closer than 1000 miles (e.g. Montreal to Toronto which is excluded in Table 2-4) may become economical due to marginal costing considerations. Therefore, a maximum of 33 percent of the traffic given in Table 2-4 could probably be achieved.

The minimum possible traffic that a satellite system can be reasonably expected to handle is determined mainly by points b) and c) above. A value of 5 percent of the interprovincial traffic (over 1000 miles) can be used as a lower limit.

As outlined above, a range of 5 through 33 percent of the interprovincial traffic given in Table 2-4 is possible for the 1977-1985 time frame. The actual value depends on many other factors, such as cost, operational integration, etc. At this time it seems that, if the promise of economical satellite communications is fully met, the high value of 33 percent is more likely to be achieved. However, rather than design a satellite system on either extreme, a value of 15 percent will be used. That is, the above informed estimate of future traffic via satellite says that while the maximum of 33 percent is more probable, a pessimistic view of the future tempers this by a factor of approximately 2. Thus 15 percent of the forecasted trunk traffic of Table 2-4 is assumed to be routed via satellite. Therefore, in 1977, satellite systems will have to carry 2200 one-way voice channels (i.e. 1100 two-way voice circuits) while in 1985 this will rise to 6600 channels.

If the maximum of 33 percent were routed via satellite, capacity for 4800 channels would be required in 1977 and 14,500 channels in 1985. An estimation tolerance of ±10 percent is considered normal for forecasts of an established service such as interprovincial telephone. This range along with those developed for each of the other services will be used placing minimum and maximum ranges on the total communications capacity required of a satellite system that is designed to carry all the services examined in this study.

Technology today can place approximately 900 one-way voice channels in one satellite rf channel. Using this as a crude, but easily visualized, unit to state the requirement to the nearest unit, the required satellite capacity for 1977 is 3 satellite rf channels and for 1985 is 7 rf channels.

Turning towards the number of ground stations, it is seen from Table 2-4 that eight major cities have been identified as traffic centers. However, there is a trend towards the reduction of the levels of hierarchy in the telephone network of Canada. This would result in a larger number of direct communications links between lower ranking telephone offices. Hence the number of earth stations may reasonably be expected to be larger than eight, while the total telephone traffic flux remains unaltered at the forecast figure. Hence the number of earth stations is estimated to increase by 50 percent above the eight indicated; and the systems design will be based on 12 earth stations for major trunk telephony needs.

Table 2-4 Interprovincial Telephone Traffic

TOTAL ONE-WAY CHANNELS IN 1977 (OVER 1000 MILES)

FROM	TO								
	VANCOUVER	CALGARY	REGINA	WINNIPEG	TORONTO	MONTREAL	MONCTON	ST. JOHN'S	TOTAL
VANCOUVER		-	740 (29.2%)	270 (10.7%)	800 (31.6%)	700 (27.7%)	20 (0.8%)	-	2530
CALGARY	-		-	-	475 (66.5%)	240 (33.0%)	-	-	715
REGINA	740 (47.1%)	-		-	530 (33.8%)	220 (14.0%)	80 (5.1%)	-	1570
WINNIPEG	270 (13.8%)	-	-		1225 (62.7%)	440 (22.5%)	20 (1.0%)	-	1955
TORONTO	800 (22.7%)	475 (13.5%)	530 (15.1%)	1225 (34.8%)		-	410 (11.6%)	85 (2.4%)	3525
MONTREAL	700 (32.6%)	240 (11.2%)	220 (10.2%)	440 (20.5%)	-		-	550 (25.4%)	2150
MONCTON	20 (2.2%)	-	80 (8.8%)	20 (2.2%)	410 (45.4%)	-		375 (41.4%)	905
ST. JOHN'S, NFLD	-	-	-	-	85 (8.4%)	550 (54.5%)	375 (37.1%)		1010
TOTALS	2530	715	1570	1955	3525	2150	905	1010	14,360

LEGEND: Each entry gives: Total one-way channels from one location to another (percent of total channels from one location to another).

e.g. From Vancouver to Regina: 740 channels (29.2 percent of a total of 2530 channels from Vancouver)

NOTE: 15 percent of above values are used in this study.

2.4.2 DEMAND ESTIMATE FOR TELEPHONE TO REMOTE AREAS

Providing reliable, preferably high quality, telephone communications to remote communities in Canada, in particular the North, has become a national priority. By 1977 there will be some 400 communities that require between one and four voice circuits each and 10 centers that require up to a maximum of 36. These 400 communities will require a total of 1200 voice channels and the 10 communities a total of 240 voice channels. By 1985, the number of larger communities can be expected to double.

There are many communities in Canada that are without reliable telephone service to other communities. Communications satellites provide the means of establishing not only reliable but good quality telephone service to all parts of Canada from these remote areas.

In the past few years much work has been done in determining which remote communities have need of better telephone service. Telecommission Studies 8(c)[2.9] gathers together this information for northern Canada plus much more. However, for this study, the communications needs can be easily summarized. There are two types of demand for telephone service in remote areas. One is that generated by large centers requiring many telephone circuits (6 to 48). At present there are between 2 and 6 communities which could generate sufficient telephone traffic. Estimates for the 1977-85 time frame are not available. A minimum of six communities can be taken as a conservative estimate for 1977. If economic activity in the North is progressively stimulated as a national goal, a more realistic estimate is likely to be of the order of 10 stations requiring 24 circuits on an average. Thus a requirement of 240 one-way voice channels is foreseen for 1977. By 1985 a doubling of this requirement would not be unlikely. Using present technology (i.e. an FDM/FM/FDMA system being deployed by Telesat Canada) this requirement could be satisfied by one rf satellite channel in 1977 and two in 1985. The other demand is from small centers which require between one and four circuits. Various estimates have been made of the number of communities that fit into this category. For example, by 1977 there may be anywhere between 200 and 500. For this study a figure of 400 communities will be used. This demand can be satisfied by using the so-called single channel per rf carrier scheme either in a pre-assigned or in a demand-assigned mode. An average of 3 circuits per community can be envisioned as follows:

a) one circuit to a major Canadian city for access to the backbone long-haul network and,

b) two circuits to the remote "communities of interest."

In a preassigned mode, a total of 1200 one-way voice channels would therefore be required. Using frequency modulation, threshold extension devices and compandors, two satellite channels should be capable of transmitting the 1200 voice channels.

The remote communities that require the telephone services outlined above are geographically dispersed across Canada. Thus Canada-wide coverage by the satellite is desirable if there is to be communications between these communities.

Providing reliable telephone service to these remote communities seems to have reached the position of a national priority in the last year. This is on two counts. Firstly, there is the social consideration of one relatively isolated and less advanced segment of the population not having a service vital to today's fast moving world. Secondly, there is the long term national economic aim of tapping the vast resources of the North which in turn needs easy communications. This is not to say that the demand for these services (measured as the potential telephone traffic carried by any circuits made available) would fully support the costs of providing the circuits. In fact in a majority of the locations this may not happen till local economic activity increases manyfold. And the estimates can only be justified on non-economic, yet vital, national goals.

For this reason, the estimates of the number of voice channels required, as given above, can be expected to "be needed" during the time frame of this study.

2.4.3 DEMAND ESTIMATES FOR AUDIO PROGRAM SERVICES

While the long-haul transmission needs of AM/FM broadcasters is increasing, the total needs are small. Thus no separate estimates are made for audio program services but rather are included in the forecasts for other services.

The provision of AM and FM radio broadcasting to remote areas of Canada by satellite in conjunction with the provision of TV and/or telephone service is a definite requirement for the time frame of this study. Local distribution of the programs will be either by cable or low-powered AM or FM transmitters. Two channels for each of AM and FM programming are required.

In the past few years, AM and FM programming broadcasters have been providing competing national news services (e.g. "News at Six," "Contemporary News.") These services are now mainly being provided for by CN/CPT on their "broadband" facilities. The news services lease 8 KHz (which is equivalent to 2 telephone channels) of bandwidth and then take turns using this facility. The receiving stations then tape the portions sent to them by their service for broadcast at the appropriate time. This type of news service is growing. If possible, provision should be made for expanded services on a flexible satellite system. The use of demand assignment and multi-destination addressing in a satellite system would provide an ideal method of catering to the growing needs of these news services in the future.

Because the audio needs are small compared to the total communications needs in Canada, they are not considered separately but rather are included in other forecasts (e.g. telephony to remote communities, telephone).

* * *

2.5.1 DEMAND ESTIMATE FOR VIDEO TELEPHONE - PICTUREPHONE

A possible estimate of the demand for this service indicates that 6 trunk video-telephone channels will be required in 1977, increasing to 12 in 1985.

The use of video telephone (PICTUREPHONE by the Canadian public may grossly be estimated at 6 trunk video-telephone circuits in 1977 increasing to 12 in 1985. Video-telephone networks in each of the provinces is a distinct possibility. This can be seen from a comparison of the stated capacity allocated to video telephony in the recent U.S. Domestic Satellite proposal for implementation in 1973. A growth factor of some 15 to 20 percent can be applied to this and the traffic scaled in proportion to population.

A satellite video-telephone network would make use of the earth stations used for interprovincial telephone service. Assuming that a maximum of 50 percent of the circuits will be routed via satellite, 6 to 12 video-telephone channels will be required. To make efficient use of this network, the channels will be demand assigned. Because of the broadcast capability of satellite, conferencing of calls will be relatively easy to accomplish. Long-haul transmission of video-telephone calls will be digital and will require 6.3 megabits per second (Mb/s). Thus, a requirement of 37.8 Mb/s in 1977 is foreseen and 75.6 Mb/s in 1985. For 6 video-telephone channels per satellite transponder, one transponder will be required in 1977 and 2 in 1985. Because video telephone is a new service, the above projected demand is subject to a ±20 percent variation.

* * *

2.5.2 DEMAND ESTIMATE FOR COMMERCIAL TELEVISION

Demand estimates for commercial TV are based on figures provided by DOC. These figures have been modified and used in this study without additional consultation with the CBC and CTV networks. A total of 7 TV networks can be expected in 1985 leading to a realistic demand for 8 satellite channels (including spare and occasional-use channels). For 1977 the demand is for 6 channels. If full time-zone coverage is desired, a reasonable demand for 12 satellite channels in 1977 and 17 in 1985 will arise.

There are at present two commercial television networks in Canada. The CTV produces some 7 hours of network programming per day for their 12 or 13 affiliated stations. The CBC produces about 10 hours of programming per day for its own and affiliated stations.

Both the CBC and CTV leased East-to-West transmission facilities form the common carriers for their network distribution. Transmission of programs on the long-haul facilities is done during prime time in the Eastern Time zone. Each station along the way then videotapes the programs for rebroadcast during its prime time. West-to-East transmissions are obtained on an occasional basis only, since most of the programs are produced in the East (e.g. Toronto and Montreal).

For the 1977-1985 time frame, various estimates of the number of TV channels required have been made. From information received by the Department of Communications, the present French and English networks of the CBC can be expected to be doubled. From discussions with the Canadian Association of Broadcasters, there is likely to be either a second private network or a third competitive network in both French and English. Thus, during 1977-1985 the following seven networks may be expected to be in operation.

2 English language CBC networks
2 French language CBC networks
2 English language private networks
1 French language private network.

Since the creation of a new television network involves time and money, the above demand is assumed to be evident at the end of the time period (i.e. 1985). Five networks in operation during 1977 would appear to be a more realistic estimate.

It is possible that the cable television systems (CATV) may desire a trans-Canada network by 1980. However, the CATV requirement is very uncertain at this time and is not included in this study.

In many of the cities along the US-Canada border the loss of viewers to cable TV systems has caused a reduction of revenue to the private broadcasters. If the trend continues, it is possible that by 1977 many of these broadcasters will neither be able to provide local programming nor be able to maintain the Canadian content level now required by the Canadian Radio Television Commission (CRTC). These stations will in all probability, become equivalent to relay stations. If this happens, a satellite system for distribution of the programs would be economically attractive. The trend mentioned above would therefore increase reliance of the private TV broadcast industry on Canadian networks, which would increase the need for more transmission facilities.

Translating the above needs into anticipated satellite capacity can be done in many ways. One method is to assume that all networks will make full use of satellite facilities. For prime time viewing in each of the five Canadian Time zones (Newfoundland excluded) 25 satellite channels will be required in 1977 and 35 in 1985. The programs would be delayed at a central location and transmitted on each channel at the proper time. In addition, each TV network will require one occasional-use or spare satellite channel. While a satellite system is ideal for TV distribution, it is unlikely that any communication user would place himself in the position of relying upon one mode of transmission to the exclusion of all other methods if he can avoid it. Thus, for reasons of availability, survivability and competitiveness, the terrestrial network will also be used for TV distribution.

One realistic method is to assume that approximately one-half of the transmission needs will be satisfied by the terrestrial networks. This leaves a minimum of three commercial networks (i.e. two English and one French) to be provided by satellite systems in 1985 and two in 1977. To satisfy the broadcasters wishing to have programs transmitted during the same prime time period in each time zone there would have to be 15 satellite channels available in 1985 and 10 in 1977 for the five Canadian zones. Two occasional-use or spare channels will also be required. While the above may be desirable, it may prove to be too costly for the commercial broadcasters and too restricting to the utilization of the satellite to be examined in this study. However, this will be examined in this study before any conclusions such as the above are drawn.

A third method is to use one satellite rf channel per network (i.e. for a total of three channels for three networks) and have video-tape equipment at each receiving station to delay and then broadcast the programs at the proper time. However, this will not allow for unmanned operation at the remote locations. To overcome this problem, Canada can be divided up into two regions, each of which would have programs at the proper time within ± one hour. That is, programs transmitted in prime Mountain Time for Alberta will be received in British Columbia and parts of Saskatchewan one hour earlier and one hour later, respectively, than the prime time. Also, transmissions in prime Eastern Time for Ontario and parts of Quebec would be received one hour earlier in Manitoba and parts of Saskatchewan and one hour later than prime time in parts of Quebec and the Maritimes. Newfoundland would be one and one-half hours later than prime time.

From the above considerations, a reasonable requirement of 4 satellite channels (2 networks × 2 regions) is needed to satisfy the projected demands of commercial television for 1977 and 6 (3 networks × 2 regions) in 1985. The addition of two spare or occasional-use channels is to be added to the above requirement to yield a total of 6 commercial TV satellite channels in 1977 and 8 in 1985. If the prime time transmission requirement is overriding, then 10 satellite channels (2 networks × 5 time zones) plus 2 occasional-use channels will be required in 1975 growing to 15 plus 2 in 1985. The above demand estimates are expected to hold to within ±10 percent.

The number of communities to be served by commercial TV using a satellite in the 1977-1985 time frame is not available at this time. However, the trend towards an increasing number of TV sets per capita should stimulate a desire for TV in remote communities in the future. In addition to major distribution (transmit and receive) earth stations at Victoria, Vancouver, Calgary, Edmonton, Regina, Winnipeg, Thunder Bay, Toronto, Montreal, Halifax, Saint John, St. John's (Nfld), there is a need for receive-only stations in other communities. While these stations are to have primarily a receive-only capability, the station design should not prejudice the future possibility of program transmission.

Telesat Canada is planning to install 26 of these receive-only stations for their 4 GHz and 6 GHz satellite system. Perhaps a dozen more communities are potential candidates for this type of station. Depending upon economic factors, frequency coordination considerations and flux density limitations, the use of receive-only stations for network distribution to urban areas is a distinct possibility. The latter two points are significantly reduced at

12 GHz and 15 GHz compared to 4 GHz and 6 GHz. Forty to sixty urban locations become likely candidates to be served by the satellite system considered in this study. The 26 to 38 locations presently being included as part of the 4 GHz and 6 GHz satellite system can also be included in a 12 GHz and 15 GHz system. To see that this is so, note that in 1985 the 4 GHz and 6 GHz system will satisfy only one-half of the 8 TV satellite channels required in Canada (see section 2.10). For the other four channels to be made available to each of the locations of the present 4 and 6 system, separate receive facilities will be required, independent of frequency band used. Thus 24 to 38 remote receive-only locations should be included in the estimates. However, some economy of operation should be possible so that not all locations need be reached by the new satellite system.

Taking into account the range of estimates given above, between 50 and 100 locations can be expected to be candidates for receive-only earth terminals of a new satellite system. Also, 12 transmit-receive stations will be required.

2.5.3 DEMAND ESTIMATE FOR EDUCATIONAL AND INSTRUCTIONAL TELEVISION

Discussions with the Ontario Education Communications Authority has led to a demand estimate for educational TV in Ontario of 3 satellite TV channels in 1977. By 1985 a flexible "programs on demand" system should be in operation requiring 3 more satellite channels. Estimates for ETV in the other provinces can be obtained by extending Ontario's demands. This yields an additional demand estimate of 4 satellite TV channels in 1977 and 5 in 1985. Thus for this service a total demand of 7 TV channels in 1977, increasing to 11 in 1985, is forecast.

Although much educational broadcasting is being done by the CBC and CTV and their affiliates, there is a growing emphasis on providing provincial networks dedicated exclusively to educational television. Ontario is leading the other provinces in establishing a provincial authority which will be responsible for educational broadcasting. The establishment of the Ontario Educational Communications Authority (OECA) by the passing of Bill 43[2.6] has given Ontario an effective means of producing and distributing educational material to its residents.

If the OECA's plans proceed as expected, there should be UHF stations located in Ottawa, Thunder Bay, Sudbury and the London-Windsor area during the 1977-1985 time frame of this study. At present the OECA is programming and operating channel 19 in Toronto which already reaches 50 percent of the population of Ontario (including transmissions that are picked up by cable operators). The Authority also plans to install low-power retransmitters in the outlying areas. However, to provide TV to the remote or northern communities of Ontario, the OECA considers that a satellite system is the best alternative. The OECA realizes that, by the late 1970's, there will be a need for distribution of programs between the five stations. While some producing will be done at each station, the bulk of producing will be done in Toronto. Most of the programs will be video-taped, filmed, or imprinted on cassettes. Distribution can either be handled by ground transport or by electronic transmission. For the permanently imprinted cassettes, the former is considered the better medium. For video-taped or filmed material either mode may prove to be more economical. For electronic transmission this can be accomplished by each UHF station either transmitting the distributed program or by delaying it for future rebroadcast.

The OECA feels that each region should have the ability to transmit its material when it is required and not under the direction of a central body. For this reason there will be different transmissions from each station during any given hour. Thus it is very unlikely, except for live transmission, that more than a few stations would be transmitting the same information at the same time. Using electronic means to distribute the program material would therefore require either five channels to each of the other stations or one channel (available to all five stations simultaneously - i.e. a TV "party line") with each station taping the transmissions for rebroadcast at a later time. A satellite system which provides one channel for distribution to these five stations would satisfy this requirement.

To produce a truly flexible educational medium, the users should have the ability to call upon program material whenever they require it. The OECA would like to have a communication system that would allow them to provide this service. This "programs on demand" service would be similar in nature to the Information Retrieval TV experiment carried out by BNR and Bell Telephone in Ottawa over the last few years in cooperation with the Ottawa School Board. Such users as schools, community centers, or the like, could then request a given educational program which would be transmitted at the next convenient time. Because some of the programs being produced by the OECA are very short in duration, it is possible that a demand system of this nature could be implemented using the proposed satellite system. Perhaps three or four channels could be put aside for this purpose as an experiment to see how it functions. This system would, by necessity, be two-way with a voice or data circuit used as the command channel for the choice of programs. Only one-way television transmission would be required. No estimate as to the number of earth terminals needed has been made at this time. If even a small percentage of Ontario's schools make use of this service, a few hundred terminals would be required.

For transmission to remote areas of Ontario, one to three TV channels would suffice. At these remote communities the transmission would be live. The TV receiver could be in a major meeting place (e.g. a school, community center) but for most locations retransmission by UHF, VHF or cable to homes is considered necessary. These channels are in addition to the "programs on demand" channels mentioned above. The number of communities that would make use of this service is unknown at this time.

However, there are perhaps some 30 communities in Ontario that can receive regularly scheduled broadcasting only by using a satellite system. Depending upon economic considerations, some 70 additional locations are candidates for a receive-only earth station. Thus, an estimate of between 30 to 100 locations in Ontario is considered reasonable and will be used in the modeling of the educational TV service.

Summarizing, the transmission channels required to satisfv the OECA's needs in the future are as follows:

1) 1 channel for program distribution
2) 2 channels for programs to remote areas
3) 3 channels for "programs on demand"

Because the timing of the OECA's plans is undefined at present, the above demand estimates are assigned to 1985. For 1977, the channels for "programs on demand" are removed to leave a demand estimate of 3 satellite channels. Due to uncertainties involved in the estimates of the Ontario ETV demand, the above figures are valid within -30 percent and +10 percent.

Because no discussions have been held with other provinces on their educational requirements, the anticipated demand for their transmission needs are only estimates. However, because of the growing feeling among the provinces that educational broadcasting can be used effectively, there is most likely to be a demand for transmission facilities in the future.

By 1977, other provinces should have established education authorities much along the lines of the Ontario authority. The needs would be quite similar for these provinces. For example, it would not seem unlikely that Quebec would require as many channels as noted above for Ontario.

Although the timing may not be exactly as follows, at least 4 provinces, other than Ontario, would probably desire one TV channel each in 1977 for either broadcast to remote areas (or schools), or for distribution between major centres. By 1985 a total of 7 provincial groups, not including Ontario (e.g. B.C., Alberta, Saskatchewan-Manitoba, Quebec, Nova Scotia-New Brunswick-P.E.I., Newfoundland-Labrador, North West Territories-Yukon), may desire one TV channel each, with 4 of them requiring 2 channels. If the "programs on demand" system gains acceptance, a national need of perhaps 9 channels is possible (again excluding Ontario). Thus a maximum of 4 channels in 1977 and 20 (7 + 4 + 9) in 1985 is possible. However, until more definite information on the plans of the other provinces is available a realistic service need for educational TV (other than Ontario) is 4 satellite channels in 1977 and 5 in 1985. Possible variation in the projected demand will be within -50 percent and +10 percent of the above values.

The number of communities in the above provinces to be served by the educational service must be estimated at this time since no discussions were held with the educational authorities of these provinces. Using the Ontario estimates as a basis, a factor of between 2 and 3 is applied to the receive-only locations to yield a possible 90 to 200 for all provinces except Ontario. At least one transmit-receive station per provincial group (i.e. 7 as indicated above) is required.

Computer-aided learning (CAL) may be another area of education that will make use of transmission facilities in the future. However, until the usefulness of the method is evaluated and the cost of the operating equipment (i.e. terminal, computer, programs) is reduced to acceptable values, this technique will not be extensively used. For these reasons, CAL is not included in this study.

2.5.4 DEMAND ESTIMATE FOR TELEVISION TO REMOTE AREAS

Television to remote areas in Canada is included in the demand estimates for educational and commercial television. Additional satellite channels are not used. Smaller receive antennas are used for reception of commercial TV with a resulting reduction of quality.

There are two alternatives in providing TV to remote areas. The first alternative is to utilize the satellite channels used for commercial TV distribution (see 2.5.2). Minimizing the receiving station cost at these remote areas will yield a reduced quality which in many cases will probably be acceptable. The second alternative is to design special satellite channels, with perhaps more power, so that the receiving stations are small and hopefully inexpensive. This method, however, would require extra satellite channels.

The first alternative is the more attractive for this study. Until further calculations are completed, TV to remote areas will be included in either the commercial or educational TV requirements (see 2.5.2 and 2.5.3).

* * *

2.6 DEMAND ESTIMATE FOR ELECTRONIC MAIL

The portion of mail that is amenable to electronic transmission will require a minimum of 18 Mb/s in 1977 and 36 Mb/s in 1985. To efficiently link the twenty-two cities which generate this demand, a satellite system using time division multiple accessing techniques is a necessity.

Postal authorities in most of the industrialized nations are examining the use of electronic transmission of mail. In the United States of America, for example, a General Dynamics study[2.7] has detailed the various methods of electronic mail handling. Also Western Union Telegraph Co. is beginning their "mailgram" scheme which will serve as a pilot program for electronic mail transmission. Throughout the various studies the use of satellite systems for efficient and cost-effective transmission is advocated. Thus, for Canada, in the 1977-1985 time frame the electronic transmission of mail by satellites is quite likely.

There are many problems to be solved before widespread electronic mail distribution can begin. There are, for example, problems of low-cost terminal devices, input and output formats, and security. A recent report prepared for the Telecommission[2.8] by representatives of the Canadian Post Office and the Department of Communications examined these problem areas. Also the type of mail traffic amenable to electronic transmission in the near future was examined. Computer-originated mail appears to be the immediate candidate for electronic distribution. Ref 2.8 calculates that of the 5 billion pieces of mail handled in 1969, some 288 million pieces (approximately 6 percent of the total) of inter-city mail could make use of electronic transmission. This figure could climb to 960 million pieces (20 percent) if all typed correspondence generated by large users (all first-class metered mail) destined for other than the originating city is included. If this electronic-amenable mail traffic grows at the anticipated rate of 10 percent per year, the projected volume in 1977 will be a minimum of 620 million pieces and a maximum of 2 billion pieces. The average transmission capability for this amount of traffic can be calculated as follows: from Ref 2.1, one letter or piece of first-class mail requires 3×10^5 bits for electronic transmission. For transmission continuously over a full year, 620 million pieces requires a bit rate in megabits per second (Mb/s) of

$$5.9 \text{ Mb/s} = \left(\frac{3 \times 10^5 \text{ bits/letter} \times 620 \times 10^6 \text{ letters}}{365 \text{ days} \times 86.4 \times 10^3 \text{ seconds/day}}\right) .$$

However, since it is unlikely that transmissions will be spread evenly over a day, this rate could rise to perhaps 3 times the above rate (18 Mb/s) during times of peak traffic. For the 2 billion pieces, a distributed traffic rate of 32 Mb/s would be required and a peak rate of 94 Mb/s. Again for 1985, using a growth rate of 10 percent, a peak rate of between 35 Mb/s and 185 Mb/s could be expected for the minimum and maximum mail volumes.

From discussions with the Post Office it became evident that if electronic transmission of mail is ever to be used in Canada, it must be cost effective with respect to today's and tomorrow's mail handling techniques and it must offer better than overnight delivery (i.e. 4- to 6-hour delivery is required).

The postal network in the late 1970's will be concentrated on some 22 major cities which will generate and receive from 70 to 80 percent of the total mail. (Table 2-5 is a list of these cities. Ref 2.11 contains an approximate breakdown of the first-class mail distribution between the 22 areas.) For an electronic mail system to be effective, these major areas must be linked so that all areas can transmit to each other. However, a major subgroup consisting of the 12 cities that are part of the interprovincial telephone system (see 2.4.1) would provide an adequate base for an electronic mail service. Also, it would be advantageous if some of the outlying areas could have receive-only equipment. The above network can be easily created using a satellite system. Each of the initial 12 cities will require a transmit-receive earth terminal. The number of receive-only terminals could be anywhere between 10 and 30 depending upon economic considerations.

To handle the estimated minimum demand, 18 Mb/s of satellite capacity will be required in 1977. For 1985, the demand is approximately double that for 1977 (i.e. 36 Mb/s). Because of the large number of stations, time division multiple-accessing techniques must be used.

Although it is highly likely that electronic mail will use a satellite facility if it is available, the actual usage will depend upon public acceptance and cost. Thus, an uncertainty of ±30 percent is to be applied to the above demand estimates.

The use of facsimile for transmission of mail electronically has not been included in the above traffic calculations. While facsimile can be used in the future, the amount of mail traffic that could be handled electronically at a cost similar to or lower than that for normal methods is unknown at this time. Many firms and organizations may use facsimile in the future to some extent (see 2.7.3), but this traffic will probably be outside the normal mail system.

Table 2-5 Major Originating Cities in the Canadian Postal System

Victoria
Vancouver
Edmonton
Calgary
Saskatoon
Regina
Winnipeg
Windsor
London
Hamilton
Toronto
Scarborough
Oshawa
Peterborough
Ottawa
Montreal
Sherbrooke
Quebec
Fredericton
Saint John, N.B.
Halifax
St.John's, Nfld.

* * *

2.7.1 COMPUTER SERVICES

Normal anticipated growth of the present computer networks is included in the demand estimates for interprovincial telephone. If a controlled and stimulated growth of the computer networks takes place, there may be a need for additional transmission capability. How much is needed is impossible to determine at present.

One of the objectives of the Canadian Computer/Communications Task Force is to describe a number of possible national computer/communications networks. While the work of the Task Force will not be finished before the end of 1971, preliminary discussions with members of the Task Force have produced some insight into what a probable computer network will be. It will consist of specialized computers and data banks located in the 10-12 major cities of Canada (see Table 2-6). Because the computers will be specialized (e.g. legal, medical, scientific) there will not be any great need for either load sharing or computer dumping between these computers. However, there will be a need for communications facilities between the geographically dispersed users and the computers. The data rate of these users will vary from below 300 bits per second through 50,000 bits per second, and beyond.

Present computer networks use common carrier facilities. Anticipated growth of the transmission needs of the present computer networks is included in the demand estimate for interprovincial telephone (see 2.4.1). Given a controlled and stimulated growth of the proposed computer networks, the future demand for transmission facilities could be anywhere from a few kilobits to many megabits. The wideband satellite service postulated in 2.7.4 should be able to satisfy the communication needs of the future computer networks.

Table 2-6 Major Cities of Canada in 1977-1985 that will be Part of a Computer/Communication Network

Vancouver
Edmonton
Calgary
Regina
Winnipeg
Windsor
Hamilton
Toronto
Ottawa
Montreal
Quebec
Halifax

* * *

2.7.2 DATA SERVICES

The demand estimate for data services is included in the estimates for interprovincial telephone. An extension of the existing computer networks could result in an increased requirement for data transmission capability.

It has proved to be very difficult to obtain information of the data traffic being generated in Canada today. Obtaining projected traffic for the 1977-1985 time period of this study has been impossible. Some of the difficulties arise from the following:

a) Many data users lease voice circuits from the common carriers. They use these circuits during the day for voice transmissions and for data transmissions during the evenings. How much data flows is, of course, impossible to determine.

b) Much data traffic is coded so that it can be transmitted on a voice channel of a common carriers' switched voice network. Many of these data users make use of special data sets, but there is a growing group of users (mainly computer-sharing terminal users) which uses acoustic couplers. Again, this makes the task of determining the amount of data traffic very difficult.

There are two important trends that will help to indicate the amount of data traffic that can be expected in the future. One is the development of pure digital networks designed specifically for the transmission of information in a digital form. This means that data users can be separated and catalogued to some extent. The other trend is the emergence of "transaction" messages. These messages are generated by such services as reservations, purchases using a credit card, and inventory control. The use of a "store and forward" digital transmission system is seen by many as being the best method of catering to the demands of these transaction oriented services.

However due to the impact of a) and b) above, any normal increase in data traffic can reasonably be considered as one of the constituent parts of the telephone traffic projections given previously. The question now to be answered is whether there is a data need which can be separated from the telephone traffic so that it can be used in this study. At the moment the answer is "no." However, the Canadian Computer/Communications Task Force is in the process of determining present and future data requirements as well as examining possible computer networks for Canada.

Regrettably, this information will probably not be available until after this study is completed. A further point to be considered is the current controversy and deliberations taking place concerning the suitability of the satellite medium to high-speed data transmission. This controversy arises due to the inherent time delay of satellite communications, which affects the connect time adversely compared to the relatively short message duration of normal high-speed data messages. Hence at this stage in this study it is not being considered as a separate service on satellites.

2.7.3 FACSIMILE SERVICES

The growth of facsimile transmission is included in the estimates for interprovincial telephone.

Many companies and organizations require the immediate transmission of written and/or printed material between distant offices. Transmission by facsimile is now normally done by using a voice channel. Average transmission times are 4 minutes for an 8 inch by 11 inch page. There is the possibility that, if a wideband service could be economically provided, equipment capable of using the higher transmission rates would be manufactured. These devices would need to produce a digital output to be compatible with the wideband satellite service postulated in section 2.7.4, providing this service should encourage the use of high speed facsimile. Some facsimile needs that could be fulfilled by this service are:

a) remote printing - e.g. newspapers, books, magazines

b) information retrieval of printed material from a central library

c) law enforcement information notices

d) course or study notes for computer-aided learning and educational TV.

Projections of demands for a facsimile service would be conjecture at this time. At present, facsimile transmission is included in the estimates for interprovincial telephone. If a low-cost, high-speed facsimile transmission capability could be provided across the country, even a small usage could generate a demand for a few megabits of transmission capacity. If the trend towards digital transmission of telephone traffic continues it may reasonably be anticipated that the digital pipe-lines set up could, with marginal increase in capacity, fulfill this need.

* * *

2.7.4 POSTULATED WIDEBAND DIGITAL SATELLITE SERVICE

Considering that the future demands of computer, data and facsimile services for communications facilities might be stimulated to exceed normal forecasts, a wideband satellite service requiring 36 Mb/s of capacity is postulated as a means of providing a flexible, adaptable transmission capability.

Each of the demand estimates for domestic digital services given in sections 2.7.1, 2.7.2 and 2.7.3 for computer, data and facsimile are, separately, difficult to obtain. At present these services are carried on the telephone network and account for only a small fraction of the total traffic. The normal anticipated growth of these three services have been included in the estimates of future demands on the telephone network. However, the uncertainties in forecasting the future demands of these "growth" services, give rise to the prospect of no demand or an abnormally high demand. The Science Council of Canada has suggested initial governmental subsidization for computer communications, in long-term national interests. This would lead to a stimulation of demand. The methods open to stimulate the demand are diverse and cross the full spectrum of options from tax relief on revenue for established networks to direct subsidization to achieve a national goal. In the context of the effect on demand the method of stimulation is immaterial. What is material is that the demand may show an unexpected increase.

To account for any such unexpected demand for transmission facilities from any and all of the services mentioned above, an "insurance" policy can be taken out. This "insurance" takes the form of providing a certain amount of additional digital transmission capacity. This amount needs to be small compared to the total service demand-constant with its role as an insurance. It is proposed that 36 Mb/s of digital capacity, designated a "wideband satellite service," be provided in the satellite demand estimates for the computer, data, and (digital) facsimile services. This bit rate requires one equivalent satellite channel (in terms of present technology). The total demand estimate of all the services requiring new satellite facilities is approximately 25 equivalent satellite channels in 1985 (see section 2.11). Thus, the cost of this "insurance" in terms of capacity is 4 percent. It is proposed that this "wideband satellite service" use the interprovincial telephone earth stations. Since the earth station cost is between 30 and 50 percent of the total cost of any service, the "insurance" cost will be between 2 and 3 percent of the cost of the total system.

Summarizing, the demand estimate for domestic digital services, using the postulated wideband satellite service, and assuming a stimulated growth of the computer network is 36 Mb/s for 1985. For 1977, an estimate of 18 Mb/s would appear reasonable. Because this new service may never get out of the planning stage before the 1980's, the above demand estimates may vary greatly. Initially, the earth stations employed in the interprovincial telephone service are the most likely candidates for use by the wideband service, due to their being located at large urban centers. However other options are now written out by taking out the insurance suggested. For example, the popular concept of roof-top terminals for major users can also be considered as part of this service. However operation in this mode will almost certainly decrease the transmission capacity of the insurance proposed earlier while retaining the premium unchanged.

2.8 OTHER SERVICE NEEDS

The needs of the Department of National Defence (DND), Ministry of Transport (MOT) and Government Telecommunications Agency (GTA) are considered. DND needs point towards a dedicated, specialized satellite. MOT and GTA needs are part of the telephone traffic forecast.

Agencies and organizations that are, today, strictly users of common carrier facilities were consulted to assess their forecasted needs. In all cases, the forecasted needs of these organizations have been included in preceding projections. For completeness, however, a summary of these "other service needs" are included here.

Department of National Defence

From the discussions with members of the Department of National Defence (DND) it was evident that there is a need for a satellite system to provide for:

(a) tactical communications
(b) search and rescue missions
(c) communications to remote locations, and
(d) communications to mobile platforms.

However, these communications requirements must not only be made secure from jamming and deciphering, but also from operating and administrative interruptions (e.g. strikes, civil emergencies). Thus, the command and control of the satellite would have to be jamproof and under secure control.

Because the requirements of DND are for one and at most two satellite channels, and in light of the above operational constraints, DND requirements are not included in projections used in this study.

Ministry of Transport

The Ministry of Transport (MOT) operates a number of national networks to provide, for example, such services as air traffic control and meteorological information collection and distribution. These networks are presently being effectively provided on the Canadian National/Canadian Pacific Telecommunications network.

There is a need for reliable communications to MOT stations in the north. This need has been included in the provisions for telephone service to remote areas (see 2.4.2).

Government Telecommunications Agency

The Government of Canada is perhaps the largest single user of communications services in Canada. The Government Telecommunications Agency (GTA) leases voice circuits from the common carriers, notably CN/CPT. GTA then either sub-leases circuits to government organizations or sets up networks to cater to the communications needs of Government agencies and organizations.

The needs of the Government of Canada for communications facilities have been included in the projections for telephone traffic previously discussed.

2.9 TOTAL SERVICE DEMAND ESTIMATES

Table 2-7 is an estimate of the total Canadian communications needs for the services examined in sections 2.4 through 2.8, in the time frame 1977-1985, expressed as equivalent satellite rf channels. As satellites will not be the sole medium of transmission in Canada, a realistic estimate of traffic carried by satellites is presented in column 1 of Table 2-8. A total of 22 equivalent satellite channels are estimated to be required in 1977 increasing to 35 in 1985.

The estimates of service demands given in 2.4 through 2.8 are combined and presented in Table 2-7, and column 1 of Table 2-8.

Table 2-7 presents the number of equivalent satellite rf channels (of current technology) that are likely to be required if the total communications needs anticipated for each of the services were carried by satellites. The rationale for each of the values is given in the appropriate section (2.4 through 2.8).

Due to considerations of communications network integrity and service reliability in the event of catastrophic failure, no single medium of transmission can ever be permitted to satisfy all service needs completely. Thus other competitive media of transmission must, and will, be used to satisfy part of the demand. This is especially so where, on individual and specific considerations like those of routing desired, method of operation, and availability of existing facilities, one medium has a marginal cost advantage over another. In view of the above, estimates of the portions of the forecasted needs that satellite systems can reasonably be expected to carry for each service have been made and are presented in column 1 of Table 2-8. The individual estimates are justified in the appropriate sections (2.4 through 2.8). As has been stated previously, the unit of traffic capacity was shown as the equivalent satellite rf channel (of current technology) only to ease visualization. Its equivalence in terms of parameters like voice-channels, video-telephone channels and megabits of digital information has been expressed in the appropriate sub-sections whose results are condensed here. The equivalence is also summarized at the bottom of Table 2-7. The basic estimate itself was made in the unit appropriate to the service. The estimates presented in Tables 2-7 and 2-8 were rounded-off to the nearest integral satellite channel for presentation only. However, as will be seen later in Table 2-9, the estimates taken as the basis of this study have been presented in the units relevant to the particular services directly from the initial data.

Since the demand estimates are no more than projections from such data as could be accessed within the time allocation compatible with the study, a confidence range has to be inputed to each estimate. This range is a subjective evaluation and states that one can be 80 percent confident that the actual value in the future will lie between the two limits of the range. The range interval is a measure of the uncertainty of the estimate. Its appearance as a fractional number of equivalent satellite channels does not detract from its use as a valid mathematical expression of uncertainty. This is as much due to the fact that the equivalent satellite channel comprises a number of units of transmission appropriate to the service, as due to the fact that the demands can be considered reasonably independent during cumulative demand assessment. In sections 2.4 through 2.8, the range corresponding to each service has been stated and the rationale for the choice of the range presented. The ranges for all the services are also presented in the form of a consolidated list as a subdivision of column 1 in Table 2-8.

Accepting the estimated range percentages given in Table 2-8, the total equivalent satellite channels required in Canada in 1977 can be estimated to be between 17 and 25 with an expected value of 22. For 1985 the corresponding numbers would be between 26 and 39 with an expected value of 35. Thus the composite limit of variance is approximately -25 percent and +15 percent. It is to be noted that TV and telephone traffic accounts for approximately 90 percent of the total requirement with telephone (including video telephone) accounting for about 30 percent of the total.

Table 2-7 Maximum Canadian Communications Needs for 1977-1985 in terms of Satellite Channels

SERVICE	MAXIMUM SATELLITE CHANNELS REQUIRED	
	1977	1985
Message		
Interprovincial telephone	16	49
Remote area telephone	3	4
Visual		
Video telephone	2	4
Commercial television		
(a) television network	25	35
(b) occasional use or spare	5	7
Educational television		
(a) Ontario	3	6
(b) other	4	20
Electronic Mail	2	4
Wideband Satellite (computer, data, facsimile)	1	2
Totals	61	131

ONE Satellite Channel equals:

Interprovincial telephone	900 one-way channels
Remote area telephone	
- Multidestination	200 - 300 one-way voice channels
- Single channel per carrier	400 - 600 voice frequency channels
Visual telephone	6 channels
Television	1 colour TV signal plus audio
Mail and Wideband service	30 - 50 Mb/s

Table 2-8 Total Canadian Service Demand Estimates for 1977-1985 requiring Satellite Systems

SERVICE	1			2	3	
	SATELLITE CHANNELS REQUIRED IN CANADA			CHANNELS PROVIDED BY TELESAT ANIK SYSTEM	ADDITIONAL SATELLITE CHANNELS REQUIRED	
	1977	1985	Estimated Range	1977-1985	1977	1985
Message						
Interprovincial telephone (via Satellite)	3	7	±10%	4	0	3
Remote area telephone	3	4	±0%	2	1	2
Visual						
Video telephone	1	2	±20%	-	1	2
Commercial television						
(a) network	4	6	±10%	3	1	3
(b) occasional use, spare	2	2	±0%	1	1	1
Educational television						
(a) Ontario	3	6	-33%, +10%	-	3	6
(b) other	4	5	-50%, +10%	-	4	5
Electronic Mail	<1	1	±30%	-	<1	1
Wideband Satellite (computer, data, facsimile)	1	2	-100%, +50%	-	1	2
Totals	22	35		10	12	25

ONE Satellite Channel equals

Interprovincial telephone	900 one-way voice channels
Remote area Telephone	
- multidestination	200 - 300 one-way voice channels
- single channel per carrier	400 - 600 voice frequency channels
Television	1 colour TV signal plus audio
Video telephone	6 channels
Mail and Wideband service	30 - 50 Mb/s

2.10 SERVICES LIKELY TO BE CARRIED BY EXISTING SATELLITE FACILITIES PRIOR TO 1977

The effects of certain facilities already deployed or shortly to be committed in fulfilling part of the expected demand are analyzed.

The number of satellite channels required during 1977 through 1985 as summarized in Table 2-8 takes into account the Canadian requirement irrespective of the number of satellite systems operating. However, the Canadian Domestic Satellite System at 4 GHz and 6 GHz will still be in existence in 1977. Because of the large investment in the ground stations a replacement satellite will probably be launched to extend the life of the system to 1985. Information to date indicates that an initial 7 satellite channels of the 4 GHz and 6 GHz Domestic System will most likely be sold to users. Before 1977 the remaining 3 operational channels will be used for other services. The Domestic System is not expected to be able to satisfy any of the ETV, electronic mail or wideband service needs. This is due to coordination problems in the 4 GHz and 6 GHz bands in the urban centers, and the associated flux density limitations of this band, even if frequency re-use with polarization diversity techniques were employed in the next generation of the 4 GHz and 6 GHz satellites. Users of the 4 GHz and 6 GHz Domestic System are thus likely to be restricted to telephone and commercial TV. While no commitments have yet been made by the users for the 10 available transponders, the allocations given in column 2 of Table 2-8 seem reasonable at this time. Usage of the capacity of the spare (back up) satellite has not been included, on two counts. Firstly, such usage postulates the need either for two separate earth station networks or the duplication of antennae and electronic facilities at the majority of the earth stations. Secondly, the use of the spare satellite cannot but adversely affect the reliability of the system.

*   *   *

2.11 DEMAND ESTIMATE FOR NEW SATELLITE FACILITIES, 1977 THROUGH 1985

The demand estimates, as equivalent rf satellite channels, for new facilities in the time frame 1977-1985 is presented in column 3 of Table 2-8. Table 2-9 presents the same information in basic units appropriate to the individual services. Table 2-10 sizes the associated earth segment for each service.

By subtracting the channels provided by the 4 GHz and 6 GHz Domestic System, the additional equivalent satellite channels required have been calculated for each service (see Table 2-8, column 3). Thus, a total of 12 equivalent satellite rf channels in 1977 increasing to 25 in 1985 are the forecasted needs for the satellite system under study.

The ranges of values stated in section 2.9, to cover the uncertainty inherent in demand estimation, are equally applicable to the residual demand. Hence the appropriate range for new satellite facilities is 7 through 15 equivalent satellite rf channels in 1977, and 16 through 29 channels in 1985.

The demand estimates presented in Table 2-8 used the unit of equivalent satellite rf channels, of current technology, to obtain a gross sizing of the system. As mentioned in section 2.9, these estimates must be made available in the units of transmission appropriate to each of the individual services such that they can be used directly in the systems modeling phase of this study. Such a presentation has the following advantages. It enables the demand estimates to be expressed in smaller units obviating any rounding off errors. It also reduces the risk of pre-disposing the systems designer towards the choice of any given number of transponders in the satellite. This has been done, with the results presented in Table 2-9; and the figures contained therein are taken as basic information for the design considerations of subsequent chapters.

From information presented in previous sections of this chapter (2.4 through 2.10), a sizing of the associated earth station network has also been done for new facilities needed in the 10 GHz and 18 GHz frequency band during 1977-1985. This is a consolidation of expected values and ranges, for the corresponding services; and the result is presented in Table 2-10.

A note regarding the estimate of multi-channel remote area telephone locations is relevant, as this is the only number not presented earlier. In section 2.4.2, an estimate of 20 locations for this service is given. By 1977, the 4 GHz and 6 GHz satellite system of Telesat Canada will have satisfied some of the estimated demand for this service. It may reasonably be anticipated that five locations with the largest requirements (approximately 240 channels) will be served by the Telesat system. This leaves 15 locations and approximately 240 channels as part of any new satellite facility.

Table 2-9 Demand Estimate for New Satellite Facilities, by service, for 1977 through 1985

SERVICE	DEMAND ESTIMATE			
	1977	1985	Unit of Capacity	Estimate Range
Message				
Interprovincial telephone	0	3000	voice channels (one-way)	±10%
Remote area telephone				
(a) multiple-channel	0	240	voice channels (one-way)	±0%
(b) single channel per carrier	600	600		
Visual				
Video telephone	38	76	Mb/s	±20%
Commercial television				
(a) network	1	3	TV channels	±10%
(b) occasional use, spare	1	1	TV channels	±0%
Educational television				
(a) Ontario	3	6	TV channels	-33%, +10%
(b) other	4	5	TV channels	-50%, +10%
Electronic Mail	18	36	Mb/s	±30%
Wideband Satellite (computer, data, facsimile)	18	36	Mb/s	-100%, +50%

Table 2-10 Estimated Number of Locations at which Service is to be Provided by a New Satellite System Prior to 1985

SERVICE	NO. OF LOCATIONS	TYPE OF EARTH TERMINAL
Message		
Interprovincial telephone	12	transmit-receive
Remote area telephone		
(a) multi-channel	15	transmit-receive
(b) single channel per carrier	200	transmit-receive
Visual		
Video telephone	12	transmit-receive
Commercial television	50-100	receive with possible future transmit capability
	12	transmit-receive
Educational television		
(a) Ontario	30-100	receive-only
	5	transmit-receive
(b) other	90-200	receive-only
	7	transmit-receive
Electronic Mail	12-22	transmit-receive
	10-30	receive-only
Wideband Satellite	12	transmit-receive

2.12 REFERENCES

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2.2 R.W. Hough, et al; "A Study of Trends in the Demand for Information Transfer," Stanford Research Institute, Prepared for NASA, Contract NAS2-5369 (SRI Project NU-7866), February 1970.

2.3 W.C. Sedlacek, et al; "Information Transfer Systems Requirement Study - Final Report," Lockheed Missiles and Space Company, Prepared for NASA, Contract NAS2-5352, 1 March 1970.

2.4 W.C. Sedlacek, et al; "Summary Report, Information Transfer Systems Requirement Study," Lockheed Missiles and Space Company, Prepared for NASA, Contract NAS2-5352, 1 March 1970.

2.5 Telecommission Studies 5 (a), (c), (d) and (e); "Policy Considerations with Respect to Computer Utilities," Department of Communications, Canada, Part II pp 10-19, 1970.

2.6 3rd Session, 28th Legislature, Ontario; "Bill 43, An Act to Establish the Ontario Educational Communications Authority," 1970.

2.7 General Dynamics; "Study of Electronic Handling of Mail," Prepared for Post Office Department, Contract No. RER 30-70, 1970.

2.8 Telecommission Studies 7(i); "Postal Services and Telecommunications," Department of Communications, Canada.

2.9 Telecommission Studies 8(c); "Northern Communications Study," Department of Communications, Canada, 1970.

2.10 Northern Electric Laboratories; "Satellite Communications in Canada," prepared for the Department of Transport, June 1967, 5 Volumes.

2.11 Letter from J. Bromley for J.S. Forester, Canada Post Office to L.B. Dunn, April 26/71 ; BNR Satellite Systems Planning File No. SE/P 21.1.

2.12 Telecommission; "Instant World, Report on Telecommunications in Canada," Department of Communications, Canada, April 7, 1971.

2.13 Department of Supply and Services; "Consulting Services for a Study of SHF Satellite Communication Systems," File No. PL.36001-02945, February 10, 1971.

3. System Constraints

3.1 LAUNCH VEHICLES

An investigation into the availability of launch vehicles suitable for launching synchronous communications satellites during the time frame indicates that only the Thor-Delta range and the Atlas Centaur should be considered, although the space shuttle and tug program is a potential source of less expensive launch capability post 1985.

At the request of the Design Authority the size of spacecraft considered will be constrained to be within the estimated capabilities of the following launch vehicles:

(a) Thor-Delta
(b) Atlas Agena
(c) Atlas Centaur.

Discussions with officials at NASA have indicated that during the time period of the study (1977-1985) the Atlas-Agena will probably not be available and that the Thor-Delta range and the Atlas Centaur will be the most likely source of launch capability.

The basic characteristics and capabilities of these vehicles are given in Appendix C where the implications of the space shuttle programs are also discussed. Although the space shuttle and tug program will eventually result in a potential launch capability for communications satellites, it is unlikely that it would be operationally and regularly available for delivery into synchronous orbit until after 1985.

* * *

3.2 MAXIMUM SYSTEM INVESTMENT COST

In order to constrain the total investment in a new satellite system for the 1977 through 1985 time period, the Design Authority suggested that the total system investment cost should not significantly exceed $100 Million.*

Although the annual charges are of prime interest in the system modeling process and when choosing primary system parameters, the total investment cost must also be considered when assessing the feasibility of establishing a satellite system. The investment costs will include the cost of manufacture of the satellites, of launching them and of the construction of the earth segment of the system. Also included in the investment cost will be the amount estimated for any special development unique to the Canadian needs, in order to advance the state of the art of the technology to the required level.

In the present study therefore the annual charges will be used during the system modeling process (as agreed with the Design Authority); but the systems modeled will be checked to make sure that the investment cost, including development, does not significantly exceed $100 Million. As is seen in later chapters, this is not an unreasonable limit. The relationship between investment cost and annual charges will be discussed in a later section of this report.

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* This and ensuing references to dollars in this report are in terms of 1971 dollars (Canadian).

* * *

3.3 AVAILABLE FREQUENCY SPECTRUM

The frequency band of primary interest for this study consists of 500 MHz space-to-earth band at 11.7 through 12.2 GHz and a corresponding 500 MHz earth-to-space band at 14.0 through 14.5 GHz. No power flux density limitations exist in these bands for satellite systems operating in region II.

The terms of reference of the study, of which this chapter is a part, were to examine the potential of satellite communications in the 10 through 18 GHz frequency spectrum for Canada. That the next stage of exploitation of the microwave radio frequency spectrum for communications would be in this frequency range is obvious, due to overcrowding in the currently used frequency ranges and the evolutionary nature of the deployment of microwave technology. This evolution has followed a continuous trend with increasing frequencies. This trend is caused by the increasing technical difficulty of producing any given rf power as the frequency increases, the increased difficulty of obtaining the same numerical frequency stability, the larger path attenuations, and the need to maintain more stringent mechanical tolerances on passive components at higher frequencies to keep losses within acceptable limits. Compensating these disadvantages, however, are the correspondingly larger absolute bandwidths that naturally arise at higher frequencies.

Any actual frequency band that can be used for any specific type of service (e.g. satellite, mobile, terrestrial, or broadcasting) is also subject to international agreement. At the start of the study precise allocations of frequencies in the frequency range 10 through 18 GHz had not been made, but it was evident that for domestic satellite systems an allocation no larger than 500 MHz was likely with no significant power flux density constraints. During June and July 1971 the World Administrative Radio Conference for Space Telecommunications[3.1] these allocations were made. These will be considered in detail below, but the major premise stated above remains unaltered as confirmed by the Design Authority, whose personnel participated in the conference. For the services in Canada estimated in chapter 2, a first estimate of the minimum satellite bandwidth revealed that approximately 500 MHz would be needed. This is further refined later in the study. Frequency re-use techniques, at the initial stage, were not postulated on two counts. Firstly, they would require a duplication of electronic hardware both on the ground and in the satellite to process signals carrying different information at the same frequency. Secondly, they would increase the complexity of the common elements like antenna feeds and rf combiners. Both factors would result in higher costs and appeared, even at the first stage of analysis, to put the initial costs beyond acceptable limits.

Constraints have generally been imposed, by international agreement, on the down-path flux density from "fixed" satellite services, when the same frequency spectrum is allocated for use by more than one generic method of transmission (e.g. satellite, terrestrial radio links, broadcasting). The levels of the allowable flux-density are determined by permissible interference. If present, such limits impose a further constraint which, in turn,affect the power/bandwidth trade-offs of the satellite system, constricting the potential capacity and economic viability of the allocated (and hence limited) bandwidth. Thus it is desirable to utilize fully any spectrum allocation where no flux density limitations exist.

The allocation of frequency bands for satellite communications took place at the World Administrative Radio Conference for Space Telecommunications[3.1] held in Geneva during June and July of this year. The frequency bands allocated for fixed-satellite services in the 10 through 18 GHz range are listed below for region II, which pertains to Canada.

FREQUENCY (GHz)	SERVICE ALLOCATED REGION II	FREQUENCY (GHz)	SERVICE ALLOCATED REGION II
10.95-11.2	Fixed Fixed-Satellite (Space-to-Earth) Mobile	12.5-12.75	Fixed Fixed-Satellite (Earth-to-Space) Mobile, except Aeronautical Mobile
11.45-11.7	Fixed Fixed-Satellite (Space-to-Earth) Mobile	14.0-14.3	Fixed-Satellite (Earth-to-Space) Radionavigation
11.7-12.2	Fixed Fixed-Satellite (Space-to-Earth) Mobile, except Aeronautical Mobile Broadcasting Broadcasting-Satellite	14.3-14.4	Fixed-Satellite (Earth-to-Space) Radionavigation-Sat.
		14.4-14.5	Fixed Fixed-Satellite (Earth-to-Space) Mobile

The two 250 MHz space-to-earth bands located at 10.95 through 11.2 GHz and 11.45 through 11.7 GHz are shared on an equal basis with fixed and mobile services and thus flux-density limits given in note 470 NQ apply. This note specifies the following power flux density limits:

-150 dBW/m^2/4 kHz for angles of arrival between 0 and 5 degrees

$-150 + \left(\frac{\delta-5}{2}\right)$ dBW/m^2/4 kHz for angles of arrival (δ) between 5 and 25 degrees

-140 dBW/m^2/4 kHz for angles of arrival between 25 and 90 degrees

Although the space-to-earth band at 11.7 through 12.2 GHz is indicated as being shared with the fixed services, note 405 BB, applicable to this band for Region II, states that terrestrial radiocommunication services will only be introduced in this band after plans for space radiocommunication services have been finalized to insure compatibility between the two types of services. Therefore flux density limits given in note 470 NU do not apply in region II for this band. This was also confirmed by the Design Authority in discussions.

As for up-path allocation, 750 MHz of the spectrum in this region has been allocated to fixed-satellite services for the earth-to-space link. The 500 MHz earth-to-space band at 14.0 through 14.5 GHz is a continuous band allocation which can be used in conjunction with the space-to-earth band at 11.7 through 12.2 GHz.

The 250 MHz earth-to-space band at 12.5 through 12.75 GHz could be used as a companion band with either of the two space-to-earth bands at 10.95 through 11.2 GHz and 11.45 through 11.7 GHz. However, it must be noted that these two bands have power flux density constraints placed on them since they are shared on an equal basis with fixed services (terrestrial radio telecommunications).

In conclusion, the 500 MHz earth-to-space band at 14.0 through 14.5 and its companion space-to-earth band at 11.7 through 12.2 GHz will be designated the primary frequency bands since these are continuous band allocations and there are no flux density limitations in the latter band.

The additional 250 MHz earth-to-space band at 12.5 through 12.75 GHz and its companion space-to-earth band at 11.45 through 11.7 GHz can be considered for those services that may not be significantly effected by the flux density constraints in the case that the prime 500 MHz allocation is not sufficient to provide all of the service requirements. This space-to-earth band was chosen over the 10.95 through 11.2 GHz band since it is contiguous with the 11.7 through 12.2 GHz band.

* * *

3.4 TECHNICAL CONSTRAINTS

This section outlines the technical constraints that are used to set the baseline for the study. Some of these constraints exist due to present and expected advances in future technology, such as rf filter design, whereas others are set on the basis of present and future trends in the satellite communications field, such as orbital spacing and launch vehicles capabilities. These constraints are used as guidelines in the system modeling considerations performed in chapters 7 and 8.

(a) Type of Satellite System

The two types of communications satellite systems used up to the present time are 24-hour synchronous and non-synchronous systems. The 24-hour synchronous satellite is stationed in the equatorial plane at an approximate distance of 22,300 statute miles above the earth's surface. Except for minor perturbations in the orbit, the satellite remains fixed relative to any location on the earth's surface, hence it is commonly referred to as geostationary satellite.

There are many pros and cons that can be considered when comparing these two types of systems but, from the past evaluation of satellite systems, it is easily seen that the general trend is towards geostationary satellite systems.

This trend obviously implies that the major exploratory and development effort in this field will be directed towards systems using geostationary types of satellites.

Therefore, to derive maximum utilization from the advances in technology, this study considers only a geostationary type of satellite system.

(b) Satellite Window

The term "satellite window" is used to describe that arc along the geostationary satellite orbit wherein a satellite handling communications for all of Canada can be effectively located. The parameter that limits the extreme East and West Longitude positions along this arc is the minimum desirable earth station elevation angle.

As is shown in chapter 5, as the earth station elevation angle drops below 10°, the rf signal loss and excess in noise temperature due to the atmosphere begin to rapidly increase.

Therefore the minimum desirable earth station elevation angle is set at 5°. A satellite at 80° West Longitude would cover all of Canada above 5° elevation angle except for the group of islands above 75° North Longitude - Banks Island and a small area of Northern Yukon Territory. Similarly a satellite located at 120° West Longitude would cover all of Canada except the islands above 75° North Latitude, and the top part of Franklin Island[3.7].

Regardless of the satellite location in the geostationary orbit, most of the territory above 75° North Latitude will lie below 5° elevation angle. Fortunately, this limitation covers only a few Arctic islands, notable among which are parts of Ellesmere Island and parts of the Axel Heidelberg Island.

Thus the satellite window for Canada lies between 80° and 120° West Longitude in the geostationary orbit.

(c) Frequency Spectrum

The frequency spectrum that is available for fixed satellite communications systems was discussed in 3.3. The choice of a frequency band for this study is constrained to lie in the 10 through 18 GHz region of the spectrum. In this region, the preferred earth-to-space band is at 14.0 through 14.5 GHz and the preferred space-to-earth band is at 11.7 through 12.2 GHz. There are no power flux density limits imposed on the satellite system operating in the latter band.

If this 500 MHz bandwidth is not adequate to meet the service demands estimated in chapter 2, there is an additional 250 MHz band located at 12.5 through 12.75 GHz for earth-to-space and 11.45 through 11.7 GHz for space-to-earth link that can be utilized. However, services operating in this band will have power flux density limits imposed on them. In summary, there is a prime allocation of 500 MHz for the satellite band with an additional 250 MHz band that can be utilized subject to power flux density limitations on the satellite space-to-earth link.

(d) Satellite Constraints

Considering the capacity requirements estimated for the various types of services in chapter 2, a multi-service satellite designed to meet the service requirements appears to be a more economical and practical method than a multi-satellite system designed for the various types of services. To add support to this is the fact that the trend in domestic satellite systems is towards multi-service satellites as discussed in Appendix B.

The size and weight of the satellite will be constrained by the types of launch vehicles considered.

As specified by the Design Authority, the maximum-size launch vehicle that can be considered in this study is the Atlas Centaur. The other type of launch vehicle that appears suitable for this time frame is the Thor-Delta. The payload capabilities of these two vehicles are given in 3.1. Along with a weight constraint there exists a size constraint for a particular launch vehicle which is set by the dimensions of the launch vehicle's fairing.

The standard fairing dimensions of these particular vehicles are shown in Figure 3-1.

Within the context of launch economics, it is patently evident that launch costs per pound are lowest when the total launch vehicle capability is utilized. This should be a goal when considering a satellite design, subject also to the size constraints placed on the satellite by the launch vehicle's fairing dimensions.

(e) Satellite Orbital Separation

The selection of a value for satellite spacing in the geostationary orbit is required for modeling purposes as performed in chapters 7 and 8.

As shown in 7.2.6, for a particular service and a given inter-satellite interference allowance, spacing of the satellites closer in orbit will normally result in an increase in the minimum size of the earth station antenna due to interference constraints. This could result in higher ground station segment costs to provide this service. On the other hand, allowing larger satellite spacings results in decreasing the ultimate capacity of the geostationary orbit which would mean poor utilization of this resource. Thus a compromise on satellite spacing must be reached concerning these two factors.

Based on present satellite spacing allocations that range from 3° through 5°, a value of 4° was chosen for the purpose of this study.

(f) Rf Filters (SATELLITE MULTIPLEX)

The design constraints placed on the rf multiplexing filters in the satellite must be considered in reference to what can be accomplished using today's technology and estimating what improvements will take place in this technology over the next few years.

Present satellites operating in the 4 through 6 GHz band (Intelsat IV) allow 4 MHz guardband in a total bandwidth of 40 MHz. Assuming that equivalent circuit Q factors and frequency stability can be maintained in translating to the 12 through 14 GHz band, this would correspond to a guardband of 12 MHz in a 120 MHz total bandwidth.

Similarly, if the bandwidth is reduced to 13 MHz at 4 through 6 GHz, the best that can be achieved with today's technology is approximately a 20 percent guardband allowance.

Scaling this up to 12 through 14 GHz would correspond to guardband allowances from 50 percent to 20 percent for bandwidths between 15 MHz and 40 MHz. Taking into consideration improvements in hardware and techniques that will take place in the next few years, it appears that the narrowest guardband achievable for rf bandwidths between 15 MHz and 40 MHz is expected to be approximately 4 through 5 MHz, consistent with filter weight and size constraints in the satellite.

For the purpose of this study, a 5 MHz guardband allowance is chosen for rf bandwidths in the order of 15 through 40 MHz.

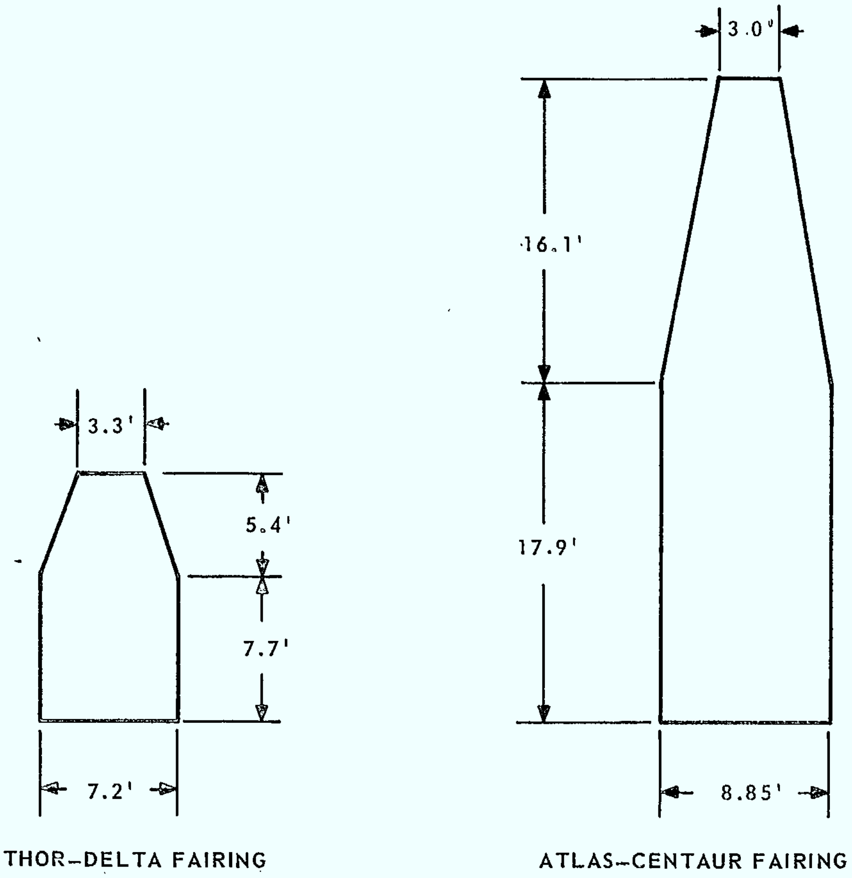

Figure 3-1 Thor-Delta and Atlas Centaur Fairings - Inner Dimensions

3.5 REFERENCES

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* * *

4. COMMUNICATIONS SYSTEM PERFORMANCE OBJECTIVES

The transmission performance objectives for communications type services, considered in this report, were agreed on with the Design Authority. These are stated in subsections of this chapter.

It is essential for the purposes of system design as well as to ensure inter-connectability with existing communications facilities to design the new facilities to compatible standards.

This aspect is considered in the specific context of message transmission by analogue means, digital message and digital service transmission and television transmission.

*   *   *

4. Communications System Performance Objectives

4.1 MESSAGE TRANSMISSION BY ANALOGUE MEANS

This section is divided into two subsections dealing with Toll message quality and single channel per carrier services to sparsely populated communities in the North.

The criteria for the choice of quality of performance needed on any connection are dependent on the degree of utilization of the facilities necessary to establish the connection. This utilization may reasonably be expected to be different for highly populated areas of the country and for very sparsely populated areas. Hence these are discussed separately.

* * *

4. Communications System Performance Objectives

4.1 Message Transmission by Analogue Means

4.1.1 MAJOR TRAFFIC TOLL QUALITY

This section sets the performance objective for analogue systems carrying message services that will be integrated into the major toll networks in southern Canada. For the satellite system to be compatible with existing design objectives, the mean weighted noise in a 3.1 kHz voice channel is set at 37.5 dBrnc0. The system carrier/noise margin shall be adequate to allow operation above threshold for 99.99 percent of the time.

Present international satellite systems have a mean voice circuit objective of 10,000 pWp of noise power in a 3.1 kHz telephone channel. This objective is based on a hypothetical reference circuit of 2,500 km in length. However the performance objective for toll systems in North America and specifically the Trans-Canada Telephone System (TCTS) are more stringent than the international objectives. Since the proposed satellite system must be integrated into the toll system, its objectives should conform to those of the TCTS.

The quality of a telephone circuit provided by the proposed satellite system is to be equivalent to that provided by the toll network of the present telephone system for a 2,000-mile connection. This distance represents the expected average connection length of a satellite system serving the major traffic centers in southern Canada. Allowing for noise contributions from multiplexing equipment and rearward facilities from the earth stations, this represents a satellite link performance objective (from modulator input to demodulator output) of 5623 pWc or 37.5 dBrnc0. This performance objective is believed to be the same as set for Telesat, Canada's domestic satellite system, and it applies under non-fade conditions.

* * *

4.1.2 SINGLE CHANNEL PER CARRIER (SC/C)

A performance objective for a SC/C system that would provide suitable communications services to sparsely populated regions in northern Canada is set forth. For reasons explained in this section, the mean weighted noise in a 3.1 kHz telephone channel is set at 44 dBrncO. The system carrier/noise margin shall be adequate to insure operation above system threshold for 99.9 percent of the time.

High transmission performance objectives must, and always do, lead to higher costs. Hence high standards are invariably associated with a service whose utilization is large. This not only economically justifies the higher costs, but also implies a high population density. However, if one considers the average population of remote northern communities, it cannot be expected that the usage will support the costs of implementing this high quality service. This has already been commented on in chapter 2, section 2.5.1.

In addition to this, present systems serving some of these communities such as hf radio and tropo-scatter systems cannot provide the quality of the major toll networks. Hf radio is substandard in the aspects of service reliability performance and signal/noise quality; and in general medium length tropo-scatter systems deployed in most parts of the world provide a performance of the order of 44 dBrncO under median signal conditions. This performance level provides an acceptable service.

Thus a performance objective of 44 dBrncO, in the remote regions of Canada, for a single channel per carrier system will provide a service that will be better in performance than the majority of systems serving the remote communities at present and will, at the same time, be more economical than a system constrained to meet the performance objectives required in the South. This performance value was agreed upon with the Design Authority as a suitable objective for system modeling purposes. The value applies under non-fade conditions.

* * *

4.2 DIGITAL MESSAGE AND DIGITAL SERVICES TRANSMISSION

The performance objective for a digital system employing pulse code modulation is set at a bit error rate of 10^{-4} at threshold, which should not be exceeded for 99.99 percent of the time and a corresponding bit error rate equal to/or better than 10^{-7} for median operational conditions. This is considered to be a suitable transmission objective for both message services and digital services.

The performance objective set for digital message services is expected to satisfy at the same time the transmission requirements for digital services including video telephone, electronic mail and any digital wideband service as discussed in chapter 2. Since the information to be transmitted in a system employing PCM digital techniques are in the form of a stream of bits, the transmission medium will not be able to distinguish one form of traffic from the other. With a suitable error performance objective, this system can be used effectively for both message and digital traffic.

Since a TDMA system is a digital modulation system as compared to analogue modulation systems such as FDMA, there is some difficulty in relating bit error rate performance for digital systems to an equivalent noise performance in picowatts as normally specified for analogue systems.

Present digital cable systems, such as T1 and T2 systems used in the toll-office to end-office links in the telephone network, have as a design objective an error rate of 1 error in 10^7. These links have a normal design objective in the order of 20 dBrnc0 (300 pWc). Thus a PSK system operating as an intertoll system is capable of very good performance as compared to analogue systems for a normal error rate of 1 in 10^7.

As for selecting a suitable error rate for the threshold point of a digital system, the problem exists of relating this to an equivalent threshold point for analogue transmission.

The bit error rate in digital systems degrades exponentially as the carrier-to-noise is reduced from the normal operation point as compared to analogue system operating above the threshold point, in which case the signal-to-noise degrades linearly with the system carrier-to-noise. In the analogue case, the median signal/noise was chosen as 37.5 dBrnc0. Thus for a 9.7 dB carrier/noise fade which corresponds to approximately 0.01 percent of the time, as shown in chapter 5, the signal/noise will degrade to 47.2 dBrnc0 (52,500 pWc) which is defined as system outage in the analogue case (99.9 percent availability objective).

Thus from Jansen's study[4.2], which states that a bit error probability of 10^{-4} for a digital system corresponds to a noise power of approximately 50,000 pWop in a telephone channel, the threshold point for the TDMA system was set at this error rate to be equivalent to the analogue systems threshold performance case.

To be equivalent to present toll circuit reliability objectives, this error rate cannot be exceeded for 0.01 percent of the time. Thus, for a bit error rate design objective of 10^{-4} at threshold corresponding to 0.01 percent of the time, the carrier/noise margin required to compensate for fading during this time duration will likely result in the bit error rate under median conditions being better than 10^{-7}. This will result in the quantization noise being the limiting performance factor under normal operating conditions.

In summary, the bit error rate performance for the TDMA system shall not exceed a threshold value of 10^{-4} for 99.99 percent of the time and under median conditions shall be 10^{-7} or better. Which one of these error rate objectives will decide the system operational carrier/noise requirements depends on the system fading margin that is required for 0.01 percent of the time, based on desired service availability. Fading margins are considered in chapter 5 of this report.

4.3 TELEVISION SERVICES

The performance objectives for educational television and commercial television systems are considered. Since these two services serve different purposes and are represented by separate system models, different performance objectives apply. The satellite system signal-to-weighted noise objectives for ETV and CTV services are set at 42 dB and 57 dB respectively. The systems carrier/noise margin shall be adequate to allow operation above the system threshold for 99 percent of the time for ETV and 99.9 percent of the time for CTV services.

This study considers two types of television distribution systems, educational television systems (ETV) employing direct reception from the satellite at the schools and institutions and commercial television systems where the signal will be received at an earth station routed to the broadcast transmitter to be transmitted to the homes.

Since two different models are presented, the satellite high performance objectives will not be identical for the two types of systems.

(a) ETV System Performance Objective

The performance objective for ETV was selected on the basis of measurements performed by the Television Allocations Study Organization (TASO). This organization selected quality ratings for TV by using viewer panels to subjectively rate pictures displayed by conventional television sets that received AM/VSB 525 line television transmission from a closed circuit. These tests provided a correlation between the picture quality and the rf carrier-to-noise at the receiver input. The TASO quality chosen for ETV services corresponds to grade 2 which was rated "fine" by 75 percent of the viewers (fine is defined in TASO terms as high quality, providing enjoyable viewing and perceptible interference). This grade corresponds to a carrier-to-noise, $(C/N)_{TASO}$, of 38 dB.

Since the TASO definition refers to carrier-to-noise of an AM/VSB TV signal at the input to a TV receiver, it differs from the CCIR definition of signal-to-noise, which is the ratio of the black-to-white signal level (excluding the synchronization pulse) to the rms noise in a video channel.

The relationship between TASO and CCIR definitions is derived from Jansen's study[4.2] with the resultant relationship given as:

$$(S/N)_{p,w} = 1/2\ (b-w)^2 \frac{B_T}{B_{N,w}}\ (C/N)_{TASO}$$

where

$(S/N)_{p,w}$ = weighted signal-to-noise (CCIR definition)

b = relative carrier amplitude for black level (AM-VSB signal)

w = relative carrier amplitude for white level (AM/VSB signal)

B_T = effective white noise bandwidth at input to television receiver

$B_{N,w}$ = effective *weighted* noise bandwidth at the output of the video i-f detector in the television receiver

$(C/N)_{TASO}$ = TASO carrier-to-noise corresponding to a specific grade of service.

For a 525 line television signal, the value of these parameters are given in Ref 4.2 as:

$$b = 0.75V,\ w = 0.15V,\ B_T = 5.5\text{ MHz},\ B_{N,w} = 0.82\text{ MHz}.$$

Thus, substituting in the above formula, one obtains the relationship between the TASO and CCIR definition as:

$$(S/N)_{p,w} = (C/N)_{TASO} + 0.9\text{ dB}.$$

For $(C/N)_{TASO}$ = 38 dB corresponding to grade 2 quality,

$$(S/N)_{p,w} = 38.9\text{ dB (CCIR-weighted)}.$$

Converting from the CCIR definition of signal-to-noise to the North American standard definition which includes the sync. pulse and is defined as:

$$(S/N)_w = \left(\frac{\text{peak picture voltage including sync.}}{\text{rms weighted noise voltage}}\right)^2$$

Then $(S/N)_W = 38.9 + 3.0 = 41.9$ dB ≈ 42 dB (under non-fade conditions).

To provide suitable availability for this service, the satellite system carrier/noise margin must be adequate to allow for system fading that will be experienced for 99 percent of the time and still remain above threshold, which for a conventional FM system occurs at a (C/N) of 10 dB. Fading margins are derived in chapter 5 of this report.

(b) Commercial Television Performance Objective

The CCIR[4.3] objective for 525 line television performance for an international satellite connection is a weighted signal-to-noise of 56 dB (in terms of North American definition of S/N, which includes the sync. pulse, the equivalent value is 59 dB).

This performance objective is based on a hypothetical reference circuit which comprises three sections, namely the communications link from the broadcast studio or pick-up point to the transmit earth station, an equivalent 2500 km (1600 miles) satellite link and finally the link from the receive earth station to the broadcast transmitter or the receive studio.

Present satellite systems operating in the 4 through 6 GHz band are shared on an equal basis with terrestrial radio communication systems operating in this frequency band. For this reason, earth stations are generally located some distance from the metropolitan centers to avoid excessive interference to and from terrestrial microwave links serving the high density centers. These rearward communication links are on the average 100 through 200 miles in length with some spanning a distance of 500 through 600 miles.

For the case of a domestic satellite system operating in the 12 through 14 GHz band, it is assumed that the transmit and receive earth station terminals will be located close to the metropolitan areas since the interference constraints placed on 4 through 6 GHz band due to sharing should not apply to this band. Thus the degradations resulting from the long rearward facilities, assumed here to be 1 dB for each end link, will not arise in this model.

Re-allocating the end link degradation to the satellite link results in the signal/noise performance objective of 57 dB (North American definition) for the satellite link. This design objective for system modeling purposes was agreed upon with the Design Authority. The signal/noise value applies under non-fade conditions.

To provide suitable availability for this service, an adequate system carrier/noise margin must be chosen to allow the system to operate above threshold for 99.9 percent of the time. The threshold point for a conventional FM system occurs at a (C/N) of 10 dB. Fading considerations are covered in chapter 5 of this report.

4.4 REFERENCES

4.1 CCIR; Report 211-2, "Active Communication Satellite Systems," XIIth Plenary Assembly, Volume IV, Part 2, New Delhi, 1970.

4.2 J. Jansen, et al; "Television Broadcast Satellite Study," TRW Systems Group, Contract NAS3-9707, October 24, 1969.

4.3 CCIR; "Requirements for the Transmission of Television Signals over Long Distances (System 1 Excepted)," Rec. 421-2, Volume V, XII Plenary Assembly, New Delhi, 1970.

* * *

5. Propagation Considerations and System Margins

5.1 GENERAL DISCUSSION

The major propagation effects that will determine the system margins in Canada are rain and cloud in the South and tropospheric effects in the North.

The propagation phenomenon that will have the greatest effect on communication services operating in the 10 through 20 GHz band in Canada turns out to be rain and tropospheric effects which are predominant at the lower elevation angles. Thus for the southern regions of Canada that experience the higher rainfall and also operate at the higher elevation angles, rain and cloud effects will determine the required system margin. For the remote northern locations rainfall rates and occurrences are much less but, due to the lower elevation angles, tropospheric fading effects determine the margins that will be required.

Other propagation phenomenon such as ducting, ray bending, cross-polarization discrimination effects, and scintillation which could affect both the systems margins and the phase coherence of the signal are expected to be negligible at the frequencies, elevation angles and rf bandwidths that are considered relevant in latter parts of this report.

Various satellite system models are considered in 5.5 and the estimated system margins required for a given percentage of the time are obtained, based on rain, cloud and tropospheric fading effects. These margins are summarized in Tables 5-1 and 5-2.

Table 5-1 Margins Required for Southern Communication Links

TYPE OF SYSTEM	REQUIRED SYSTEM MARGIN (dB)		
	99.999%	99.99%	99.9%
1. Satellite Transponder operating in Linear Region			
a) TDA Receiver	16.0	9.5	3.0
b) Uncooled Parametric Amp. Rec.	16.0	9.7	3.3
2. Satellite Transponder operating at Saturation			
a) TDA Receiver	11.0	8.0	2.0
b) Uncooled Parametric Receiver	13.0	9.0	2.0

Table 5-2 Margins Required for North/South Communication Links

TYPE SYSTEM	REQUIRED SYSTEM MARGIN (dB)		
	99.99%	99.9%	99%
1. Satellite Transponder Operating in Linear Region (FM/FDMA Systems)			
a) $4^{\circ} - 5^{\circ}$ Elevation Angle in the North	10.5	6.0	3.0
b) 20° Elevation Angle in the North	7.6	4.7	2.2
2. Satellite Transponder Operating at Saturation (Television, TDMA)			
a) $4^{\circ} - 5^{\circ}$ Elevation Angle in the North	8.4	4.6	2.6
b) 20° Elevation Angle in the North	6.0	3.0	1.7

These margins are obtained from the effects of rain and cloud attenuation in the South and by considering tropospheric effects in the North.

Other effects of rain on the signal such as reduction in polarization discrimination and bandwidth coherence are expected to be negligible at the frequencies and bandwidths being considered.

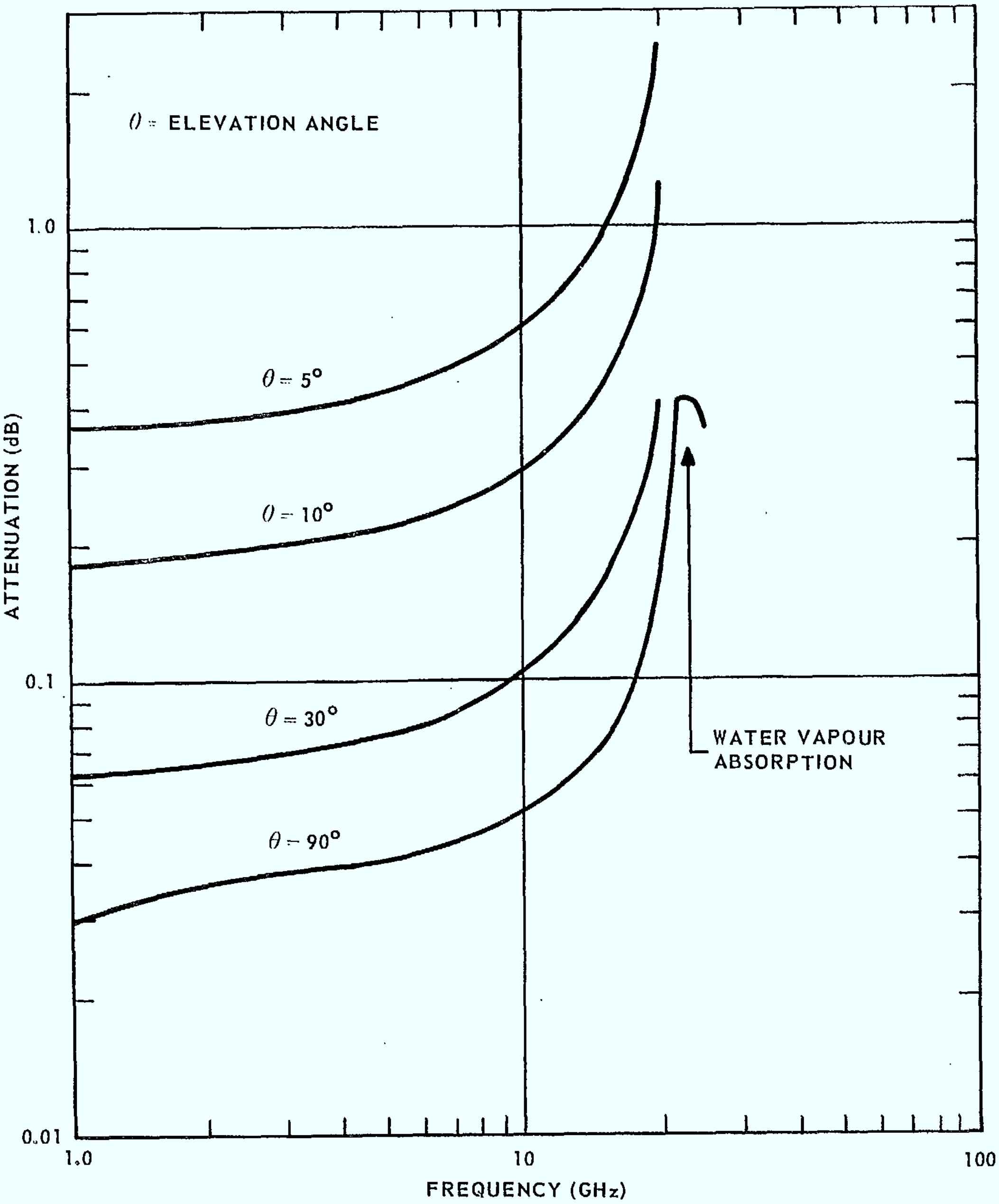

Figure 5-1 Signal Attenuation due to Atmosphere

5.2.1 ATMOSPHERIC ABSORPTION

The phenomenon of atmospheric absorption is briefly described and quantitative estimates are made. It is significant only at elevation angles lower than 30°.

Radio-frequency signals passing through the atmosphere experience attenuation due to molecular absorption of the energy by the gases comprising the atmosphere. The two main contributors to the attenuation are oxygen and water vapour. The oxygen molecule has resonant lines located at 60 GHz and 118.8 GHz and water vapour has absorption lines at 22.2 GHz, 183.3 GHz and higher frequencies.

Atmospheric attenuation is also dependent on meteorological conditions, mainly, atmospheric pressure, temperature and relative humidity.

Figure 5-1 shows the expected atmospheric attenuation versus frequency for standard atmosphere of the United States for July at 45° North Latitude from Ref 5*. These values agree closely with those reported by Crane[5.1] and Wulfsberg[5.6]. The values given in Table 5-3 are for attenuation at 12 GHz and 15 GHz for various elevation angles.

The attenuation for elevation angles other than zenith was derived using the cosecant rule for flat earth approximation. This method provides sufficient accuracy for elevation angles above 5°, with the error at 5° elevation using the cosecant method being less than 1 percent of that employing the 4/3 earth radius method.

Table 5-3 Estimated Attenuation Due to Atmosphere
(θ = Elevation Angle)

FREQUENCY GHz	ATTENUATION (dB)			
	$\theta = 5°$	$\theta = 10°$	$\theta = 30°$	$\theta = 90°$
12	0.71	0.36	0.13	0.06
15	0.85	0.43	0.16	0.07

*References (Ref) are given in 5.7.

* * *

5.2.2 NOISE TEMPERATURE DUE TO ATMOSPHERE

From technical literature, estimates of the contribution to noise temperature from atmospheric absorption is made. This contribution increases in significance as the elevation angle becomes smaller.

Since the atmosphere absorbs energy, it also radiates energy in the form of noise which is picked up by an antenna beam intersecting the medium. The effective noise temperature from clear sky is related to the medium temperature and attenuation by:

$$T_s = (1 - 1/\alpha)\, T_m$$

where T_s = noise temperature (°K)

α = attenuation coefficient of the atmosphere

T_m = temperature of absorbing medium at zenith

and T_m is related to the ground temperature by the following formula[6]:

$$T_m = 1.12\, T_g - 50°K$$

T_g = ground temperature °K.

Wulfsberg[5.6] has demonstrated with radiometric measurements performed near Boston that the variance of the sky noise temperature with the secant of the zenith angle holds zenith angles up to 80° (10° elevation angle). At lower elevation angles a correction factor has to be employed to compensate for the temperature gradient of the sky and earth noise temperature which is radiated into the near sidelobes and main beam of the antenna. Thus at 5° elevation angle an additional 10°K was added to compensate for these factors. Table 5-4 shows medium sky noise temperature versus elevation angle for 12 GHz and 15 GHz and a ground temperature of 30°C.

Table 5-4 Apparent Sky Noise Temperature versus Elevation Angle

(T_m = 286°K)

FREQUENCY GHz	NOISE TEMPERATURE (°K)			
	θ = 5°	θ = 10°	θ = 30°	θ = 90°
12	53°	23°	8.6°	4.3°
15	62°	27°	10°	5°

5.3 EFFECTS OF PRECIPITATION

Technical literature on the attenuation due to precipitation at frequencies above 10 GHz is briefly reviewed in the content of its applicability to satellite links.

The effects of precipitation on a radio-frequency signal propagating through it has been an area of intensive study both theoretical and experimental over the past few decades. Ryde was the first to develop a theoretical procedure to obtain attenuation coefficients due to rain based on Mie's theory. This was further improved in computational accuracy by Medhurst[5.2] who also included the Laws and Parsons raindrop size distribution and intensity into the formula. Others such as Oguchi[5.17] analyzed the effects that non-spherical raindrops have on electromagnetic waves such as attenuation effects on vertical and horizontal polarized signals.

Figure 5-2 gives the theoretical attenuation coefficient due to rain at 12 GHz and 15 GHz from the two source references as noted. The theoretical minimum and maximum attenuation at 15 GHz given by Medhurst[5.2] is shown dotted on the figure. The two sets of curves agree fairly well. The relationship between rain rate and attenuation can be expressed fairly accurately by

$$A = \alpha R^{\beta}$$

where A = attenuation coefficient (dB/km)

α, β = coefficients dependent on frequency, temperature

R = rain rate (mm/h)

At 12 GHz and 15 GHz these equations based on Ref 5.5 are:

$$A_{12} = 0.0152\ R^{1.250} \quad \text{(dB/km) at 12 GHz}$$

$$A_{15} = 0.0278\ R^{1.21} \quad \text{(dB/km) at 15 GHz}$$

The problem still remains for the application of this theory to actual paths, especially satellite links. A fair amount of measurement and experimentation has been carried out over terrestial paths but,up until recently, little experimental work has been performed on space links. Path lengths through rain and the spatial distribution of rain intensity over the path length are parameters that are still being investigated to arrive at a suitable model for rain attenuation. Measurement data for earth-space paths comes mainly from two sources at present; the sun tracker and radiometric experiments carried out at Crawford Hill, N.J.[5.12] at 16 GHz and 30 GHz, and experiments being carried out with the ATS-S satellite operating at 15.3 GHz on the downlink and 31.65 GHz on the uplink[5.8], as reported by Ippolito[5.8]. He shows that measurement results generally provide a scatter diagram rather than a 1:1 correspondence and, by experiment, has indicated there is very poor correlation between estimated and measured attenuation using point rain rate data. Improved correlation resulted from using average rainfall rate data measured by rain gauges spaced evenly along the ground in the azimuth direction of the path. Best correlation was obtained by height averaging the rainfall rate along the path.

Possibly the largest source of space-link measurement data is provided from the sun tracker experiment being carried out at Bell Labs, Crawford Hill, N.J. Measurements at 16 GHz and 30 GHz make possible, by using theory, the extrapolation of attenuations at other frequencies. The sun tracker is being equipped to receive a third frequency in order to verify the extrapolation process.

Hogg and Evans[5.10] used the ratio of attenuation measured at 16 GHz and 30 GHz by the sun tracker to arrive at an apparent rain rate. From the apparent rain rate and a calculable attenuation factor for this rain rate, the apparent distance was calculated. This apparent distance varies with rain rate, it being asymptotic to one kilometer at extreme rain rates and increasing up to 11 kilometers for low rain rates. This is to be expected since high rain rates are formed by local rain cells which are small in area whereas the low rain rates tend to be from rain cells covering a large area. The model was developed from measurement data for elevation angles above 30°. Data for angles below 30°, unfortunately, was ignored. This data would have been more appropriate for elevation angles that would be experienced in Canada. The apparent path length for rain used in this study was taken from the CCIR report[5.14].

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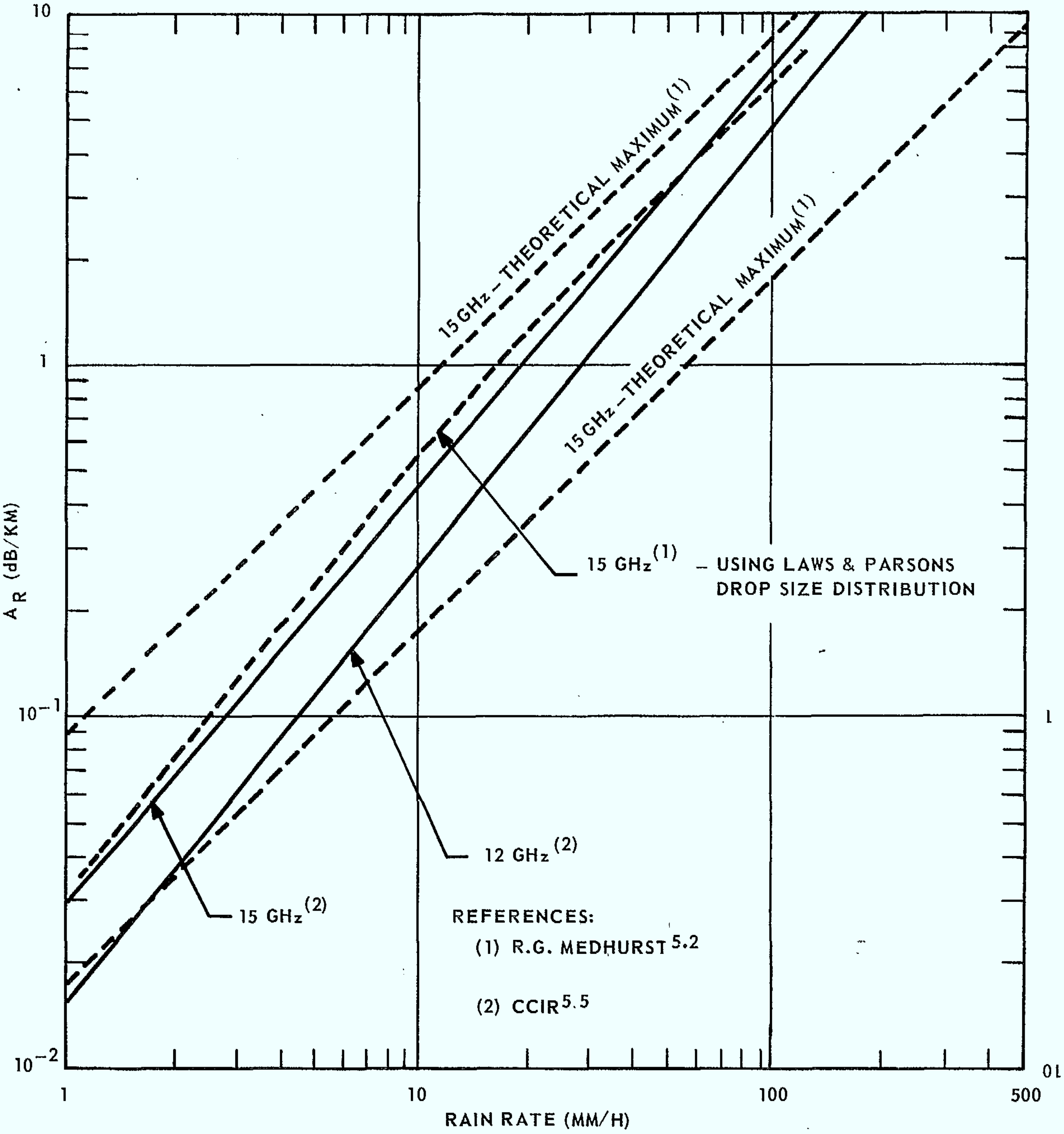

Figure 5-2 Rain Attenuation, A_R, versus Rain Rate

5.3.1 RAIN ATTENUATION IN CANADA

Estimates of the temporal distribution of attenuation due to rain are made for Canada, based on available metrological data for the Ottawa region and extrapolation for other regions. The allowance necessary to overcome this attenuation increases sharply at these frequencies as the associated time percentage is decreased.

Adequate data required for estimation of rainfall rates in the form suitable to predict cumulative rain attenuation for the various regions of Canada is not available. However, data obtained from CRC[5.9] providing cumulative rainfall rate for the Ottawa region was used to estimate cumulative attenuation for the Ottawa region and perhaps can be used for estimating the rainfall attenuation expected for the southern Ontario region. For correlating the rainfall intensities for other regions of Canada compared to that of Ottawa, meteorological maps developed by Bruce[5.15] were used. More detailed data than this for determining rainfall intensities in other areas are available from the meteorological department, but this information is stored in unprocessed form on magnetic tape and time did not permit of analysis.

Figure 5-3 shows the cumulative rainfall rate for the Ottawa region based on data obtained from CRC. Figures 5-4 and 5-5 show the cumulative rainfall attenuation at 12 GHz and 15 GHz based on the data of Figure 5-3. For a satellite located between 85° and 115° West Longitude in synchronous orbit, the minimum elevation angle to the satellite would be 25°. Table 5-5 gives the rain attenuation margins required for the Ottawa region at 12 GHz and 15 GHz at 25° elevation angle. As can be seen from the figures, using the apparent distance through the rain given by Evans and Hogg[5.10], results in lower value of attenuation at high rain rates compared to the CCIR curves[5.14] give higher total attenuation for the lower rainfall rates. The crossover is at a rainfall rate of approximately 40 mm/h.

To estimate the rain attenuation expected for other Canadian locations, meteorological data comparing extreme rainfall rates in other regions to the Ottawa region were used. Data[5.15] giving the extreme 5, 15 and 30 minute rainfall accumulation for 2, 5 and 10 year return periods were analyzed and compared to the Ottawa region. The average 5, 10 and 30 minute rainfall rates for various Canadian locations compared to Ottawa region are given in Table 5-6. However, note must be taken that the frequency of occurrence of these extreme rainfall rates cannot be obtained from Ref 5.15.

Table 5-5 Estimated Rain Attenuation Margins at 12 GHz and 15 GHz
(Location - Ottawa, Ontario)

FREQUENCY GHz	ELEVATION ANGLE DEGREES	EXCESS ATTENUATION DUE TO RAIN NOT EXCEEDED FOR % OF TIME INDICATED			
		99%	99.9%	99.99%	99.999%
12	10°	<0.2	1.6	9.5	16.0
	15°	<0.2	1.3	7.5	12.5
	25°	<0.1	1.0	6.0	10
15	10°	0.3	3.0	15	26
	15°	0.2	2.0	11.5	20
	25°	0.1	1.7	9.0	16

To obtain some indication of the occurrence of high rainfall rates, use was made of the average occurrence of thunderstorm activities at these locations for the month of July[5.16] since these extreme rainfall rates, usually convective in nature, are generally associated with thunderstorm activity.

Table 5-6 Average Rainfall Rates Compared to Ottawa

LOCATION	AVERAGE RAINFALL RATE (COMPARED TO OTTAWA)	AVERAGE NO. OF THUNDERSTORMS (JULY)
St. John's, Nfld.	80 - 85%	1.0
London, Ontario	110 - 120%	6.0
Ottawa, Ontario	100%	6.0
Ft. William, Ont.	105 - 110%	7.0
Regina, Sask.	105%	7.0
Penhold, Alt.	90 - 93%	8.0
Vancouver, B.C.	-	0.5
Goose Bay, Lab.	20 - 40%	1.0

Again it is stressed that thunderstorm activity can only give an indicative measure of high rainfall rate occurrence and in some cases it can be misleading, as mentioned in Ref 5.3.

Rainfall accumulation information was not available for British Columbia due to the extremely variable precipitation rates that occur over short geographical distances. In general, using thunderstorm activity as a guide, it would be expected that extreme rainfall rates would be less than that of south-eastern Canada. Since the local weather conditions are so variable, caution must be exercised in the selection of specific site locations. This is borne out in Ref 5.14 which places the West coast of Canada in region 3 of rainfall rate intensity (Maritimes climate) compared to region 2 for most of southern Canada (continental temperature). Region 3 has rain rates of 50 through 75 percent of those for region 2. However, since the local weather conditions are so variable on the West coast, caution must be exercised in selecting specific site locations.

Thus for the purpose of this study, rain margins calculated for Ottawa region represent the requirements for most of the southern regions of Canada. Although St. John's and Vancouver have less extreme rainfall, their elevation angles will generally be lower and thus the increase in path length through the rain will partially compensate somewhat for the lower rainfall rates. The margins estimated for Goose Bay, located at approximately 54° North Latitude are 0.7 and 1.6 dB for 0.1 percent of the time and 2.3 and 4.8 dB for 0.01 percent of the time at 12 GHz and 15 GHz respectively. For higher latitudes the effect of rainfall will be negligible compared to tropospheric effects that are discussed in a later section.

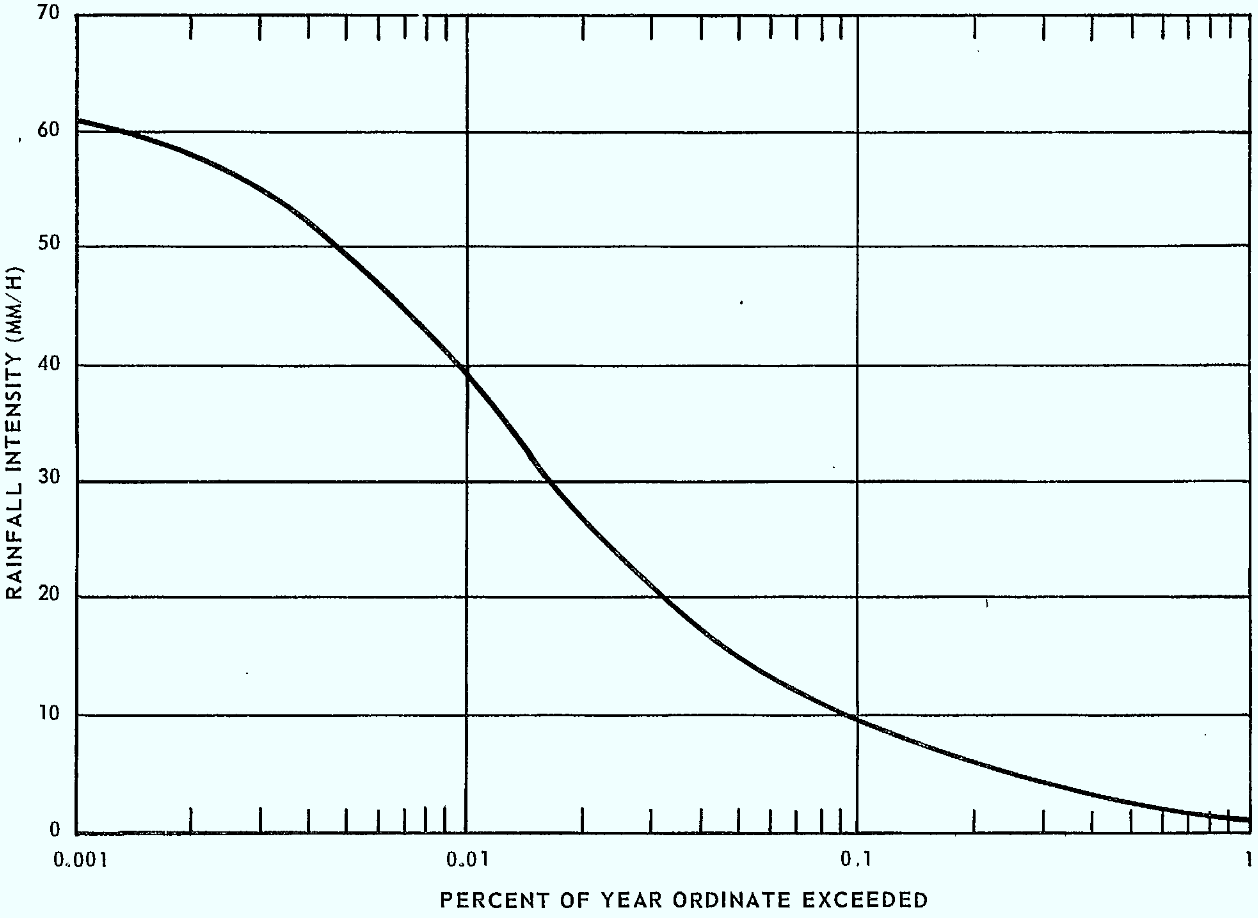

Figure 5-3 Cumulative Rainfall Rate for Ottawa

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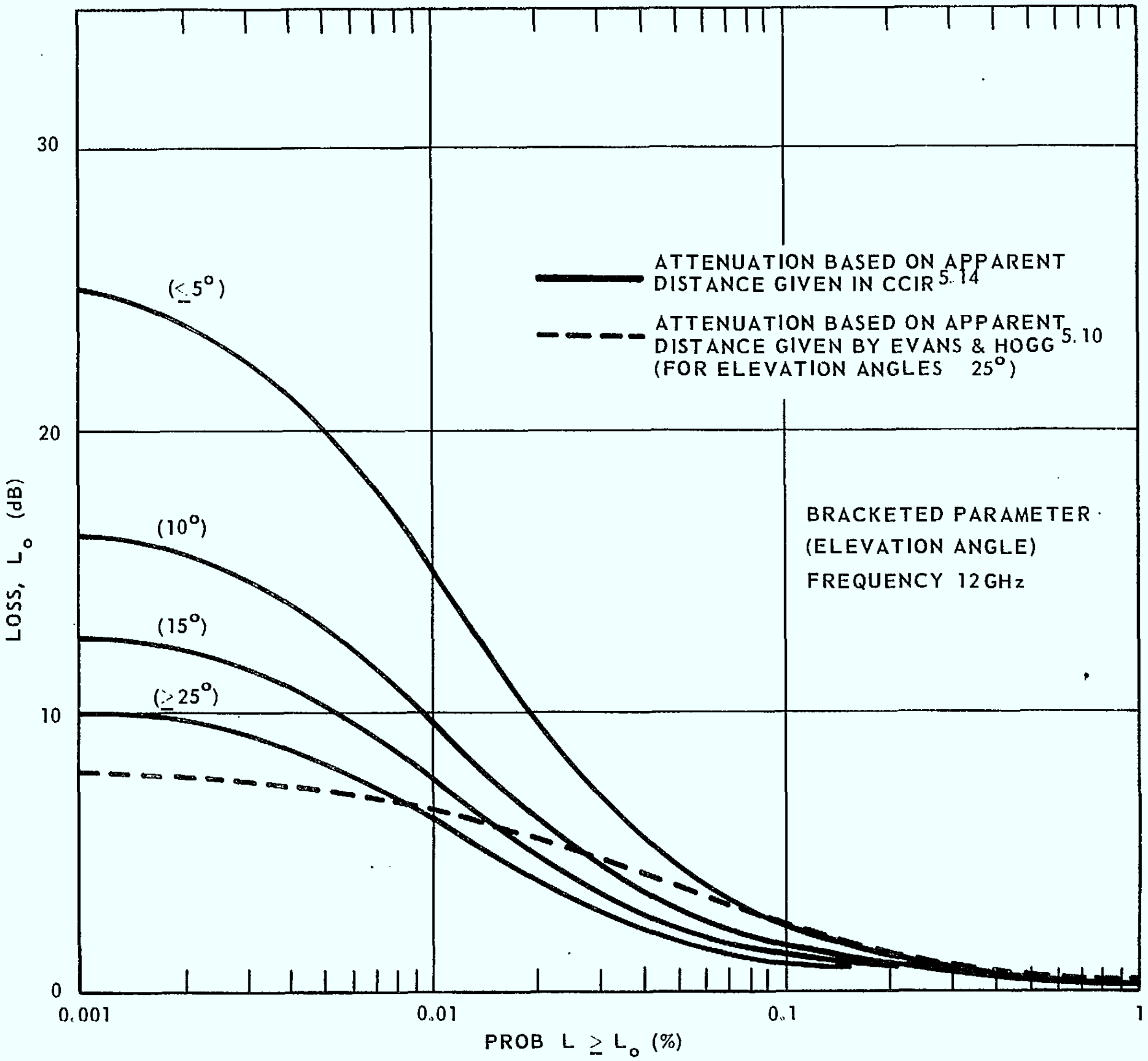

Figure 5-4 Cumulative Probability of Path Attenuation due to Rain (Ottawa Region) at 12 GHz

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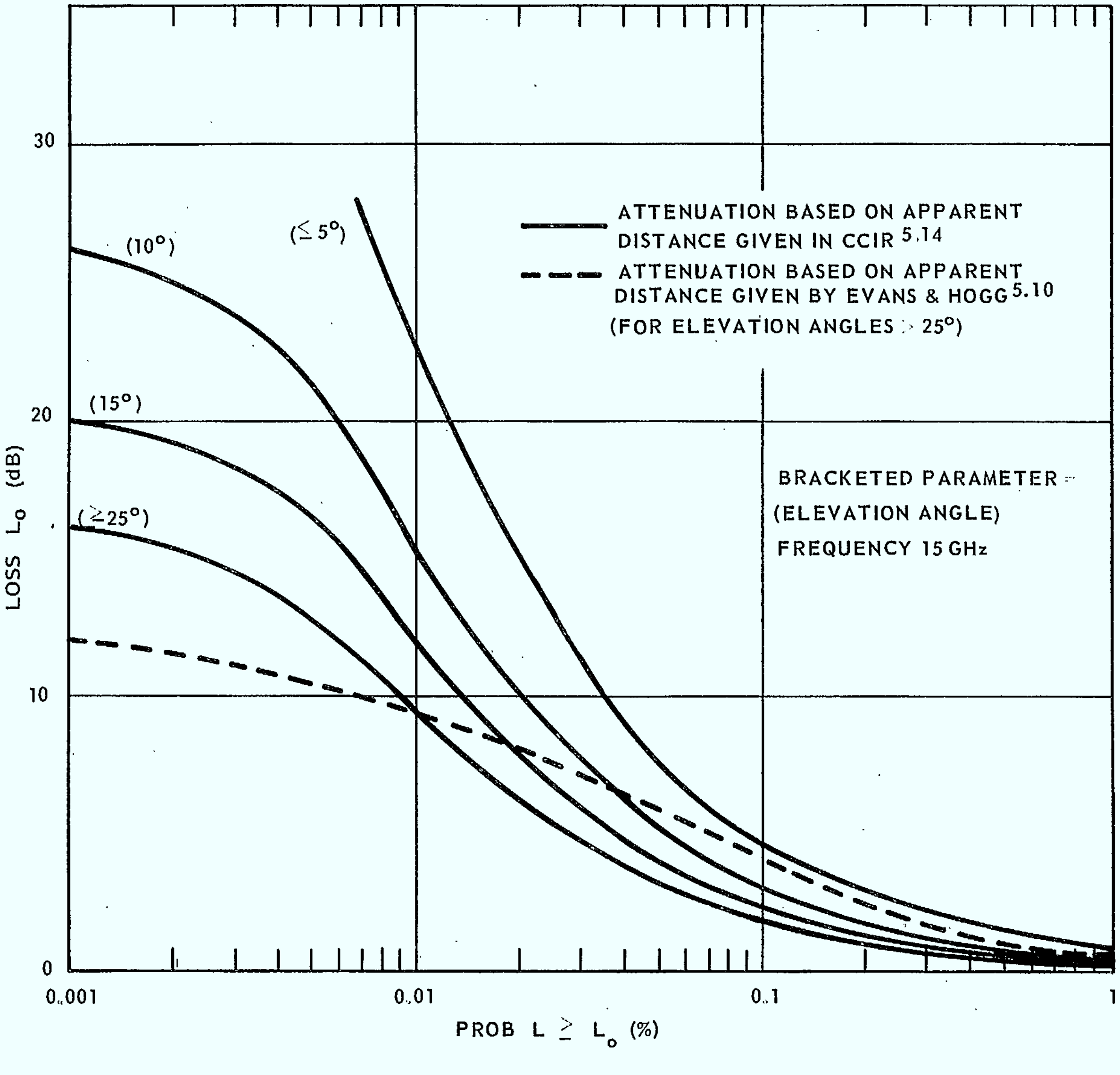

Figure 5-5 Cumulative Probability of Path Attenuation due to Rain (Ottawa Region) at 15 GHz

5.3.2 SPACE DIVERSITY

The pros and cons of overcoming the large attenuations due to rainfall by space diversity techniques are examined. It is concluded that for those services whose availability requirements do not exceed 99.99 percent, space diversity is not needed in Canada.

One technique of effectively reducing the large margins required for extreme rainfall rates occurring for a small percentage of the time is to employ space diversity. Earth stations separated at some distance apart are much less likely to have their paths intercepted simultaneously by intense rain cells. Data from space diversity measurements performed at Bell Labs, Crawford Hill, N.J. were used to estimate the improvement that could be expected for Ottawa locations.

Figure 5-6 shows the rain attenuation which can be expected employing space diversity compared to non-diversity reception. Table 5-7 lists the margins required and improvement factor if space diversity was employed for 0.001, 0.01 and 0.1 percent of the time.

Table 5-7 Estimated Improvement Employing Space Diversity

FREQUENCY	MARGIN REQUIRED (dB) (SPACE DIVERSITY)			DIVERSITY IMPROVEMENT (dB)		
	99.9%	99.99%	99.999%	99.9%	99.99%	99.999%
12	1.0	2.0	2.2	0	4.0	7.8
15	1.7	4.8	6.8	0	4.2	9.2

As can be seen from Figure 5-6, space diversity affords significant improvement for small percentages of the time which corresponds to high rain rates. The rain cells producing intense rainfall tend to cover a small area and thus it is quite improbable that two beams, separated in distance, will simultaneously intersect the rain cell. The attenuation for the larger percentage of the time results from low rainfall rates and cloud which generally covers large areas. In this case, space diversity affords much less of an improvement for earth station separation distances of the order of 10 through 20 km.

Although space diversity is one method of reducing the system margins required, it is also rather a costly method since each earth station plus rearward facilities must be duplicated, effectively doubling the ground segment cost. This is especially the case for systems that have a large number of earth stations such as television distribution systems. Thus, space diversity should be compared with other methods of providing the desired availability, such as designing the required margins into the system and employing up-path power control. It appears that for required margins of less than 10 dB, these alternatives will be more economical than employing space diversity. Therefore, if service availability better than 99.99 percent is not required, space diversity techniques for most locations in Canada would not appear to be needed. In the unlikely event that service availability better than 99.99 percent is required, the only effective method of obtaining this higher reliability for many locations in southern Canada may be the use of space diversity.

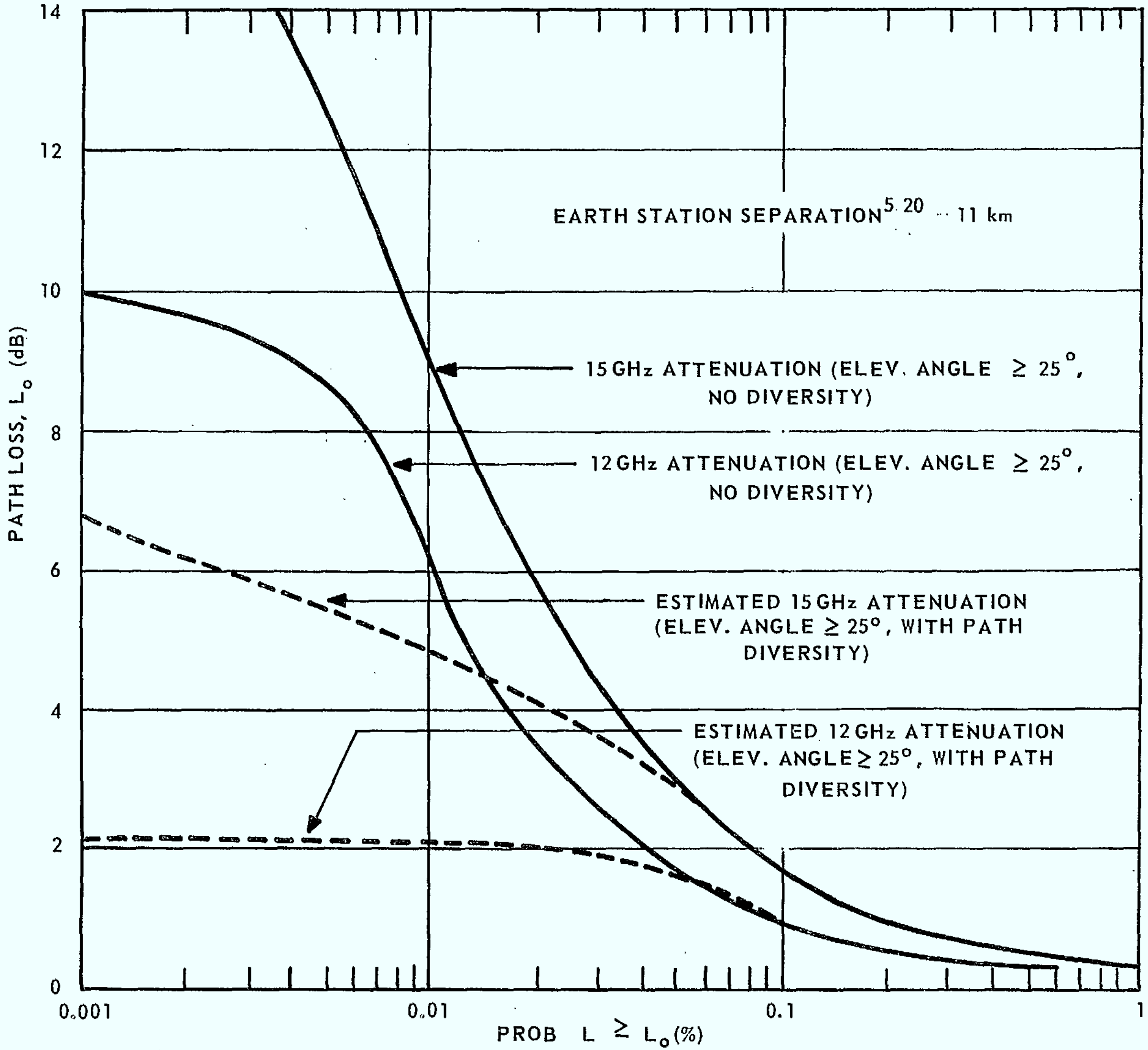

Figure 5-6 Estimate of Earth Station Diversity Improvement on Rain Attenuation (Ottawa)

5.3.3 NOISE EFFECTS DUE TO RAIN

The equivalent increase in noise temperature of a receiving sub-system, due to rain attenuation and scattering, is estimated to the first order of approximation. It is seen to be a significant, though not controlling component of system design.

Rain attenuation consists of two components, namely, an absorption component and a scattering mode. The noise increase into a receiver from rain attenuation is caused by the absorption part of the attenuation. The scattering component, assuming a relatively narrow beam antenna, causes only attenuation of the signal. At the frequencies under consideration (12 GHz) and the rain rates involved (<60 mm/h) the absorption component makes up more than 85 percent of the total attenuation. Therefore, with a slight error, the total rain attenuation value is used to calculate the noise increase which will give a slightly pessimistic value for noise due to rain.

The increase in noise temperature is given by:

$$T_r = (1 - \alpha)\ T_m$$

where T_r = noise temperature due to rain attenuation

α = transmission loss due to rain

T_m = temperature of the absorbing medium.

This relationship has been used to predict, with good correlation, attenuations up to 15 dB at 15.3 GHz based on radiometric measurements[5.8].

Table 5-8 gives the expected noise temperature due to rain versus percentage of the time for Ottawa. The total down-path degradations due to the combined effects of a decrease in the received signal and increase in noise temperature are also given for an uncooled parametric amplifier and a TDA receiver.

As can be seen from Table 5-8, the amount of degradation for the TDA is less than that for the uncooled parametric amplifier, since it is more sensitive to noise increase from the rain.

Table 5-8 Noise Temperature Effect on Down-Path Margin

TIME EXCEEDED (%)	T_r (°K)	$\Delta(C/N)_T$ (dB) (UN-COOLED PARAMP)	$\Delta(C/N)_T$ (dB) (TDA)
0.001	252	12.8	10.9
0.01	210	8.5	6.7
0.1	58	1.8	1.2

For T_m = 280°K:

Receive system noise for un-cooled paramp = 274°K;

Receive system noise for TDA = 1157°K.

f_r = 12 GHz.

5.3.4 OTHER EFFECTS DUE TO RAIN

Differences in attenuation for vertical and horizontal polarization are estimated for oblate raindrops. Cross polarization discrimination and bandwidth coherence phenomena are considered. Attenuation estimates based on spherical raindrops are adopted for later calculations of margins, while the latter two effects are insignificant.

(a) Polarization Effects

Since raindrops tend to be oblate in shape rather than true spheres, rain attenuation will effect vertical and horizontal polarized waves differently.

Oguchi$^{5.17}$ has performed theoretical calculations of this effect. At a rain rate of 12.5 mm/h, he estimates that horizontal polarized waves will experience 11 percent higher attenuation than vertical polarization. For rain rates of interest in Canada and at frequencies below 20 GHz a vertically polarized signal is likely to experience some 15 through 25 percent less attenuation (expressed in dB), due to rain, than a horizontally polarized signal at the same frequency. However, it is noted that all the attenuation calculations in the preceding sub-sections of this section were based on spherical raindrops, which very closely approximate the attenuation for horizontal polarization with oblate raindrops. Thus the calculated figures can be used for both vertical and horizontal polarization, whereas if the system margins were reduced to take advantage of the lower attenuation of the vertically polarized signals, they would be inadequate for the other polarization, imposing an avoidable constraint on system design.

The effect of oblate-shaped raindrops on cross-polarization discrimination is not well known and very meagre experimental data are available. These data which are available refer to specific frequencies and to terrestrial paths. Theoretical estimates have been made for the case of least cross-polarization expected at 12 GHz and 18 GHz operating over a 3 km horizontal path and are given in Table 5-9. Cross-polarization discrimination is expected to improve with increasing elevation angle for an identical propagation path reaching infinity (theoretically) at zenith angle.

Table 5-9 Estimation of Cross Polarization Discrimination vs. Rainfall Rate[5.3]

PATH RAIN RATE	CROSS POLARIZATION DISCRIMINATION (dB)		
	12 GHz	15 GHz	18 GHz
25	36.2	31.8	27.5
50	29	25.4	21.8
75	25.0	21.7	18.5
100	22.3	18.9	15.5
125	20.0	16.9	13.8
150	19.0	15.6	12.3

The values at 15 GHz are only estimates made on the assumption that discrimination is a linear function of frequency between 12 GHz and 18 GHz whereas it is probably a more complex relationship than this. The conclusion from this data is that for rain rates and path angles expected in Canada, the effect of rain on polarization discrimination will not be significant.

(b) Bandwidth Coherence

Due to the frequency dependence of attenuation and phase shift introduced by rain, it can be expected that there would be an upper limit on bandwidth placed on coherent transmission systems.

Experimental evidence of this phenomenon is very meagre. The only measurements known for earth-space paths are reported by Ippolito[5.8] using the ATS-V. Limited sideband data obtained prior to a 9 dB transponder power degradation occurring showed no de-correlation effects in amplitude or relative sideband phase. The sidebands on the down link could be set at four positions from the 15.3 GHz carrier, specifically ±0.1, ±1.0, ±10, or ±50 MHz. Also a theoretical study performed by Crane[5.1] indicates that transmission bandwidths up to 3.5 GHz would not experience any bandwidth coherence problem, and it is expected that an outage due to excess attenuation will occur before a measurable bandwidth limitation would be reached.

5.3.5 CLOUD ATTENUATION

Attenuation and noise temperature increase due to the moisture content of clouds are estimated. These are combined with the effects of rain calculated in previous sub-sections.

The attenuation coefficient due to cloud can be obtained easily from theoretical considerations once the statistics of the cloud structure are known (liquid water content, vertical and horizontal dimensions and temperature). However, adequate data is not available in Canada on cloud statistics and their frequency of occurrence.

Evans[5.10] has analyzed over 10,000 hours of sun tracker and radiometric measurements performed at Crawford Hill, N.J. at 16 GHz and 20 GHz. From these data, the attenuation due to cloud coverage was extracted from the measurements after making the intuitive assumption that small attenuations measured for the larger percentage of the time were generally due to cloud coverage, and the large attenuations occurring for small percentage of the time were due to rainfall along the path. Since the two events will be mutually exclusive in this case, their cumulative attenuation is added on a percentage basis and not on a decibel basis. On the assumption that the cloud statistics for regions in southern Canada are similar to those experienced in New Jersey, and from the data supplied, the cumulative attenuation due to clouds was obtained by extrapolating from 16 GHz to 12 GHz and 15 GHz using the standard theory.

Figure 5-7 gives the attenuation due to clouds for 12 GHz and 15 GHz obtained from Ref 5.20. Figure 5-8 gives the noise temperature increase due to clouds for the 12 GHz down-path and for a cloud temperature of 10°C. Table 5-10 gives the margins required for a given service reliability.

Table 5-10 Attenuation and Noise Temperature Due to Clouds

FREQUENCY	CUMULATIVE ATTENUATION (dB)			CUMULATIVE NOISE TEMP (°K)		
GHz	0.001%	0.01%	0.1%	0.001%	0.01%	0.1%
12	3.5	2.1	1.0	153	109	55
15	7.4	4.2	1.9	-	-	-

Based on the rule that rain attenuation and cloud attenuation are mutually exclusive events, the two attenuations are added on a percentage basis to give a total attenuation at 12 GHz and 15 GHz as shown in Figures 5-9 and 5-10. Figure 5-11 gives the cumulative noise temperature from clouds and rain at 12 GHz. Table 5-11 summarizes the degradations from the combined clouds and rain.

Table 5-11 Cumulative Degradation From Clouds and Rain

FREQUENCY GHz	CUMULATIVE ATTENUATION (dB) NOT EXCEEDED FOR PERCENTAGE OF TIME INDICATED			CUMULATIVE NOISE TEMP (°K) NOT EXCEEDED FOR PERCENTAGE OF TIME INDICATED		
	0.001%	0.01%	0.1%	0.001%	0.01%	0.1%
12	10.0	6.0	1.5	255	210	85
15	16.0	9.2	2.7	-	-	-

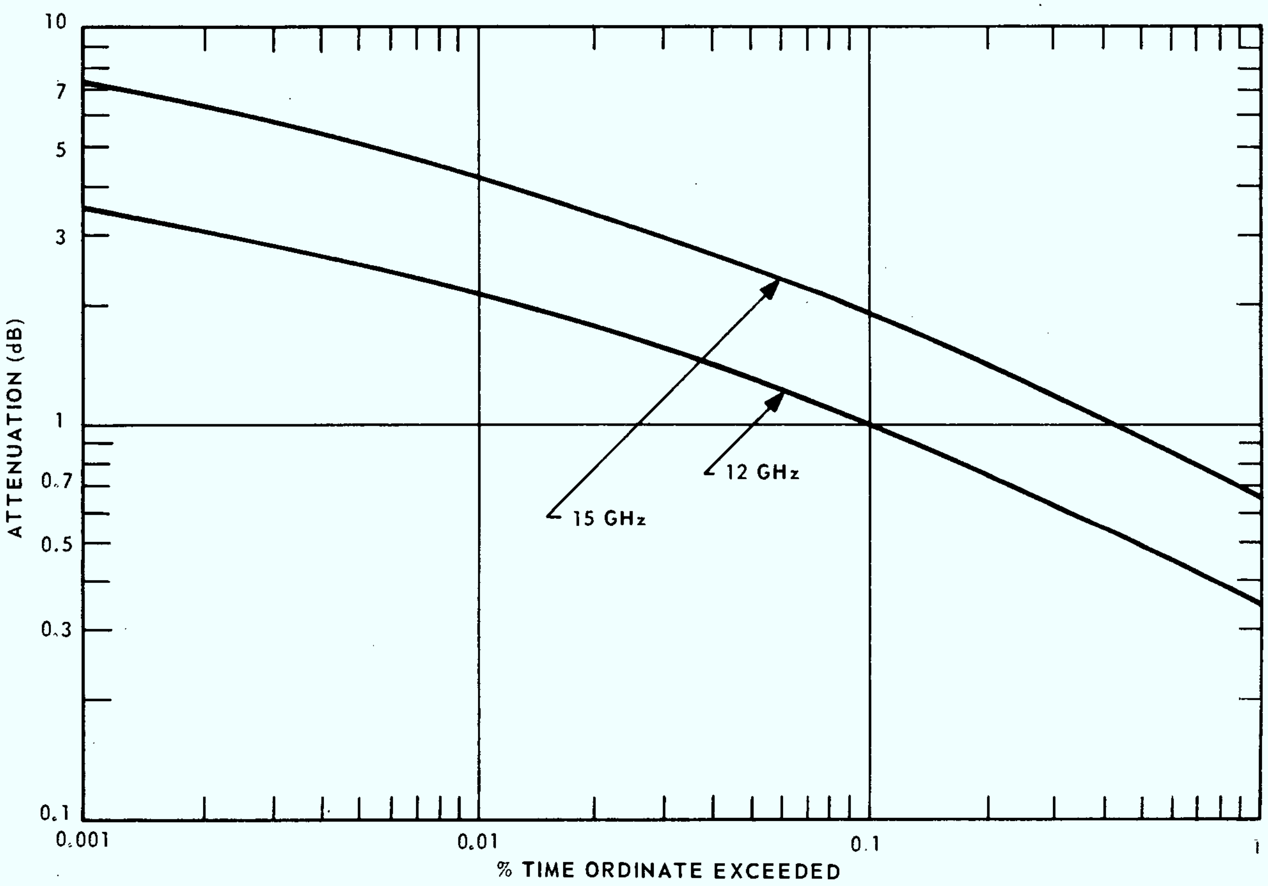

Figure 5-7 Attenuation due to Cloud[5.20]

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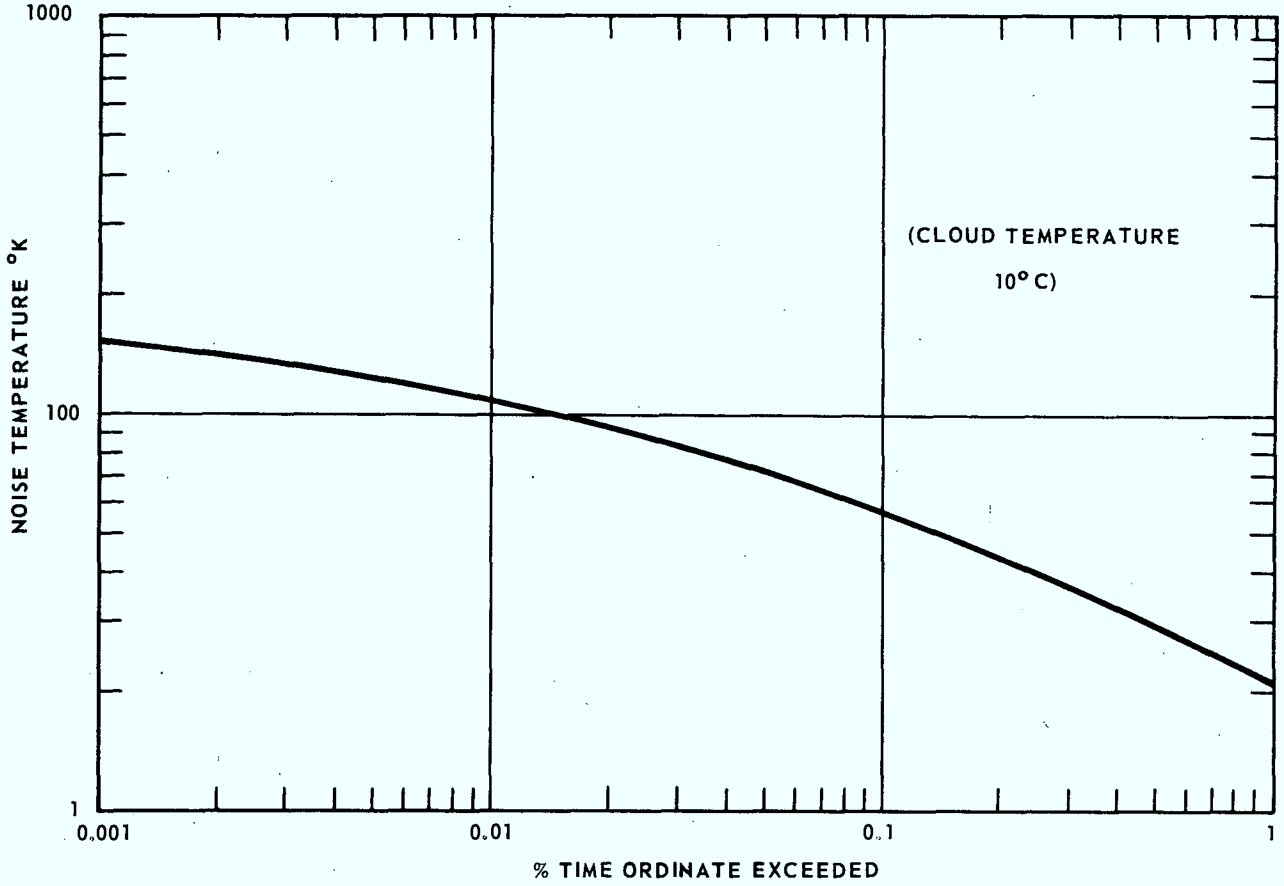

Figure 5-8 Noise Temperature due to Cloud at 12 GHz

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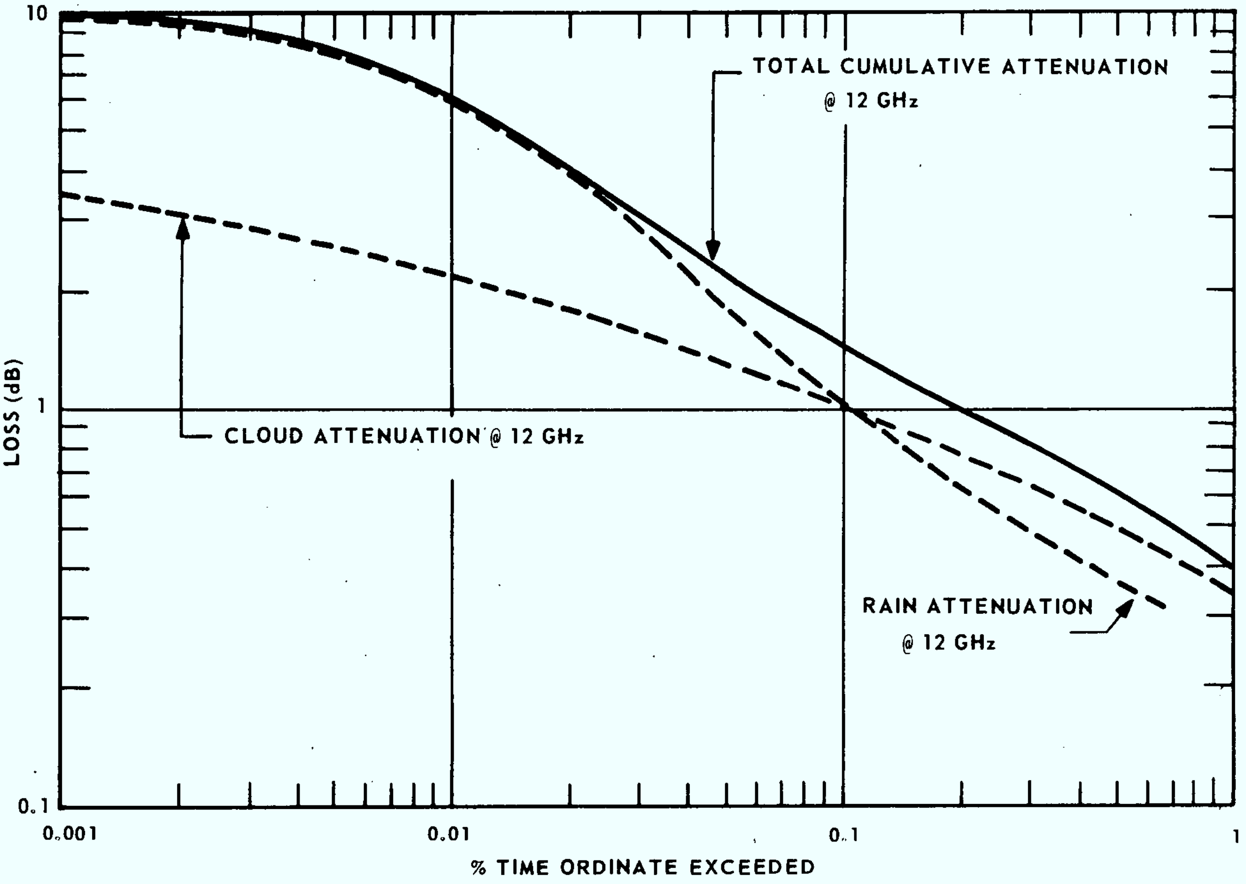

Figure 5-9 Combined Loss for Rain and Cloud at 12 GHz

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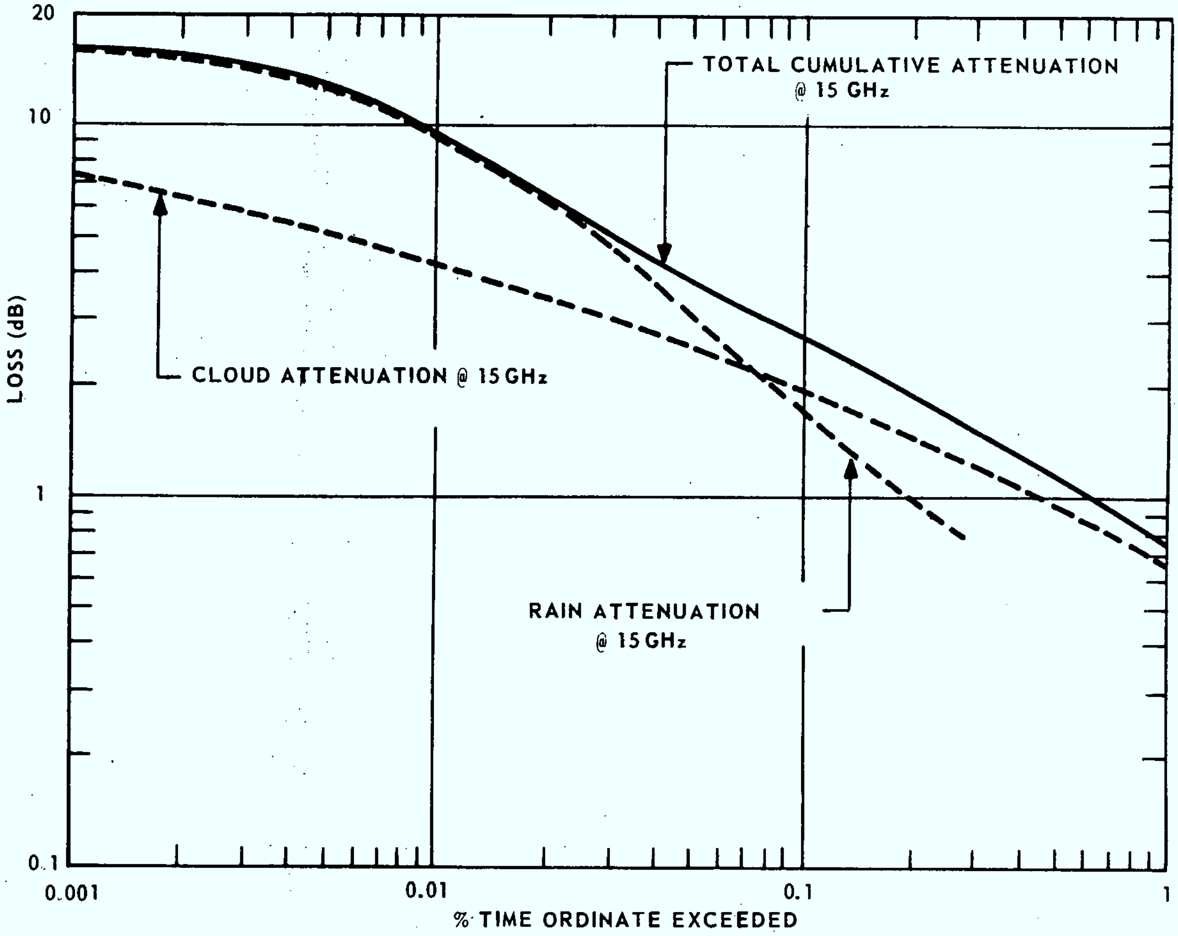

Figure 5-10 Combined Loss for Rain and Cloud at 15 GHz

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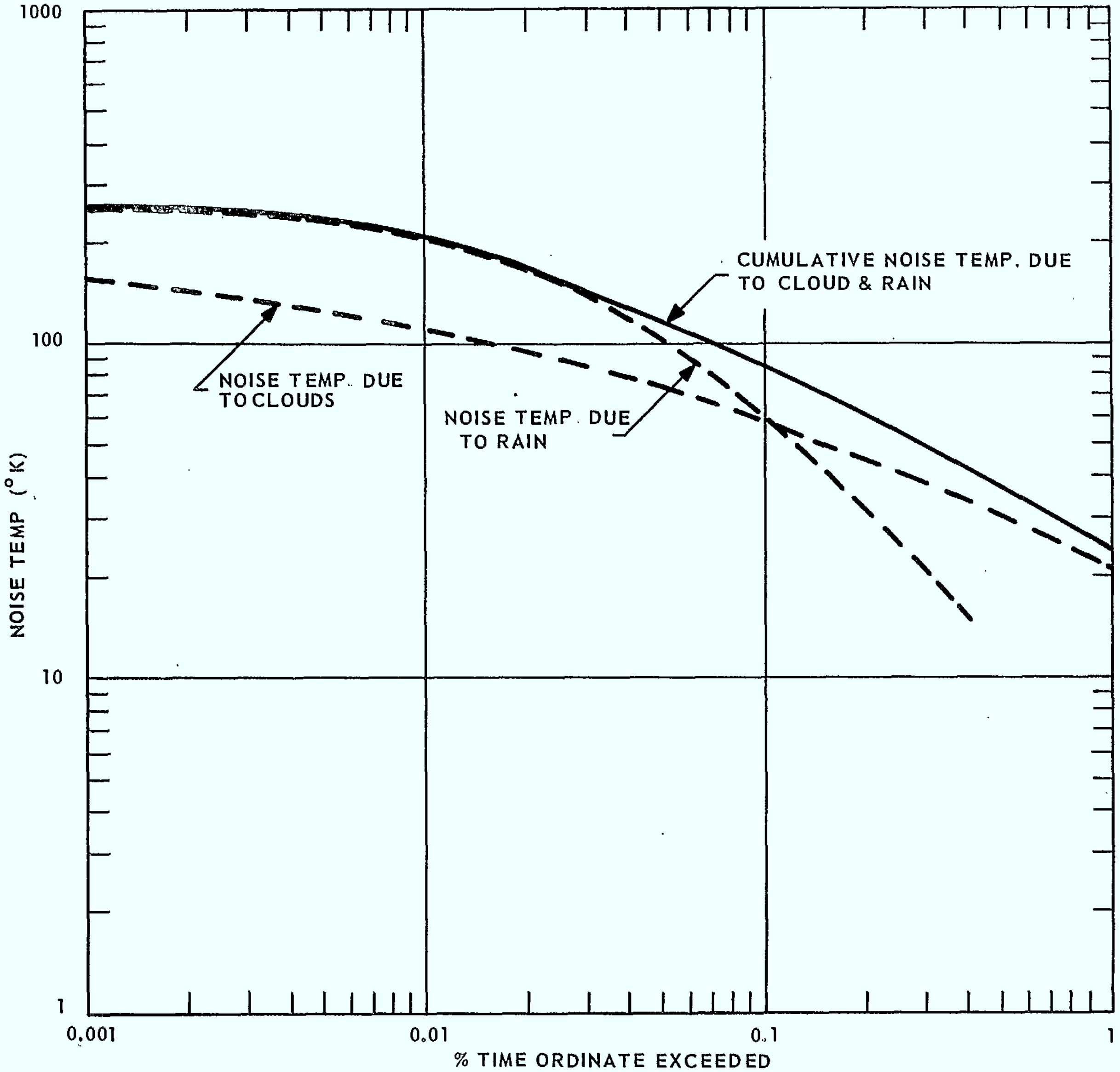

Figure 5-11 Cumulative Noise Temperature for Rain and Cloud (12 GHz)

5.4.1 TROPOSPHERIC EFFECTS

Low rainfall in northern Canada would indicate smaller acceptable systems margins, but this improvement is offset to a large extent by tropospheric effects at low elevation angles.

For frequencies above 10 GHz, the ionospheric effects are expected to be negligible but this is expected to be partially replaced by tropospheric effects especially when operating at low elevation angles. Measurements performed by CRC[5.9] at 7.3 GHz indicate that fluctuations in the amplitude of the signal take place which are believed to be due to inhomogeneties in the refracture structure of the troposphere. Systems operating at low elevation angles, such as in the northern regions of Canada, must take into consideration the margins required for this tropospheric scattering phenomena.

Figure 5-12, derived from data given in Ref 5.21, shows the margins required at 12 GHz and 15 GHz for elevation angles of 4° through 5° and 20°. The margin required at 4° through 5° can be considered quite pessimistic, since for a satellite located in the equatorial belt between 80° and 120° West Longitude the elevation angles for the majority of earth stations in the North will be larger than 5°. In fact, the majority of the stations will probably have elevation angles of the order of 15° through 20°. Since this fading phenomena diminishes with increasing elevation angle, the 5° elevation case can be considered the worst-case fading that will occur in the North and the margins for the 20° elevation angle case to be more representative of the fading for the majority of the northern stations. Table 5-12 gives the margins at 12 GHz and 15 GHz for various percentages of the time at 5° and 20° elevation angles.

Table 5-12 Estimated Tropospheric Fading versus Percentage of Time

(θ = Earth Station Elevation Angle)

TIME %	TROPOSPHERE FADING (dB)			
	$\theta = 5°$		$\theta = 20°$	
	12 GHz	15 GHz	12 GHz	15 GHz
0.01	8.8	10.5	6.5	7.8
0.1	5.0	6.0	3.2	4.0
1.0	2.8	3.1	1.8	2.2

If this effect is caused by inhomogeneties in the troposphere, then it is reasonable to assume that 'tropospheric' fading would not occur simultaneously with rain or will, at least, be diminished significantly since precipitation will tend to create a mixing of the tropospheric layers, making it more homogenous.

Since tropospheric fading as predicted at 12 GHz and 15 GHz will determine to a large extent the service reliability, and thus to some extent the cost of earth stations in the North, further experimentation should be carried out at the frequencies of interest to verify these predicted margins.

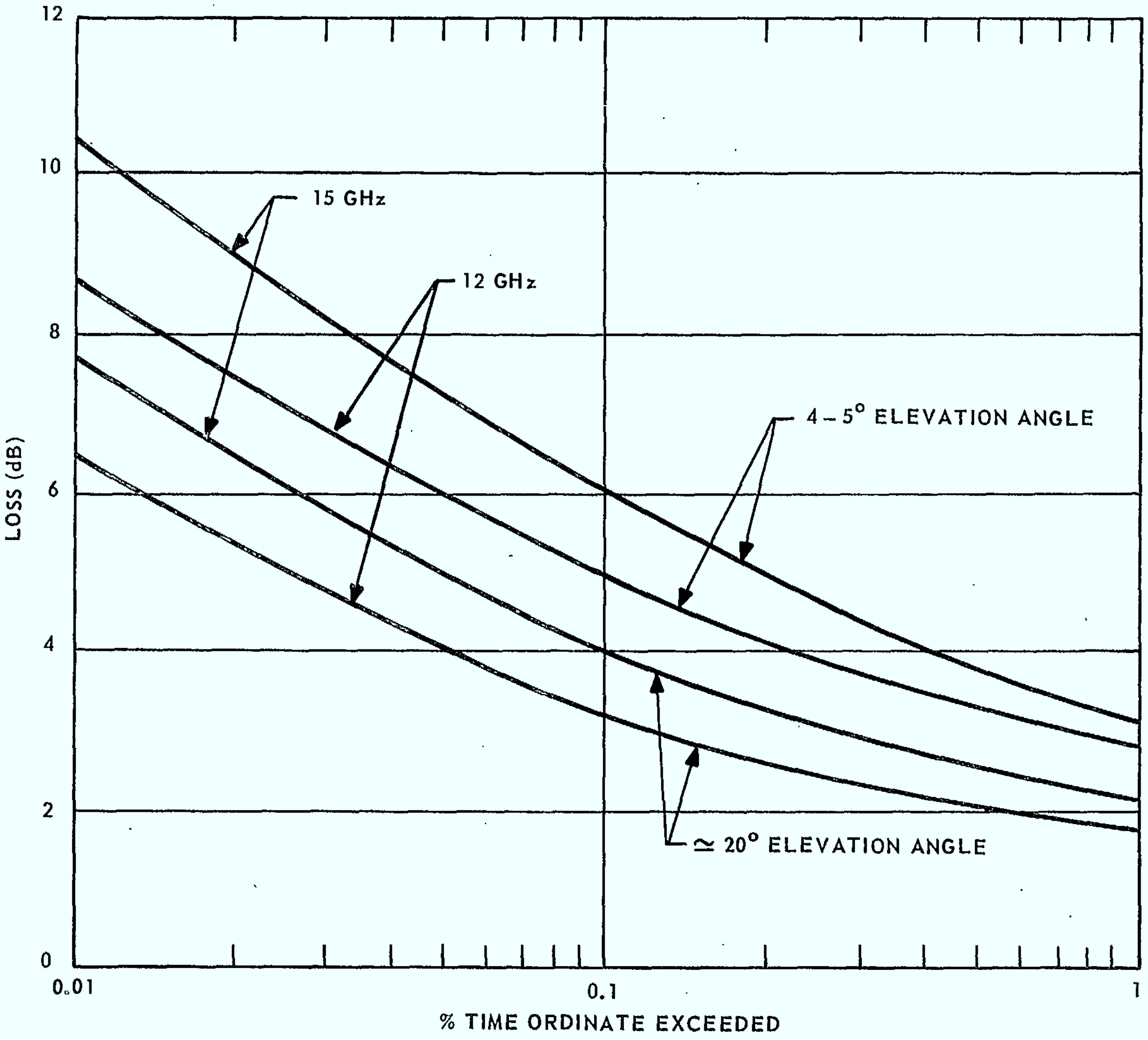

Figure 5-12 Tropospheric Fading Loss at 12 GHz and 15 GHz[5.21]

5.4.2 IONOSPHERIC EFFECTS

At the frequencies under consideration, propagation anomalies due to the ionosphere are expected to be negligible. This has been borne out by experiments performed up to the present time.

An amplitude scintillation phenomenon has been measured by COMSAT[5.18] at earth stations operating at 4 GHz and 6 GHz which has been attributed to the ionosphere, although the theory behind it is not known. Scintillation activity, with amplitudes as large as 6 dB, has been measured generally at earth stations located at the low latitudes (high elevation angle), but also has been measured to a lesser extent at earth stations with elevation angles as low as 5°, e.g. earth station 1 at Goonhilly. From data that have been analyzed so far the following characteristics have been observed:

a) The activity generally occurs in the late summer and autumn months.

b) The activity usually begins approximately an hour after local station sunset and lasts for 3 to 4 hours.

c) The activity measured simultaneously at 4 GHz and 6 GHz appears to be substantially less than that at 4 GHz.

Assuming that this anomaly follows the $1/f^2$ frequency relationship generally attributed to ionospheric disturbances, this effect will be negligible at frequencies above 10 GHz.

Another anomaly measured was a relative slow scintillation of peak-to-peak amplitude at 6 dB. This was measured only for stations operating below 10° elevation angle, (Goonhilly 1 station operates at approximately 5° elevation angle).

This effect was not measured at the Goonhilly 2 station which operates at a greater elevation angle. Thus it was attributed to tropospheric fading effects.

* * *

5.5 SYSTEM MARGIN REQUIREMENTS

Two distinct and separate modes of operation of a satellite are indicated, and the system margin requirements for each mode depend on the mode of operation as well as on the propagation fading allowances. In Canada the propagation fading allowances also depend on the geographical direction of the link (E-W or N-S).

The method of combining the up-link and down-link fading to obtain the total system fade margin required depends on the type of system being considered. There are two basic types of system; one that operates at full satellite output power (non-linear operation of the satellite TWT) and the other that operates in the linear region of the satellite transponder, characteristically employing input power back-off at the satellite. The first type of system normally has only one rf carrier at a time accessing the transponder such as television transmission, and Time Division Multiple Access (TDMA) systems. The second type of system has more than one carrier simultaneously accessing the satellite transponder and, to avoid excessive intermodulation in the final rf amplifier, generally operates in the linear region of the transponder. Frequency Division Multiple Access (FDMA) system is a typical system that operates in this mode.

In both cases of the margins to be calculated, up-path power control is not utilized.

For the southern area of Canada, the fading is caused by rain and cloud attenuation as described in 5.3.5 with C/N degradations given in Table 5-11. For earth stations located in the northern regions of Canada, where fading from precipitation is minimal, the major fading results from tropospheric effects as described in 5.4.1. Thus the system margins for satellite communication systems will be dependent on the geographical direction of the link. The two geographical directions consist of the East-West links for which both stations of the link are located in the South and the North-South link where fading is dependent upon rain and cloud for the southern station and tropospheric effects for the northern station.

The required margins for these two types of communication are determined in 5.5.1, 5.5.2, and 5.5.3.

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5.5.1 C/N VARIANCE FOR SYSTEMS OPERATING EAST-WEST IN SATURATION MODE

Curves of total system degradation versus percentage of time occurrence are developed for this mode of operation. Two types of earth station receivers are considered, specifically an uncooled parametric amplifier and a tunnel diode amplifier receiver. Down-path fading is controlling.

In this case, the system carrier-to-noise for fair weather is given by:

$$\left(\frac{C}{N}\right)_T = \frac{1}{1/(C/N)_U + 1/(C/N)_D} = \frac{C}{N_U + N_D}$$

For a fade of L dB (ℓ in numerical value) on the up-path, the system carrier-to-noise is given by:

$$\left(\frac{C}{N}\right)_T = \frac{1}{\left(\frac{1}{\frac{C}{\ell\ N_U}}\right) + \left(\frac{1}{\frac{C}{T(\ell)N_D}}\right)} = \frac{C}{\ell N_U + T(\ell)N_D}$$

where $T(\ell)$ is the transfer function of the input/output power of the rf amplifier in the satellite. Using a typical TWT transfer function and with the up-path (C/N) 10 dB better than the down-path (C/N) under fair weather, Figures 5-13 and 5-14 show the system degradation due to rain and cloud on the up-path $^{5\cdot 21}$.

For a fade on the down-path due to rain, two effects cause the system to degrade. The first is an attenuation of the rf carrier and the second is an increase in the receiver noise temperature caused from rain or cloud absorption. These two effects can be expressed as follows:

$$\left(\frac{C}{N}\right)_T = \frac{C/\ell}{\frac{N_U}{\ell} + N_D + N_R}$$

where ℓ = rain or cloud attenuation on the down-link

N_U = up-path noise

N_D = down-path noise

N_R = rain or cloud noise.

Figures 5-13 through 5-15 show the total degradation due to down-path fading for two types of receiving earth station, specifically an uncooled parametric amplifier in Figures 5-13 and 5-14, and a tunnel diode amplifier in Figure 5-15.

Assuming that the up-path fading is uncorrelated with down-path fading, the two effects were added on a percentage time basis to obtain the total system degradation for the two types of earth station receivers. Figures 5-13 and 5-14 are curves for an uncooled parametric receiver with 5-13 representing the condition of up-path carrier-to-noise 10 dB higher than the down-path carrier-to-noise during fair weather. Figure 5-14 is the same except that the up-path carrier-to-noise is set at 6 dB better than the down-path carrier-to-noise during fair weather conditions. Figure 5-15 shows the total link degradation for a TDA type of receiver.

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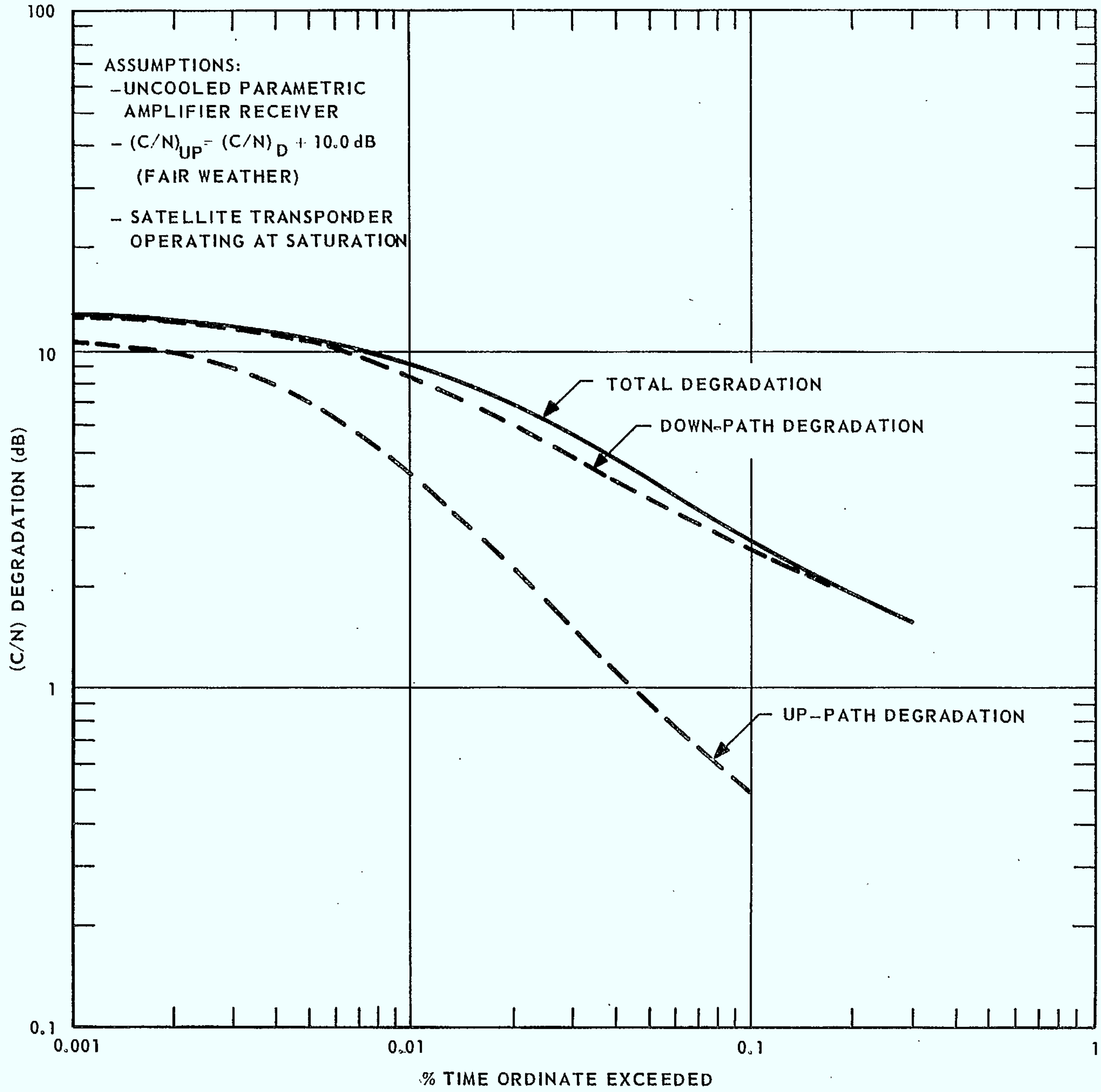

Figure 5-13 System Degradation for Rain and Cloud
(see Assumptions)

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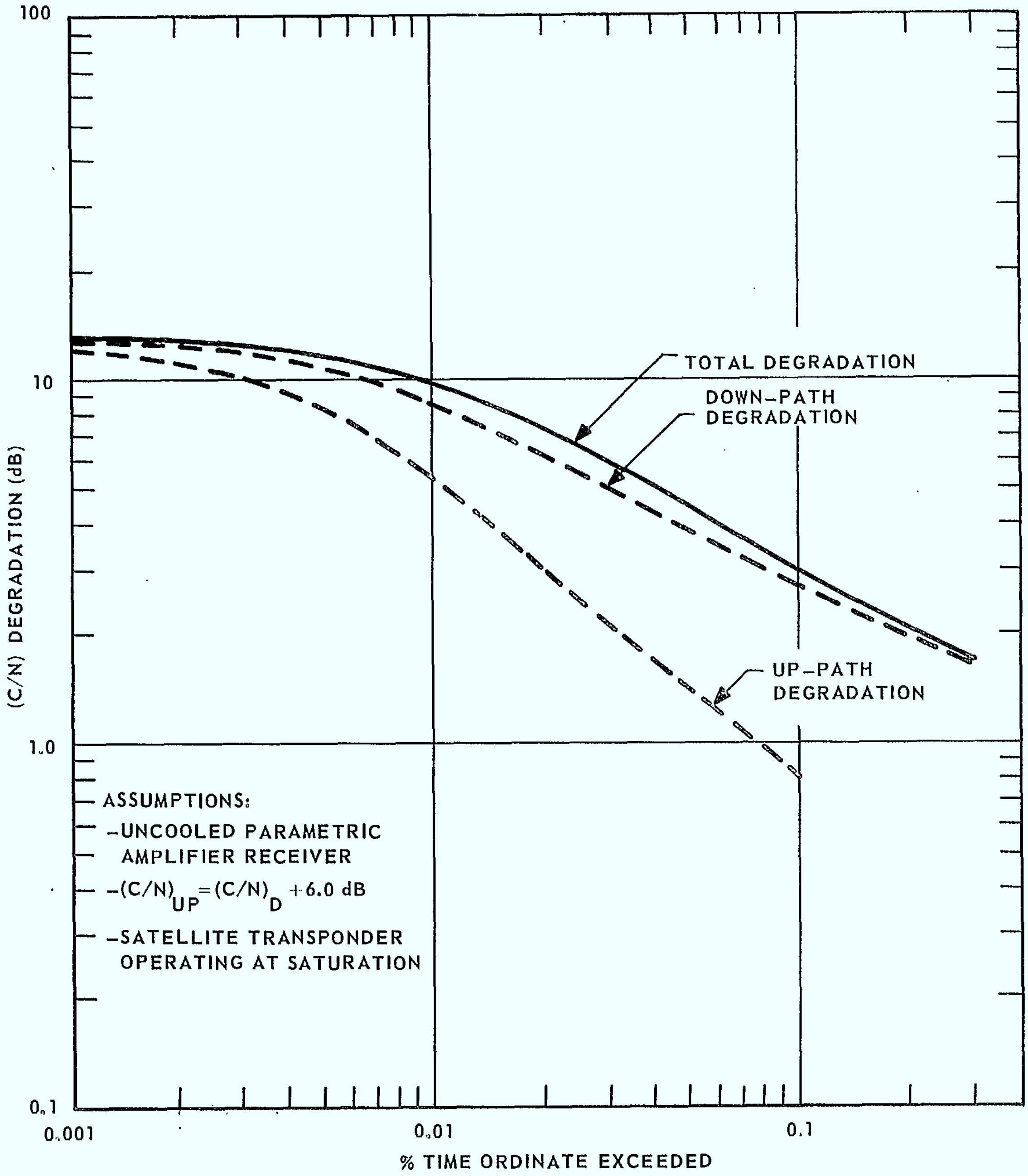

Figure 5-14 System Degradation for Rain and Cloud
(see Assumptions)

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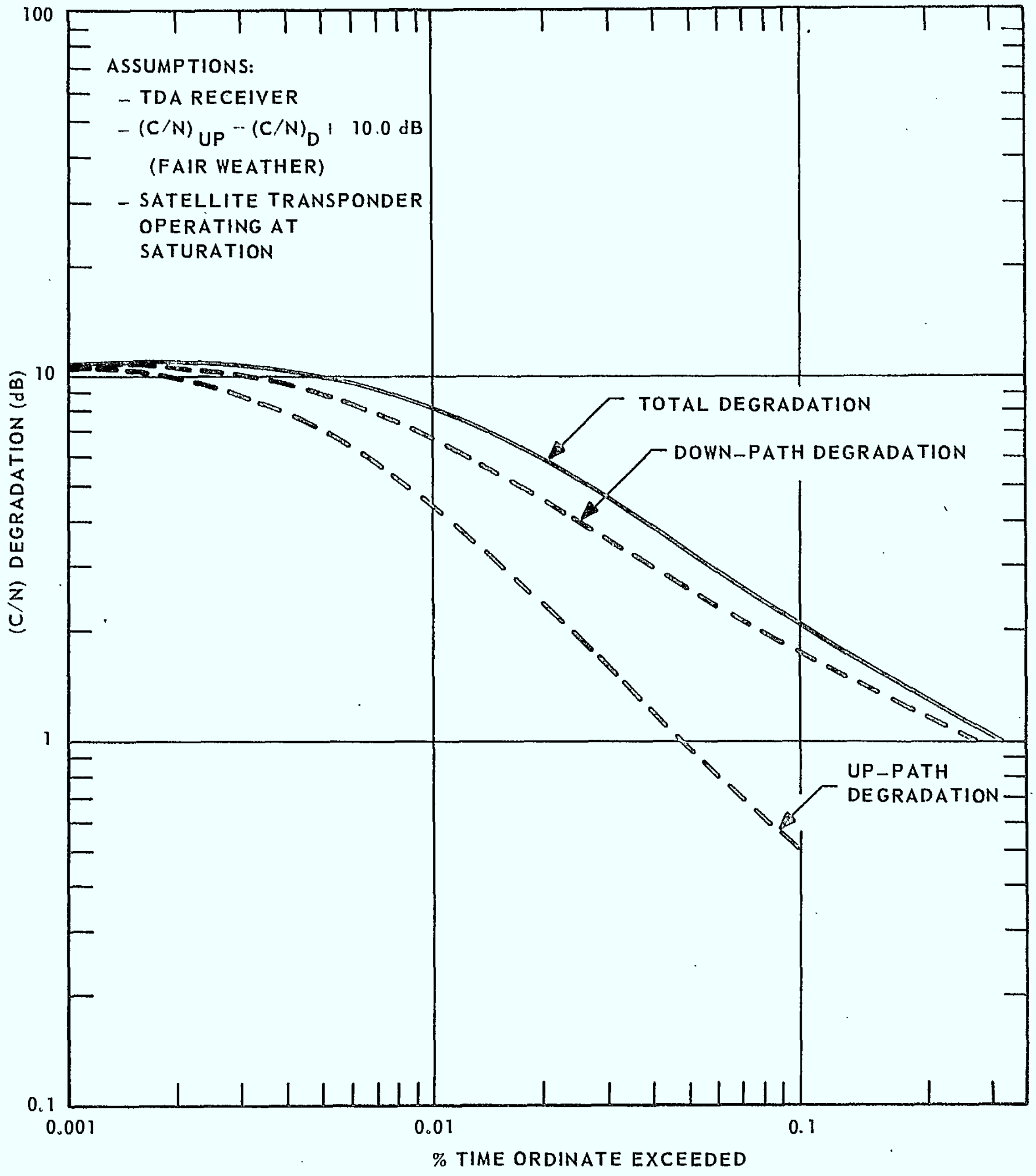

Figure 5-15 System Degradation for Rain and Cloud
(see Assumptions)

5.5.2 C/N VARIANCE FOR SYSTEMS OPERATING EAST-WEST IN LINEAR MODE

Curves of total system degradation versus percentage of time occurrence are developed for this mode of operation. Two types of earth stations are considered, specifically an uncooled parametric amplifier and a tunnel diode amplifier. Up-path fading is controlling.

This case pertains to FDMA and single-channel-per-carrier types of multiple access systems.

For these cases the total carrier-to-noise for the system during fair weather is given by

$$\left(\frac{C}{N}\right)_T = \frac{C}{N_U + N_D + N_I}$$

where C = carrier power
N_U = up-path noise
N_D = down-path noise
N_I = intermodulation noise.

Since it is assumed that the transponder is operating in the linear region, an up-path fade of L dB will cause a total system degradation given by:

$$\left(\frac{C}{N}\right)_T = \frac{C/l}{N_U + N_D + N_I} .$$

where $l = \text{Antilog}\left(\frac{L}{10}\right)$.

Therefore an up-path fade of L dB will cause a total systems degradation of L dB also.

For a fade of X dB on the down-path, the system degradation can be developed as follows:

$$\left(\frac{C}{N}\right)_T^{-1} = \left(\frac{C}{N_U}\right)^{-1} + \left(\frac{C}{N_I}\right)^{-1} + \left[\frac{C}{x(N_D + N_R)}\right]^{-1}$$

$$\therefore \left(\frac{C}{N}\right)_T = \frac{C}{N_U + N_I + x(N_D + N_R)} \quad \text{(for X dB fade)}$$

where N_U = up-path noise

N_I = intermodulation noise contributed by satellite transponder

N_D = down-path noise (fair weather)

N_R = increase in noise temperature due to rain and cloud absorption on down-path

x = down-path fade (numerical value) = Antilog $(\frac{X}{10})$.

Therefore the change in the system carrier-to-noise is given by:

$$\Delta\left(\frac{C}{N}\right)_T = \left[\frac{C}{N_U + N_I + N_D}\right] \Big/ \left[\frac{C}{N_U + N_I + x(N_D + N_R)}\right]$$

$$\Delta\left(\frac{C}{N}\right)_T = \frac{N_U + N_I + x(N_D + N_R)}{N_U + N_I + N_D} .$$

Figures 5-16 and 5-17 give the cumulative system degradation due to up-path and down-path fades due to rain and clouds for the linear system operation. The total degradation due to up-path and down-path degradation is arrived at based on the assumption that the fades on the two paths are independent. Figure 5-16 is the case for an uncooled parametric amplifier receiver and Figure 5-17 is for a tunnel diode amplifier receiver. As can be seen, there is little difference in system degradation between the two curves since in both cases the up-path fading is the controlling factor.

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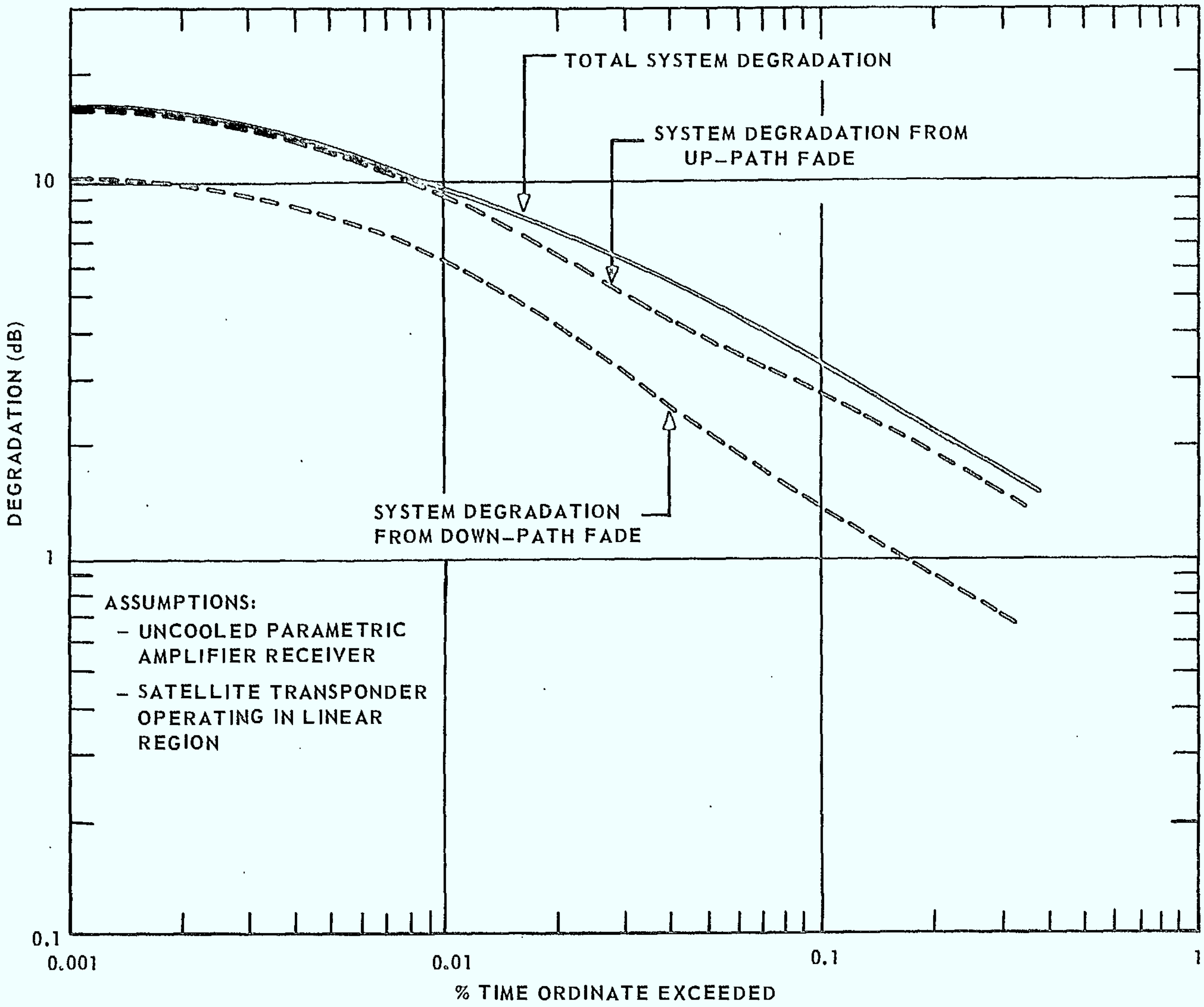

Figure 5-16 Cumulative System Degradation for Rain and Cloud (see Assumptions)

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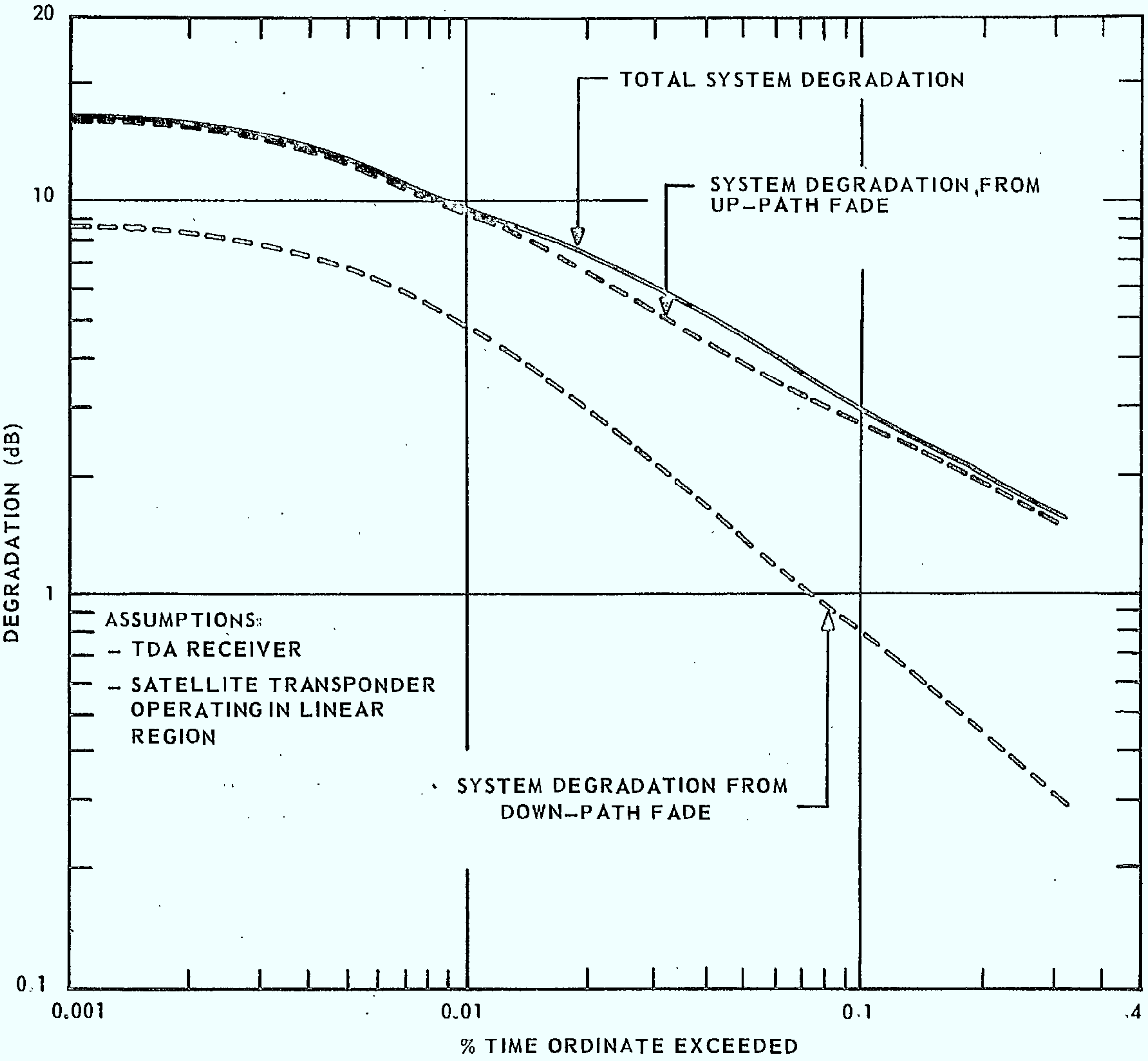

Figure 5-17 Cumulative System Degradation for Rain and Cloud (see Assumptions)

5.5.3 SYSTEM C/N VARIANCE FOR NORTH-SOUTH LINKS

Both the saturation and linear modes of operation for North-South links are considered, and it is seen that in all cases tropospheric fading controls the C/N degradation. Graphs of C/N variance for two elevation angles are presented for each case.

Up to the present, only rain and cloud attenuation has been analyzed for the southern communication links. For the North/South links, the tropospheric effects must be included in the system margins.

Figure 5-18 shows curves of up-link fading in the South due to rain and clouds (15 GHz) and corresponding down-link fading due to tropospheric effects in the North (12 GHz) and at an elevation angle of 4° through 5°. The two curves are combined on the basis of the two effects being independent. The curves are based on a system operating in the linear region of the transponder gain characteristics. Figure 5-19 is the same except that the up-link fading is due to tropospheric fading and the down-link fading is due to rain and cloud in the South. As can be seen, this case presents the worst total degradation of the two curves with the tropospheric fading on the up-link controlling the total system degradation.

Figure 5-20 is similar to Figures 5-18 and 5-19, except it gives the system margins required for earth stations in the North operating at 20° elevation angle. Since the tropospheric fading is less severe than at 5°, the system margins required are less than in the first case.

Figures 5-21 and 5-22 are curves giving system degradations for North-South links for the case of a satellite transponder operating at saturation corresponding to television and TDMA systems. For a North-South system operating in this mode, the South to North direction is more severely affected than the reverse direction, with tropospheric fading controlling the total system degradation.

Figure 5-23 is similar to Figures 5-21 and 5-22 except that it is for the case of northern stations operating at a 20° elevation angle. The required margins for this case is less than for earth stations operating at 5° elevation angle in the North since tropospheric fading is less severe.

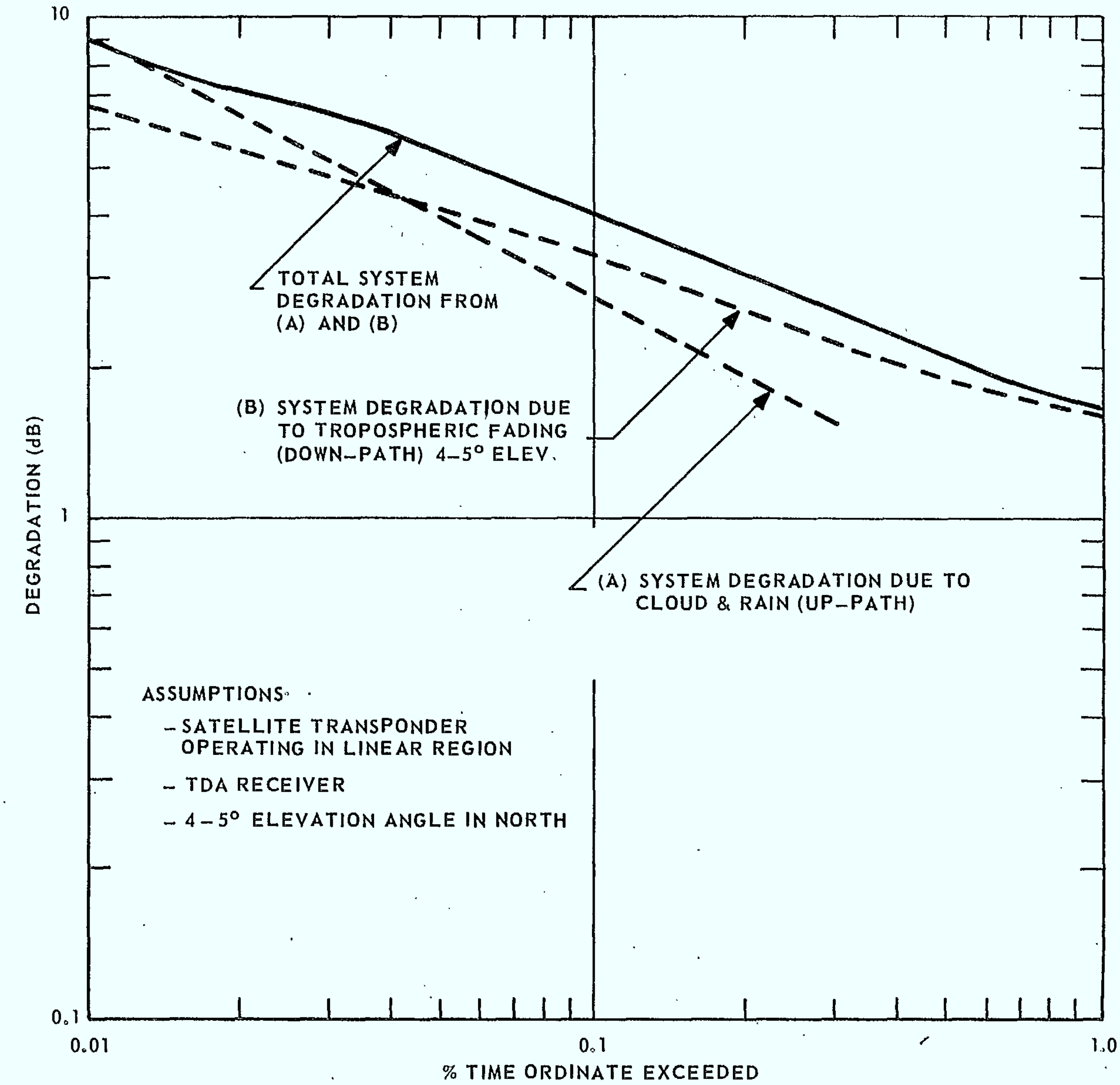

Figure 5-18 Cumulative System Degradation for Rain and Cloud (Up-path) and Tropospheric Fading (Down-path) - Linear System

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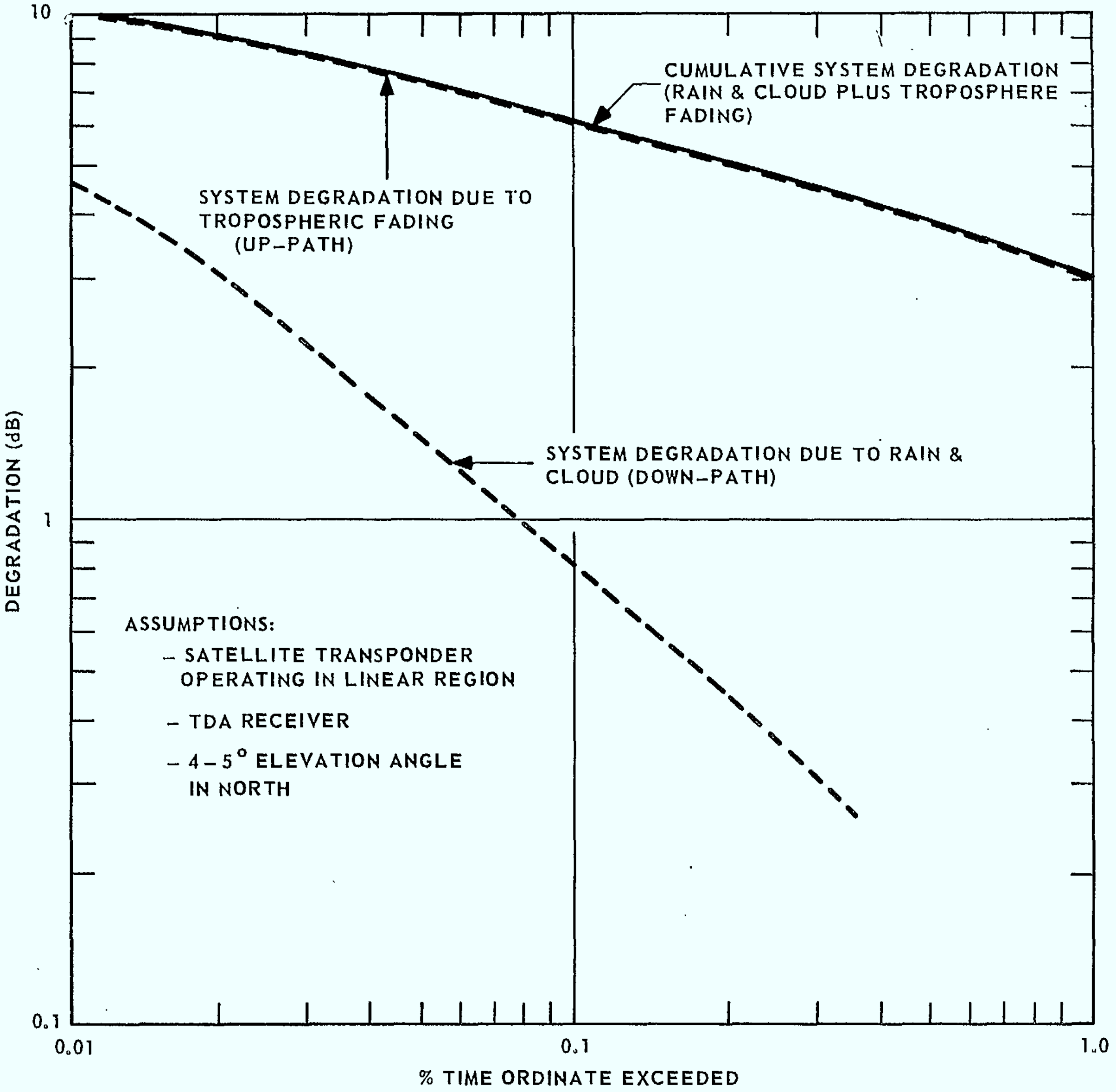

Figure 5-19 Cumulative System Degradation for Rain and Cloud (Down-path) and Tropospheric Fading (Up-path) - 5° Elevation Angle

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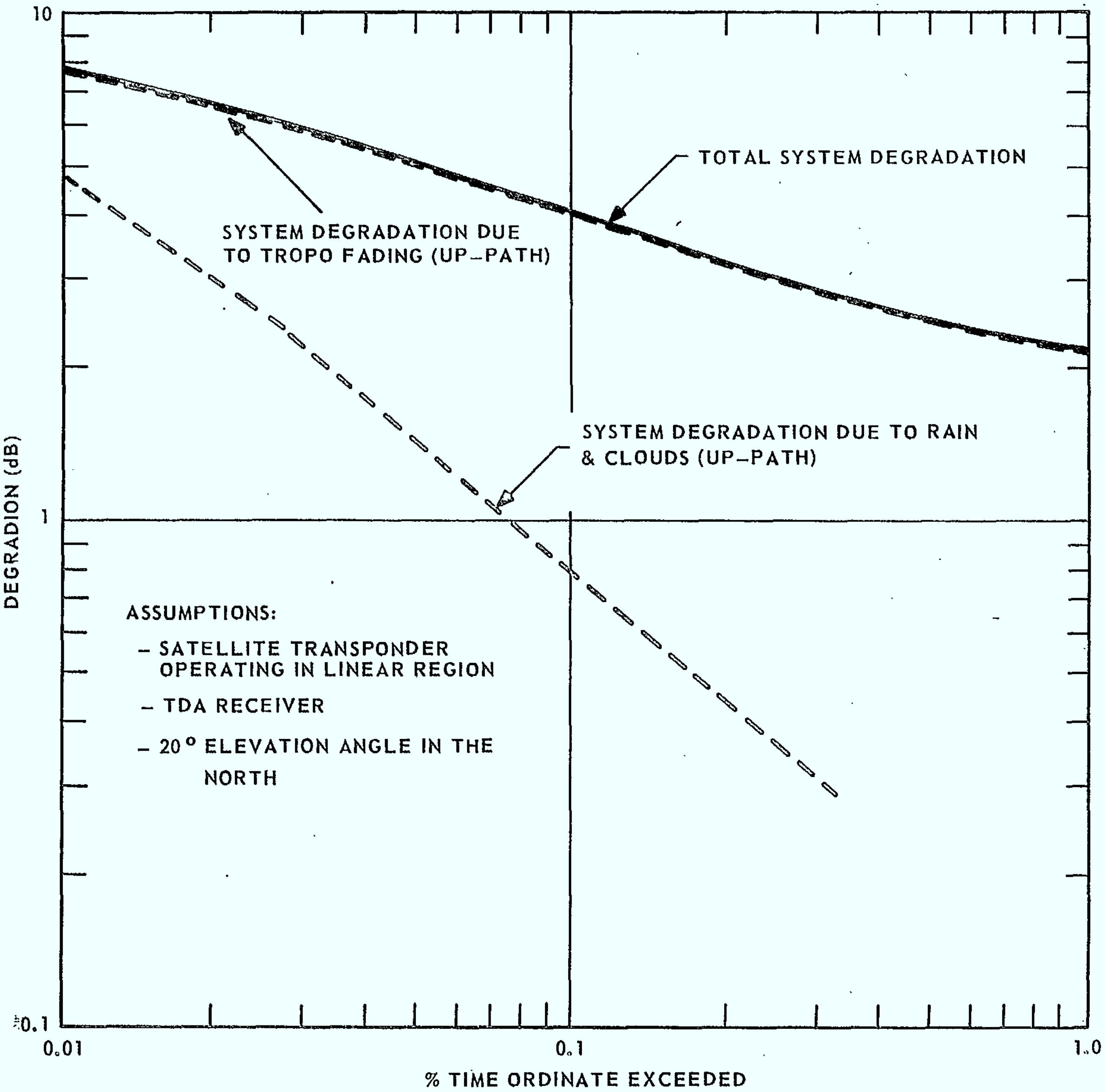

Figure 5-20 Cumulative System Degradation for Rain and Cloud (Down-path) and Tropospheric Fading (Up-path) - 20° Elevation Angle

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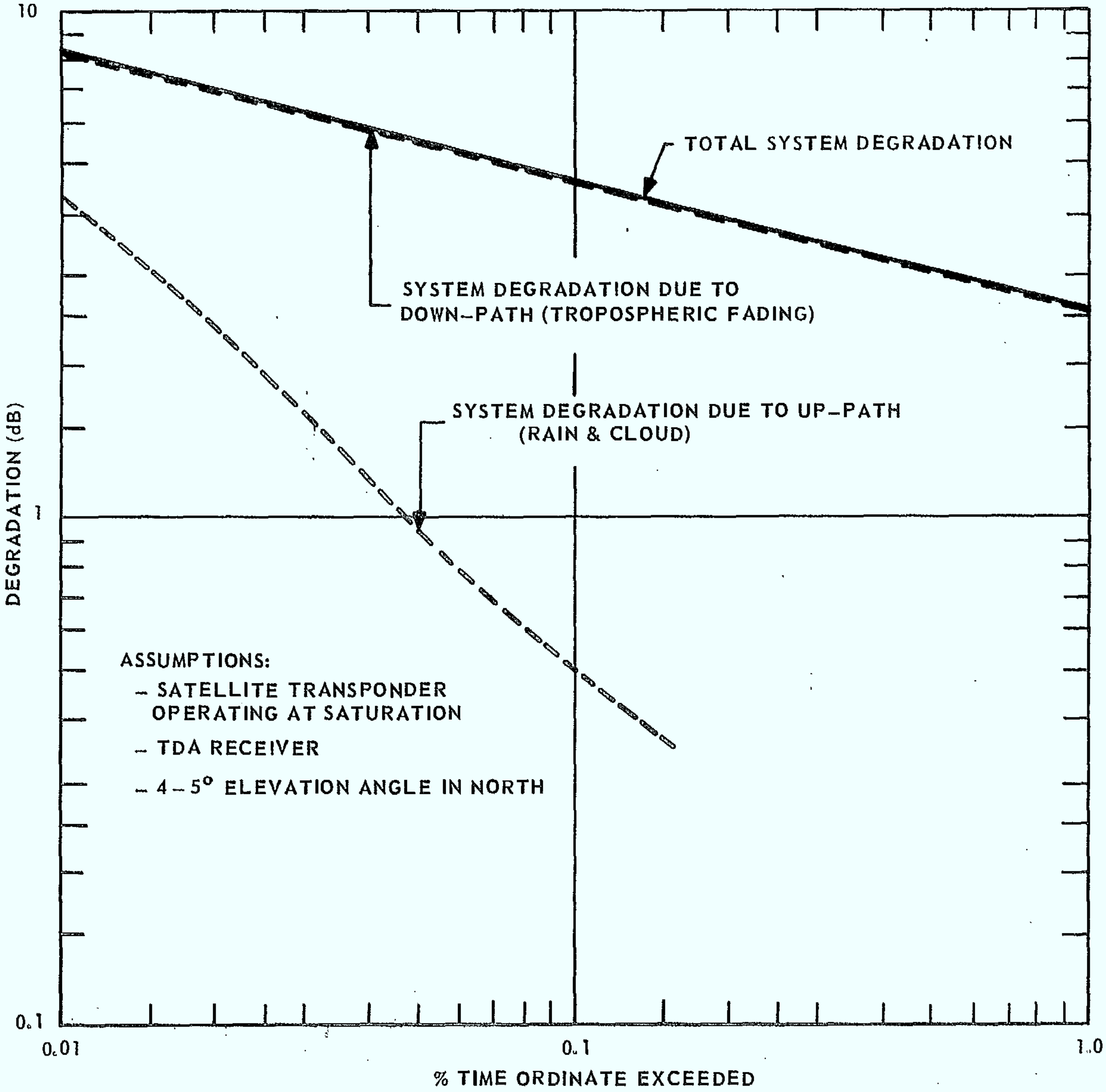

Figure 5-21 Cumulative System Degradation for Rain and Cloud (Up-path) and Tropospheric Fading (Down-path) - 5° Elevation Angle

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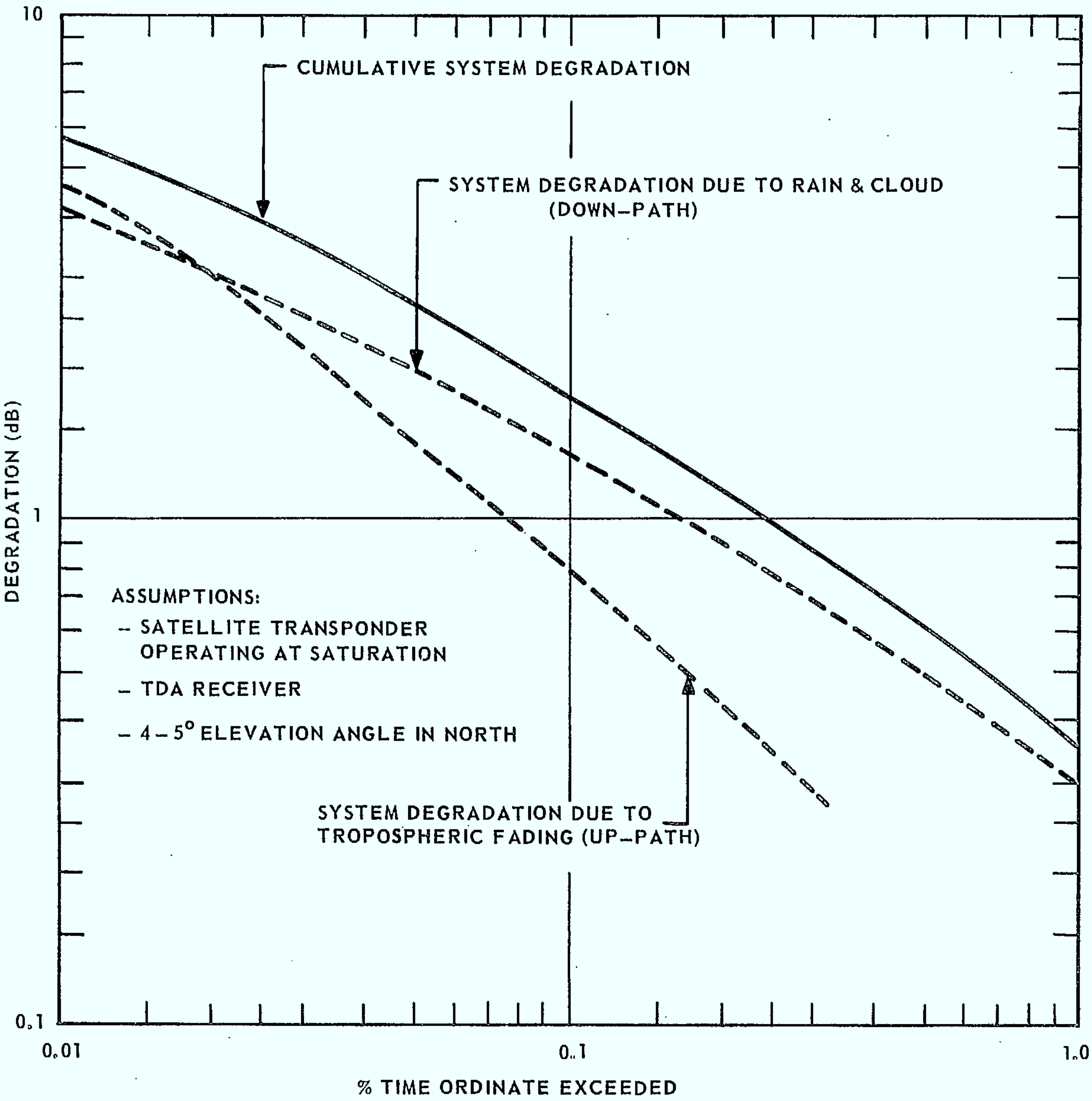

Figure 5-22 Cumulative System Degradation for Rain and Cloud (Down-path) and Tropospheric Fading (Up-path) - 5° Elevation Angle

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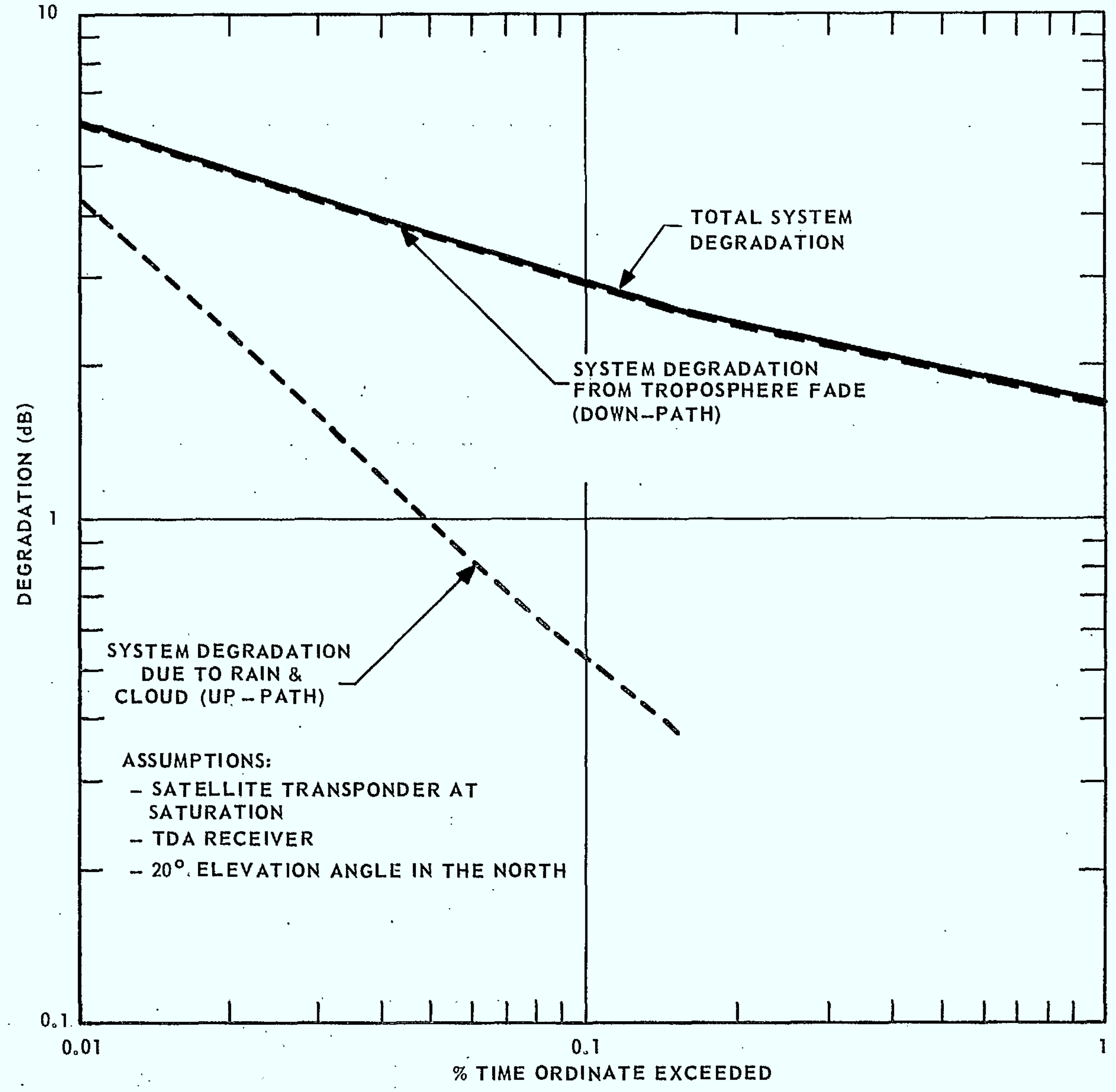

Figure 5-23 Cumulative System Degradation for Rain and Cloud (Up-path) and Tropospheric Fading (Down-path) - 20° Elevation Angle

5.6 SYSTEMS MARGIN SUMMARY

The recommended systems margins used in later chapters of this study are presented in two tables.

Various satellite system models were considered in 5, and the estimated system margins for these various models were obtained based on rain, cloud and tropospheric fading effects. These margins are summarized below for given percentages of the time.

Table 5-13 Margins Required for East-West Communication Links

TYPE OF SYSTEM	SYSTEM FADING† (dB) FOR GIVEN % OF TIME		
	99.999%	99.99%	99.9%
1. Satellite Transponder Operating in Linear Region			
a) TDA Receiver	16.0	9.5	3.0
b) Uncooled Parametric Amp. Rec.	16.0	9.7	3.3
2. Satellite Transponder Operating at Saturation			
a) TDA Receiver	11.0	8.0	2.0
b) Uncooled Parametric Amp. Rec.	13.0	9.0	2.0

NOTE:

† This is based on limited data and the percentage of time is considered applicable for periods of the order of one month. Long term data are not yet available.

Table 5-14 Margins Required for North/South Links *

TYPE OF SYSTEM	SYSTEM FADING† (dB) FOR GIVEN % OF TIME		
	99.99%	99.9%	99%
1. Satellite Transponder Operating in Linear Region (FM/FDMA Systems)			
a) 4° - 5° Elevation Angle in the North	10.5	6.0	3.0
b) 20° Elevation Angle in the North	7.6	4.7	2.2
2. Satellite Transponder Operating at Saturation (Television, TDMA)			
a) 4° - 5° Elevation Angle in the North	8.4	4.6	2.6
b) 20° Elevation Angle in the North	6.0	3.0	1.7

Other effects of rain on the signal such as reduction in polarization discrimination and bandwidth coherence are expected to be negligible at the frequencies and bandwidths being considered.

NOTES:

*Margin calculations were also performed for North/North links and it was concluded that the margins presented in Table 5-14 are equally applicable.

†This is based on limited data and the percentage of time is considered applicable for periods of the order of one month. Long term data are not yet available.

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6. Available Technology

6.1 Satellite Technology and Configuration

6.1.1 GENERAL DISCUSSION

For the implementation of a system in the 1977 through 1985 time frame improvements in satellite hardware design will result in less expensive, larger capacity, more reliable satellites which will result in more efficient use of launch vehicle capabilities and available frequency spectrum, and hence reduce unit transmission costs from present-day levels.

In order to reduce the cost and increase the efficiency of communications satellite systems improvements in satellite technology are continuously being made. This is evidenced by reference to Table 6-1, which shows the evolution of satellites launched by Intelsat since 1965. Information concerning proposed models for an Intelsat V satellite for launch around 1978 indicates that the 12 through 15 GHz bands will be used (among others) and the satellite will make use of technology discussed in this report.

Investigation of the trends in communications satellite systems shows that multi-service satellites are generally preferred over those dedicated to any one particular type of communications service. The reasons for this general preference are as follows. Economically, as multi-service satellites are larger their unit transmission costs are lower than those of physically smaller single-purpose satellites. Co-located earth stations, requiring a number of types of services can share the costs of common facilities, thus lowering earth segment costs. Technically, among other factors, orbit and spectrum utilization is improved thus conserving limited natural resources. Socially, some services which may be inherently non-economic but which may be essential for achieving national or social goals can be provided on a marginal costing philosophy.

There is also a trend towards satellites operating simultaneously in more than one frequency band. Because of the multi-service requirement antenna beams of different sizes ranging from earth coverage to spot beams (perhaps less than half-a-degree in diameter) are being proposed. Coupled with the use of spot beams is the re-use of the available frequency spectrum, which in turn increases spacecraft size and capacity, thus driving down unit costs. In this respect satellite communications medium is following the trend in terrestrial systems where unit transmission costs are being driven down by increasing system capacity[6.1]. This increase in traffic carried by the Intelsat system arises from the prior deployment of the high capacity satellites which tends to generate an increase in traffic.

The advanced technology which may be considered for use during the 1977 through 1985 time period is briefly discussed in the following sections. Some of this technology is available now, but in some areas additional research and development effort will be required. The use of body stabilization methods and improvement in the reliability of spacecraft components will increase the operational lifetime of future communications satellites, For a 1977 launch it is not unreasonable to predict a spacecraft lifetime of ten years.

Table 6-1 Intelsat Series of Satellites

PARAMETER	I	II	III	IV
Launch Dates	1965	1966-67	1968-69	1971-73
Circuit Capacity	240	240	1200	6000
Design Life, Year	1.5	3	5	7
Frequency, GHz	4 & 6	4 & 6	4 & 6	4 & 6
Diameter, ft.	2.4	4.7	4.7	8.9
Height, ft.	1.9	2.2	3.4	18
Weight, lb.	85	190	322	1250
DC Power, W	33	75	125	550
Antenna Beam, deg.	11 × 360	12 × 360	20 × 20	17 × 17 & 4.5 × 4.5
Transponders	1	1	2	12
Bandwidth*, MHz	25	130	225	36
EIRP*, W	10	35	150	200**

* Per transponder

** Using global (17°) beam antenna.

6.1.2 SATELLITE ANTENNAS

A review of the trends in communications satellite systems has identified a future requirement for satellites with multiple narrow beams directed towards centers of high traffic density, with provision for the switching of channels between beams to enhance system flexibility.

While future communications satellites will continue to make use of the inherent advantage of wide and simultaneous geographical coverage for certain services, a number of advantages accrue from the use of numerous narrow beams which may be directed towards centers of high traffic density. Among the major advantages is the increased EIRP available due to increased antenna gain, which results in increased beam capacity and/or reduced earth station G/T. The achievable EIRP per beam, however, may be subject to flux density limitations. The geographical separation between beams will result in more efficient use of the available frequency spectrum. For example, a satellite which re-uses the 4 through 6 GHz band eight times has recently been proposed.

In the past, most communications satellites have used parabolic reflector type antennas because of the electrical simplicity and light weight of this approach. This method has limitations when considering narrow beams because of launch vehicle volume requirements and the generation of a large number of beams by one reflector presenting mechanical problems of feed location, especially at higher frequencies.

Because volume and weight will continue to be a problem, alternative methods of generating multiple narrow beams must be found. There are a number of potential methods of generating multiple narrow beams which are under active investigation. Among these methods, those receiving most attention are parabolic reflectors with offset feed matrices, lens-type antennas and phased arrays in conjunction with switching matrices for the interconnection of beams in the TDMA mode. This would apply in the case of high-capacity beams directed towards centers of high traffic density. The required on-board signal processing would increase system flexibility, but would also increase spacecraft weight. Other methods may find application in certain situations such as multiple unfurlable reflectors which can overcome some of the launch vehicle volume problems. This method, however, increases mechanical complexity and weight. It is also desirable to provide beam steering by electronic means because mechanical gimbaling systems comprise a large proportion of antenna weight.

For the coverage of larger geographical areas for distribution and similar services parabolic-type antennas may continue to be the most suitable, especially in the 12 through 15 GHz band where space reflector sizes are relatively small. With the advent of three-axis stabilized satellites these reflectors may be mounted flat on the earth-facing side of the spacecraft, thus reducing structure weight by the simplification of support structure and also decreasing the impact of launch vehicle volume constraints.

Because of the relatively small number of beams required to fulfill the forecast needs in this study multiple-feed parabolic antennas are suggested. This is due to their light weight and because they have the highest probability of successful development and implementation in the time frame under consideration.

6.1.3 POWER SUBSYSTEM

The specific power ratio of the satellite power subsystem will be increased beyond that attainable with spinning spacecraft by the use of sun-oriented solar arrays for the generation of prime power and the use of rechargeable hydrogen-oxygen fuel cells for power storage.

The power subsystem of a communications satellite is required to provide the prime power necessary to drive the communications transponders as well as the housekeeping subsystems. The weight of a major part of the power subsystem is therefore proportional to the total rf transmit power requirements of the satellite. The total power subsystem weight is also dependent, to a lesser extent, upon the requirements of the housekeeping subsystems. Because it is one of the heaviest subsystems of the satellite, considerable emphasis is being placed upon investigation of methods of improving the power-weight relationship, which is generally referred to as the specific power ratio and expressed in watts of power obtained from 1 pound of satellite hardware deployed.

In the past, the source of prime power has been solar cells and this will continue to be the most attractive approach, at least up until 1985. An alternative to this approach would be nuclear power, but safety problems will most likely hamper its early introduction. Up until the present time commercial communications satellites have been of the spin-stabilized type with the solar cells mounted on the outer cylindrical surface. Under these conditions the conversion efficiency of solar energy into electrical energy is reduced because all the cells do not maintain sun-orientation. Significant improvements may be achieved if the solar cells could be continuously sun-oriented. This is most economically implemented in three-axis stabilized spacecraft where large, deployable arrays can easily be maintained in a sun-oriented position by suitable control mechanisms.

The most promising form of solar array which will be suitable for use on a communications satellite in the 1977 through 1985 time period is the flexible roll-up array (FRUSA) currently under development.* Figure 6-1 shows the range of specific power which can be achieved.

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* JPL Contract 952314 "30 Watts Per Pound Roll-Up Solar Array" Hughes Aircraft Company Contract F33615-68-C-1676 to U.S. Air Force. Lockheed Contract to NASA/MSC. Technical feasibility of 10,000 square foot solar array for NASA 12-man Space Station.

Another major requirement of synchronous communications satellites is the storage of power to operate the communications and other subsystems during eclipse periods. At the present time the main source of power storage is nickel cadmium batteries. As spacecraft weight will always be at a premium, any possibility of increasing the power/weight efficiency of a component is an obvious requirement. At the present time nickel cadmium batteries are able to produce storage of power in the order of 7 watt hours per pound weight. A promising weight effective alternative to the nickel cadmium battery is the rechargeable hydro-gen oxygen fuel cell. Experimental models of such storage devices have shown that figures of merit of the order of 15 watt-hours per pound are easily achieved[6.2]. Investigation of hydrogen-oxygen fuel cell technology is being undertaken as part of Intelsat funded research by Comsat Laboratories. A contract for the development has been let to Xerox Corporation and is currently in progress[6.3]. Because of the development programs currently in progress for roll-up solar arrays and hydrogen-oxygen fuel cells it is highly likely that this technology will be available for deployment in 1977.

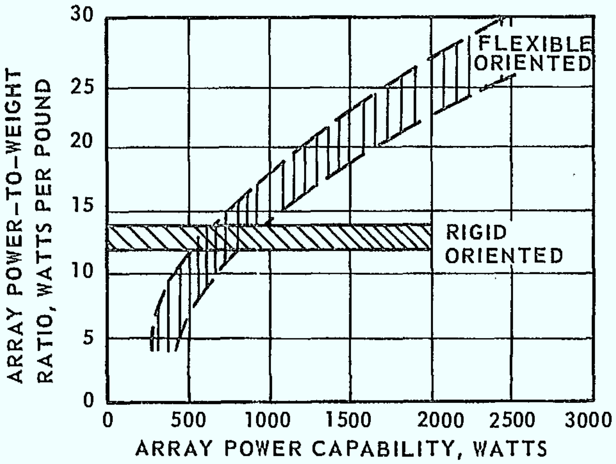

Figure 6-1 Solar Array Power Capability

Other improvements in the power subsystem specific power will result from the use of thinner cover glass for the solar cells (although this must be considered in relation to the cell lifetime) and the reduction of weight and power loss by the use of liquid metal slip rings.

Figure 6-2 shows the improvements possible using these new concepts for the prime power source. For the trade-off calculations of this study a figure of 10 watts per pound has been used as an estimate of the total power subsystem specific power (regulated power delivered to the subsystems). This is a realistic estimate for deployable hardware (including batteries for eclipse operation) for the 1975-1977 time frame because it is common for an implementation margin to exist between the development of a new technology and the time when its deployment fully meets its forecast potential.

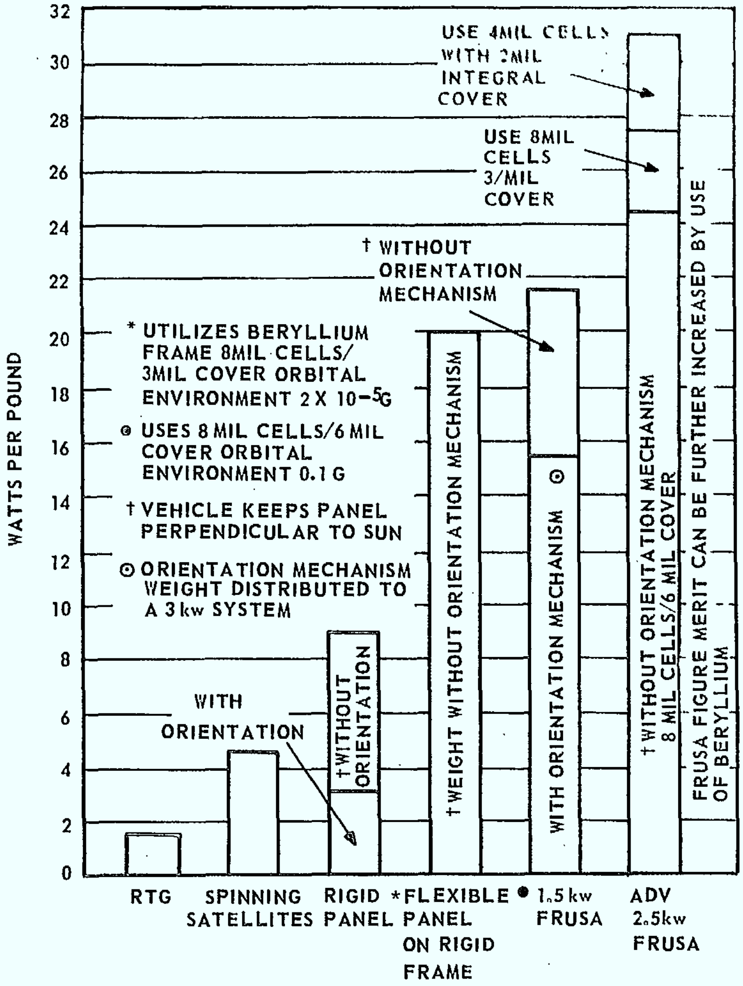

*Figure 6-2 Prime Power Sources Figure of Merit Comparison

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* Figures 6-1 and 6-2 extracted from G. Wolff; "Oriented Flexible Rolled-Up Solar Array," AIAA 3rd Communications Satellite Systems Conference, L.A., California, 6-8 April, 1970.

6.1.4 COMMUNICATIONS SUBSYSTEM

The trends in communications satellites indicate that the communications subsystem will increase in complexity and will become more reliable with the advent of solid state devices for power generation and amplification. It will use an increasing amount of solid state techniques and stripline technology, but TWT amplifiers will continue to be used in the 12 through 15 GHz band for some time.

Having taken account of the increased efficiency of communications satellites resulting from improvements in the available technology for power subsystems, other methods of further improving the capacity of the communications medium must be investigated. In general terms, the major objective is to provide the most economical communications systems possible within the constraints of the available technology and limited natural resources. The only way to achieve this end is to maximize the communications capacity which may be launched by a chosen launch vehicle.

One trend already established is to move to higher frequency bands where higher capacity may be achieved by the use of higher EIRP obtained by using narrow beams directed to locations with high message traffic density. Also, in order to make maximum use of the capacity of a satellite the ability to switch this capacity from link to link in the network is a desirable feature, and this leads to the requirement of switching matrixes in the satellite for the interconnection of the various beams. In the medium term the requirement will be for the interconnection of beams at intermediate frequencies. In the larger term the requirement may be for the switching of individual bit streams or messages in the TDMA mode. For message and data services the trend appears to be towards digital modulation techniques. For systems to be deployed in the time frame 1977 through 1985 PCM-CPSK appears to have the greatest probability of success although other more efficient modulation schemes using combinations of phase, amplitude and frequency modulation are currently being studied.

Regarding single conversion versus double conversion the trend appears to be towards single conversion whenever possible to increase reliability. However, for applications where cross-strapping between frequency bands is required, double conversion would be used. Double conversion would also be required in the 19 through 30 GHz bands in order to achieve the required gain. As the frequencies considered by this study are confined to the 12 through 15 GHz bands there is no justification for proposing double conversion.

A further increase in satellite communications capacity can be obtained by re-use of the available frequency band and this is feasible in the 12 through 15 GHz band although its introduction will increase system complexity and cost. Initially, re-use of the frequency band by cross-polarization or geographical separation of beams has not been considered as a desirable feature for a system for Canada in the time period covered by this study because these measures are not justified by the service demands of chapter 2.

The availability of power amplifiers is an important factor which will effect the capacity of future satellites. In the frequency band under consideration solid state amplifiers are not considered suitable for use in the 1977 through 1985 time period mainly because devices with sufficient power capability will likely not be well proven. At the present time, emphasis is being placed on the development of high power travelling wave tubes, mainly for direct broadcast needs, with efficiencies greater than 50 percent. As transponder bandwidths will continue to be relatively modest, in the 12 through 15 GHz band and above, the klystron is a potentially useful device for this application although it requires high supply voltages which will probably impose penalties on power subsystem design. The use of high-power wide-bandwidth transponders is not considered appropriate because, if such transponders were used for the multiple access of a large number of carriers, back-off would be required, hence defeating the objective of a high-power tube. Also if such transponders were used for individual services the increased weight requirements would restrict the number of services which could be carried on a particular satellite. This becomes clear from the results of the system optimization discussed later, in chapters 9 and 10 of this report. However, there may be advantages for direct broadcasting and non-communications type services to be gained from the use of such transponders and further study would be worthwhile. Investigations indicate that for modest amounts of rf power travelling wave tubes will be readily available in the 1977 through 1985 time period, although modest amounts of development effort may be required in certain cases.

Regarding the specific availability of travelling wave tubes the Hughes Aircraft Company 20-watt Skylab tube (851-H) will be commercially available for deployment before 1977. The Hughes 274-H is a 5-watt tube which is also commercially available. Tubes covering the power range 5 to 10 watts can be made available with the expenditure of small amounts of development funds due mainly to optimization of tube parameters and re-organization of tube mechanical fixtures. Doubtless by 1975 to 1977 other sources will also be available.

Because of the desirability for flexible communications the trend towards a common type of transponder has been established even for satellites shared by a number of different services. This will have the effect of reducing satellite development costs, but may result in an increase of system annual charges. This approach also enables equalization of forecast demand variance for individual services.

In the foreseeable future, therefore, transponder configuration will be similar to that of Intelsat IV, except where cross-strapping between bands requires the use of double conversion techniques. Switching matrices for the interconnection of beams will be a requirement of satellites, requiring the rapid re-routing of message traffic between a large number of high density traffic sources and sinks.

A major contribution to weight in the communications subsystem, especially when using channelized transponders, is due to microwave filters. Recent advances in this area have reduced the weight of filters considerably by choice of light weight material, improved manufacturing techniques and electrical design. Still further improvement could be achieved by the use of stripline techniques although this technology may be confined to low power applications, such as input multiplex filters, until power handling capability can be improved. Radio-frequency shielding considerations in the confined volume of satellites are likely to prevent the full potential of this approach to be realized. Yet the partial achievement of the potential will enable some reduction in weight to be achieved in near-future designs. This is an area where further study is required before the full advantage of this technology can be realized.

* * *

6.1.5 OTHER SUBSYSTEMS

The housekeeping subsystems of the spacecraft play a supporting role to the EIRP-producing subsystems and, as such, their weight and volume should be minimized in order to maximize the communications capability. This may be achieved by selecting the best available technology in keeping with the system reliability and lifetime requirements.

With the experience gained so far in the implementation of synchronous communications satellite systems the technology for the housekeeping functions is well established, especially in the case of spin-stabilized spacecraft. The subsystems referred to here as housekeeping subsystems are those whose function is to support the mission subsystems, and they may be broadly classified as follows:

Structure

Thermal Control

Station Keeping

Attitude Control

Telemetry and Command

In most designs so far implemented and proposed, these subsystems constitute approximately half of the spacecraft weight. Hence any new technology which will reduce the weight of any of them while maintaining or improving their performance is worthy of consideration. In the present study the detailed design of satellites is not called for nor has it been allowed for in the resource allocation. The major trends in satellite housekeeping subsystem design have been examined and are discussed below as far as they can be identified.

(a) Structure

The major changes in structure will result from the advent of body-stabilized spacecraft. In the past, stabilization was achieved by spinning all or part of the body of the spacecraft with the result that a cylindrical shape was necessary. The torques resulting from this spin technique increased the structural requirements and necessitated great attention to the layout of components. Another major disadvantage of spinning spacecraft was the requirement for rotary waveguide joints which introduced additional rf losses and were heavy and unreliable. With body stabilized spacecraft the structure may be made static and rectangular, hence improving the packing density of components and subsystems. As one face of the spacecraft is continuously earth-pointing, antennas may be mounted directly on this face, if desired, which will reduce the structure weight and overall volume of the spacecraft.

(b) Thermal Control

With spinning spacecraft the solar heat was evenly distributed around the perimeter of the cylinder whereas with body stabilized spacecraft of rectangular shape one side of the spacecraft will always receive more solar heat than the others. This will therefore require a change in the techniques for thermal control. Some of the techniques which may be used include thermostatically-controlled louvers to modulate the rate of heat radiation, and heat pipes to conduct heat away from hot spots. Super-insulation material will be used to cover most exposed areas of the spacecraft structure and thermal conducting materials will continue to be used to improve conductivity between heat-dissipating components.

(c) Station Keeping

Historically, station keeping has been achieved by the controlled operation of hydrazine thrusters and this technology is now well established. One of the disadvantages of this method is the fact that fuel must be carried into orbit in sufficient quantities to maintain the spacecraft on station throughout its lifetime. With improvements in spacecraft technology the lifetime is now controlled, not by the reliability of electronic or other components, but by the amount of station keeping fuel which may be carried. The introduction of three-axis stabilization techniques using momentum wheels may result in a higher fuel requirement because of the requirement to unload the momentum wheel whenever it approaches saturation.

The presence of this fuel constitutes a weight penalty and an alternative method of providing propulsion in a more efficient manner is desirable. Ion engine propulsion is a suitable alternative, especially in the case of long-life missions. Its main disadvantage lies in the requirement for high input power and, although the specific power of prime power sources will have reduced significantly by 1977, the weight advantages to be gained and other factors would require detailed further study before the use of ion engine propulsion could be recommended.

(d) Attitude Control

The major change which will take place in satellite technology will be the introduction of three-axis stabilization. The performance of such systems using momentum wheels has been demonstrated on relatively small satellites such as the NIMBUS and VELA programs. Larger systems are now being developed and will be used in the ATS F and G satellites. One of the major advantages resulting from the use of three-axis stabilization is the opportunity to use sun-oriented solar panels (which could also be used with spin-stabilized spacecraft with additional weight penalties) which greatly enhances the specific power of the power subsystems. While for high-capacity, high-power satellites three-axis stabilization appears to be mandatory, medium power satellites will follow suit to take advantage of the favourable specific power ratios.

In addition to the introduction of three-axis stabilization the use of improved sensing and control methods will allow attitude control accuracies as small as 0.05° to be achieved as compared with the 0.35° of the Intelsat IV satellite. However, unless very small antenna beam sizes are required there would be no reason to control the spacecraft attitude to better than 0.1°.

(e) Telemetry and Command

The telemetry and command subsystem is necessary for the monitoring and control of the various spacecraft functions. But, as it does not contribute directly to the spacecraft mission its weight and complexity should be no greater than absolutely necessary to perform its function reliably. The technology employed is now well established and no major breakthrough is foreseen for the 1977 through 1985 time period.

The improvements in the technology for the housekeeping subsystems could tend to decrease marginally the proportion of the total satellite weight devoted to them. However, the complexity and weight of these subsystems are closely related by laws of mechanics to the total weight, thus leaving a relatively constant proportion of the total satellite weight for the EIRP producing subsystems. Improvements in the latter will result in increase of total transmission capacity for any given total satellite weight.

* * *

6.2 SATELLITE WEIGHTS AND RADIO-FREQUENCY POWER

As the system optimization process is based on parametric trade-offs, it is vital to recognize and identify relationships between associated parameters. A predictable relationship exists between the total weight of a communications satellite and the weight of its EIRP producing subsystems.

There is a 'prime-facie' case to expect that a relationship exists between the total satellite weight and the total weight of its EIRP-producing subsystems.

A heavier satellite working with the same ground environment must provide larger capacity of services. This it does by producing more rf power over a fixed coverage area (determined by services) this produces an increase of EIRP. Thus for a satellite providing a given mix of the type of services over a given coverage area a variance in EIRP must be accompanied by a corresponding variance in weight.

The satellite subsystems can generally be divided, for a communications satellite, into mission subsystems (including their prime power sources) and the house-keeping subsystems. The most significant weight contributors among the latter are the structure and the station keeping subsystems followed by the Attitude control, Telemetry and command and Thermal control, which have a lower order of magnitude of weight. The structure is intended to support the weight of the satellite. It has also to support its own weight, and has to withstand the accelerations of launch without damage to the components and configurations it supports. As such the weight of the structure (assuming it is optimally designed) can be expected to bear a direct relationship to the total satellite weight. Similarly the impulse required to correct the drift of a satellite is directly proportional to its total weight, and the weight of the station keeping subsystem and associated fuel can be expected to bear a reasonably direct relationship to the total satellite weight. The attitude control stabilization subsystem also falls into the same category. The telemetry and command subsystem, and the thermal control necessary for the satellite are combined functions of the support subsystem and the mission subsystem complexity and weights. Sufficient to say that for a heaver satellite which produces more power, and hence has either larger and more complex amplifying devices or has a larger number of transponders, the associated TT&C subsystem and thermal control will be heavier. Fortunately also these two subsystems have a lower magnitude of weight compared to the structure and station keeping subsystems. Thus any direct correlation will only cause minimal variance. At this point it must also be noted that for any arbitrarily chosen satellite weight the sum of the mission and house-keeping subsystem weights must equal the total satellite weight. This implies that if a direct empirical correlation can be established between the house-keeping subsystem weights and the total weight a direct correlation exists between the mission subsystem weights and the house-keeping subsystem weights.

An examination of historic data shows that the proportion of the total weight of a communications satellite imputed to the communications subsystems had reached about 50 percent by 1968, having increased from about 40 percent achieved by the Syncom satellite (1962). Examination of current satellite proposals contained in the recent submissions to the FCC for United States Domestic Satellite Systems indicates that this figure of 50 percent is not likely to change for satellites proposed for 1973/74 deployment. Whereas it might be assumed that improvements in the technology in the house-keeping subsystems would tend to reduce the proportion of the total satellite weight imputed to them, simultaneous improvements in technology in the communications subsystems are counteracting this tendency. Because of this it is expected that the proportion of total satellite weight imputed to the communications subsystems will be about 50 percent for hardware to be deployed in 1977, and this has been confirmed as realistic by discussions with experts in the field during visits to COMSAT Laboratories, Bell Telephone Laboratories and NASA.

From a knowledge of the service requirements, satellite antenna coverage requirements and EIRP ranges required for the systems optimization, and from past experience in communications satellite transponder design the weights of the communications subsystem for the various services can be calculated. This leads directly to the total satellite weight by application of the predictable relationship between the house-keeping and communications subsystem weights. This method of satellite weight calculation is the only realistic method for use in an optimization study of this type. In the design of a satellite to given specifications the weights of the various subsystems would be calculated accurately. Because any change in the satellite specification would require detailed re-calculation of each subsystem weight this is not a realistic approach for a system trade-off study. It is however vital to subsystem or hardware optimization considerations.

In order to establish accurate relationships between the weights of the different subsystems a number of recent satellite proposals were examined and it was found that on the average the percentage weight allocations shown in Table 6-2 are realistic. The total satellite weight referred to is the on-station synchronous orbit weight at the beginning of life including station keeping fuel and spent apogee motor case, if any.

Table 6-2 Relationship of Satellite Subsystem Weights

SUBSYSTEM	PERCENTAGE OF TOTAL SPACECRAFT WEIGHT	SUBTOTALS %
Structure	20	
Thermal control	2	
Station keeping	22	
Attitude Control	3	
TT and C	4	
Power-housekeeping	1	52
Power-mission	19	
Communications	25	
Antennas	4	48
		100

The subsystems listed in Table 6-2 may be classified into two categories; the communications payload constitutes the spacecraft mission and may be referred to as the "mission subsystems", the remainder of the subsystems are required to support the mission subsystems and are commonly referred to as the housekeeping subsystems. The spacecraft power subsystems supplies the power requirements of the spacecraft as a whole and its weight is proportional to the total power requirement. This power requirement is in two parts, that power required for the housekeeping subsystems and that required for the communications subsystems. As the satellite total rf power varies, the housekeeping power requirement remains essentially constant. The power requirement for the communications subsystem however varies with the total satellite rf power. In order to isolate the variable portion of the satellite weight it is convenient to separate the housekeeping power requirements from the mission requirements.

From Table 6-2 it can be seen that the mission subsystems; namely, mission power, a communications, and antennas, constitute 48 percent of the spacecraft total weight which is in keeping with the previously established trend of about 50 percent. The procedure used to establish the satellite total weight is to estimate the weight of the mission subsystems as the satellite EIRP varies over the ranges required in the optimization process. In order to simplify the estimation process, it is convenient to isolate the variable weight of the mission subsystems from the fixed weights. In the mission subsystems there are certain items of hardware whose weight is constant as EIRP varies, such as the communications receivers and that portion of the power subsystem weight imputed to the power supplies for the housekeeping subsystems and to communications receivers. In addition, due to the unique service requirements, the antenna beams are fixed and hence the weight of the antenna subsystem will not vary with EIRP. These fixed weights of the mission subsystem may be calculated and lumped together with the fixed weight of the housekeeping subsystems, leaving the remaining weight, which includes travelling wave tubes and their power supplies, multiplex filters, and that portion of the power subsystem weight imputed to the supply of power for the transmitters. The effect of this reallocation of weights is to change the 48 percent weight relationship previously established by a small amount. This change is discussed in 6.2.1, but it should be noted that it differs from the previously established relationship for reasons unique to the present study, the 50 percent trend remaining valid for general application.

6.2.1 MISSION SUBSYSTEM WEIGHT

The mission subsystems are defined as the communications, power, and antenna subsystems and, in addition to contributing the greatest weight variations as EIRP changes, they also establish the total weight of the spacecraft.

The mission subsystems are the main contributors to weight variations as EIRP varies and, in order to establish a model for the calculation of their weight, an equation of the following form will be used:-

$$W_c = W_k + N_1W_1 + N_2W_2 + \ldots\ldots\ldots\ldots\ldots N_n W_n$$

where W_c = total mission subsystem weight

W_k = fixed mission subsystem weight

N_n = number of rf channels per service

W_n = transmit-channel weight per service

The fixed mission subsystem weight, W_k, includes the weight of the antennas (assuming fixed antenna sizes), the wideband communications receivers, driver amplifier, and the proportion of the power subsystem weight required to provide power to the receivers and driver, which is assumed to be constant. The transmit channel weight, W_n, includes the weight of the TWT and electronic power conditioner (EPC) (including any associated thermal control requirement), the weight of the power subsystem required for the TWT, and the weight of the input and output multiplexer filters (pro-rated).

The estimates for the fixed mission subsystem weights are derived as follows:-

(a) Antenna Weight

The antenna complement of the satellite is obtained from 7.2.1 where it is shown that the requirement can be met by three reflectors - two having dimensions 1 foot by 2 feet 5 inches and one reflector 5 feet by 5 feet in size. The weight of the antennas may be estimated by using a specific weight of 0.5 pound per square foot, which includes the reflectors and feeds. Structure weight is taken into account by adding 25 percent. The antenna weight estimates are therefore as follows:-

QUANTITY	AREA (ft^2)	WEIGHT (lb)
1	25	15.6
2	2.42	1.5
		17.1

(b) Weight of Receivers and Driver

Assuming a transponder model as shown in Figure 6-3 the weight of the wideband receiver and associated hardware plus the driver amplifier will be essentially constant as the EIRP of the transmitters is varied. An estimate of 12 pounds is made for the redundant receivers, driver amplifier, and associated hardware. The prime power estimated for the receiver and driver amplifier is 12 watts. This results in a prime power subsystem weight of approximately 1 pound. In order to simplify the weight calculation, it is assumed that the driver weight remains constant.

The total fixed weight of the mission subsystems is therefore approximately 20 pounds. As previously discussed, this fixed weight will be added to the weight of the housekeeping subsystems in order to isolate the variable weight of the transmit channels. This will modify the percentage relationship between the EIRP-producing subsystems and the housekeeping subsystems from 48 percent to 45 percent which is sufficiently accurate for the performance of trade-offs over the satellite weight range appropriate for the launch vehicles considered in this study.

In order to estimate the total satellite weight, it is now only necessary to estimate the weight of the EIRP-producing hardware for each service separately, total them, and apply the 45 percent relationship. The transmit-channel weight includes the input and output multiplexer, travelling wave tube, and power conditioner. As any changes in EIRP will affect the prime power requirement, it is convenient to include the prime power weight requirement in the transmit channel weight. This power requirement depends upon the efficiency of each element although, for this trade-off, wiring losses are ignored and the efficiency of the power regulation and transfer is assumed to be included in the prime power subsystem specific power. Although the EPC efficiency could be as high as 90 through 95 percent, 85 percent will be used for the trade-off, as this is considered to be more realistic for implementation prior to 1977. A simplified block diagram of the power subsystem model is shown in

Figure 6-4.

The EPC weight varies with power (and also input and output voltage) and increases according to a square-root law* The TWT weights for various saturated output powers have been taken from known manufacturers information (the TWT weights may be somewhat pessimistic because for a chosen power the tube weight would be optimized). The TWT efficiency in general increases with power. For the purposes of the trade-off a constant efficiency of 30 percent will be used, although this may be somewhat pessimistic at higher power and optimistic at lower powers. This figure includes the PEC efficiency of 85 percent. The power-supply weight necessary to provide the TWT power requirements is therefore

$$W_{PT} = \frac{P}{0.3\ k_1} \quad \text{pounds}$$

where P = TWT saturated output power

k_1 = power subsystem specific power (10 W/lb).

$$\therefore \quad W_{PT} = \frac{P}{3.0} \quad \text{pounds.}$$

The per-channel weight allotted to the input and output multiplex filters also has to be added to the transmit-channel weight. The input multiplexer could use stripline or similar technology, in which case an allotment of 0.1 pound per channel would be appropriate. For the output multiplexer, waveguide techniques would be used and a weight allowance of 0.5 pound per channel will be used. In order to allow some margin for additional cabling switches and other hardware a total allowance of 2 pounds per channel has been used. The output multiplexer losses have been taken into account in the systems calculations.

The results of the satellite weight estimation method used in this study are in close agreement with those of other independent studies and proposals and are therefore considered reasonable for the broad systems approach taken. The detailed design and weight calculation of a satellite is, of course, much more time consuming and would require far more effort than this study allows. This should be taken into account when reviewing the procedure used and the results thereof.

The total satellite weight on a per-transponder basis is plotted versus the saturated output power in Figure 6-5.

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* As established by Aiken - Report on a trip to Hughes Aircraft Company, etc., 4 to 6 February, 1970.

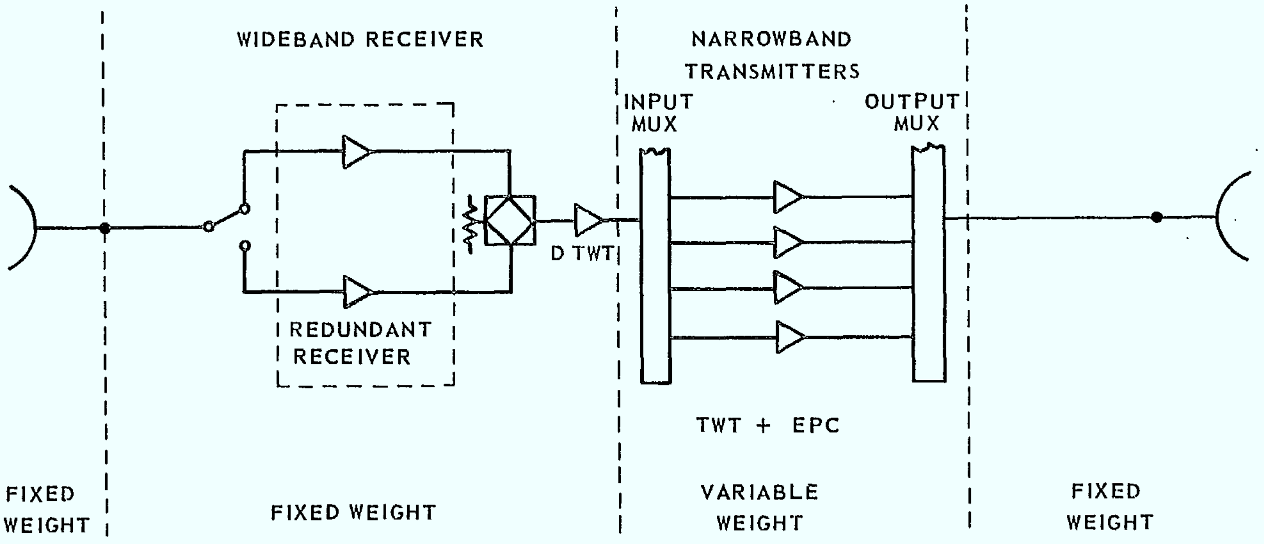

Figure 6-3 Antenna and Communications Subsystem Model

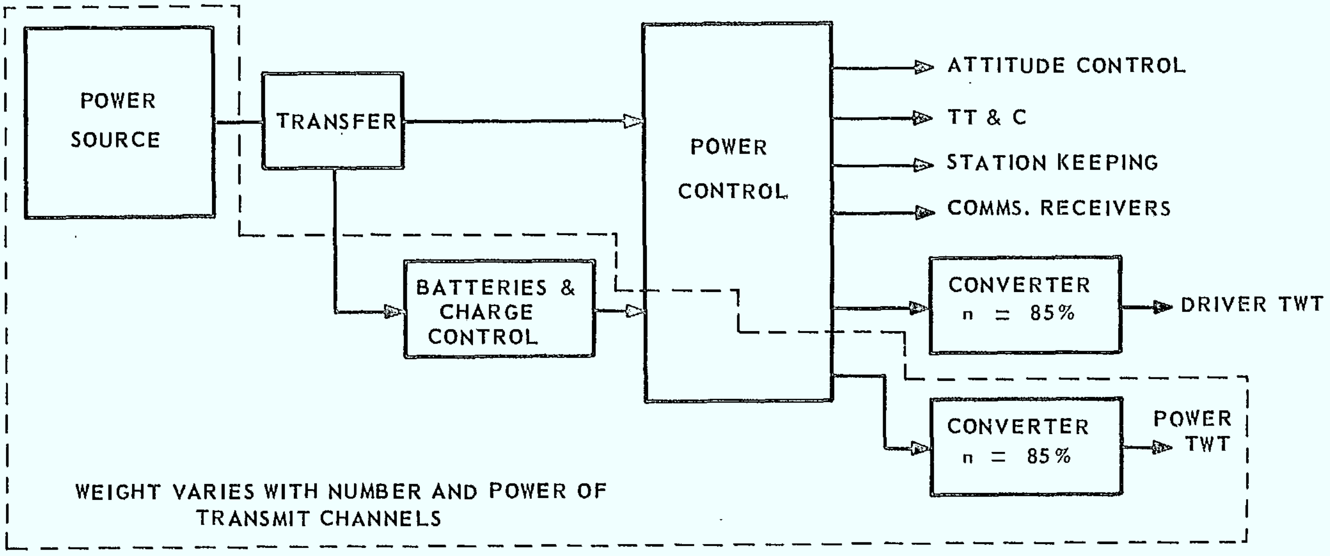

Figure 6-4 Simplified Power Subsystem Model

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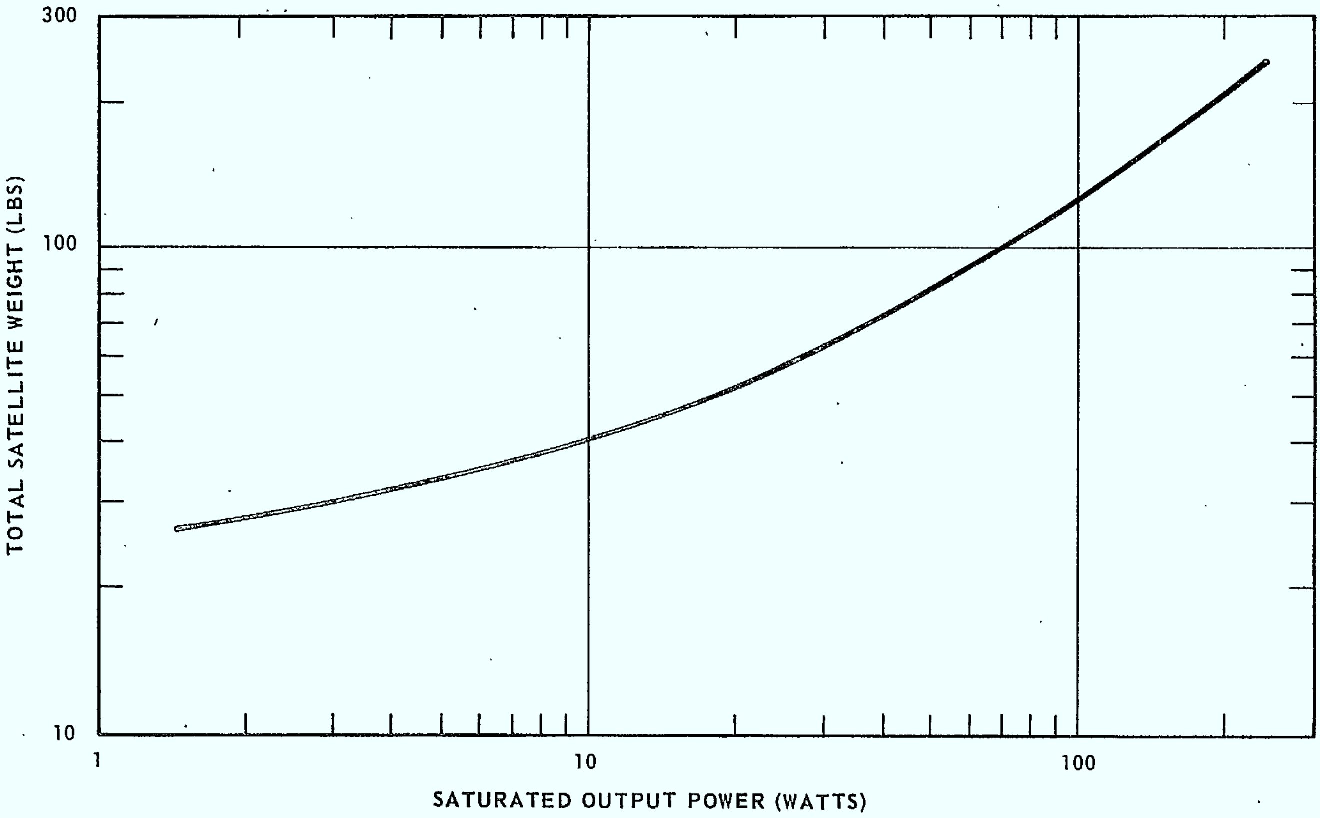

Figure 6-5 Total Satellite Weight for One Transponder

6.3 EARTH STATION TECHNOLOGY

The basic technology, both electronic and mechanical, is being developed or refined for operation in the 12 through 15 GHz frequency bands; and earth stations can be constructed in 1977 with minimum additional development.

As in the case of the space segment, it was not the intention to carry out detailed design of earth stations, nor would the resource allocation for the study allow for this. It is also appropriate to point out that at the system identification stage this would not have served any useful purpose. The significant factors thus were once again to establish trends of technology and establish relationships between major blocks which could assist in realistic first cost estimation. The trends would identify the technological and deployment availability, and first estimates of costs could then be performed within compatible limits. The latter is considered in chapter 9. The subsections of this section comment on the technological aspects only. Particular attention is drawn to the operation in the Time Division Multiple Access (TDMA) and single channel per carrier modes, where equipment specially suited to the traffic needs of each country will have to be individually designed.

Generally, in U.S.A., Europe and Japan considerable development effort is afoot in rf component designs specifically in frequency bands allocated in the 10 through 18 GHz range for terrestrial communications. There is also evidence of activity - though not on the same scale - to extend the designs to cover the specific satellite communications frequency bands in the U.S.A.

* * *

6.3.1 EARTH STATION ANTENNAS

Antennas and tracking systems are considered in the context of this study. No startling advances are foreseen, and breakpoints in methods of manufacture and tracking will continue to exist, affecting costs.

Antennas up to 30 through 40 feet in diameter, with adequate surface accuracy for use in the 10 through 15 GHz band, are already easily available. Smaller diameter metal dishes will continue to be manufactured by employing spun techniques. Compressed fiber-glass dishes will become available, but their long term profile-holding properties need to be established in severe climatic conditions. There is no evidence to suggest that, above about 6 through 10 feet in diameter, these will be significantly cheaper than their metal competitors. Spun techniques will almost certainly advance marginally to extend the diameters of spun metal dishes up to 17 feet by the mid-Seventies. Mass production techniques, if applied, are potentially capable of reducing costs by an order of magnitude for smaller antennas as also for electronic equipment associated. In both cases, however, continuous production with total quantities of the order of a million and batches of the order of 20 through 50 thousand will be required. At any given level of production the relative relationship between antenna costs for small antennas, which require no tracking, and the minimal electronics for the simplest receiver is likely to remain substantially unaltered, with the antenna being a relatively small percentage of total hardware costs.

Antennas with diameters larger than 17 feet, at these frequencies will continue to be manufactured using fabrication techniques. Also, in spite of the high station-keeping accuracies of future satellites, such antennas are most likely to require tracking due to the small beamwidths involved. Up to about 30 feet diameter, the relatively modest wind gust and gravity deflection effects will most likely not require complex servo systems. Simple step-track servo subsystems, which already exist, would appear to be adequate. Beyond about 30 feet diameter structural deflections and narrow beamwdiths will be such that more complex servos will most probably be used. It does not appear likely that standard design, and reasonably priced antennas beyond about 60 feet in diameter (and associated servos), will be available with surface accuracies required at these frequencies.

Thus, broadly speaking, there would appear to be two technical break points, one at about 17 feet and the other at about 30 feet, which will reflect themselves also as price discontinuities.

6.3.2 RECEIVER FRONT ENDS

Uncooled parametric amplifiers, mixers and tunnel-diode amplifiers will be available.

Exploratory development work in U.S.A., Europe and Japan has established the feasibility of mixer, tunnel-diode, and uncooled parametric amplifier designs in the band 10 through 15 GHz to an extent that manufacturers are prepared to supply these devices against orders. The effective bandwidths of these devices increase with the absolute frequency and will most likely be restricted by the allocated rf spectrum of 500 MHz. Current interest is mainly centred on the bands in this frequency range specifically allocated to terrestrial microwave communications. The forecasts for deployable hardware in the late 1970's for these front ends are:

DEVICE	NOISE TEMPERATURE
Mixer	4350°K (12 dB NF)
Tunnel Diode	870°K (6 dB NF)
Parametric Amplifier (uncooled)	200°K

Polarizers, filters, and other low loss rf components required at the front end, will most likely be derived from standard designs by plating or by using extremely pure copper. Average losses will be marginally higher than at 4 and 6 GHz, but not substantially so.

* * *

6.3.3 INTERMEDIATE FREQUENCIES, MODULATORS AND DEMODULATORS

Intermediate frequencies at 12 through 15 GHz will most likely be the same as those currently used at 4 through 6 GHz; both single and double conversion schemes will continue to be used; multiphase PSK modulators and demodulators will become available and some improvements in FM demodulators are possible.

The intermediate frequencies both for single and double conversion schemes are most likely to be in the same frequency bands (800 - 1200 MHz first i-f; 70 - 140 MHz (second i-f) as currently used. If the use of 140 MHz i-f becomes accepted in terrestrial microwave in this frequency range there is a likelihood that it will be used at earth stations also as the second i-f. The bandwidths of these i-f's for domestic systems will not necessarily follow the same standardization as is vital in Intelsat, the coice being dependent on the requirement to utilize the available spectrum to best meet the specific service pattern of the region or country.

Feed back and phase lock techniques will be used employing minimal-delay integrated circuitry to improve the performance of FM demodulators. In particular, this is expected to result in a lowering of the extended threshold for very narrow band demodulators, and in a reduction of the 'click-noise' of television demodulators working close to threshold.

Development of high speed 4-phase and 8-phase PSK modulators and demodulators will continue. For proven and deployable hardware in the next five to seven years speeds are likely to be confined to about 100 to 150 Mb/s, with impelemntation margins (which represent the difference between ideal theoretical performance and practical repeatable hardware performance and includes the effects of intersymbol interference and TWT non-linearities) of 4.0 dB for 4-phase and 4.5 dB for 8-phase schemes.

More sophisticated and inherently more complex modulation and demodulation techniques are currently under study to improve the frequency utilization of digital transmissions. These are mostly in the stage of theoretical analysis. While there is some evidence of their potential in the time frame of the next five to seven years, they are most unlikely to result in deployable hardware. These have to undergo extensive laboratory and field testing, like other modulation schemes which preceded them, before general acceptance is achieved.

* * *

6.3.4 TIME DIVISION MULTIPLE ACCESS (TDMA)

Digital transmission will become an accepted mode in satellite communications as in other transmission media in the time scale of this study, and TDMA techniques will become established in civil satellite communications. Special development to serve the specific traffic needs of Canada will be required.

The trend towards the introduction of digital modulation techniques on most high-capacity transmission media is accelerating, and the satellite communications medium is no exception to this general trend. This mode of transmission will certainly be used in the time scale considered in this study. To obtain full advantage of the area-coverage properties of satellites, TDMA schemes will be essential. Experimental work so far completed for Intelsat will result in hardware deployment in the near future. Considerable development work has been carried out in Japan, U.S.A. and Europe, and there are significant differences between the capacities and detailed methods in each scheme. While there is little doubt that standardization will be achieved to enable the international network to operate, it is significant that work still continues along the separate approaches. The reasons for this are that in any domestic or regional satellite systems the limitations of flux density and the pattern of traffic will be different from those for the international system. The requirement for a country will likely be a specific mixture of specific beams covering specific areas, with a number of stations in these beams connected in a flexible quantity relationship but with a well defined and unique pattern. Considerations of synchronization inter-operability and 'burst' control will most likely involve development of specific hardware and the integration testing on a reasonably large scale. An estimate of this development cost in the context of this study is given in chapter 11.

* * *

6.4 REFERENCES

6.1 J.V. Charyk; "Future Prospects of Satellite Telecommunication Systems," ITU. Telecommunication Journal, Vol. 38, V. 1971 pp. 296-300.

6.2 Intelsat Data Handbook. Vol. 2 Pt. 3, 1970, Section 2 - XIV.

6.3 Intelsat Data Handbook. Vol. 2 Pt. 1, 1970, Section 3 - X.

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7. Technical Trade-offs and System Modeling

7.1 SATELLITE SYSTEM MODELING METHODOLOGY

The concept of a 'systems modeling map' is introduced. For a given type of service, whose performance requirements are known, unique parametric relationships exist between major systems parameters. These relationships can be graphically represented. The services identified in chapter 2 are grouped into three classes for further analysis.

The strategy adopted in the system modeling is to lay out in graphical representation all the major system parameters associated with each type of service, in such a way that any point on a diagram defines a system completely. This graphical representation may be thought of as a system modeling "map". The map is drawn initially without any system constraints being imposed. Any point on the map gives the following inter-related fundamental system parameters:

1) Radio-frequency bandwidth of transponder
2) EIRP of transponder (as any combination of transponder TWT power and antenna beam size)
3) Earth station figure-of-merit G/T (as any combination of antenna size and type of low noise receiver)
4) System capacity per transponder.

To draw the system modeling map for any specific service, the following need to be known:

1) Type of modulation
2) Fade margin for the given service reliability
3) Up-link noise contribution
4) Quality of the system performance in terms of signal/noise ratio or in bit error rate (at threshold).

A variation of any of the four above-mentioned factors results in a unique systems modeling map for the service considered. The system modeling maps are derived from the basic theoretical equations of each type of modulation concerned, i.e. FDM-FM, PCM-CPSK, etc.

The systems constraints can be represented on the maps as boundaries. Some of the systems constraints are basis, such as FM threshold. Most systems constraints, however, are derived from practical and economic considerations. As the system trade-off progresses, these boundaries will be more and more clearly defined. The core of the system modeling exercise is really the determination and refinement of the systems boundaries so as to narrow down the area of system choice.

The development of the systems models will be dealt with for each of the following classes of service separately:

- (a) Commercial Television
- (b) Educational Television
- (c) Telephony (and Data)
    - (i) Major Traffic Communications (Multi-channel)
    - (ii) Remote Communications (Multi-channel)
    - (iii) Single Channel per Carrier

The facilities for data services which include the electronic mail and video telephone requirements will be incorporated as part of the digital system for major traffic communications. This is justified in view of the fact that the centers of appreciable data traffic are expected to be also the centers of major telephone communications.

For each of the above classes or sub-classes of service the system modeling maps will be derived and the system boundaries will be narrowed down as much as possible based on technical considerations. These will be described in chapter 8. The final choice of an optimum system for any particular service will be discussed in chapters 9 and 10, when the economic trade-offs and aspects common to all the services will be considered.

7.2 GENERAL SYSTEMS CONFIGURATION AND RANGES OF PARAMETERS

The ranges between which two of the four major systems technical parameters (EIRP and G/T) may vary are affected by the geographical distribution of the services to be provided and the technological constraints of chapter 3, section 3.4. These effects are analysed and parametric relationships graphically presented in 7.2.1 through 7.2.5.

Certain basic and general systems parameters which are required in subsequent sections for systems modelling will now be presented.

The satellite postulated in this study will be of multi-purpose type catering to the needs of the commercial television, educational television, telephony and data services. There will be one satellite in operation and a fully duplicated satellite as standby in a parking orbit. This is considered to be a minimum redundancy requirement. The satellite will have a common wideband receiver with full redundancy and the receive antenna will cover essentially the whole of Canada. Multiple spot beam receive antennas are not favoured because of the complexity of multiple receivers each connected to its antenna. Moreover, up-link transmit power is generally not a critical cost element and the gain of a Canada-wide coverage beam gives reasonable satellite receive G/T. A Canada-wide coverage beam is therefore chosen. The down-links will comprise various transponders feeding antennas of specific coverage areas for the various services. The down-link antenna coverage beams chosen (see 7.2.1) are as follows:

(a) Two half-Canada coverage beams of 1.75° × 4.5° each, one for West Canada and one for East Canada. These will be for the commercial television, and major traffic communications telephony and data services. The single channel per carrier telephony and remote communications systems will have a full-Canada coverage beam obtained by combining the two half-beams.

(b) A 1.5° by 1.5° spot beam for educational services to the Maritime provinces.

(c) Two 1° by 2.5° spot beams for educational services, one each for the provinces of Quebec and Ontario.

(d) Two 1.5° by 2.0° spot beams for educational services to cover the provinces west of Ontario, including the North-West Territories and Yukon.

For the purposes of technical analysis, it is assumed that there is a separate network of earth stations for each of the services.

* * *

7.2.1 CHOICE OF SATELLITE ANTENNA BEAMS

This choice is primarily determined by the patent economy and frequency coordination advantage of confining the radiation from a spacecraft to the geographical area in which the service carried by the associated radiation is needed. Four types of beams are needed and their arrangement is graphically presented.

The choice of a suitable antenna configuration, for the spacecraft, is primarily dependent on the following:

a) Service requirements

b) Desired minimum coverage of each service

c) Physical constraints of maximum spacecraft size and smallest possible rf components

d) Permissible levels of interactions between radiations to and from the satellite

Factors a) and b) are interdependent since the various service requirements will dictate to a large extent the coverage area that will be needed.

Restricting the primary radiation at any frequency from the spacecraft to the geographical area required for the service is an important consideration for economical and future spectrum utilization reasons.

For a given capacity and quality of service, and a fixed earth station figure of merit (G/T), a calculable and fixed power flux density at the ground will be required. This latter quantity, in turn, is determined by the satellite effective isotropic radiated power (EIRP). The EIRP is the product of the transponder output power and the transmit antenna gain. For any antenna, at a fixed distance above the earth's surface (as is the case with one on a synchronous satellite), the coverage area and the gain are inversely related to each other. An increase of coverage area automatically implies a decrease in gain. Thus if the EIRP has to be given fixed value, as stated earlier, an increase in coverage area can only be achieved by increasing the transponder output rf power to compensate exactly the decrease in satellite antenna gain. As the primary power system is one of the costlier items in the spacecraft, this results in an economic penalty that one would pay for providing excessive antenna coverage.

The other advantage of restricting beams to the required coverage area concerns spectrum utilization. Frequencies that are restricted to specific geographical regions of Canada (regional beams) can easily be reused in other geographical regions when the need for frequency reuse arises, otherwise the potential of a limited material resource would be needlessly mortgaged. Thus, use will be made of regional beam coverage where it is practical to do so.

Referring to chapter 2, which identifies the service needs of the satellite, one can disseminate these needs into two coverage categories - regional and national. The service that primarily operates on a regional basis is the educational television (ETV) distribution since this service will most likely be operated under provincial jurisdiction. For these services narrow spot beams would be appropriate. The remaining services namely telephony, digital services, and commercial television (CTV) distribution, will require national or multi-provincial coverage. A full-Canada coverage beam would provide maximum system flexibility and simplicity in the earth-segment network. This coverage beam is chosen for the remote communications and single channel per carrier systems. With two half-Canada coverage beams, one East and one West, there is an immediate advantage of 3 dB of power gain at the expense of a slight decrease in system flexibility and an increase of earth-segment network complexity. On balance, it is considered that for the CTV services and major traffic communications, the advantage outweighs the disadvantages and half-Canada coverage beams are chosen for these services. It is considered that further narrowing down of the coverage beams would severely limit operational flexibility and is not desirable.

Based on the above, the number of beams, their respective coverage areas and corresponding minimum gain at beam edge are given in Table 7-1.

As the coverage area is somewhat dependent on the satellite location in the geostationary orbit, some beam shaping will be required to obtain optimum coverage at other locations in the orbit. However, this variance should not effect the gain of the respective beams significantly. Thus, the beam pattern and gains given below for a satellite located at 100° West Longitude in the geostationary orbit can be considered as typical values for the purposes of this study.

The gain of the respective beam edges is given by the empirical formula:

$$G\ (\text{dB}) = 10 \log_{10} \left(\frac{6000\ \pi}{\theta_H \times \theta_E}\right) - 2.0$$

where θ_H, θ_E are the antenna coverage beams in degrees in orthogonal planes.

The gains given in Table 7-1 include an additional loss factor of 0.5 dB to allow for an antenna pointing instability of ±0.1°.

Table 7-1 Proposed Satellite Transmit Beams

SERVICE	COVERAGE AREA	BEAM SIZE (DEGREES)	GAIN AT BEAM EDGE (dB)
ETV Distribution	British Columbia Alberta	1.5 × 2.0	35.5
	Saskatchewan Manitoba	1.5 × 2.0	35.5
	Ontario	1 × 2.5	36.3
	Quebec	1 × 2.5	36.3
	Maritime Provinces	1.5 × 1.5	36.8
Telephony Data Commercial TV	Eastern Canada	1.75 × 4.5	31.3
	Western Canada	1.75 × 4.5	31.3

Figure 7-1 shows the various satellite transmit coverage beam patterns for the ETV service representative of a satellite located at 100° West Longitude in the geostationary orbit. Similarly Figure 7-2 shows the beam coverage pattern for the two half-Canada coverage beams.

The two half-Canada coverage beams will be utilized for the satellite receive antenna for all the services. The inputs from the two separate antenna feeds will be combined via a magic tee network prior to the input to the common receive amplifier. The 3 dB penalty of loss in receive gain due to the combining is compensated for by the convenience of having the satellite receive configuration common to the total Canadian coverage area giving maximum flexibility in the earth station transmitting arrangments.

To avoid phasing problems in the common area where the two half-Canada beams overlap will require that the transmit and receive beams must be isolated from each other. This phasing problem could arise from the fact that an earth station located in the common area of the two beams will receive from and transmit to the satellite signals of approximately equal strength along two separate paths. Thus, if these two paths do not have equal lengths, losses due to phase changes between the two signals can arise. To overcome this problem the two receive and transmit beams can be cross-polarized to avoid this mutual interference.

The satellite transmit and receive arrangement for these two beams is illustrated in Figure 7-3.

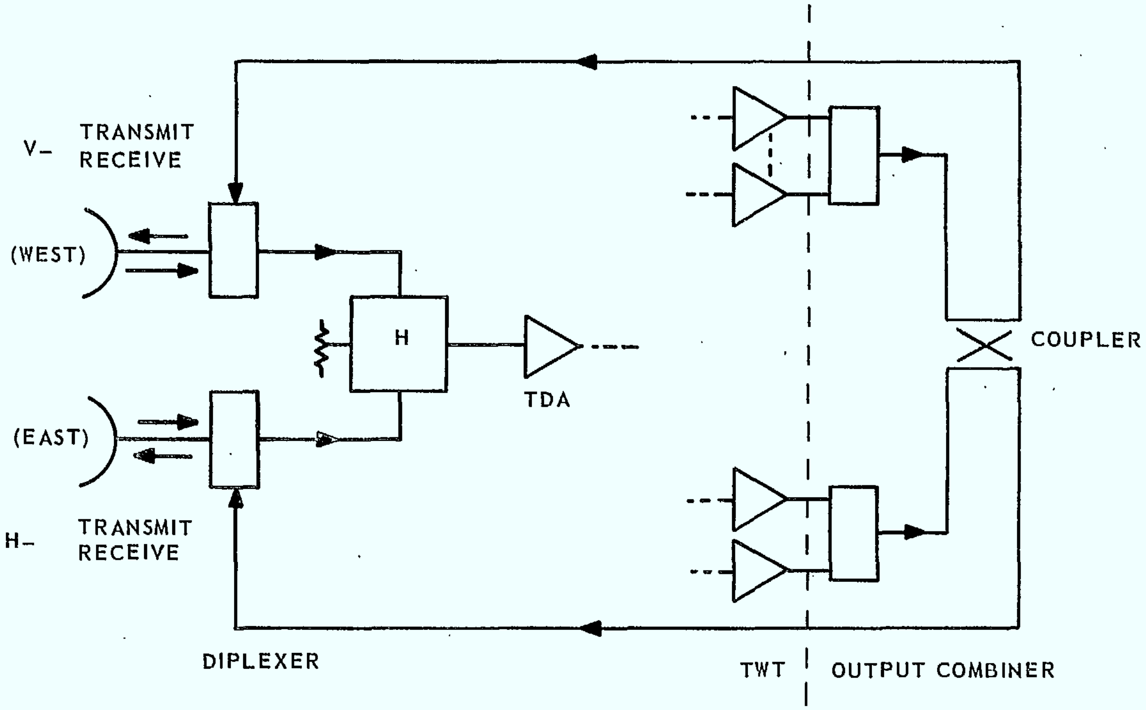

Figure 7-3 Proposed Satellite Transmit and Receive Arrangement for Half-Canada Coverage Beams

The design of the antenna assembly must consider the size and weight constraints of the launch vehicle and its shroud. The objective of the design will be to produce a light and efficient antenna array that could be fitted into the shroud of a Thor-Delta type launch vehicle which has the smallest shroud of the launch vehicles considered suitable for this study. With these considerations in mind, a parabolic reflector type aperture with front feed system results in a light and efficient type of antenna arrangement that will meet the design objectives.

The ETV beams will require the largest aperture size since they correspond to the smallest beams. It will be possible to obtain this beam pattern using a single aperture of approximately 5 feet by 5 feet in size and a multiple off-set feed horn arrangement. Three of the feed horns will be horizontally (East-West) off-set from the center focus to obtain the two western and the maritime beams and two feed horns vertically off-set from center-focus (North-South) to produce the Ontario and Quebec beams. The beams are suitably spaced apart to allow adequate space for the feed horns.

To obtain the two half-Canada beams, two apertures will be needed, each having dimensions of 1 foot by 2 feet 5 inches. A multiple feed horn arrangement for these two beams is not possible since the two horns are not adequately separated to provide suitable space for the larger feed horns.

An arrangement of the antennas suitable to fit into a Thor-Delta shroud is shown in Figure 7-4.

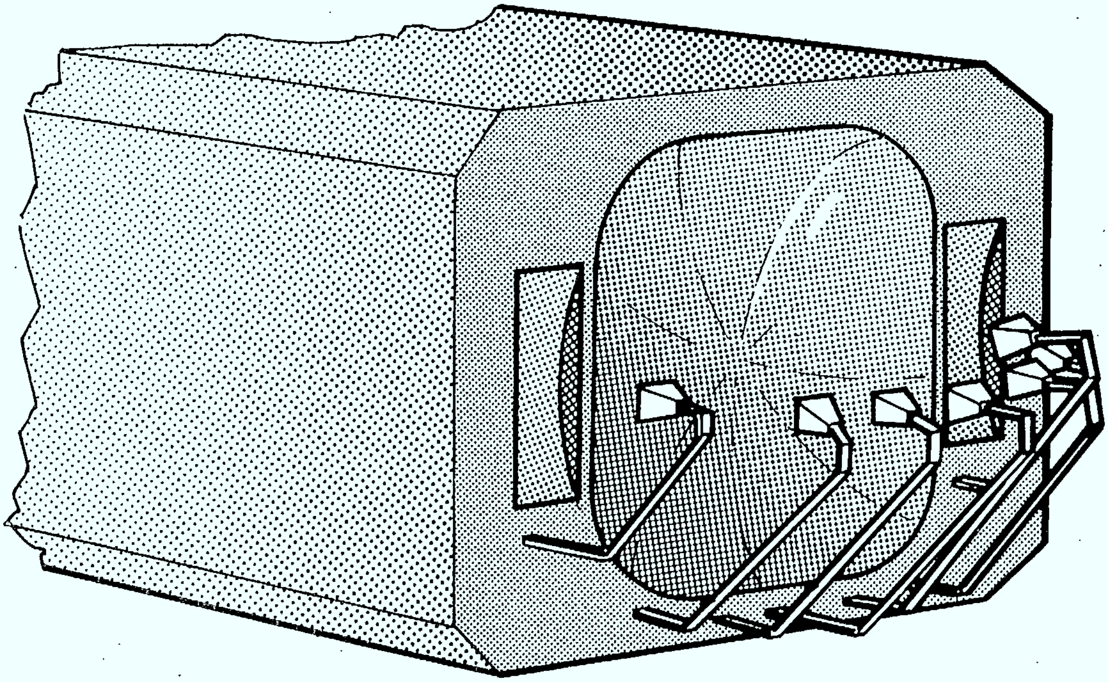

Figure 7-4 Proposed Mechanical Layout of Satellite Antennas

In summary, a satellite antenna coverage scheme was described that would meet the demands of the various services the satellite is intended to fulfill. An antenna form utilizing parabolic reflectors with multiple feed horns capable of fulfilling the coverage requirements, and fit into a Thor-Delta shroud, was briefly described. Future exploratory and development efforts of some considerable magnitude will be required in this area if the concepts of antenna forms and multiple beam arrangements are to be employed in Canada. For reasons stated above, this is considered to be a major area where future technical effort must be deployed to obtain the fullest advantage of these techniques for Canada.

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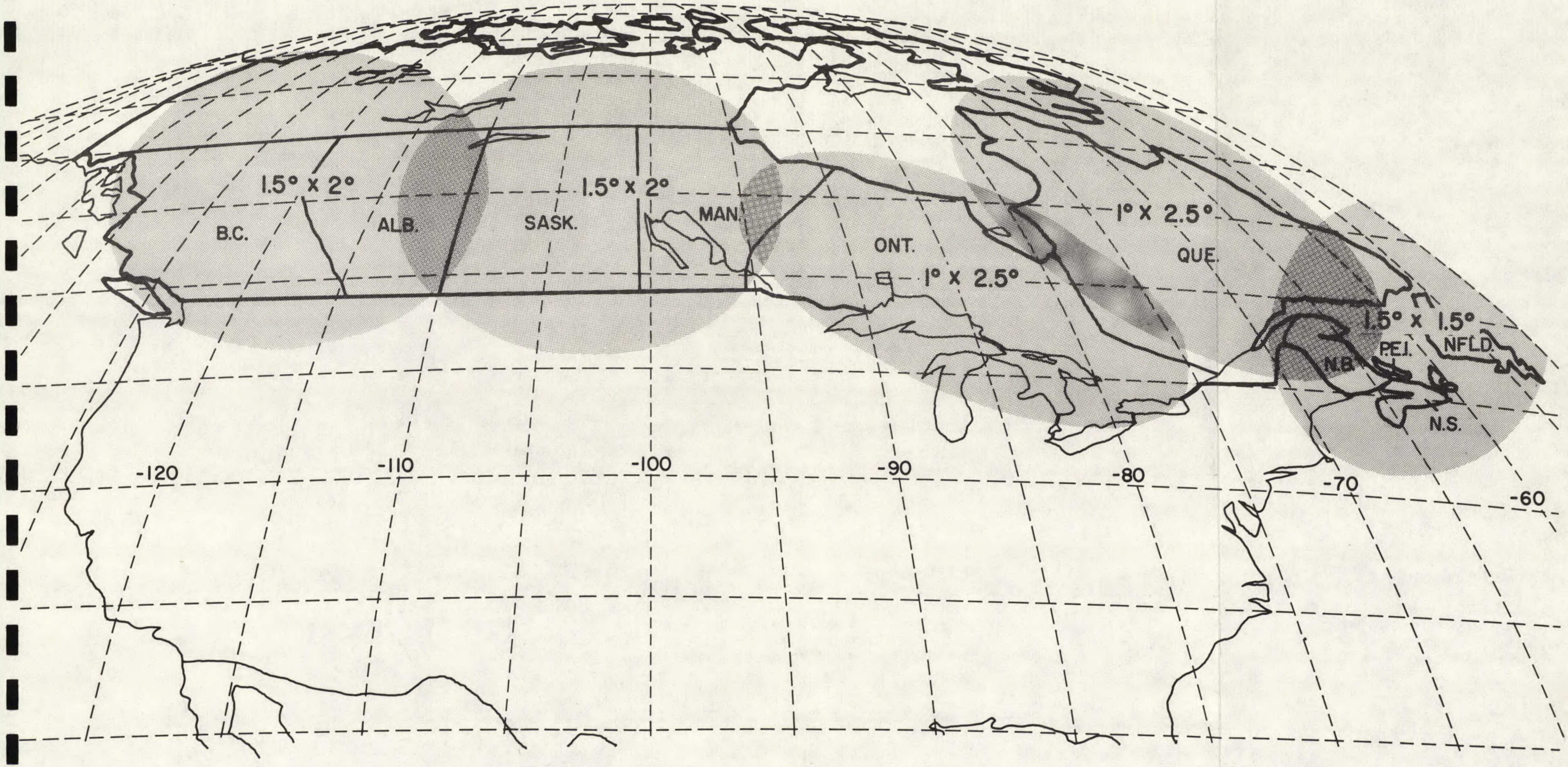

Figure 7-1
Coverage Patterns

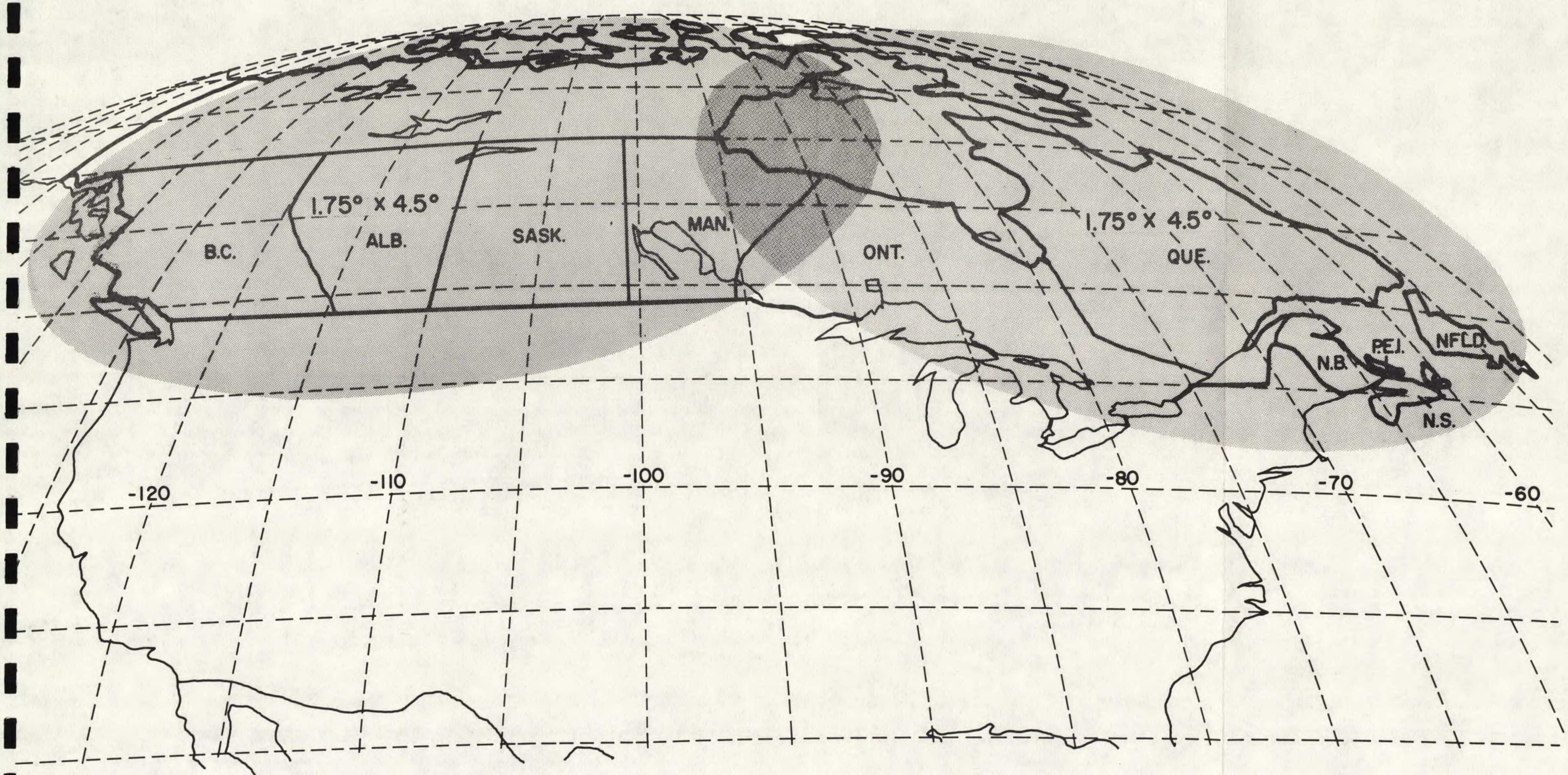

Figure 7-2
Total Coverage Patterns

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7.2.2 RANGE OF EARTH STATION G/T

The anticipated range of "figure of merit" of earth stations with antennas up to 60 feet in diameter with three types of receiver front ends is presented.

Three types of front end receivers are considered for the earth stations, namely:

(a) Uncooled Paramp

(b) Tunnel Diode Amplifier (TDA)

(c) Mixer

The earth station system noise temperatures using the above receivers are tabulated in Table 7-2.

Assuming antenna efficiencies of 55 percent at 12 GHz, the antenna gains and earth station G/T's are given in Table 7-3 for various antenna sizes. The G/T values are also presented in graphical form in Figure 7-5. For the purpose of estimating antenna noise temperature (and propagation loss) the antenna elevation angle is assumed to be at 10° elevation. This will cover nearly all cases likely to be met in Canada.

Table 7-2 Earth Station System Noise Temperatures

	UNCOOLED PARAMP	TUNNEL DIODE AMPLIFIER	MIXER
Low Noise Receive Noise Temperature	200°K	870°K (N_F = 6 dB)	-
Low Noise Receiver Net Gain	30 dB	13 dB	-
Down Converter Noise Temperature (N_F = 12 dB)	4350°K	4350°K	4350°K
Antenna Noise Temperature at 12 GHz at 10° Elevation	70°K	70°K	70°K
System Noise Temperature of Earth Station	274°K	1157°K	4420°K
System Noise Temperature in dB - °K	24.4	30.7	36.4

Table 7-3 Earth Station G/T Values and Antenna Gains

ANTENNA DIAMETER	4'	6'	8'	10'	15'	20'	25'	30'	35'	40'
Gain dB (η=55%, 12 GHz)	41.1	44.6	47.2	49.0	52.5	55.1	57.0	58.6	60.0	61.1
3 dB Beamwidth°	1.5	0.99	0.75	0.60	0.40	0.30	0.24	0.20	0.16	0.15
1 dB Beamwidth°	0.85	0.56	0.42	0.34	0.23	0.17	0.14	0.11	0.09	0.08
G/T (Paramp) dB	16.7	20.2	22.8	24.6	28.1	30.7	32.6	34.2	35.6	36.7
G/T (TDA) dB	10.4	13.9	16.5	18.3	21.8	24.4	26.3	27.9	29.3	30.4
G/T (Mixer) dB	4.7	8.2	10.8	12.6	16.1	18.7	20.6	22.2	23.6	24.7

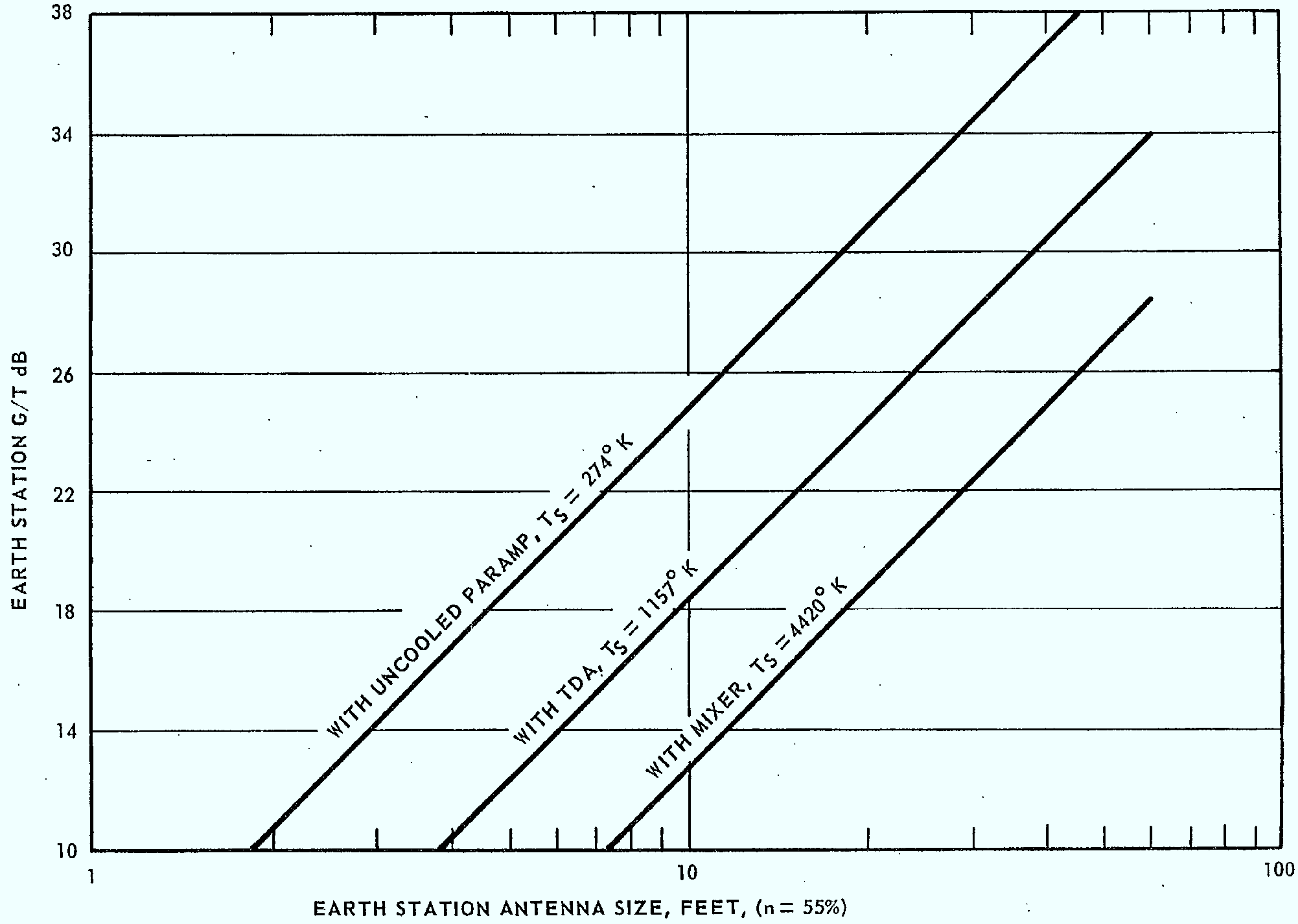


Figure 7-5 Earth Station G/T versus Antenna Size

7.2.3 SATELLITE RECEIVE G/T

An estimate of achievable satellite G/T, compatible with technical forecasts for 1975 through 77, is made.

As stated in 7.2.1 the satellite receive system is generally configured as follows:

(a) The receive antenna coverage is Canada-wide, obtained typically by combining (as in Figure below) two 1.75° by 4.5° half-Canada coverage beams.

(b) A TDA is used as the low noise receiver with a bandwidth of 500 MHz.

(c) A down-converter or frequency translator follows the TDA.

A model of the satellite receive system for estimation of the satellite G/T is given in Figure 7-6.

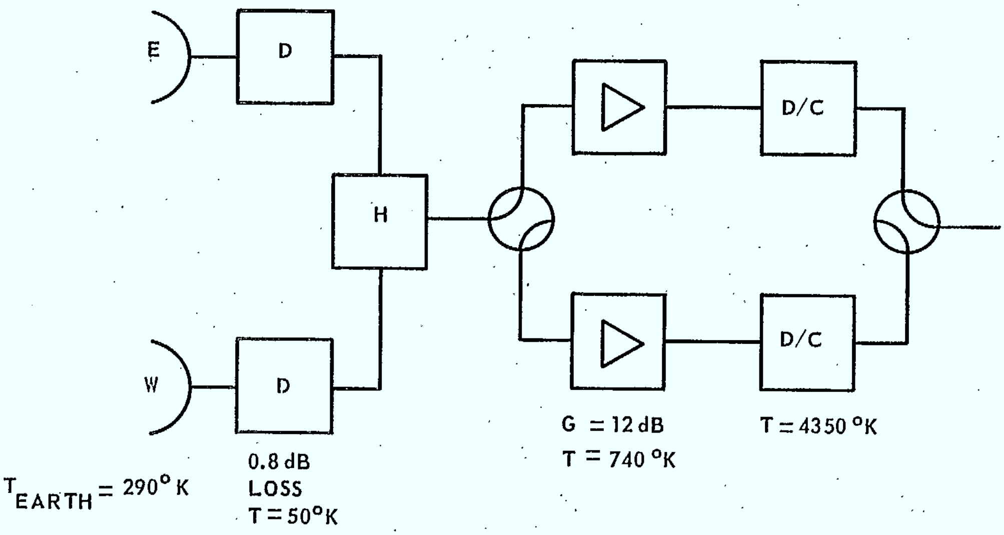


Figure 7-6 Model of Satellite Receive System for Estimation of G/T

The satellite parameters, compatible with technology forecast for the period of this study, are estimated to be as follows:

Minimum antenna gain at edge of Canada-wide coverage zone = 28.3 dB

Input diplexing loss = 0.8 dB

Diplexing loss noise temperature = 50°K

TDA noise temperature (N_F = 5.5 dB) = 740°K

TDA net gain = 12 dB

Down-converter noise temperature (N_F = 12 dB) = 4350°K

Noise temperature of earth as seen by antenna = 290°K

Total systems noise temperature

$$Ts = 740 + \frac{4350}{16} + 50 + \frac{290}{1.2} \qquad = 1300°K$$

∴ Satellite Receive G/T within coverage zone is:

$$G/T = 28.3 - 0.8 - 31.2 \quad = \quad -3.7$$

7.2.4 UP-LINK CARRIER-TO-NOISE TEMPERATURE RATIOS

The parametric relationships between the EIRP, size of the earth station antenna, transmitter power and the up-link C/T are graphically presented.

The up-link carrier-to-noise temperature ratios are derived based on the following:

(a) Center band frequency = 14.25 GHz, which is the center of the up-frequency band identified in 3.3.

(b) Earth station antenna efficiency = 55%, at transmit frequency.

(c) Transmit station waveguide losses = 2 dB

(d) Propagation loss, including 0.4 dB clear weather atmospheric absorption = 208.2 dB = L_p

(e) $G/T_{(sat)}$ = G/T of satellite = -3.7 dB (as in 7.2.2).

Figure 7-7 gives the relationship between antenna size and earth station EIRP for transmitter powers from 10 to 10 kW. Figure 7-8 gives the relationship between up-link carrier-to-noise temperature ratio and earth station EIRP, calculated as follows:

$$\left(\frac{C}{T}\right)_u = EIRP - L_p + G/T_{(sat)} \cdot$$

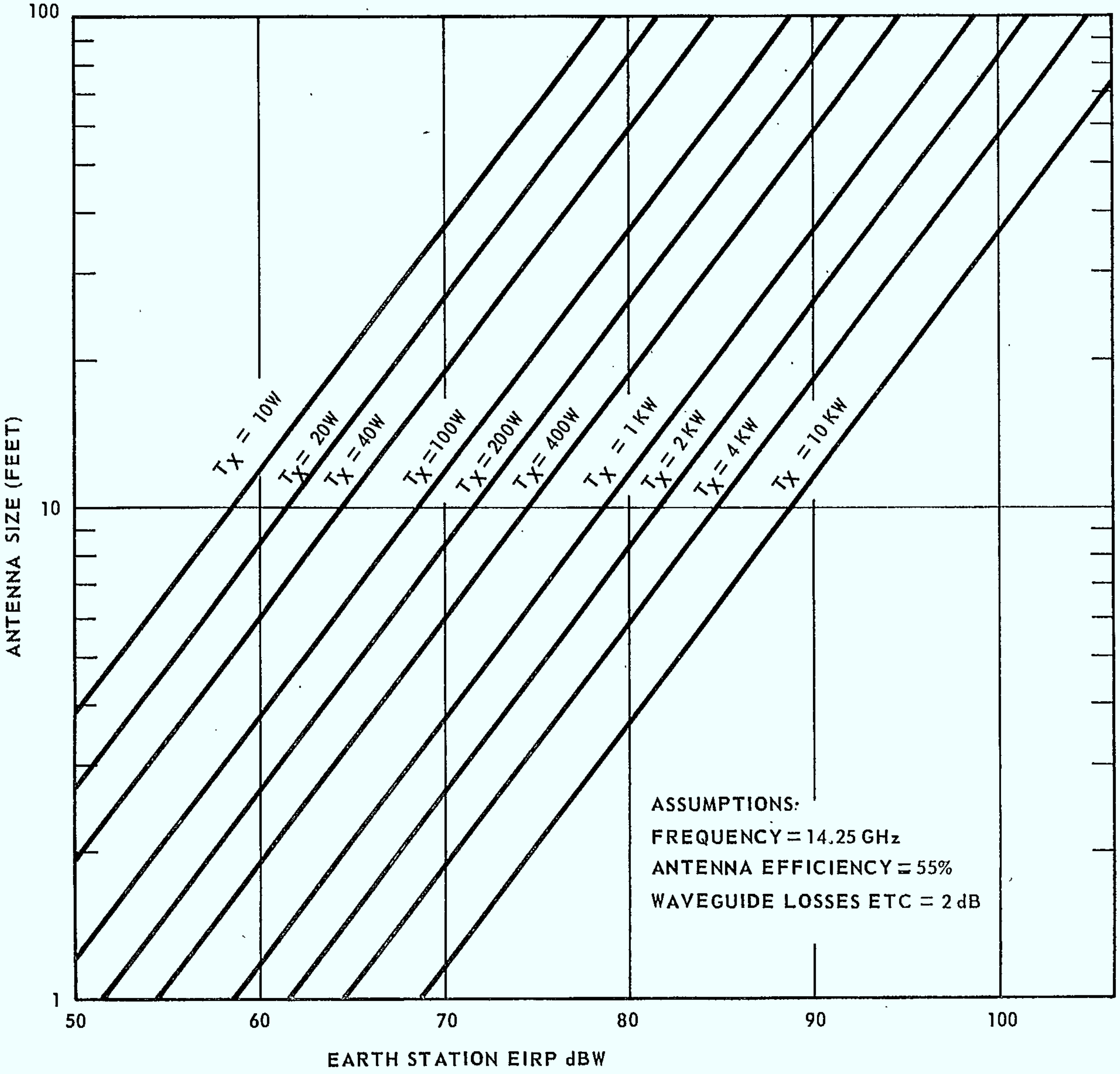


Figure 7-7 Earth Station EIRP versus Antenna Size
for Various Transmitter Powers

* * *

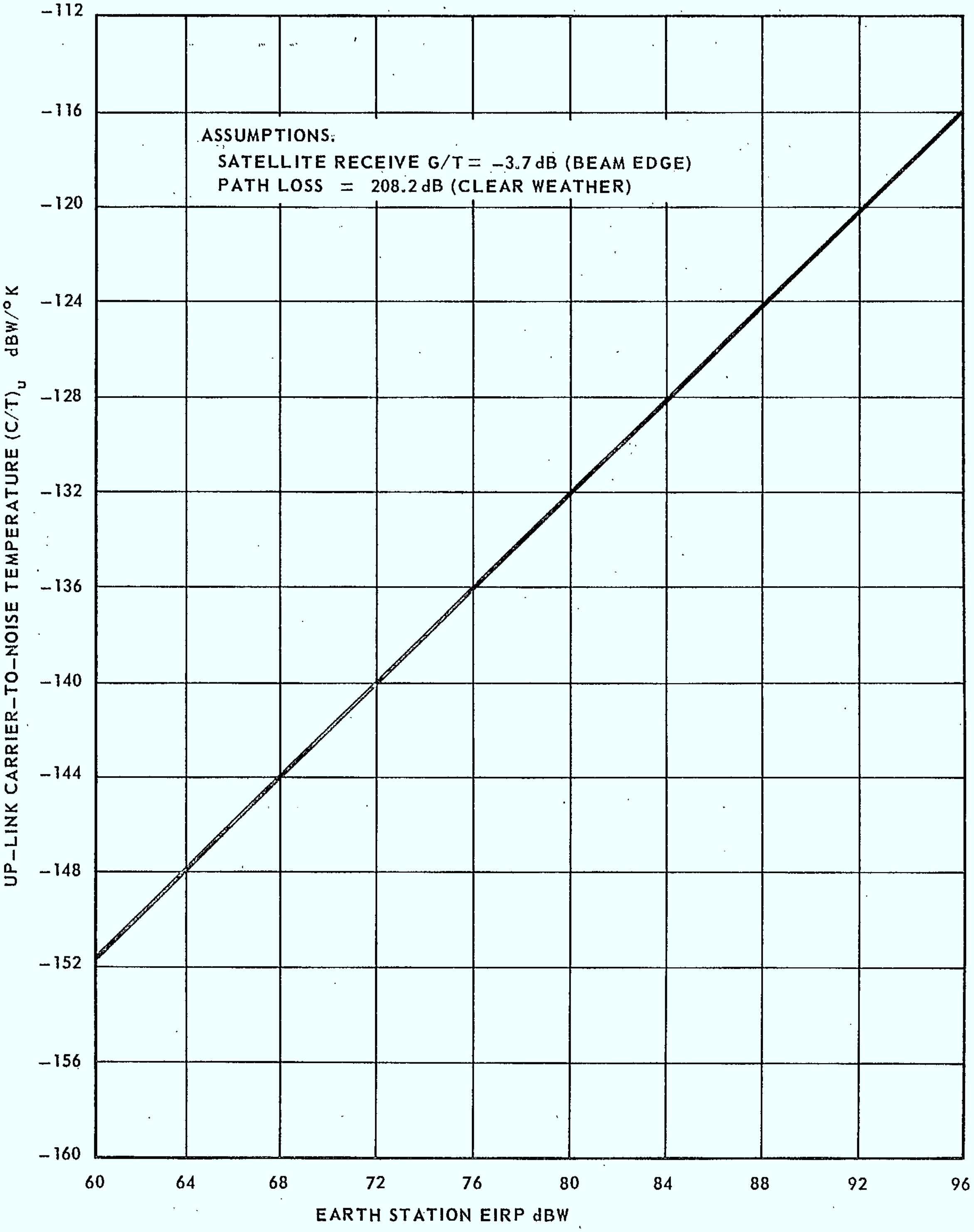


Figure 7-8 Up-Link Carrier-to-Noise
Temperature versus Earth Station EIRP

7.2.5 DOWN-LINK CARRIER-TO-NOISE TEMPERATURE RATIOS

The parametric relationship between the down-link C/T and the earth station G/T is graphically presented for a representative range of satellite EIRP's compatible with the technical constraints of chapter 3, section 3.4.

The down-link carrier-to-noise temperature ratios depend on the satellite EIRP and earth station G/T. Given the satellite antenna coverage in degrees, the minimum satellite antenna gain within the coverage zone is estimated from an empirical formula[7.1] as follows:

$$G = 10 \log \left(\frac{6000\pi}{\theta_H \times \theta_E} \right) - 2 \text{ dB}$$

where θ_E and θ_H are the antenna coverage beams in degrees in orthogonal planes. The gains of the satellite antennas and the EIRP for the corresponding coverage zones are given in Table 7-4, for the case of 20 watt and 200 watt transponder TWT's. These coverage zones correspond to those derived in chapter 3.

Table 7-4 Satellite Antenna Gain and EIRP

ANTENNA BEAM	1.5° × 1.5°		1° × 2.5°		1.5° × 2.0°		1.75° × 4.5°	
Min. antenna gain within coverage zone (dB)	37.3		36.8		36.0		31.8	
rf combining and diplexing loss (dB)	1.0		1.0		1.0		1.0	
Allowance for antenna pointing instability (dB)	0.5		0.5		0.5		0.5	
Transponder TWT Power (Watts)	20	200	20	200	20	200	20	200
Min. satellite EIRP within coverage zone	48.8	58.8	48.3	58.3	47.5	57.5	43.3	53.3

The down-link carrier-to-noise temperature ratio is given by the following:

$$(\frac{C}{T})_D = EIRP - L_p + G/T$$

where L_p = path loss = 206.8 dB at 12 GHz at 10° elevation, including 0.4 dB clear weather atmospheric absorption.

The above equation is plotted in Figure 7-9 with $(\frac{C}{T})_D$ as a function of G/T at various satellite EIRP's.

* * *

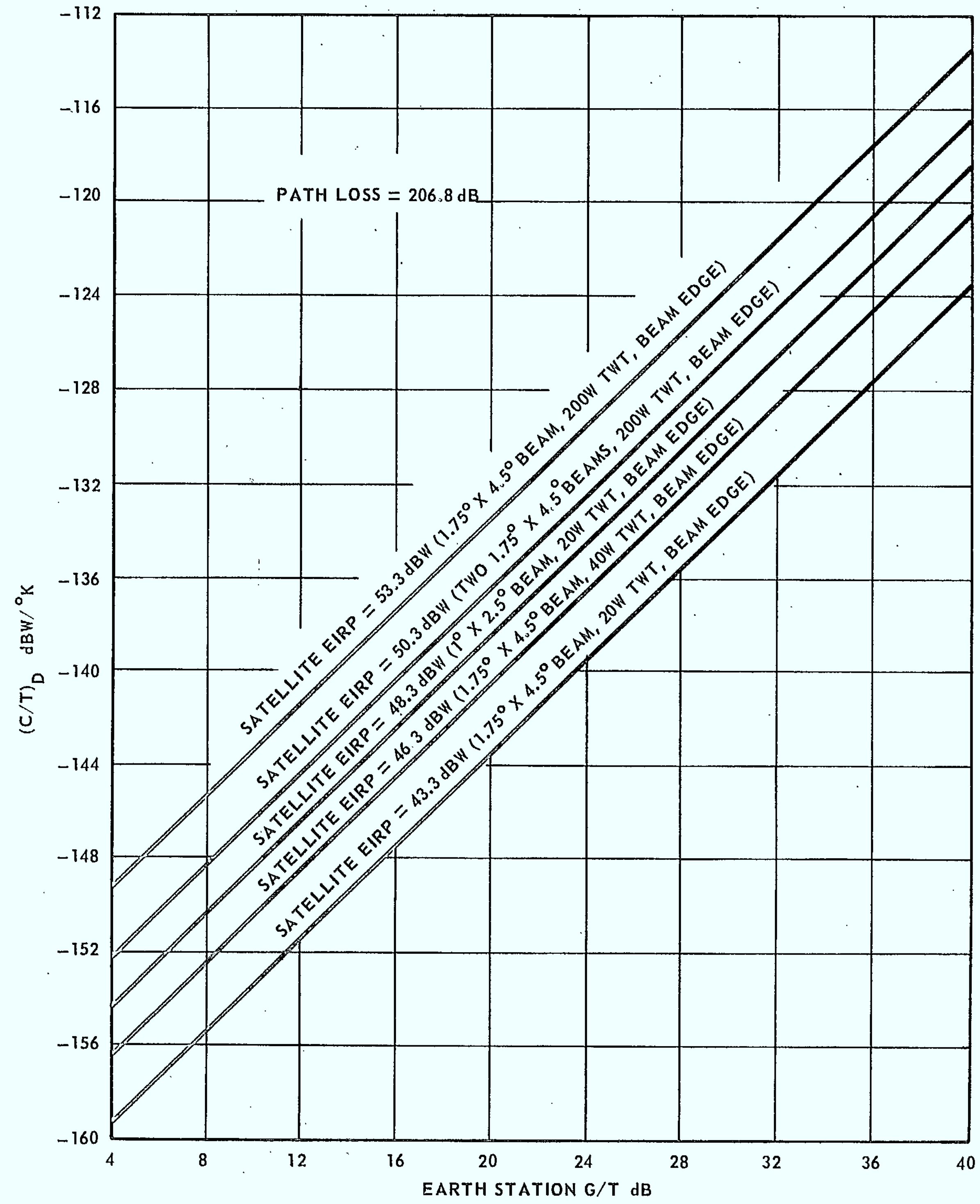
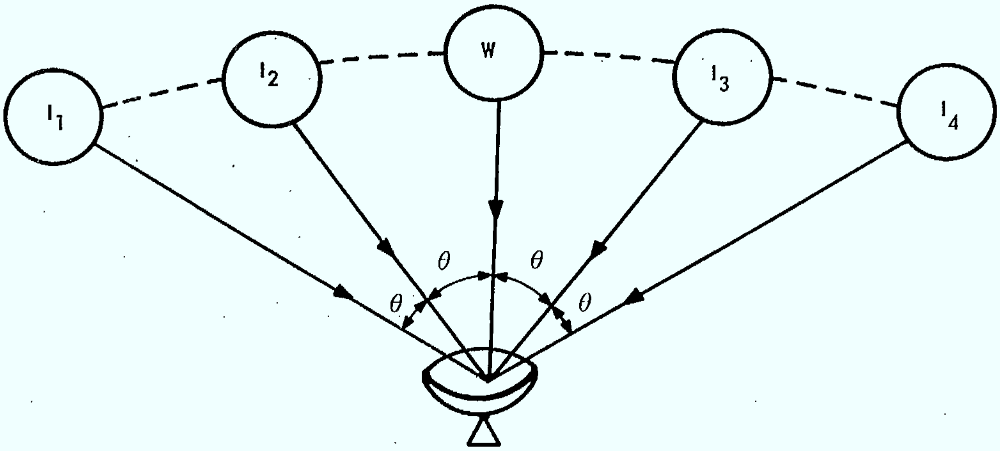


Figure 7-9 Curves of $(C/T)_D$ versus Earth Station G/T

7.2.6 INTERFERENCE ANALYSIS

Interference is recognized as a possible limiting factor for system design. Analysis requires a credible model for distribution of satellites in the geostationary orbit, and typical antenna characteristics. These are presented. Subsections of this section deal with interference effects and limitations for digital and FM modulation of TV and message signals.

For the analysis, homogeneous satellites were considered to be spaced equal distances apart in the geostationary orbit as shown in Figure 7-10.



θ = Satellite Orbital Separation (degrees)

Figure 7-10 Satellite System Model for Interference

It is assumed for the purposes of this study that all the satellites are homogeneous (i.e. same EIRP, transponder bandwidths, receive sensitivity, etc). Also to consider the system under the maximum constraint, no cross-polarization discrimination or any advantage due to satellite antenna directivity is assumed.

The CCIR formula[7.1] which gives the earth station antenna gain for angles greater than 1° off beam center

$$32 - 25 \log_{10} \theta \text{ dB*}$$

where θ = off-axis angle.

Employing this formula, the discrimination for an interfering satellite at angle θ off-axis will be:

$$D = G - 32 + 25 \log_{10} \theta \text{ (dB)}$$

where G = on-axis gain of earth station antenna.

Thus for satellites 2 and 3 the total discrimination will be:

$$D_{2,3} = G - 35 + 25 \log (\theta)$$

For satellites 1 and 4 the total discrimination will be:

$$\begin{aligned} D_{1,4} &= G - 35 + 25 \log (2\theta) \\ &= G - 27.5 + 25 \log \theta. \end{aligned}$$

Combining discrimination from satellites 2, 3 and 1,4

$$D_{1,2,3,4} = G - 35.7 + 25 \log_{10} \theta.$$

Figures 7-11 and 7-12 give the angular discrimination versus satellite separation for various antenna diameters at 12 GHz and 15 GHz.

---

* This formula is stated as generally applicable for antennas and frequencies where $D/\lambda = 100$. In the frequency bands being considered (12 through 15 GHz) the minimum size antenna corresponds to 7 through 8 feet in diameter. Thus, this relationship is considered in the study for antenna diameters larger than 6 feet.

* * *

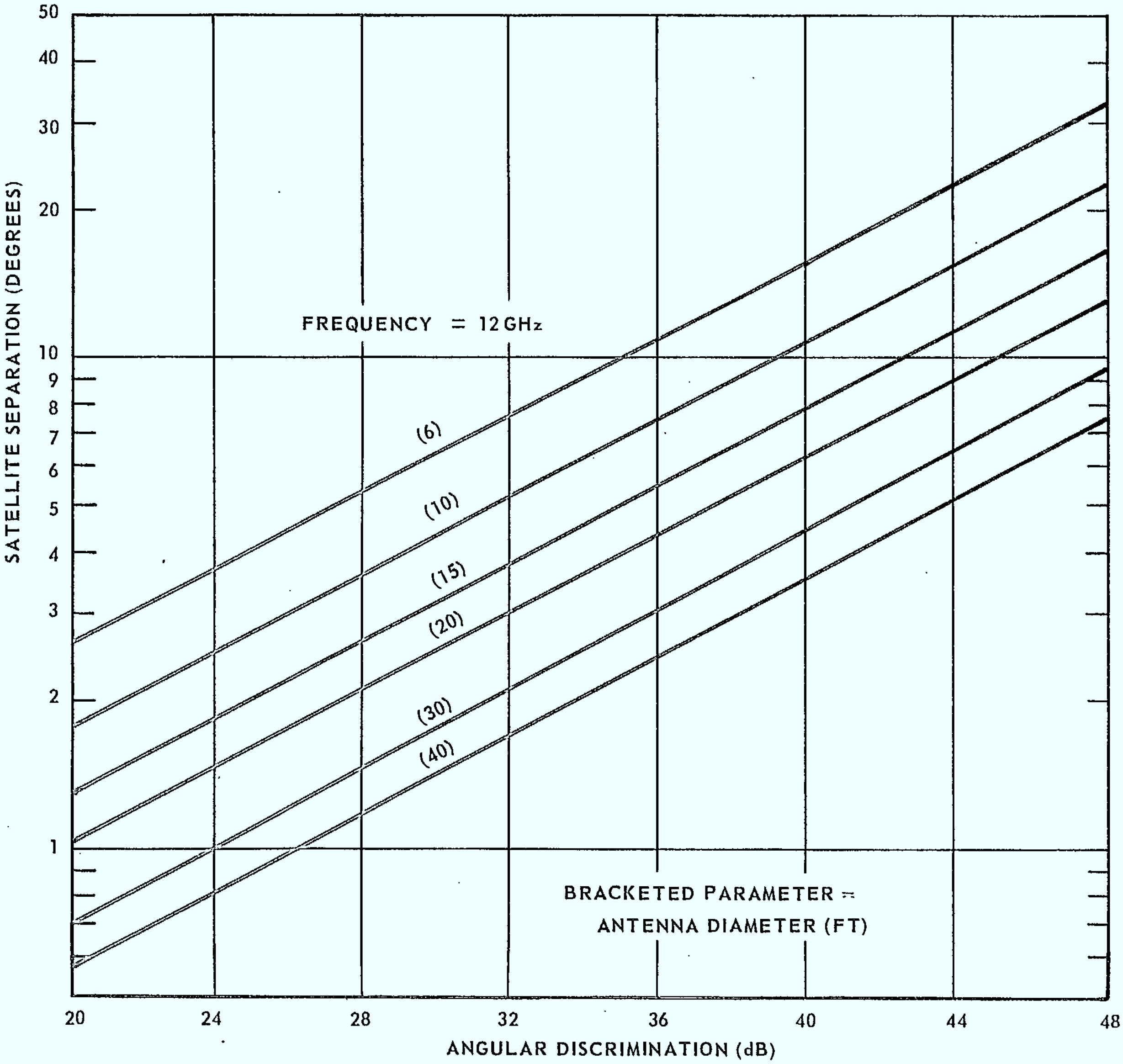


Figure 7-11 Antenna Angular Discrimination (12 GHz)

* * *

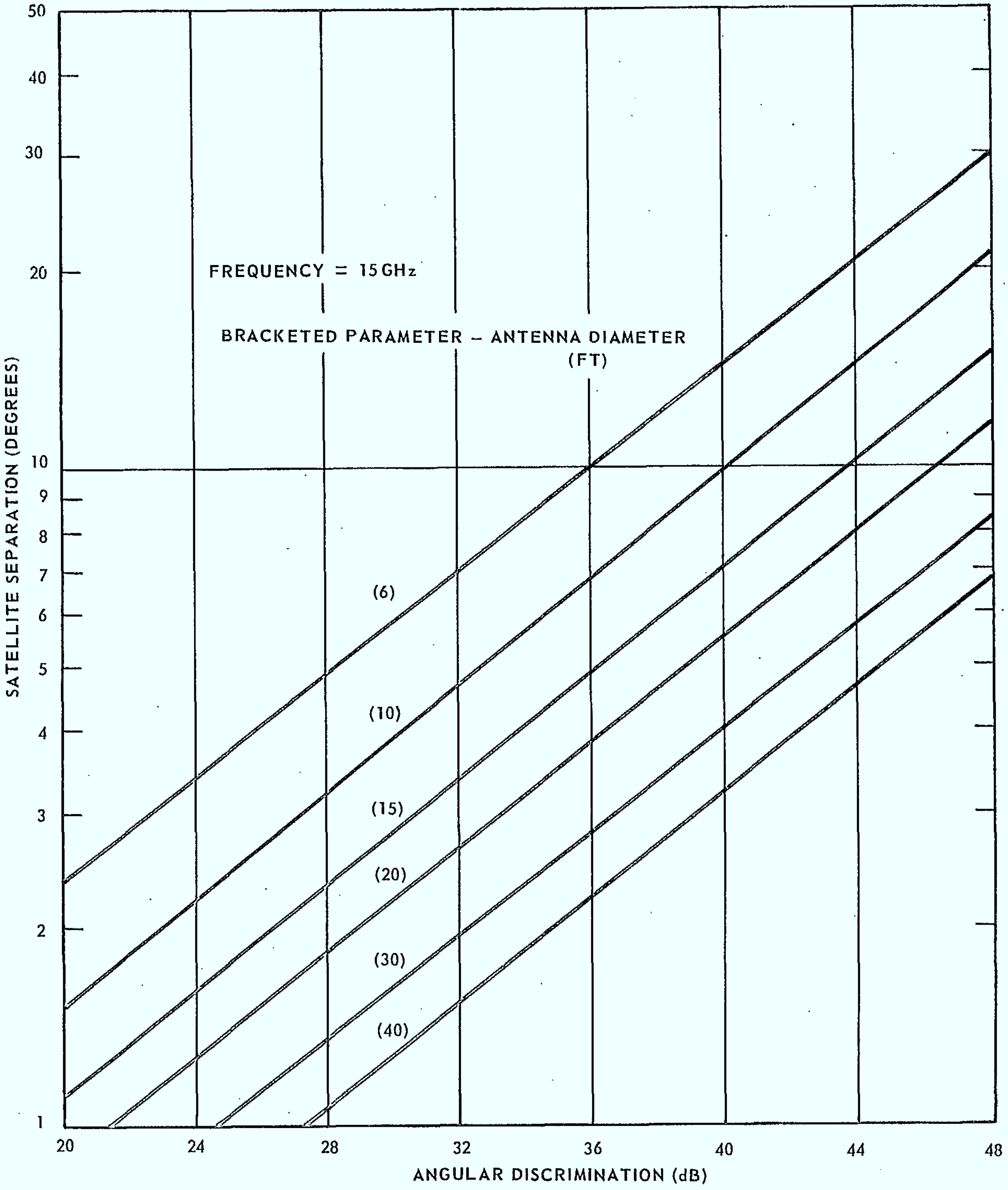


Figure 7-12 Antenna Angular Discrimination (15 GHz)

7.2.6.1 DIGITAL TRANSMISSION (CPSK)

Interference from angle modulated signals into 2ϕ, 4ϕ, 8ϕ and 16ϕ digital systems is examined. A graph of required satellite separation versus earth station antenna diameter is obtained.

The case of an interfering angle-modulated signal into a coherent phase shift keying modulation carrier is considered. The amount of degradation in error performance due to co-channel angular modulated carrier is given by Prabhu[7.2]. For 4ϕ, 8ϕ and 16ϕ systems the carrier to interference ratio C/I is given as:

$$2\phi \text{------------------} (C/I)_T \geq 20 \text{ dB}$$

$$4\phi \text{------------------} (C/I)_T \geq 25 \text{ dB}$$

$$8\phi \text{------------------} (C/I)_T \geq 30 \text{ dB}$$

$$16\phi \text{------------------} (C/I)_T \geq 35 \text{ dB}$$

The C/I for the various levels of modulation was chosen so that the degradation in signal to noise ratio is less than 0.5 dB at an error rate of 1 in 10^7, with C/I degradation taken into account.

Using these values of required C/I the separation requirements of satellites are given in Figure 7-13 for the various antenna sizes.

The interference requirement was split equally between the up-path and down-path thus making the spacing for the down-path slightly higher due to the lower frequency.

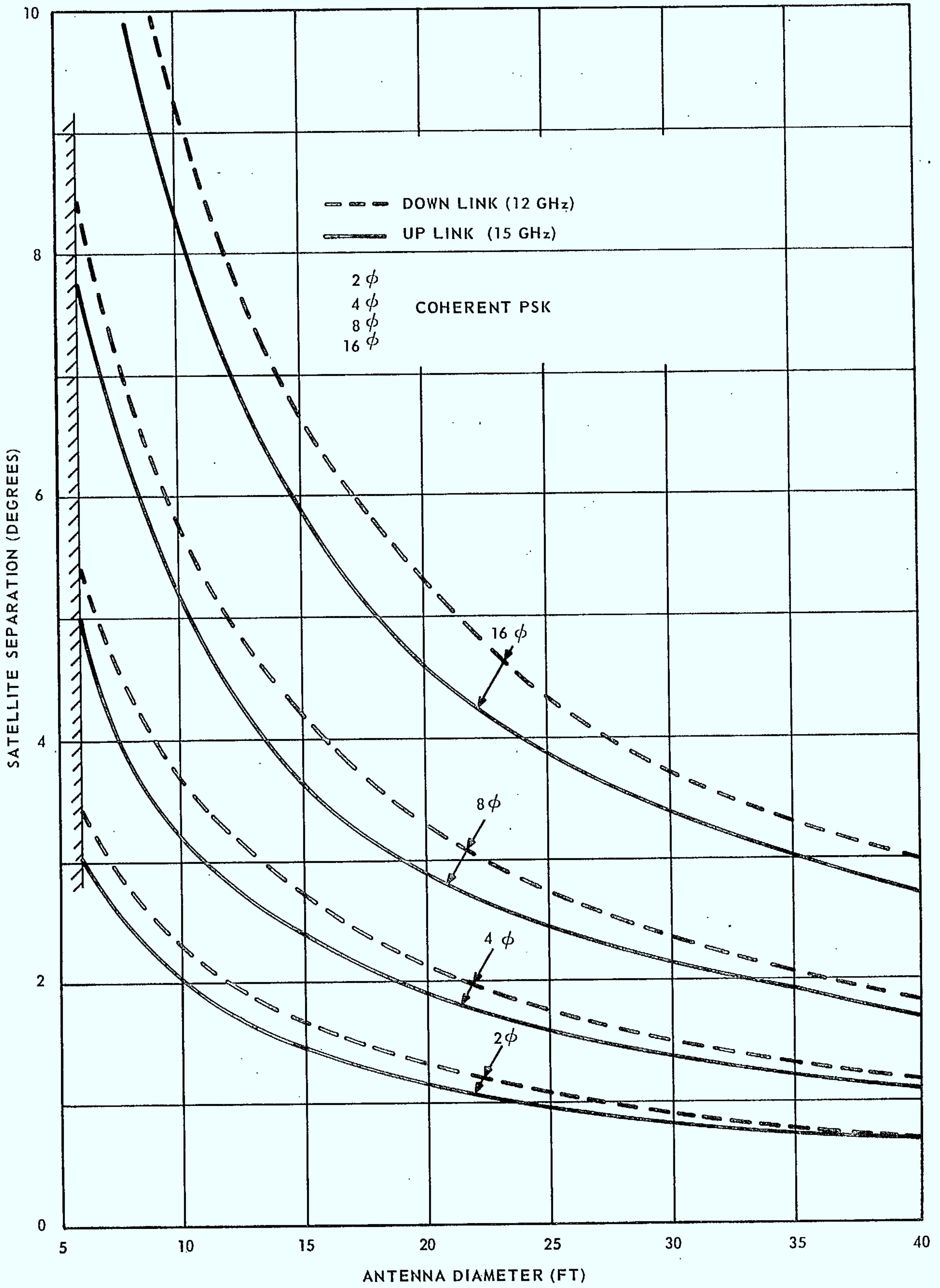


Figure 7-13 Satellite Separation versus Antenna Diameter

7.2.6.2 INTERFERENCE CONSIDERATIONS FOR TELEVISION

The C/I that is tolerable for a television signal is dependent upon the performance quality required and the deviation of the video rf signal. Interference objectives for commercial and educational television systems are determined along with minimum satellite separation versus earth station antenna size for the two systems.

There are two types of television systems that are being considered, commercial television transmission and ETV. Since the quality of the two services differ, their interference requirements will be different.

(a) Commercial Television

The signal-to-rms weighted noise performance chosen for commercial television is 54 dB (not including sync pulse).

The interference objectives for television were obtained from a CCIR report[7.3]. For the case of co-channel television interference, the report provided the following relationship between the permissible signal-to-interference (S/I) in the baseband and the carrier-to-interference ratio (C/I) in the IF.

$$S/I = C/I + B_V$$

where S = black to white picture signal level (in baseband)

and B_V is the video interference reduction factor given by:

$$B_V = 6 + 20 \log_{10} \Delta f$$

where Δf = peak-to-peak frequency diviation.

The above equation assumes interference noise in the absence of thermal noise. In the presence of thermal noise it is suggested that the total weighted baseband noise power is obtained by the power sum of the two noise sources for carrier-to-interference ratios greater than 15 dB, which is the case under consideration (as will be seen in the technical trade-offs of chapter 8) needs a bandwidth of approximately 32 Mhz.

Hence

$$\Delta f_{p-p} = B_{rf} - 2f_m$$

$$= 32.0 - 8.4 = 23.6 \text{ MHz}$$

and $$B_v = 6 + 20 \log_{10} 23.6 = 33.4 \text{ dB.}$$

$$\therefore \quad S/I = C/I + 33.4.$$

The choice of the appropriate value of S/I is based on the considerations that the power sum of S/I and S/N thermal is 54 dB as justified in chapter 4, section 4.2, and that the S/N thermal is not set unnecessarily high, with all the consequent penalties. A value of 8 through 10 dB for the difference is reasonable. In particular a difference of 8.7 dB yields a degradation not in excess of 0.7 dB, and is chosen. This corresponds to an S/I requirement of 62.7 dB, hence,

$$(C/I)_T = 62.7 - 33.4$$

$$= 29.3 \text{ dB.}$$

Splitting this allowance equally between up-link and down-link, the spacing requirements are given in Table 7-5.

Table 7-5 Minimum Satellite Spacing Requirements
(Commercial Television)

ANTENNA DIAMETER (FEET)	SATELLITE SPACING (DEGREES)	
	UP-LINK	DOWN-LINK
10	4.8	5.4
15	3.5	4.0
20	2.8	3.2
30	2.0	2.2
40	1.7	1.8

(b) ETV Objectives

The model chosen for ETV, as justified in chapters 4 and 8, has the following parameters:

$(S/N)_W$ -------------------------- 39 dB (CCIR)

(C/N) clear weather ------------ 15.1 dB

rf bandwidth ------------------- 16 MHz.

Thus,

$$\Delta f_{p-p} = 16 - 8.4 = 7.6 \text{ MHz}$$

$$B_v = 6 + 20 \log_{10} (7.6) = 23.6 \text{ dB}.$$

For reasons stated in the commercial television interference considerations, S/I is chosen as 39 + 8.7 = 47.7 dB.

$$\therefore \quad (C/I)_T = 47.7 - 23.6 = 24.1 \text{ dB}.$$

Table 7-6 gives the satellite spacing requirements to meet this objective on the up-link and down-link, splitting the contributions equally between the up- and down-links.

Table 7-6 Minimum Satellite Spacing Requirements (ETV)

ANTENNA DIAMETER (FEET)	SATELLITE SPACING (DEGREES)	
	UP-LINK	DOWN-LINK
6	4.4	4.8
10	3.0	3.3
15	2.2	2.4

* * *

7.2.6.3 FDM/FM TELEPHONY

An interference noise allowance of 1000 pWc is set for this type of modulation. Curves of satellite separation versus station antenna size with the satellite link carrier/thermal noise as a parameter are derived. The results indicate that this type of modulation is more sensitive to interference than the digital modulation case.

In considering interference constraints for FDM/FM systems, only single access cases will be considered. In multiple access FDM/FM system, the channel test-tone deviations tend to be larger than for the single access cases to compensate for the lower system carrier-to-noise density resulting from intermodulation condition. Thus the larger test-tone deviations generally make these systems less sensitive to interference (i.e. can tolerate lower carrier-to-interference ratios for the same interference budget). Hence the considerations for single carrier are more stringent than the ones for multiple-access, and are presented.

Noise Objective of Satellite Link

The overall noise objective from earth station modulator input to demodulator output was set at 37.5 dBrnc0. This is equivalent to 5630 pWc. An allowance of no more than 1000 pW is considered reasonable. It is also the generally accepted value for current systems. Thus divide up this allowance equally

Up-link interference	500 pWc
Down-link interference	500 pWc

Interference Calculation

For the case of an FM system being disturbed by another co-channel FM system, the ratio of average coherent interference power to average message power in a small band is given by[7.4]:

$$n(w) = r^2 \sqrt{\frac{a^2\ e^{-a^2/4}\ \underline{D}^2{}_e}{2\sqrt{\pi}\ \underline{D}^2{}_1\ \underline{D}_e}} \qquad \ldots \qquad (1)$$

where

$r^2 = \frac{1}{C/I}$ (carrier-to-interference ratio)

$a = f/fm$ (fm = maximum baseband frequency)

f = mid frequency of the desired channel

D = RMS deviation ratio of wanted system

$D_e = \frac{1}{2}\sqrt{(\underline{D}^2{}_1 + \underline{D}^2{}_2)}$

$\underline{D}_2$ = RMS deviation ratio of interfering carrier.

This formula applies for systems that have gaussian modulation which is a good approximation for large capacity systems.

The relationship between test-tone (TT) to interference (I) and n(w) is given by:

$$\frac{TT}{I} = \frac{fm}{l^2 \; n(w) \; b} \qquad \ldots \qquad (2)$$

where

fm = maximum modulating frequency

$l = \text{Antilog}_{10}\left(\frac{-15 + 10 \log n}{20}\right)$ (multi-channel loading factor)

b = voice channel bandwidth (3.1 KHz)

n = number of telephone channels.

For the case of large deviation FM systems, the worst case interference (for co-channel case) occurs in the top baseband of the system which will be considered here. Also the assumption is made that the interfering carrier is an identical FM system (i.e. $D_1 = D_2$).

As can be seen from equations (1) and (2), the test-tone to interference ratio TT/I is dependent only on the rms deviation ratio and the C/I. Also the rms deviation ratio of an FM system depends only on the thermal noise allowance and the system carrier-to-noise ratio C/N. Table 7-7 gives the required C/I ratio for various system carrier-to-noise ratios for an allowable interference noise of 1000 pWc. Pre-emphasis improvement is included in the calculations.

Table 7-7 Required C/I Ratios

C/N (dB)	RMS DEVIATION RATIO D	C/I (1000 pWc)
15	1.88	30.0
20	1.25	35.0
25	0.88	37.5
30	0.54	40.0
35	0.342	42.0

The C/I given in Table 7-7 corresponds to the total allowable interference noise in the system. Assuming equal up-link and down-link contributions, the C/I for up- or down-link would be 3 dB higher than given in Table 7-7.

Figures 7-14 and 7-15 give the required satellite separation versus antenna diameter for various system carrier-to-noise ratio.

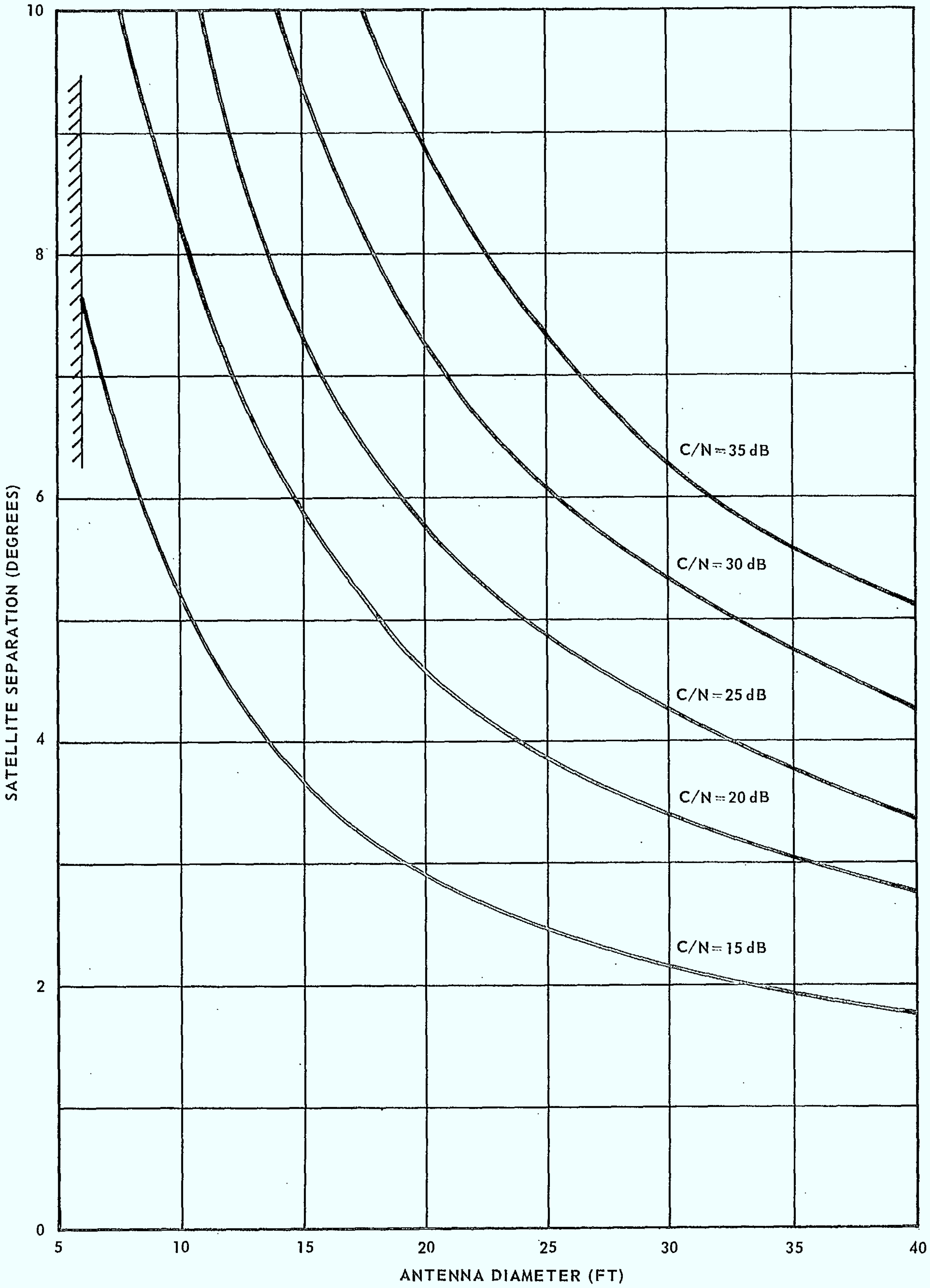


Figure 7-14 Required Satellite Separation for Interference Contribution of 500 pWc (Up-Link)

* * *

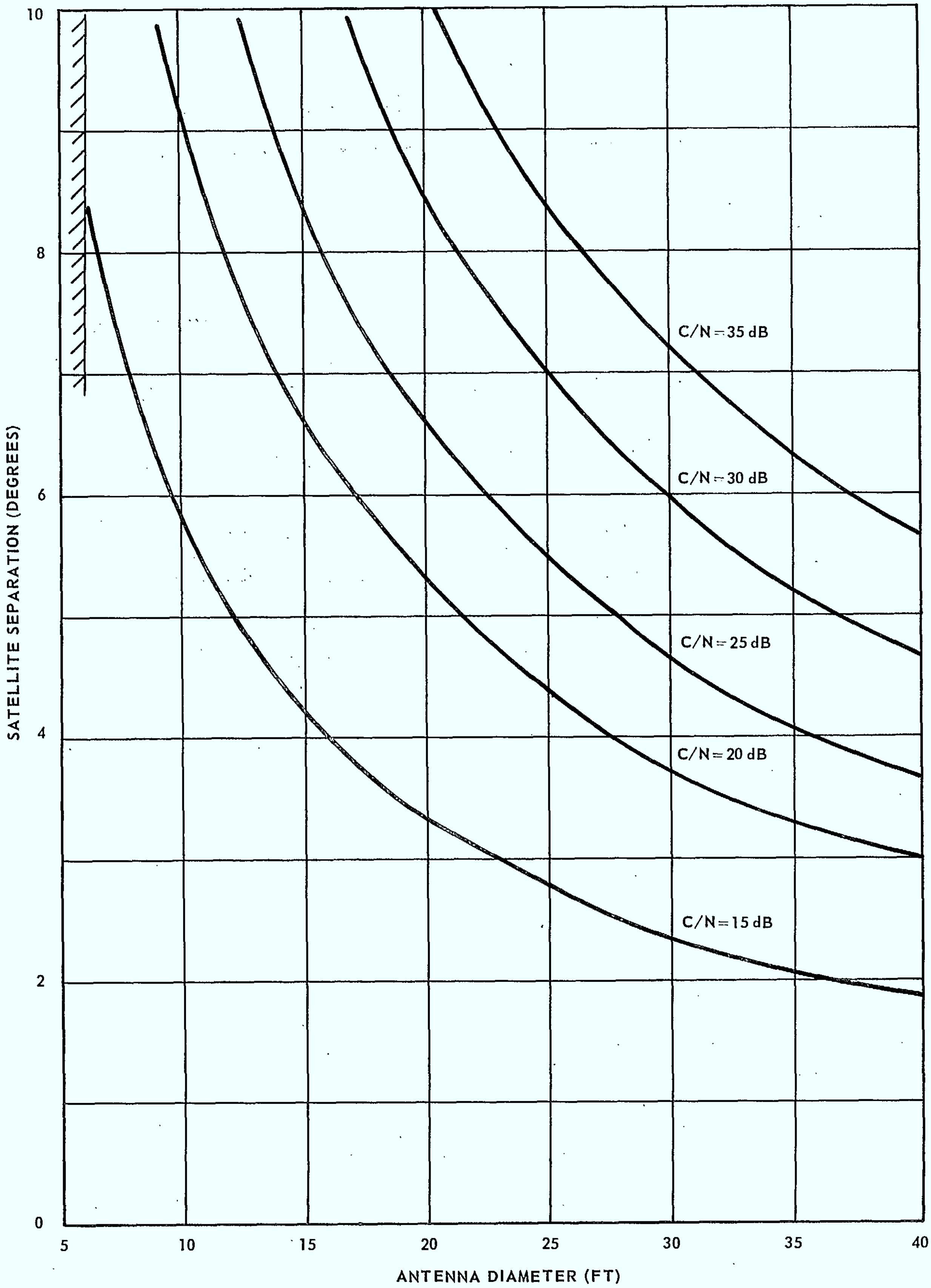


Figure 7-15 Required Satellite Separation for Interference Contribution of 500 pWc (Down-Link)

7.3 REFERENCES

7.1 CCIR; "Radiation Diagrams of Antenna at Communication Satellite Earth Stations for Use in Interference Studies," Report 391-1, Vol. IV, part 2, New Delhi, 1970.

7.2 V.K. Prabhu; "Error Rate Consideration for Coherent.....With Co-channel Interference," B.S.T.J., March 1969.

7.3 CCIR; "Frequency Sharing between Communication Satellite Systems and Terrestial Radio Relay Systems," Report 449, Vol. IV, part 1, XIIth Plenary Assembly, New Delhi, 1970.

7.4 E.D. Sunde; "Communication Systems Engineering Theory," John Wiley & Sons Inc., New York, pp 437-441, 255-256.

* * *

8. System Modeling Maps and Technical Constraints

8.1 INTRODUCTION

In this chapter specific system modeling maps are derived for each of the identified services, and technical constraints are discussed in depth.

In this chapter the system modeling maps for the following services will be developed and technical constraints will be discussed in depth.

a) Commercial Television

b) Educational Television

c) Telephony (and Digital Services)

  1) Major Traffic Communications

    i) PCM-8ϕ CPSK-TDMA

    ii) PCM-4ϕ CPSK-TDMA

    iii) FDM-FM-FDMA

  2) Remote Communications

    i) PCM-4ϕ CPSK-TDMA

    ii) PCM-2ϕ CPSK-TDMA

    iii) FDM-FM-FDMA

d) Telephony using single channel per carrier systems.

The results of this chapter are bounded 'systems modeling maps' for the above.

* * *

8.2 COMMERCIAL AND EDUCATIONAL TELEVISION SERVICES

System modeling maps for commercial and educational services are presented and systems boundaries are delineated.

Commercial and educational services are considered together because, for the technical point of view, the information that needs to be transferred is identical in format and content. The only major difference is the quality of transmission desired as indicated in chapter 4 section 4.2. Hence the derivation of the modeling maps, until the parameter of transmission quality is introduced, is identical in both cases. The choice of modulation is discussed and the systems boundaries are presented individually for commercial and educational television services.

* * *

8.2.1 MODULATION CONSIDERATIONS

FM is considered the appropriate modulation for the television services.

In a satellite system for television, both FM and PCM-CPSK modulations are practical. In the study here, FM has been selected for detailed consideration for the following reasons:-

a) For a transmission system that does not use video bandwidth compression or special encoding techniques, FM is more efficient than PCM-CPSK as FM requires less power-bandwidth product to give the same quality of service. For example, a PCM-CPSK system would require a bit rate of about 92 Mb/s to transmit one channel of television of commercial quality. With 8-phase CPSK, this would require a system carrier-to-noise ratio of about 23 dB and a bandwidth of about 37 MHz. To give the same quality of performance, as will be shown later, FM requires a carrier-to-noise ratio of only about 15 dB and a bandwidth of about 30 MHz (see 8.2.3.1). While there is little doubt that bandwidth compression, redundancy removal and special coding techniques will continue to be investigated in the foreseeable future, it is not likely that there will be a universal acceptance of these techniques resulting in large-scale deployment of the appropriate hardware at the beginning of the time period covered by this study. There are two reasons for this view. Firstly, a new and universally accepted standard of redundancy removal related to subjective quality of television will have to be established. Secondly, the principle of transmission facilities processing and reconstructing information independent of the program originating source will have to be accepted. Both questions are likely to take considerable time to resolve, as they are subjects of controversy, both technical and non-technical.

b) FM is a well-proven and simple technique and standard equipment is readily available at low cost. These are important factors in the earth segment as the number of earth stations is large.

For the television sound channel, a subcarrier modulation scheme is assumed. Calculations in another study[8.1] for satellite systems similar to this study have indicated that to accommodate one sound subcarrier, the increase in bandwidth and power is about 6 percent for a quality of video signal corresponding to TASO grade 2 or better. (TASO grade 2 is fine quality with just perceptible interference). The increase in power is negligibly small (0.3 dB) and will be ignored in this study. The increase in bandwidth will be allowed for when considering the total satellite system models in chapter 10.

8.2.2 DERIVATION OF SYSTEM MODELING MAPS FOR TELEVISION SERVICES

The theoretical equations required for plotting the system modeling maps are derived.

This subsection will first consider the fundamentals of a television transmission system using FM. The system modeling maps will then be derived.

The well known FM equation relating signal/noise ratio to the system parameters is:-

$$\frac{S}{N} = 12 . \frac{C}{T} . \frac{1}{k} . \frac{1}{fm} \left(\frac{\Delta Fp}{fm}\right)^2 P_W \qquad \text{(weighted)} \qquad (1)$$

where

$$\frac{S}{N} = \left(\frac{\text{syn. tip to white level voltage}}{\text{weighted rms noise voltage}}\right)^2$$

$\frac{C}{T}$ = carrier to noise temperature ratio

k = Boltzman's constant

fm = max. baseband frequency

ΔFp = one-sided peak frequency deviation

P_W = pre-emphasis and weighting factor.

By Carson's Rule, the rf bandwidth B is given by:-

$$B = 2(\Delta Fp + fm)$$

or

$$\left(\frac{\Delta Fp}{fm}\right)^2 = \frac{1}{4}\left(\frac{B}{fm} - 2\right)^2 \qquad (2)$$

Substituting equation (2) in equation (1):-

$$\frac{S}{N} = 3 \frac{C}{T} . \frac{1}{k} . \frac{1}{fm}\left(\frac{B}{fm} - 2\right)^2 P_W \qquad \text{(weighted)} \qquad (3)$$

For 525 line television as used in Canada:-

$fm = 4.2 \times 10^6$ Hz.

$10 \log P_W = 12.8$ dB.

Expressing all the parameters in equation (3) in dB, we then have:-

$$\frac{C}{T} = \frac{S}{N} - 180 - 20 \log \frac{B}{4.2 \times 10^6} \quad \text{dBW/°K} \qquad (4)$$

Given any desired S/N equation (4) gives a direct relationship between C/T and rf bandwidth B necessary to maintain the stated S/N. The parameters in equation (4) are tabulated in Table 8-1 and plotted in Figure 8-1.

Table 8-1 Tabulation of Values from Equation (4)

B (MHz)	OVERALL C/T(dBW/°K)					
	S/N = 42 dB	S/N = 45 dB	S/N = 48 dB	S/N = 51 dB	S/N = 54 dB	S/N = 57 dB
10.5	-132.0	-129.0	-126.0	-123.0	-120.0	-117.0
12.6	-138.0	-135.0	-132.0	-129.0	-126.0	-123.0
16.8	-144.0	-141.0	-138.0	-135.0	-132.0	-129.0
21.0	-147.5	-144.5	-141.5	-138.5	-135.5	-132.5
25.2	-150.0	-147.0	-144.0	-141.0	-138.0	-135.0
29.4	-152.0	-149.0	-146.0	-143.0	-140.0	-137.0
33.6	-153.6	-150.6	-147.6	-144.6	-141.6	-138.6
37.8	-154.9	-151.9	-148.9	-145.9	-142.9	-139.9
42.0	-156.1	-153.1	-150.1	-147.1	-144.1	-141.1
46.2	-157.1	-154.1	-151.1	-148.1	-145.1	-142.1
50.4	-158.0	-155.0	-152.0	-149.0	-146.0	-143.0
54.6	-158.8	-155.8	-152.8	-149.8	-146.8	-143.8
58.8	-159.6	-156.6	-153.6	-150.6	-147.6	-144.6

The curves in Figure 8-1 give the fundamental trade-offs of rf bandwidth versus carrier/noise temperature ratio. For any given S/N it is possible, within limits, to decrease C/T and compensate for it by increasing bandwidth B.

Unfortunately, an increase of B and a decrease of C/T both work to reduce the total carrier/noise ratio C/N_oB. In an FM system

In an FM system there is a minimum acceptable C/N_oB known as threshold which is generally taken as 10 dB.

For any selected C/T the bandwidth at threshold is a fundamental constraint and on the system modeling map appears as one of the fundamental boundaries. For any desired S/N the lowest C/T is obtained at the corresponding threshold bandwidth (Figure 8-1). Larger bandwidths can only be sustained at higher values of C/T, and if so sustained, yield a higher S/N ratio than that desired.

The system modeling maps for commercial television and educational television will now be derived. First it is necessary to define the quality of service, that is, the desired S/N.

(a) Commercial Television

The desired S/N will be defined as 57 dB (weighted). The choice of this S/N is based on the following considerations. CCIR requires an equivalent of 59 dB (56 dB in the CCIR definition of S/N) for a long haul terrestrial link. It is assumed that the two end-links at the studio and broadcast stations would each degrade the system by 1 dB. In a satellite network using 12 through 14 GHz, where no flux density limits apply (see chapter 3, section 3.3) the transmit and receive earth stations would be located close to the studio and broadcast stations respectively and therefore the 2 dB end-link contributions may be allocated to the satellite system. Hence S/N = 57 dB.

(b) Educational Television (ETV)

Define the desired S/N as 42 dB (weighted). The choice of this S/N is based on the assumption that TASO grade 2 quality for the 75% opinion level is adequate. (fine quality with just perceptible interference). This requires a TASO C/N = 38 dB. The conversion factor[8.2] to S/N is 3.6 dB. Hence the desired S/N = 41.6 dB which is rounded up to 42 dB. This figure was also confirmed with the Design Authority as an acceptable performance level for this service. Substituting the desired S/N values in equation (4) gives:-

(a) Commercial TV

$$\frac{C}{T} = -123 - 20 \log \left(\frac{B}{4.2 \times 10^6} - 2 \right) \text{ dBW/°K} \qquad (5)$$

(b) <u>ETV</u>

$$\frac{C}{T} = -138 - 20 \log \left(\frac{B}{4.2 \times 10^6} - 2 \right) \text{ dBW/°K} \qquad (6)$$

The threshold conditions are given as follows:-

(a) Commercial TV

$$\frac{C}{N_o B} = 10 = \frac{C}{T} - k - 10 \log B$$

Substituting for C/T from equation (5), we have:-

$$20 \log\left(\frac{B}{4.2 \times 10^6} - 2\right) + 10 \log B = 95.6 \text{ dB.}$$

Solving, we get the threshold bandwidth = 46 MHz.

(b) <u>ETV</u>

$$\frac{C}{N_o B} = 10 = \frac{C}{T} - k - 10 \log B.$$

Substituting for C/T from equation (6), we have:-

$$20 \log\left(\frac{B}{4.2 \times 10^6} - 2\right) + 10 \log B = 80.6 \text{ dB.}$$

Solving, we get the threshold bandwidth = 19 MHz.

One more system parameter is needed before the system modeling maps can be derived; the up-link noise contribution. It is true at present and in the foreseeable future that satellite down-link power is much more expensive than up-link power. Under such a situation, it is more economical to design a system in which the up-link noise contribution is negligible. Also, it is desirable that a fade in the up-link should not cause a threshold condition in the overall system. A fade in the up-link causes not only a degradation in the up-link noise, but also a certain amount of down link noise degradation as the TWT output is lowered due to a decrease in the TWT input signal. The up-link noise should therefore be low under normal operating conditions. An up-link C/T 10 dB better than the down-link C/T would contribute about 0.4 dB in overall system degradation under clear weather conditions. Calculations have indicated that reducing the difference between up-link and down-link C/T's to 6 dB would require an increase of down-link EIRP of about

1.2 dB and this is considered excessive. Therefore, a difference of 10 dB seems reasonable and for the system models in the rest of this section this amount of up-link noise contribution will be used.

$$(C/T)_D = C/T + 0.4 \text{ dB} \tag{7}$$

where $(C/T)_D$ = down-link carrier-to-noise temperature ratio

C/T = overall system carrier-to-noise temperature ratio.

Now, the down link equation is:-

$$(C/T)_D = \text{EIRP} - L_p + G/T \tag{8}$$

where EIRP = EIRP of the satellite.

L_p = propagation path loss under clear weather (L_p = 206.8 dB).

G/T = G/T of earth station.

For commercial TV, equations (5), (7) and (8) can be combined to give:-

$$\text{EIRP} = 84.2 - G/T - 20 \log \left(\frac{B}{4.2 \times 10^6} - 2 \right) \tag{9}$$

This is the equation required to plot the system modeling map for commercial TV with S/N = 57 dB. Values of equation (9) are tabulated in Table 8-2 and Figure 8-2, plotted from these values, gives the system modeling map.

Table 8-2 Tabulation of Values from Equation (9)

B(MHz)	SATELLITE EIRP(dBW)						
	G/T = 16 dB	G/T = 20 dB	G/T = 24 dB	G/T = 28 dB	G/T = 32 dB	G/T = 36 dB	G/T = 40 dB
10.5	74.2	70.2	66.2	62.2	58.2	54.2	50.2
12.6	68.2	64.2	60.2	56.2	52.2	48.2	44.2
16.8	66.2	62.2	54.2	50.2	46.2	42.2	38.2
21.0	58.2	54.2	50.7	46.7	42.7	38.7	34.7
25.2	56.2	52.2	48.2	44.2	40.2	36.2	32.2
29.4	54.2	50.2	46.2	42.2	38.2	34.2	30.2
33.6	52.7	48.7	44.7	40.7	36.7	32.7	28.7
37.8	51.3	47.3	43.3	39.3	35.3	31.3	27.3
42.0	50.2	46.2	42.2	38.2	34.2	30.2	26.2
46.2	49.1	45.1	41.1	37.1	33.1	29.1	25.1
50.4	48.2	44.2	40.2	36.2	32.2	28.2	24.2
54.6	47.4	43.4	39.4	35.4	31.4	27.4	23.4
58.8	46.6	42.6	38.6	34.6	30.6	26.6	22.6

For ETV, equations (6), (7) and (8) can be combined to give:

$$\mathrm{EIRP} = 69.2 - G/T - 20 \log \left(\frac{B}{4.2 \times 10^6} - 2 \right) .$$

This is normally the equation needed to plot the system modeling map for ETV with S/N = 42 dB. However, for the ETV system, it is assumed that satellite tracking antennas would not be used. As explained in 8.2.3.2 an allowance of 2 dB is needed to compensate for the loss in down-link signal due to the satellite movement. Therefore the above equation may be modified to give:

$$\mathrm{EIRP} = 71.2 - G/T - 20 \log \left(\frac{B}{4.2 \times 10^6} - 2 \right) \qquad (10)$$

Values of equation (10) are tabulated in Table 8-3 and plotted in Figure 8.3 as the system modeling map for ETV.

Table 8-3 Tabulation of Values from Equation (10)

B (MHz)	SATELLITE EIRP (dBW)						
	G/T = 6 dB	G/T = 9 dB	G/T = 12 dB	G/T = 15 dB	G/T = 18 dB	G/T = 21 dB	G/T = 23 dB
10.5	71.2	68.2	65.2	62.2	59.2	56.2	54.2
12.6	65.2	62.2	59.2	56.2	53.2	50.2	48.2
16.8	59.2	56.2	53.2	50.2	47.2	44.2	42.2
21.0	55.7	52.7	49.7	46.7	43.7	40.7	38.7
25.2	53.2	50.2	47.2	44.2	41.2	38.2	36.2
29.4	51.2	48.2	45.2	42.2	39.2	36.2	34.2
33.6	49.7	46.7	43.7	40.7	37.7	34.7	32.7
37.8	48.3	45.3	42.3	39.3	36.3	33.3	31.3
42.0	47.2	44.2	41.2	38.2	35.2	32.2	30.2
46.2	46.1	43.1	40.1	37.1	34.1	31.1	29.1
50.4	45.2	42.2	39.2	36.2	33.2	30.2	28.2
54.6	44.4	41.4	38.4	35.4	32.4	29.4	27.4
58.8	43.6	40.6	37.6	34.6	31.6	28.6	26.6

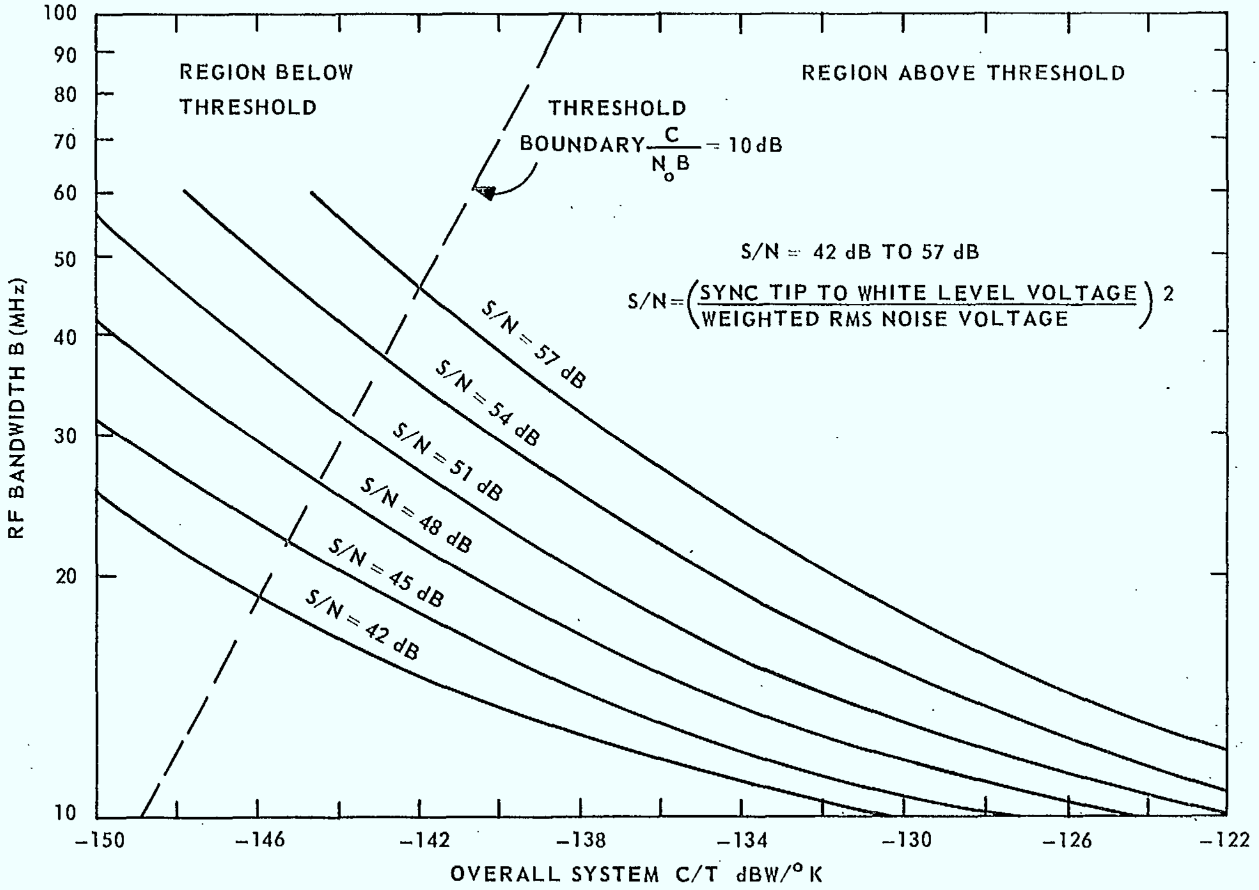


Figure 8-1 Television System Using FM Plots of RF Bandwidth versus C/T

* * *

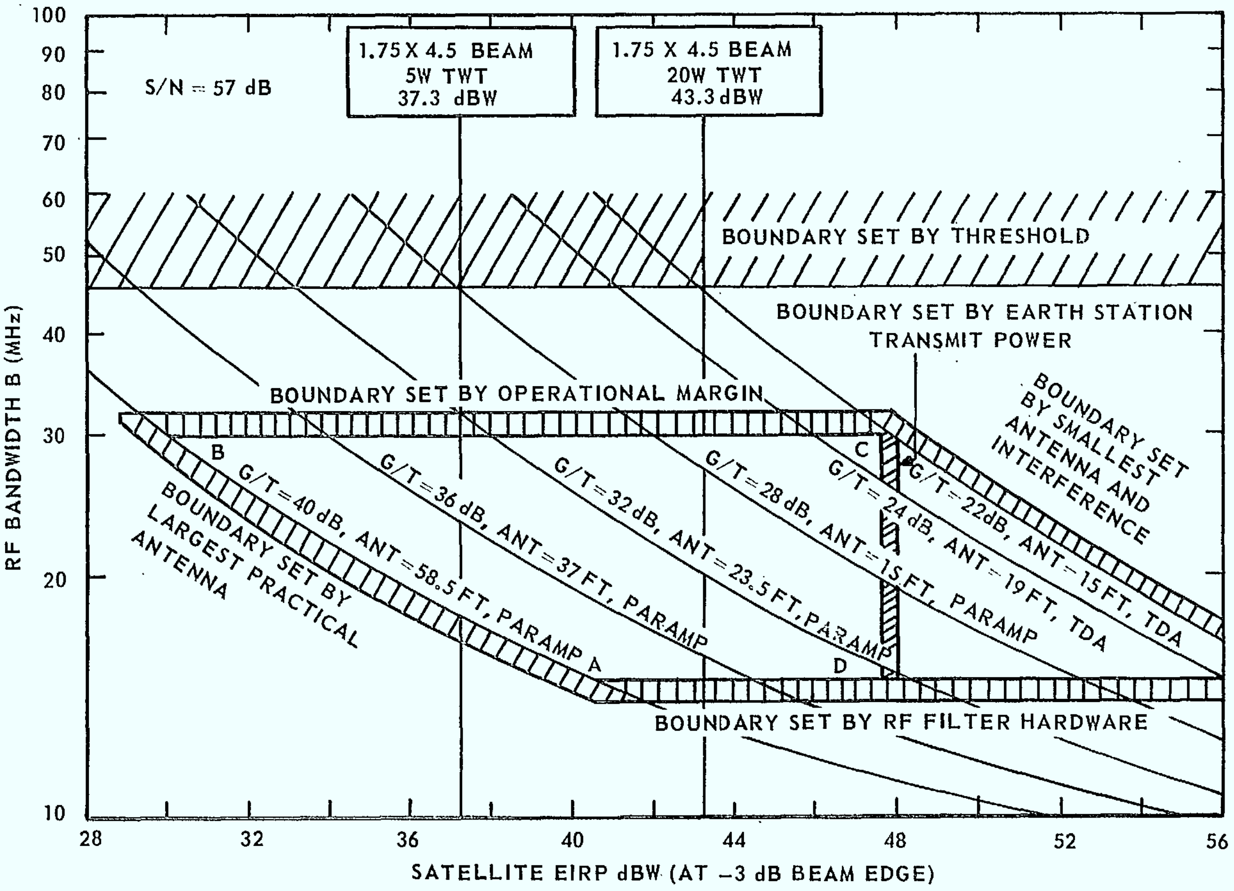


Figure 8-2 System Modeling Map for Commercial Television

* * *

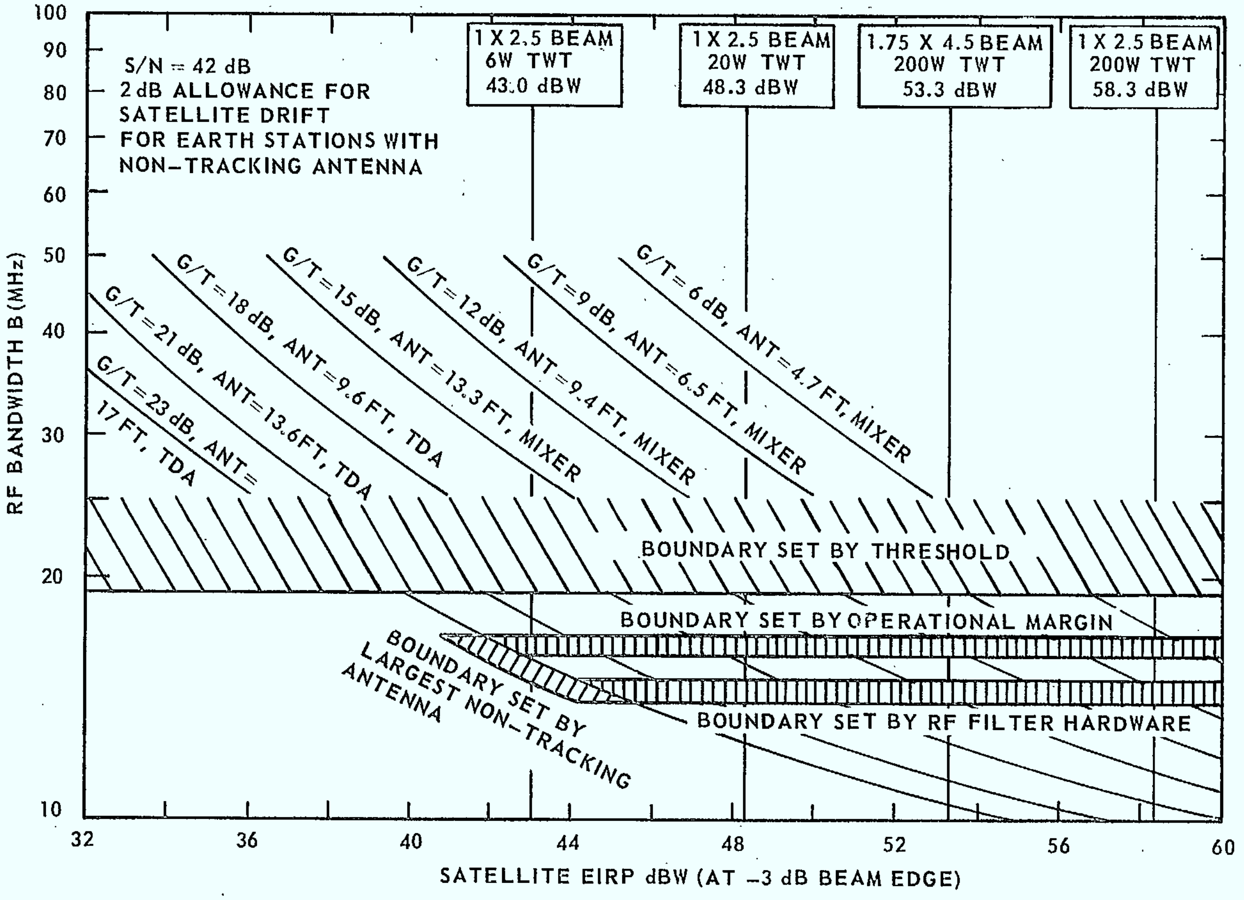


Figure 8-3 System Modeling Map for Educational Television

8.2.3 SYSTEMS BOUNDARIES

In the two subsections of this section, technical systems constraints for commercial and educational television are separately discussed.

Figures 8-2 and 8-3 are system modeling maps for commercial and educational television respectively. The system boundaries for these maps will now be defined and the area of systems choice will be narrowed down. It should be stressed that in most cases the systems boundaries are not rigid and should be regarded as general guides. Commercial and educational television services will be considered separately.

* * *

8.2.3.1 COMMERCIAL TELEVISION

Systems boundaries for commercial television are considered. Five boundaries are identified, quantified and plotted on the system modeling map for commercial television.

Reference will be made to system modeling map, Figure 8-2, when considering each of the system boundaries below:

1) Boundary set by Threshold and Operational Carrier-to-Noise Ratios

For commercial television in which the desired S/N = 57 dB, it has been shown that a threshold is reached when the rf bandwidth is 46 MHz. This is a fundamental system boundary and is the upper limit of desirable transponder bandwidth for this service. Designing a system for this bandwidth would mean operation is at threshold at most of the time, and this is unacceptable. Normal systems should have a margin for down-link fade and for equipment inperfections.

For the fade margin, it is assumed acceptable that the system should not reach threshold for more than 0.1 percent of the time. As most of the commercial TV receive earth stations will be located in the southern belt of Canada and, therefore earth station elevation angles would be reasonably high, it is expected that the main fading would be due to rain and cloud attenuation. However, it is expected that a number of the stations may be in the belt 10° through 20°N where tropospheric fading may be significant. From chapter 5 it is seen that the fade for 0.1 percent of the time would give rise to an overall system degradation of about 3 dB for the northern stations. Therefore 3 dB will be used as the fade margin.

In an FM system, it is generally not desirable to operate too close to threshold as additional noise (mainly click noise) is generated which is not indicated in the FM equation. Moreover, this click noise has a uniform spectrum rather than triangular and, therefore, the weighting factor is lower for this noise. To avoid this additional noise during clear weather, a further margin of 2 dB is allowed. The total system margin therefore will be 15 dB.

Therefore, the operational carrier-to-noise ratio C/N_0B should be 15 dB. This sets the upper transponder bandwidth limit to 30 MHz. This 30 MHz is a new boundary superceding the threshold boundary at 46 MHz.

2) Boundary Set by RF Filter Hardware

In a satellite system using multiple transponders, it is necessary to combine the rf output of each transponder in some manner to feed the antenna or antennas. Also, there are generally some channeling filters necessary to divert the received carriers to the appropriate transponders. To design and build filters for these functions a certain amount of transponder guard band is necessary. The wider the guard band the easier it is to accomplish these. However, guard bands represent wasted bandwidths and should be minimized. Present day satellite systems in the 4 GHz and 6 GHz bands have guard bands of 4 MHz in transponder bandwidths of 36 MHz. Proposed U.S. Domestic Satellite systems in the 12 GHz and 13 GHz bands also have transponder bandwidths of 36 MHz each and guard bands of 4 MHz. That is to say, the guard band is about 10 percent of the transponder band. If the transponder bandwidth is reduced, it is not possible to reduce the guard band in the same ratio. Indeed, the minimum practicable guard band (in MHz) is determined by the resonator Q achievable in the filters. As the transponder bandwidth is reduced a higher percentage of the frequency spectrum will be used as guard bands. For example, a transponder bandwidth of 15 MHz in the 12 GHz band is estimated to need a guard band of 30 through 50 percent, with increasing hardware complexity as the guard band is reduced.

Hence, it is not desirable to reduce the transponder bandwidth too low. For the purpose of setting an approximate boundary in the system modeling, it is proposed to use a lower limit of 15 MHz.

3) Boundary set by Largest Practical Antenna

It is necessary to consider separately two possible types of earth station network, one with antenna tracking and one without.

(a) Network With Antenna Tracking

Apart from cost, which will be considered in chapter 9, the largest practical antenna for this earth station network will be limited by the following constraints:

i) Surface Accuracy

Present day largest antennas in the 4 GHz band for satellite communications purposes are around 100 feet in diameter. The rms surface errors of such antennas are typically 45 thousandths of an inch. This gives an acceptable degradation in efficiency in the 4 GHz band. If the same efficiency criterion were to apply in the 12 GHz band, the rms surface accuracy should then be about 15 thousandths of an inch. The practical rms surface accuracy is related to the antenna diameter approximately as follows:[8.3]

$$\varepsilon \propto D^{3/2}$$

where ε = RMS surface error

D = antenna diameter

Therefore, if the rms surface error were to be reduced by a factor of 3, the largest practical diameter should be reduced by a factor of $3^{2/3}$ or roughly 2. Hence, scaled down from the 100 feet antenna, the largest antenna at 12 GHz should be about 50 feet.

ii) Tracking Accuracy

Present day 100 feet antennas at 4 GHz have a 3 dB beamwidth of about 0.15°, and antenna tracking accuracy with winds up to 30 mph, is typically 0.01°. It is expected that antenna tracking in the 12 GHz satellite system would have about the same order of accuracy. Antenna beamwidth should therefore be not much lower than the present day 0.15°. An antenna beamwidth as low as 0.1° may be acceptable, that is, an antenna beam 10 times the tracking accuracy. This will indicate an upper range of antenna size of about 58 feet at 12 GHz.

Therefore, in summary, the largest practical antenna seems to be about 58 feet for earth stations with tracking. This is not a rigid boundary, but is rather an indication that much larger antennas should not be considered in the systems modeling.

(b) Network Without Satellite Tracking

It is assumed that satellite station keeping will be such that the satellite will be maintained throughout its life at its normal position with allowable drifts ±0.1 degree in Longitude and ±0.1 degree in orbital inclination. Viewed by any earth station in Canada, to a first approximation, the satellite will move within a solid angle of 0.2° by 0.2°. This will be called the 0.2° by 0.2° box. At an extreme position of 0.1 degree longitudinal drift and 0.1 degree orbital inclination, the satellite will be 0.1 by $\sqrt{2}$ = 0.14° from its nominal position as viewed by an earth station. Assume that at such an extreme position a reasonable loss of down path signal is 2 dB (this is justified later). The 3 dB beamwidth of an earth station antenna which will give a 2 dB loss in gain at an off-axis angle of

ϕ degrees can be obtained from:-

$$G/G_o = 2^{-\left(\frac{2\phi}{b}\right)^2}$$

where G_o = antenna gain on the axis

G = antenna gain at angle ϕ off the axis

b = half-power beamwidth in degrees

ϕ = angle off-axis in degrees

Substitution of the appropriate values in the above equation gives:

Half-power beamwidth b = 0.34°

To obtain this half-power beamwidth at 12 GHz, the earth station antenna size would be about 17 feet. Hence, if the earth station network is to have non-tracking antennas, the antenna size is limited to a maximum of 17 feet. This antenna size may be drawn as a boundary on the system modeling map.

For a network with non-tracking earth stations for commercial TV, it is not considered necessary to increase the satellite EIRP to allow for the 2 dB loss due to satellite drift. The reasons are as follows:-

i) The precentage of time the satellite hovers around the extreme corner of the 0.2° by 0.2° box is very small, as periodic satellite position adjustments are to be made. For most of the time, the satellite will therefore be around its nominal position and the signal loss is less than 2 dB.

ii) The satellite system is designed with a weather fade margin of 3 dB to give 99.9 percent service reliability. There is a further margin of 2 dB to avoid click noise near threshold. A loss of 2 dB of signal during the short percentage of time the satellite is at the corner of the 0.2° by 0.2° box would mean that the service reliability is slightly reduced. It is assumed that this slight penalty is acceptable. It must be remembered that the penalty applies only to those stations located near the edge of the satellite antenna coverage area. Since the antenna beam has half-Canada coverage, it is expected that a majority of the earth stations would be located closer to the beam center and would therefore enjoy a higher down-link EIRP. These stations would not have to suffer the penalty.

4) Boundary set by Smallest Antenna and Inter-Satellite Interference Considerations

There is a minimum antenna size set by inter-satellite interference considerations. In considering the inter-satellite interference problem, it is assumed that there will be four other satellites identical to the wanted satellite in all respects, two on each side along the equatorial orbital arc. The spacing between adjacent satellites is θ degrees. Additional satellites beyond four do not add significantly to the interference problem and can be ignored.

It will be assumed that interference suppression is obtained only through the antenna beam characteristics of the earth stations as any other assumption would imply a restriction on future satellites in adjacent locations in the orbital arc. No allowance will therefore be made for other interference suppression mechanisms such as spot beam satellite antennas pointing away from the wanted coverage zone, polarization discrimination or interspersed frequency allocation of the transponder bands among the satellites. In any practical situation some or all of these other interference suppression techniques will be used. The present considerations would then lead to the worst case limit.

In Appendix B the required interference suppression ratio is shown to be 29.3 dB. For satellite spacings of θ = 4°, this corresponds to earth station antennas no smaller than 15 feet in diameter. Since this satellite spacing is reasonable, therefore 15 feet may be used as the lower bound of earth station antenna size for commercial television. A boundary may be drawn on the system modeling map corresponding to this antenna size.

5). Boundary set by Earth Station Transmitter Power

An up-link power limitation imposes a constraint on the down-link power because of the condition that the up-link has to be a certain number of dB better than the down-link in thermal noise.

Present-day earth station transmitters can operate up to about 8 KW in the 6 GHz band. It is expected that transmitters in the 14 through 15 GHz band in the same power range might be available during the time frame under consideration. While it is most desirable to operate at a lower power level, nevertheless, for the purpose of setting an upper design limit, the 8 KW or 39 dBW will be taken as the upper bound.

The up-link and down-link equations are as follows:-

$$(C/T)_u = (EIRP)_{E/S} - L_u + (G/T)_{sat.} \qquad dBW/°K$$

$$(C/T)_D = (EIRP)_{sat} - L_D + (G/T)_{E/S} \qquad dBW/°K$$

$$(C/T)_D = (C/T)_u - 10 \qquad dBW/°K$$

where $(C/T)_u$ = Up-link carrier-to-noise temperature ratio

$(C/T)_D$ = Down-link carrier-to-noise temperature ratio

$(EIRP)_{E/S}$ = Earth Station EIRP

= $G_T - 2 - 39$ dBW (where the 2 dB is waveguide loss

$(EIRP)_{sat}$ = Satellite EIRP

L_u = Up-link propagation loss = 208.2 dB at 14.25 GHz

L_D = Down-link propagation loss = 206.8 dB at 12 GHz

$(G/T)_{E/S}$ = Earth Station G/T

= $G_R - T$

$(G/T)_{sat}$ = Satellite G/T = -3.7 dB

G_T = Transmit Antenna gain of earth station

G_R = Receive antenna gain of earth station

T = Earth station system noise temperature in dB - °K.

Combining the equations we get:-

$$EIRP_{Sat} = 21.9 + T + (G_T - G_R).$$

For transmit and receive antennas of the same size and for an earth station with paramp, we have:

$$T = 24.4 \text{ dB} - {}^\circ K$$

$$(G_T - G_R) = 1.5 \text{ dB} = \text{Difference in antenna gain at 14.25 and 12 GHz}$$

∴ For the commercial TV system the maximum satellite EIRP is:

$$(EIRP)_{Sat} = 47.8 \text{ dBW.}$$

This EIRP value therefore constitutes a system boundary and is drawn on the system modeling map of Figure 8-2.

6) Area Enclosed by System Boundaries

The system boundaries on the system modeling map of Figure 8-2 have been drawn based on the foregoing arguments. The area enclosed by the boundaries will be the area within which a system may be selected. This area is the area A, B, C, D in Figure 8-2. Any point in the area represents a complete system model. The selection of an optimum system will be done after the economic trade-offs, total satellite weight, rf bandwidths, and other aspects common to all the other services have been considered.

* * *

8.2.3.2 EDUCATIONAL TELEVISION (ETV)

Five systems boundaries for educational television are identified and drawn on the systems modeling map for this service.

Reference will be made to Figure 8-3, the system modeling map for ETV, when each of the systems boundaries below is considered.

1) Boundary set by Threshold and Operational Carrier-to-Noise Ratios

For ETV, in which the desired S/N = 42 dB, it has been shown that the threshold is reached when the rf bandwidth is 19 MHz. This is an upper limit of desirable transponder bandwidth.

In any operational system there should be an operational margin above threshold. As in the case of commercial television, an allowance of 2 dB will be made to avoid the click noise problem close to threshold. In the case of propagation fades, it is assumed that a system reliability of 99 percent is acceptable. In chapter 5 it is shown that the fade due to rain and cloud for 1 percent of the time is about 0.5 dB. This attenuation contributes a negligible rise in system noise temperature for an earth station with a tunnel diode amplifier or mixer as front end. Hence the total operational margin required is 2 + 0.5 = 2.5 dB. This margin will apply to most ETV stations which will be located in the southern belt of Canada. For the few stations in the far North at which the satellite elevation angle is low, the main propagation attenuation may not be due to rain but to tropospheric effects. For these few stations a larger margin is necessary (margin required is 2.0 + 2.6 = 4.6 dB). From the economic and practical standpoint, it seems reasonable to design the satellite system based on the system requirements of the majority of the stations in the South and compensate for any additional margins for the stations in the extreme North by having stations with a larger G/T value. This approach is adopted in view of the very large number of stations involved in the South.

For the educational television system with an operational carrier-to-noise ratio of 12.5 dB or 2.5 dB above threshold it would mean a new upper limit of transponder bandwidth. This limit is 16 MHz. This then is another boundary to be drawn on the system modeling map and supercedes the threshold boundary at 19 MHz.

2) Boundary set by RF Filter Hardware

The same arguments apply as for the commercial TV system (see 8.2.3.1).

3) Boundary set by Largest Practical Antenna

For the educational television network, it is reasonable to assume that the earth station antennas should not have tracking facilities, as cost and equipment complexity are of prime importance. For non-tracking earth stations which can tolerate a 2 dB decrease in down path signal, it has already been shown previously that the station antenna diameter should not exceed 17 feet. Recall above that the fade margin is only 0.5 dB. This margin is inadequate to cater for the 2 dB loss in signal due to satellite drift. Moreover, the ETV services would use narrow beam antennas in the down-link and it is anticipated that a fair number of ETV earth stations would be located near the edge of the beam coverage area. Hence it is essential to design an additional allowance of 2 dB into the system. It has already been shown that the transponder bandwidth has been brought down to 16 MHz. As indicated previously, further reduction of transponder bandwidth is not advisable. There is, therefore, no choice but to increase the down-link carrier-to-noise temperature ratio by 2 dB. This can be achieved by either increasing the earth station G/T or the satellite EIRP by 2 dB. In either case, the television signal/noise ratio is now 44 dB when the satellite is at the beam center of the earth station antenna, dropping to 42 dB when the satellite is in its extreme corner of the 0.2° by 0.2° region of allowable drift. The corresponding operational carrier-to-noise ratios are 14.5 dB and 12.5 dB respectively. This additional 2 dB allowance has been included in the system modeling map of Figure 8-3.

4) Boundary set by Smallest Antenna and Inter-satellite Interference Considerations

As before, it is assumed that the interfering satellites are identical to those considered here, broadcasting similar ETV signals to other networks and satellite spacings are at θ degrees apart. In Appendix B it is shown than an interference suppression ratio of 16.6 dB is required. For satellite spacings of 4 degrees the earth station antenna should be no smaller than about 3.5 feet. This is the lower bound of antenna size for ETV.

5) Boundary set by Earth Station Transmitter Power

As before, the equation limiting the maximum satellite EIRP is as follows:-

$$(\mathrm{EIRP})_{\mathrm{Sat}} = 21.9 + T + (G_T - G_R).$$

For earth stations with a tunnel diode amplifier (TDA), from 7.2.2 -

$$T = 30.7 \text{ dB - °K.}$$

It is most likely that for the ETV services the program will be transmitted from an earth station larger than the receiving stations. Assuming that the transmitting station antenna is about 3 times larger than the ETV receiving stations then:-

$$(G_T - G_R) = 20 \log (3) + 20 \log \left(\frac{14.25 \text{ GHz}}{12 \text{ GHz}}\right) = 11 \text{ dB}$$

$$\therefore \quad (\text{EIRP})_{\text{Sat}} = 63.6 \text{ dBW.}$$

This is very high and does not pose any practical limitation on the system modeling maps.

6) Area Enclosed by System Boundaries

The area enclosed by the boundaries in the system modeling maps, Figure 3-3, (marked A, B, C, D) is the area within which a practical system may be selected. Any point in the bounded area represents a complete system model. The actual selection of a system will be left to a later chapter after the economic, satellite weight and other problems have been considered.

* * *

8.3 MULTI-CHANNEL TELEPHONY AND DIGITAL SERVICES

In the subsections of this section, system modeling maps for multi-channel telephony and digital services are derived and systems constraints discussed.

This subsection will derive the system modeling maps for the telephony and digital services and discuss the various technical constraints. By telephony is meant the multi-channel systems. The study for the single channel per carrier telephony will be left to a separate subsection.

The present study will be divided into two major areas as below. This is because of the different emphasis on systems parameters and costs.

i) Major Traffic Communications

ii) Remote Communications

An explanation of the basis on which Digital Services have been grouped with telephony in the considerations of this chapter is relevant. Digital Services including video-telephone, electronic mail, and any digital "wideband" service (see chapter 2), from the point of view of transmission,provide, at the input to the transmission medium, signals which are streams of bits of information. If telephony signals are transmitted using PCM digital techniques the input to the transmission medium is still in the form of a stream of bits. The transmission medium is unable to distinguish one from the other. Thus, if in later economic analysis (chapters 9 and 10), the economic choice for telephony is to use PCM the digital services become an adjunct to this need and the technical analysis of this section is applicable to both. If on the other hand it should turn out that the transmission of telephony is more economic by analogue means, the technical considerations of the digital sections of this chapter are relevant only to the digital "services". At the risk of some discontinuity in presentation, the reader is re-assured at this point that in the context of the demand estimates of chapter 2 it is seen in chapters 9 and 10 that the economics for telephony transmission clearly favour the digital mode.

* * *

8.3.1 MODULATION CONSIDERATIONS

Digital and analogue modulations are briefly examined. PCM-CPSK and FM are selected for further analysis in subsequent sections.

For multi-channel telephony, there are basically two practical modulation techniques at present:-

a) Analogue

b) Digital

Complex modulation schemes such as hybrid analogue-digital modulation and "twisted modulation" will not be considered[8.4]. In theory these new modulation techniques may give better bandwidth utilization at the expense of higher power, but their practical implementation has to be proven.

Of the analogue modulation systems, the one which is most suited to satellite communications, and is widely used today, is frequency modulation (FM). Of the digital modulation schemes, the most efficient is coherent phase shift keying (CPSK). These two modulation schemes, FM and CPSK, will therefore be considered and compared with each other in detail.

* * *

8.3.2 PCM-CPSK-TDMA SYSTEMS FOR TELEPHONY AND DIGITAL SERVICES

System modeling maps based on PCM-CPSK-TDMA techniques are derived and systems boundaries discussed. The considerations are divided into major traffic and remote communications categories, and considered separately.

PCM-CPSK-TDMA Systems for Telephony and Digital Services

This subsection will first consider the basic equations of a PCM-CPSK system and will derive the "critical" carrier-to-noise ratios. The considerations will then be sub-divided into the following two categories:

(a) Major Traffic Communications

(b) Remote Communications

Consideration will be given for the 8ϕ CPSK and 4ϕ CPSK for the major traffic communications and 4ϕ CPSK and 2ϕ CPSK for the remote communications.

Appropriate system modeling maps for all four combinations stated above will be developed in the subsequent subsections of this section.

* * *

8.3.2.1 PCM-CPSK SYSTEMS EQUATIONS

The theoretical equations are manipulated and the "critical" carrier-to-noise ratios are derived. A bandwidth utilization index (n/B) is introduced.

There are two basic equations which govern the system performance of a digital radio link using phase shift keying. These are:

(a) Under Power Limitation

$$10 \log_{10} R = C/T - E/N_o - k - M_i \qquad (11)$$

(b) Under Bandwidth Limitation

$$R = \frac{B \log_2 (L)}{1.2} \qquad (12)$$

where R = transmission bit rate (b/s)

C/T = system carrier to noise temperature ratio (dB)

E/N_o = energy per bit to noise density (dB)

k = Boltzman's constant dBW/oK

M_i = implementation margin which accounts for the difference between theory and actual practice, and includes the effects of intersymbol interference, TWT non-linearities, etc. (dB)

L = number of phase positions in phase shift keying (2, 4, 8, etc)

1.2 = bandwidth allowance factor.

For a coherent PSK system in the presence of white gaussian rf noise, the theoretical value of E/N_o for any particular bit error rate is well known[8.5]. In a digital radio system, for design purposes, the threshold value of bit error rate is taken as 1×10^{-4}.

This gives approximately a noise of 50,000 pWop in a telephone channel[8.6]. This noise is also roughly the threshold noise of an FDM-FM system and is therefore a reasonable criterion. Table 8-4 gives the values of E/N_o for a bit error rate of 1×10^{-4} for coherent PSK systems with 2, 4, 8 and 16 phase modulations. The same table also gives the implementation margins M_i. These margins were estimated from the measured results of tests conducted by the Kokusai Denshin Denwa Company (Japan) through Intelsat III[8.7].

COMSAT (U.S.A.) has recently published certain figures which differ only fractionally from those in Table 8-4[8.8]. The figures in Table 8-4 may therefore be used with reasonable confidence.

Table 8-4

Lϕ CPSK	E/N_o (dB) (for error rate of 1×10^{-4})	M_i (dB)
2ϕ CPSK	8.4	3.5
4ϕ CPSK	8.4	4.0
8ϕ CPSK	11.8	4.5
16ϕ CPSK	16.1	5.0

Referring to equations (11) and (12), the optimum point of operation is when the transmission bit rates given under power limitation and bandwidth limitation coincide. That is:

$$10 \log_{10} \left(\frac{B \log_2 L}{1.2} \right) = C/T - E/N_o - k - M_i$$

or

$$\frac{C}{N_oB} = \frac{C}{T} - k - 10 \log_{10} B = 10 \log_{10} \left(\frac{\log_2 L}{1.2} \right) + \frac{E}{N_o} + M_i \qquad (13)$$

Substituting the values of L, E/N_o and M_i from Table 8-4 into equation (13) gives the "critical" values of carrier-to-noise ratio C/N_oB. These are presented in Table 8-5.

Table 8-5

MODULATION	CRITICAL C/N_OB (dB)
2ϕ CPSK	11.1
4ϕ CPSK	14.6
8ϕ CPSK	20.3
16ϕ CPSK	26.3

A system operating at these critical values of C/N_OB would be using both power and rf bandwidth optimally. Below the critical value, the operation would be in the "power limited" region. Conversely, above the critical value, the operation would be in the "bandwidth limited" region. A practical system cannot, however, operate under the "power limited" region for the following reasons:

(a) The system is operating at the threshold bit error rate of 1×10^{-4} at all times. This is not acceptable.

(b) Any system fade must be immediately accompanied by a corresponding reduction in system bandwidth in order to maintain the same C/N_OB. This is not practical. Further, even if this were practical, a reduction in bandwidth means a reduction in transmission bit rate. This is not acceptable for a normal communications system.

Hence, all digital systems must operate in the "bandwidth limited" region with adequate fade margins to give the desired service availability.

In order to compare among the digital systems and also with the single access FDM-FM system, it is most useful to introduce the concept of "number of telephone channels per MHz of rf bandwidth", (n/B). This enables direct comparison of the efficiency of each system (both PSK and FM) at any particular carrier-to-noise ratio (C/N_OB), using a common criterion. The higher the n/B ratio, the more efficient is the system.*

---

* This method of comparison of the bandwidth utilization efficiencies between various modulation techniques was, to the best of our knowledge, first used in an internal Bell-Northern Research study.

In a PCM system, the standard now adopted is 64 kb/s per voice channel of 4 kHz. However, in the multiplexing process, framing and synchronizing (stuffing) bits are added. It is envisaged that for the satellite system under study, the Bell T1 (24 channels) and T2 (96 channels) PCM systems would be largely used as the basic systems for the digital telephone network. For the T2 system the average is 66 kb/s per 4 kHz voice channel. For a time division multiple access (TDMA) satellite network, additional bits are necessary for the preamble word and guard time between adjacent bursts. However, by using a superframe bit stream structure, each superframe containing a multiple of the standard frame of 125 microseconds, the percentage loss in efficiency due to the preamble word and guard time can be made very small. Current thinking seems to favour a superframe of 1 millisecond duration containing 8 standard frames of 125 microseconds each. Work on some typical systems using this superframe duration, indicates that some 67.5 kb/s per 4 kHz voice channel would be needed for a system with 14 accesses of 96 channels each. As the loss in channel capacity per additional access is very small (less than fraction of one percent), variations in this figure of 67.5 kb/s with the number of accesses may be ignored. This 67.5 kb/s per voice channel will therefore be adopted.

The system transmission bit rate is therefore:-

$$R = 67.5n \times 10^3 \text{ b/s} \tag{14}$$

Substituting equation (14) into equation (11) and equation (12) gives:

(a) Under Power Limitation

$$10 \log (n/B) = C/N_oB - E/N_o - M_i + 11.7 \text{ dB} \tag{15}$$

(b) Under Bandwidth Limitation

$$(n/B) = 12.35 \log_2 (L) \tag{16}$$

In both equation (15) and equation (16) the bandwidth B in the parameter (n/B) has been expressed in MHz.

Equations (15 and (16) are plotted in Figure 8-4 with "number of channels per MHz rf bandwidth" (n/B) versus carrier-to-noise ratio C/N_oB, for the various phase shift keying systems. The sloping portion of each curve represents "power limited" region. The flat top portion represents the "bandwidth limited" region. The point at which the curve turns around from sloping to flat top is the critical C/N_oB. As already explained, any practical system must operate in the bandwidth limited region. Therefore a system must operate at a point *x* dB above the critical C/N_0B where *x* dB is the fade margin desired. In Figure 8-4, the operational C/N_0B will be *x* dB to the right of the turn-around point along the flat top portion of the curve concerned.

In Figure 8-4, the parameter n/B is plotted against C/N_0B for the single access FDM/FM system also, for comparison. The derivation of this curve is given in 8.3.3.1. The curve is valid for channel capacities larger than 240 channels, and these capacity sizes are reasonable for single access satellite systems. The noise performance objective assumed was 37.6 dBrnc0 (5630 pW) with thermal noise allowance of 35.6 dBrnc0 (3630 pW).

The curves in Figure 8-4 are basic and present succinctly the system bandwidth utilization efficiency in a normalized form. The higher the n/B ratio, the better is the system. From Figure 8-4, it is to be noted that the superiority or otherwise of any system depends on the operational system carrier-to-noise ratio. The carrier-to-noise ratio must always be specified whenever one system is being compared with another. Table 8-6 gives a brief comparison of the various systems shown in Figure 8-4, over certain ranges of carrier-to-noise ratios.

Table 8-6

RANGE OF C/N_0B (dB)	MODULATION SYSTEM COMPARISON
11.1 - 14.6	Only FM and 2ϕ CPSK are workable. FM is better.
14.6 - 20.3	FM, 2ϕ CPSK and 4ϕ CPSK are workable. 4ϕ CPSK is best, followed by FM. 2ϕ CPSK is poorest.
20.3 - 26.3	FM, 2ϕ CPSK, 4ϕ CPSK and 8ϕ CPSK are workable. Order of merit: 8ϕ CPSK, FM, 4ϕ CPSK, 2ϕ CPSK.
26.3 - 32	All systems shown are workable. Order of merit: 16ϕ CPSK, FM, 8ϕ CPSK, 4ϕ CPSK, 2ϕ CPSK.
> 32	All systems shown are workable. Order of merit: FM, 16ϕ CPSK, 8ϕ CPSK, 4ϕ CPSK, 2ϕ CPSK.

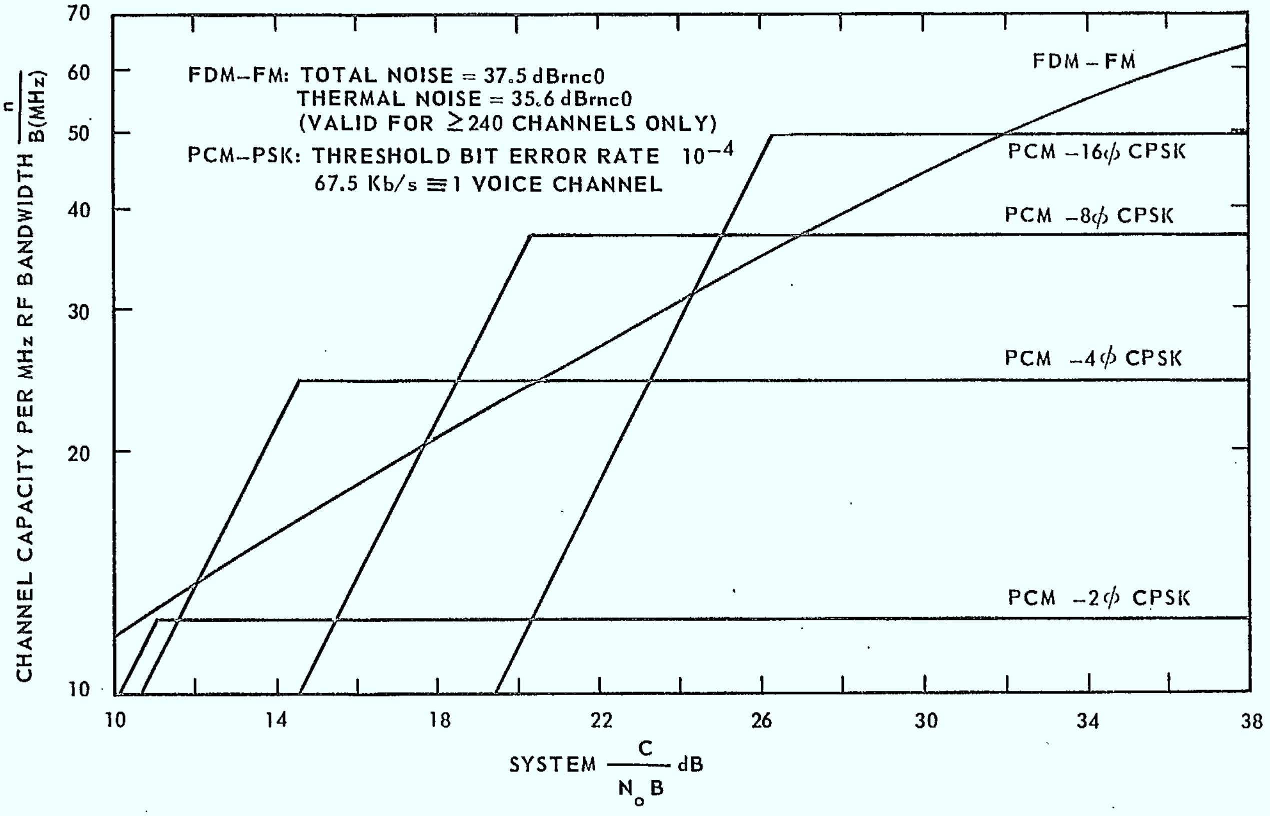


Figure 8-4 Satellite Systems: Telephone Channel Capacity - PCM-PSK-TDMA and FDM-FM (Single Access)

8.3.2.2 MAJOR TRAFFIC COMMUNICATIONS

Systems models and constraints for major traffic communications using digital techniques are considered.

The system modeling maps for 8ϕ CPSK and 4ϕ CPSK will now be derived for the major traffic communications. But first the following need to be defined:

(a) Up-Link Noise Contribution

This will be 10 dB below the down-link noise contribution under clear weather conditions for the same reasons as stated in 8.2.2. The up-link therefore contributes 0.4 dB to overall system degradation under clear weather.

(b) Weather Margin

The system will be designed to give a service reliability of 99.99 percent due to rain and cloud attenuation. In chapter 5 it is shown that for a system with uncooled paramps, the system margin necessary is 9.2 dB.

* * *

8.3.2.2.1 SYSTEM MODELING MAP FOR 8ϕ CPSK

The system modeling map for PCM-8ϕCPSK-TDMA for major traffic communications is derived.

Critical $C/N_oB = 20.3$ dB (from Table 8-5)

Weather Margin = 9.2 dB

$\therefore$ Operational $C/N_oB = 29.5$ dB (clear weather).

Down-link $(C/N_oB)_D = 29.5 + 0.4 = 29.9$ dB (clear weather).

$$\text{Now EIRP} = (C/N_oB)_D + k + 10 \log (B) + Lp - G/T$$

where EIRP = EIRP of satellite

k = Boltzman's constant

B = bandwidth in Hz

Lp = path loss (Lp = 206.8 dB)

G/T = G/T of earth station.

$$\therefore \quad \text{EIRP} = 8.1 + 10 \log (B) - G/T. \qquad (17)$$

Further, from equation (16) we have for 8ϕ CPSK:

$$n/B = 12.35 \log_2 (8) \text{ channels/MHz of rf bandwidth}$$

$$\therefore \quad n/B = 37.05 \text{ channels/MHz rf bandwidth.} \qquad (18)$$

Equation (17) is the desired formula to plot the system modeling map for an 8ϕ coherent PSK (CPSK) system. This map is plotted as Figure 8-5. For any satellite EIRP and earth station G/T, the rf bandwidth can be determined. The number of telephone channels in the system is then given from equation (18), i.e:

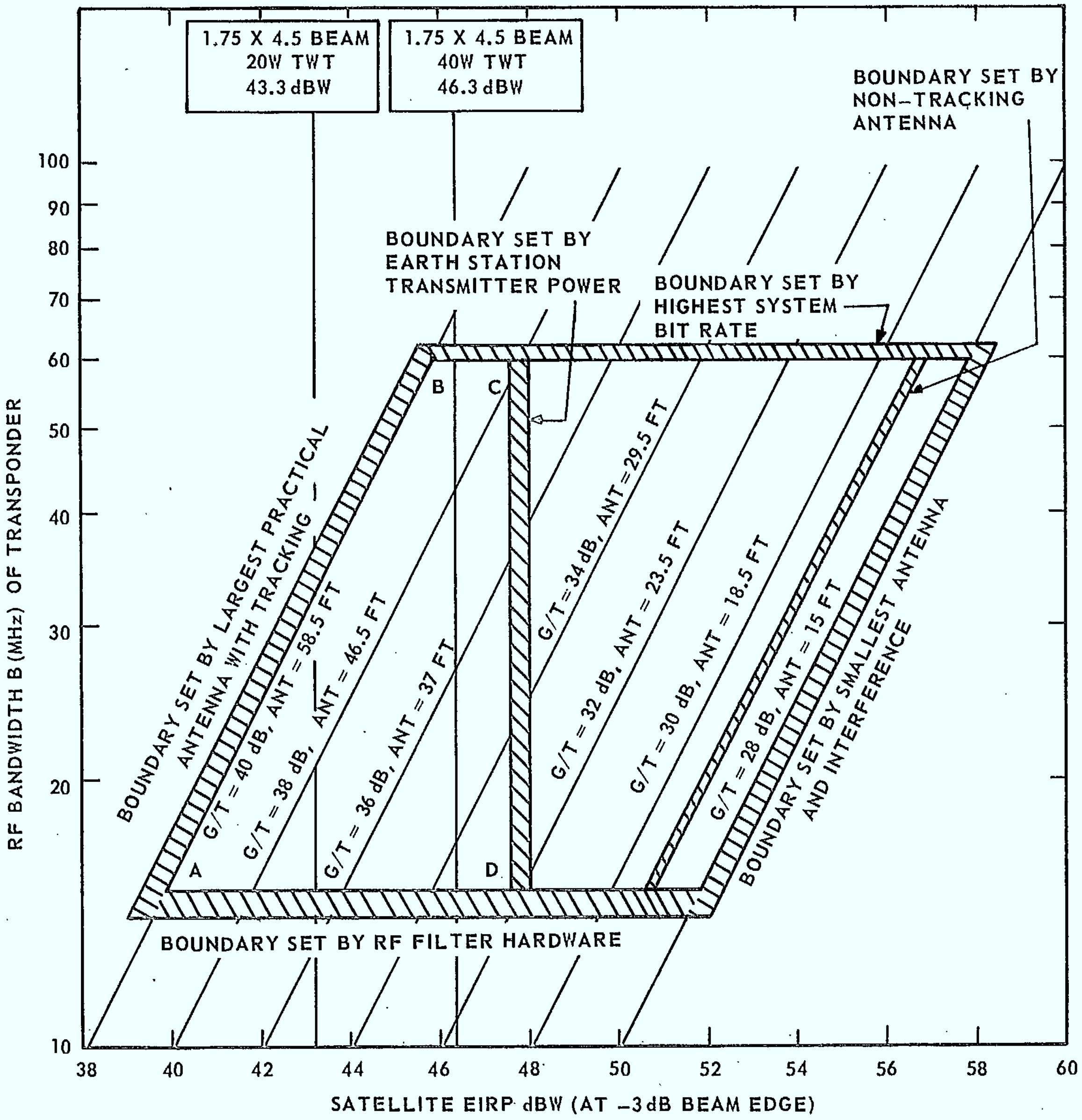
$$n = 37.05 \times B \text{ (MHz) channels.}$$

Digital services capacity is given by:

$$D = 37.05 \times 67.5 \times 10^3 \times B(\text{MHz}) \text{ Mb/s}$$

$$D = 2.5 \times B(\text{MHz}) \text{ Mb/s.}$$

* * *



TELEPHONE CAPACITY, $n = 37.05 \times B$ (MHz) CHANNELS

DIGITAL CAPACITY, $D = 2.5 \times B$ (MHz) Mb/s

OPERATIONAL $\frac{C}{N_o B} = 29.5$ dB

FADE MARGIN = 9.2 dB (99.99% SERVICE RELIABILITY)

LOW NOISE RECEIVER = UNCOOLED PARAMP

Figure 8-5 Major Traffic Communications: System Modeling Map For Telephony and Data Using PCM-8ϕ CPSK-TDMA

8.3.2.2.2 SYSTEM MODELING MAPS FOR 4ϕ CPSK

The system modeling map for major traffic communications using PCM-4ϕ-CPSK-TDMA is derived.

$$\text{Critical } C/N_oB = 14.6 \text{ dB (from Table 8-5)}$$

$$\text{Weather Margin} = 9.2 \text{ dB}$$

$$\therefore \text{ Operational } C/N_oB = 23.8 \text{ dB}$$

$$\text{Down-link } (C/N_oB)_D = 23.8 + 0.4 = 24.2 \text{ dB}$$

$$\text{EIRP} = (C/N_oB)_D + k + 10 \log (B) + Lp - G/T$$

$$\therefore \quad \text{EIRP} = 2.4 + 10 \log (B) - G/T. \qquad (19)$$

Further, from equation (16), for 4ϕ CPSK,

$$n/B = 12.35 \log_2 (4)$$

$$\therefore \quad n/B = 24.7 \text{ channels/MHz rf bandwidth.} \qquad (20)$$

∴ Telephone channel capacity:

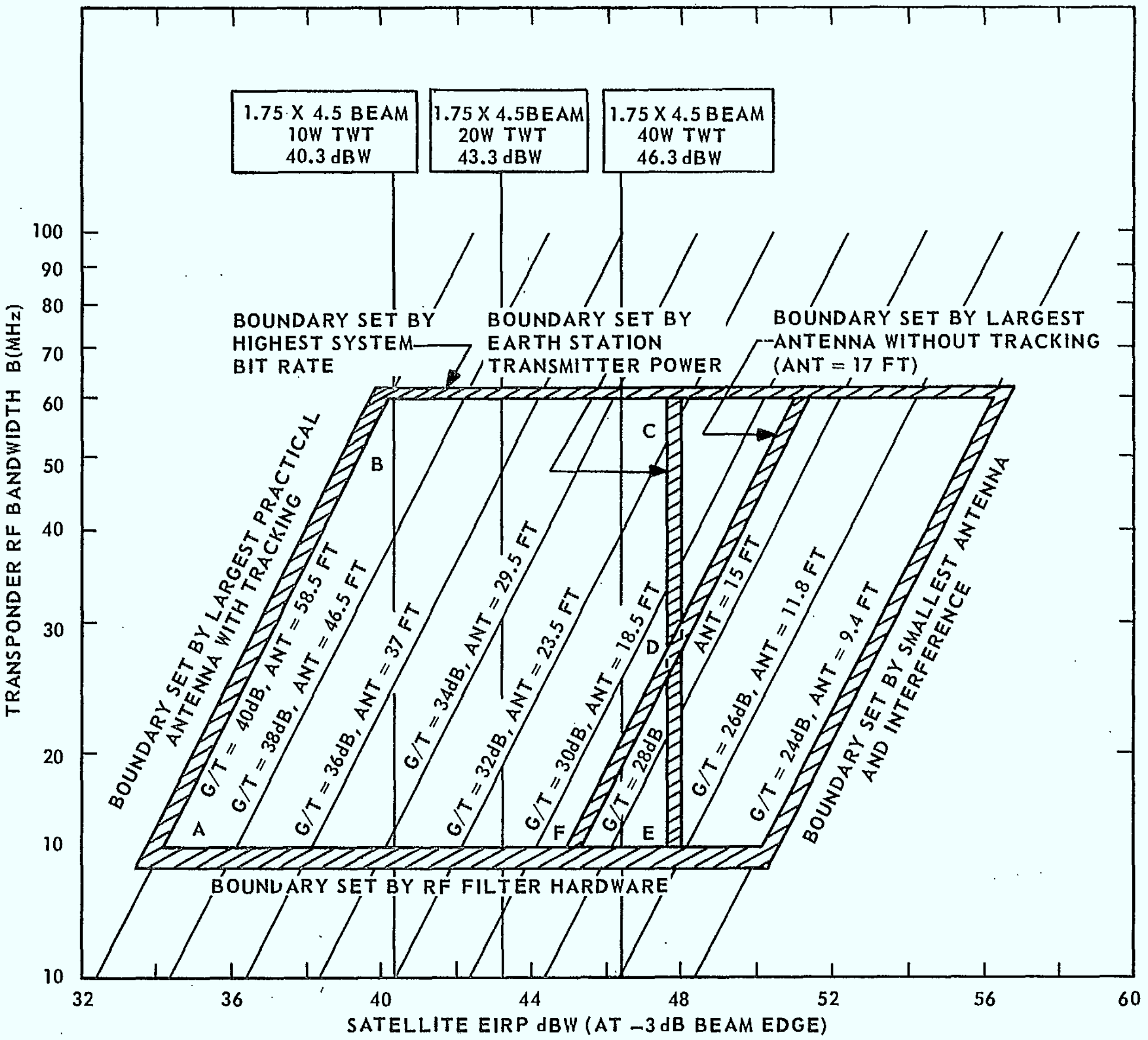
$$n = 24.7 \times B \text{ (MHz) channels.}$$

Digital service capacity:

$$D = 24.7 \times 67.5 \times 10^3/10^6 \times B \text{ (MHz) Mb/s}$$

$$\therefore \quad D = 1.67 \times B \text{ (MHz) Mb/s.}$$

Equation (19) is the desired formula for plotting the system modeling map for 4ϕ CPSK system. This plot is presented as Figure 8-6.



TELEPHONY CAPACITY, n = 24.7 X B (MHz) CHANNELS

DIGITAL CAPACITY, D = 1.67 X B (MHz) Mb/s

OPERATIONAL $\frac{C}{N_o B}$ = 23.8 dB

FADE MARGIN = 9.2 dB (99.99% SERVICE RELIABILITY)

LOW NOISE RECEIVER = UNCOOLED PARAMP.

Figure 8-6 Major Traffic Communications: System Modeling Map for Telephony and Data Using PCM-4ϕ CPSK-TDMA

8.3.2.2.3 SYSTEMS BOUNDARIES

The systems constraints for the 8ϕ CPSK and 4ϕ CPSK systems are considered and systems boundaries delineated.

This subsection will discuss in detail the systems boundaries as shown in Figure 8-5 and Figure 8-6 for the 8ϕ CPSK and 4ϕ CPSK systems respectively. It should be stressed that in most cases the systems boundaries are not to be regarded as rigid; they merely represent broad constraints within which an optimum system may be selected.

1) System Boundary Set by Highest System Bit Rates

In a PCM-CPSK system using TDMA, every earth station participating in a particular network must operate at the same bit rate, regardless of the channel capacity of each earth station. For example, in a network which operates at 100 Mb/s bit rate, every participating earth station must have modems and memory devices operating at this bit rate, regardless whether a station has a capacity of hundreds of channels or a few channels. Since the cost of modems and memory and timing devices goes up rapidly with the bit rate, it is clearly advantageous to have multiple transponders each with a low or medium bit rate (say 100 Mb/s) rather than one large transponder which must operate at an exceedingly high bit rate (say 500 Mb/s) in order to provide the total system capacity. Since the earth station network is large, this cost of high speed equipment is a very important factor. Moreover, multiple transponders have the additional advantage of inherent system flexibility and provide diversity against total failure.

The bit rates of present day experimental digital satellite systems range from 50 Mb/s to 100 Mb/s, using 4ϕ CPSK. A 100 Mb/s system would give a total capacity of about 1480 channels [Ref equation (14)]. This seems to be a reasonable size capacity, and modems and memory devices at these bit rates should be economical in the time frame under consideration. Therefore, the maximum bit rates will be set as follows:

a)	8ϕ CPSK	150 Mb/s
b)	4ϕ CPSK	100 Mb/s.

The corresponding maximum transponder bandwidth is given as follows:

a) 8ϕ CPSK $B = 150/2.5 = 60$ MHz

b) 4ϕ CPSK $B = 100/1.67 = 60$ MHz.

The transponder bandwidth will therefore be constrained to a maximum of 60 MHz. This is a system boundary marked on the system modeling maps, Figures 8-5 and 8-6.

2) Boundary Set by Radio-Frequency Filter Hardware

The same arguments as presented in 8.2.2 apply.

3) Boundary Set by Largest Practical Antenna

The same arguments as presented in the case of commercial television in 8.2.2 apply, and two boundaries arise with and without tracking stations.

4) Boundary Set by Smallest Antenna Size and Inter-Satellite Interference Considerations

The interference model assumed will be the same as before. Chapter 7 gives the interference suppression requirements. For satellite spacings $\theta = 4°$, the smallest antenna size for 8ϕ CPSK is shown to be about 15 feet. This antenna size may therefore be used as a boundary on the system modeling map, Figure 8-5, for the 8ϕ CPSK network. In the 4ϕ CPSK case, the smallest antenna size is about 9.4 feet, and this is a system boundary marked in Figure 8-6.

5) Boundary Set by Earth Station Transmitter Power

For an earth station network with transmitting and receiving antennas of the same sizes and with uncooled paramp low-noise receivers, the maximum down-link EIRP is the same as given in 8.2.3.1, namely:

$$(\mathrm{EIRP})_{\mathrm{Sat}} = 47.8 \text{ dBW.}$$

This boundary is marked in Figures 8-5 and 8-6.

(6) Area Enclosed by System Boundaries

The area enclosed by the boundaries will be the area within which a working system may be selected. For a network with tracking earth station antennas, the area enclosed should be A, B, C, D in Figure 8-5 and A, B, C, D, E in Figure 8-6. For a network without antenna tracking, the possible operational points are enclosed within the small area D, E, F in Figure 8-6 for 4ϕ CPSK only.

Referring to the two system modeling maps, it is clear that any point on the 8ϕ CPSK map gives systems parameters quite different from a corresponding point on the 4ϕ CPSK map. In other words, a point optimum for the 4ϕ CPSK system will not be optimum for the 4ϕ CPSK system and vice versa. The decision on the choice of a system will be made in another chapter of this report after the economic trade-offs and other constraints common to all the other services have been examined.

* * *

8.3.2.3 REMOTE COMMUNICATIONS

Systems models and constraints for remote communications using PCM-CPSK-TDMA are considered.

The system modeling maps for remote communications will now be derived. Both 4ϕ CPSK and 2ϕ CPSK will be considered. But first the following need to be defined:

(a) Up-link Noise Contribution

As before, the up-link noise will be set 10 dB below the down-link noise under non-fade conditions. The up-link therefore degrades the system by 0.4 dB under these conditions.

(b) Weather Margin

Remote communications requirements differ somewhat from those of high capacity routes in that low cost and station simplicity are of prime importance whilst service reliability due to propagation fades may be relaxed a little. For the remote communications systems therefore, service reliability will be assumed to be 99.9 percent instead of 99.99 percent used for the heavy route systems. The threshold performance objective of bit error rate of 1×10^{-4} will, however, remain.

In remote communications, it is assumed that a substantial number of earth stations will be in the North where the satellite elevation angle would be centered around 10 through 20 degrees. Hence it is assumed that the tropospheric fade effects would be significant. In chapter 2 it is shown that for the remote communications network with a service reliability of 99.9 percent of 3.0 dB is necessary for the PCM-CPSK-TDMA system.

* * *

8.3.2.3.1 SYSTEM MODELING MAP FOR 4ϕ CPSK

The system modeling map for remote communications using PCM 4ϕ CPSK TDMA is developed.

$$\text{Critical } C/N_oB = 14.6 \text{ dB (from Table 8-5)}$$

$$\text{Margin} = 3.0 \text{ dB}$$

$$\therefore \text{ Operational } C/N_oB = 17.6 \text{ dB}$$

$$\therefore \text{Down-link } (C/N_oB)_D = 17.6 + 0.4 = 18.0 \text{ dB.}$$

$$\text{EIRP} = (C/N_oB)_D + k + 10 \log (B) + Lp - G/T$$

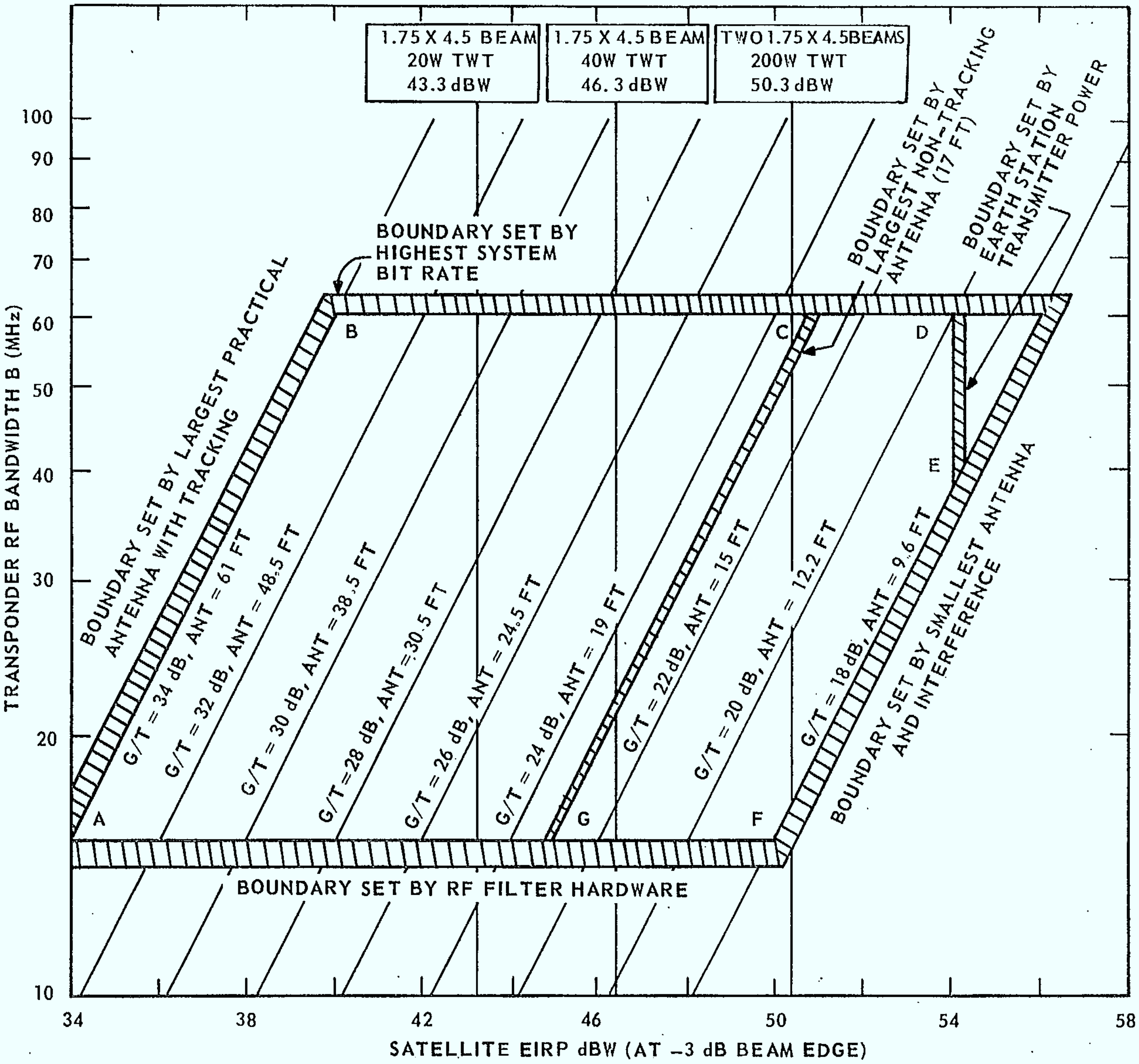
$$\therefore \qquad \text{EIRP} = -3.8 + 10 \log (B) - G/T. \qquad (21)$$

Equation (21) is the expression required to plot the system modeling map for 4ϕ CPSK for remote communications. This plot is presented as Figure 8-7.

From equation (16) the system capacity is given as:

Telephony : $n = 24.7 \times B$ (MHz) channels.

Data: $D = 1.67 \times B$ (MHz) Mb/s.



TELEPHONE CAPACITY, $n = 24.7 \times B\,(\text{MHz})$ **CHANNELS**

DIGITAL CAPACITY, $D = 1.67 \times B\,(\text{MHz})$ Mb/s

OPERATIONAL $\frac{C}{N_0 B} = 17.6$ dB

FADE MARGIN = 3.0 dB

LOW NOISE RECEIVER = TUNNEL DIODE AMPLIFIER

Figure 8-7 Remote Communications: System Modeling Map for Telephony and Data Using PCM-4ϕ CPSK-TDMA

8.3.2.3.2 SYSTEM MODELING MAP FOR 2ϕ CPSK

The system modeling map for remote communications using PCM 2ϕ CPSK TDMA is derived.

$$\text{Critical } C/N_oB = 11.1 \text{ dB (from Table 8-5)}$$

$$\text{Fade Margin} = 3.0 \text{ dB}$$

$$\therefore \quad \text{Operational } C/N_oB = 14.1 \text{ dB}$$

$$\therefore \quad \text{Down-link } (C/N_oB)_D = 14.1 + 0.4 = 14.5 \text{ dB.}$$

$$\text{EIRP} = (C/N_oB)_D + k + 10 \log (B) + Lp - G/T$$

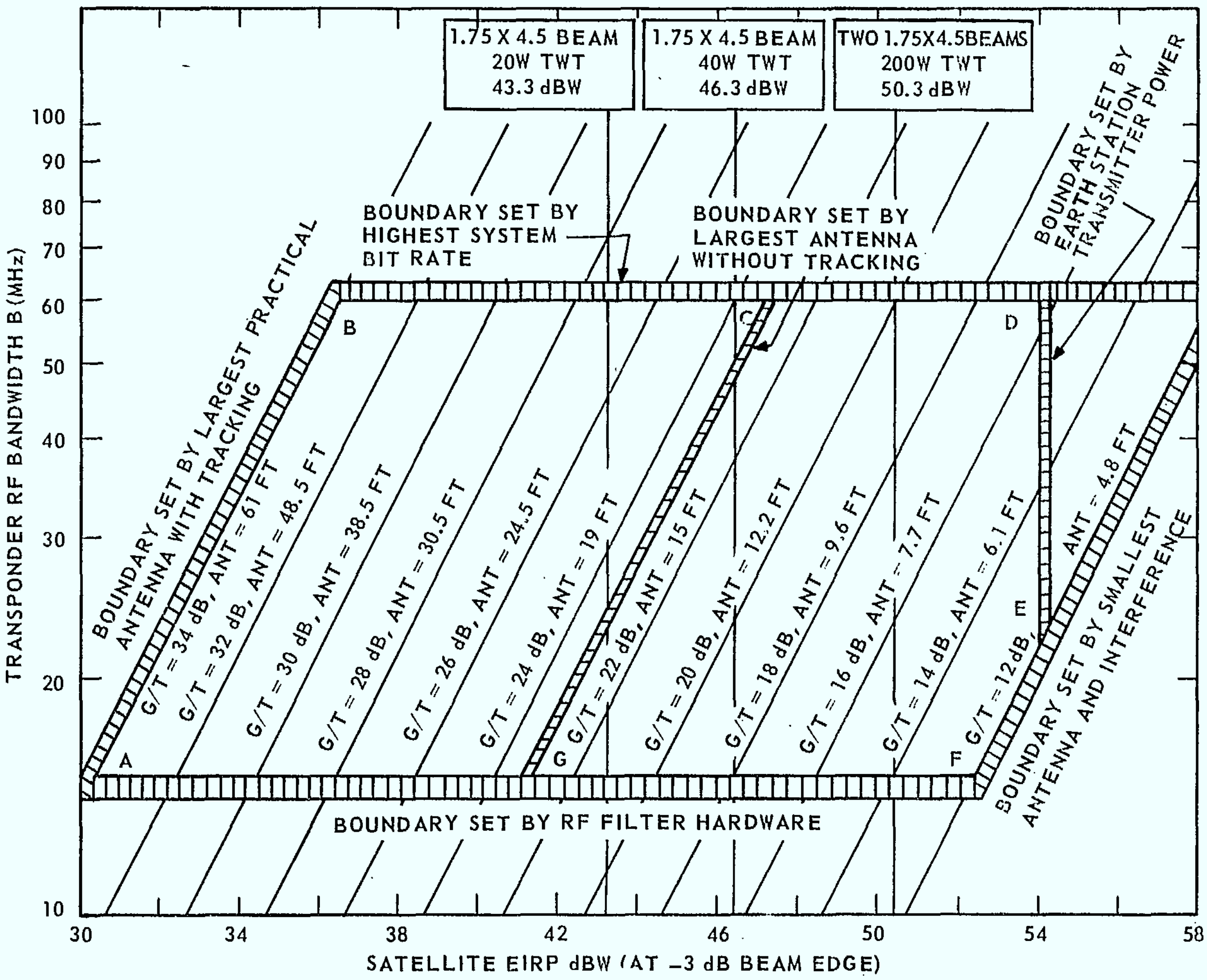
$$\therefore \quad \text{EIRP} = -7.3 + 10 \log (B) - G/T. \qquad (22)$$

Equation (22) is the formula used to plot the system modeling map for 2ϕ CPSK for remote communications. The plot is as shown in Figure 8-8.

From equation (16) the system capacity is:

Telephony: $n = 12.35 \times V$ (MHz) channels

Data: $D = 0.83 \times B$ (MHz) Mb/s.



TELEPHONY CAPACITY, n = 12.35 X B (MHz) CHANNELS

DIGITAL CAPACITY, D = 0.83 X B (MHz) Mb/s

OPERATIONAL $\frac{C}{N_0 B}$ = 14.1 dB

FADE MARGIN = 3.0 dB
LOW NOISE RECEIVER = TUNNEL DIODE AMPLIFIER

Figure 8-8 Remote Communications: System Modeling Map for Telephony and Data Using PCM-2ϕ CPSK-TDMA

8.3.2.3.3 SYSTEMS BOUNDARIES

Systems boundaries for remote communications are considered both for 4ϕ and 2ϕ CPSK and delineated on the modeling maps.

The systems boundaries shown in Figures 8-7 and 8-8 for the 4ϕ CPSK and 2ϕ CPSK systems will be discussed below. These boundaries represent broad constraints within which a working system may be selected.

1) Boundary Set by Highest System Bit Rates

The arguments presented before in 8.3.2.2 about the desirability of a low bit rate capacity for each transponder also apply. Indeed, as system simplicity and low earth station costs are prime objectives for remote communications, the strength of the arguments is stronger here. Along the lines as previously adopted, the maximum bit rates may therefore be set as follows:

a) 4ϕ CPSK 100 Mb/s

b) 2ϕ CPSK 50 Mb/s

These give the corresponding maximum transponder bandwidths as follows:

a) 4ϕ CPSK $B = 100/1.67 = 60$ MHz

b) 2ϕ CPSK $B = 50/0.835 = 60$ MHz.

Therefore, the maximum transponder bandwidth should be restricted to 60 MHz. This system boundary has been marked on the system modeling maps.

2) Boundary Set by Radio-Frequency Filter Hardware

The same arguments as the previous cases apply.

3) Boundary Set by Largest Practical Antenna

Essentially the same arguments as in 8.2.3.1 apply, and two boundaries arise one with and the other without tracking.

4) Boundary Set by Smallest Antenna and Inter-Satellite Interference Considerations

As shown in chapter 7, the smallest antennas for a system with adjacent satellite spaced 0 = 4 degrees are given as:

4ϕ CPSK	9 ft antenna
2ϕ CPSK	4.8 ft antenna

Boundaries corresponding to the above have been drawn on the system modeling maps.

5) Boundary Set by Earth Station Transmitter Power

Assuming that an upper limit of transmitter power is still 8 KW, the maximum down-link EIRP is given as:

$$(\mathrm{EIRP})_{Sat} = 21.9 + T + (G_T - G_R)$$

where $(G_T - G_R) = 1.5$ dB.

For a system with a tunnel diode front end:

$$T = 30.7 \text{ dB} - {}^\circ\text{K}$$

$$\therefore \quad (\mathrm{EIRP})_{Sat} = 54.1 \text{ dBW.}$$

While the 8 KW transmitter is more or less based on a technological limit, for remote communications, it would hardly be logical to use this large power. The practical limit might be somewhat lower. The maximum down-link EIRP would also be lowered by the corresponding amount.

6) Area Enclosed by System Boundaries

The results of the above discussion on systems constraints are indicated on the system modeling maps, Figures 8-7 and 8-8, as systems boundaries. In both these figures, for an earth station network with satellite tracking, the bounded areas are A, B, C, D, E, F, G. For a network without antenna tracking, the bounded areas are C, D, E, F, G.

Similar to the major traffic communications case, a system is optimum for 4ϕ CPSK will not be optimum for 2ϕ CPSK and vice versa. A choice will have to be made and this will be done after the economic and other aspects common to the other services have been considered.

* * *

8.3.3 FDM-FM-FDMA SYSTEMS FOR TELEPHONY

This subsection will examine satellite systems for telephony using FDM-FM-FDMA instead of PCM-CPSK-TDMA considered previously. It will begin by considering the system fundamentals and will then derive the system modeling maps and channel capacity. The system modeling maps will be developed for the two networks under consideration, namely:

i) Major Traffic Communications

ii) Remote Communications.

Single channel per carrier systems will be dealt with separately.

The theoretical considerations for an FM system with capacity greater than 240 channels are slightly different from those for a system with less than 240 channels. These considerations will be presented in 8.3.3.1 and 8.3.3.2.

* * *

8.3.3.1 FDM-FM SYSTEM EQUATIONS FOR SYSTEM CAPACITY GREATER THAN 240 CHANNELS

Values of (n/B), the number of channels per MHz rf bandwidth, versus carrier-to-noise ratio are derived.

The well-known FM equation gives:

$$S/N = \frac{C}{N} \cdot \frac{B}{b} \cdot P \cdot (\delta f_{rms}/fm)^2 \qquad (23)$$

where S/N = test-to-tone-to-noise ratio in the top channel

C/N = carrier-to-noise ratio

B = radio-frequency bandwidth.

b = channel bandwidth ($b = 3.1$ KHz)

δf_{rms} = rms test tone deviation

fm = highest baseband frequency

P = pre-emphasis advantage.

By Carson's Rule:

$$B = 2(p\Delta F_{rms} + fm) \qquad (24)$$

where p = peak factor of multiplex signal

ΔF_{rms} = rms frequency deviation of multiplex signal.

For systems greater than 240 channels, we have:

$$fm = 4.2 \times 10^3 \times n \qquad (25)$$

$$20 \log \left(\frac{\Delta F_{rms}}{\delta f_{rms}}\right) = -15 + 10 \log n = 10 \log \frac{n}{31.6} \qquad (26)$$

where n = number of channels.

Assume:

a) Pre-emphasis advantage of 4 dB $\therefore$ $p = 2.5$ (27)

b) Peak Factor of 10 dB $\therefore$ $p^2 = 10.$ (28)

From equations (23) through (28) we can easily show that:

$$\frac{S}{N} = 2.68 \frac{C}{N} \cdot \frac{B}{4.2 \times 10^3 \times n} \left(\frac{B}{4.2 \times 10^3 \times n} - 2\right)^2$$

Expressing all the parameters in dB, we have:

$$\frac{C}{N} = \frac{S}{N} - 4.3 - 10 \log \left(\frac{B \times 10^3}{4.2\ n}\right) - 20 \log \left(\frac{B \times 10^3}{4.2\ n} - 2\right) \qquad (29)$$

where the bandwidth B is now expressed in MHz.

Equation (29) is of fundamental importance. Given any desired performance objective in terms of S/N, equation (29) presents the direct relationship between carrier-to-noise ratio C/N and the number of channels per MHz rf bandwidth, (n/B). The parameter (n/B) is a very useful efficiency index when comparing systems of entirely different basic characteristics such as between PCM-CPSK and FDM-FM. The higher this index the better is the system.

For the FDM-FM system under study, the following noise budget is representative and considered reasonable:

Thermal noise	= 3630 pWp
Earth station equipment noise (excluding thermal noise)	= 600 pWp
Transponder non-linear group delay and AM/PM noise	= 400 pWp
Interference noise	= 1000 pWp
TOTAL	= 5630 pWp (37.5 dBrnc0)

Since thermal noise = 35.6 dBrnc0 (3630 pWp).

Therefore:

S/N = 88 - 35.6 = 52.4 dB unweighted. Substituting this value of S/N into equation (29):

$$\frac{C}{N} = 48.1 - 10 \log \left(\frac{B \times 10^3}{4.2\ n} \right) - 20 \log \left(\frac{B \times 10^3}{4.2\ n} - 2 \right) \quad (30)$$

Values of C/N versus (n/B) from equation (30) are tabulated in Table 8-7 and plotted in 8.3.2.1. This curve will be made use of later on.

Table 8-7

$\frac{n}{B(\text{MHz})}$	$\frac{C}{N}$ (dB)
12.5	10.7
17.0	15.0
19.8	17.3
23.8	20.1
29.8	23.5
34.0	26.6
39.7	28.3
47.6	31.6
79.5	43.3
95.2	50.1
119	∞

* * *

8.3.3.2 FDM-FM SYSTEM EQUATIONS FOR SYSTEM CAPACITY LESS THAN 240 CHANNELS

The relationship between channel capacity, rf bandwidth and carrier-to-noise ratio is derived.

The FM equation is the same as in the previous case, namely:

$$\frac{S}{N} = \frac{C}{N} \cdot \frac{B}{b} \cdot P \cdot \left(\frac{\delta f_{rms}}{fm}\right)^2 \quad \text{unweighted} \qquad (31)$$

where the parameters have the same meanings as in equation (23).

By Carson's Rule:

$$B = 2p\ \Delta F_{rms} + 2\ fm \qquad (32)$$

where p = peak factor of multiplex signal

ΔF_{rms} = rms frequency deviation of multiplex signal.

For systems with less than 240 channels, the multi-channel loading is given as follows:

$$20 \log \left(\frac{\Delta F_{rms}}{\delta f_{rms}}\right) = -1 + 4 \log n \qquad (33)$$

where n = number of channels.

In general:

a) Pre-emphasis advantage is 4 dB, i.e. $10 \log P = 4$ dB

b) Peak Factor is taken as 10 dB, i.e. $20 \log p = 10$ dB.

Then, from equations (31), (32) and (33) it can be shown that:

$$\frac{C}{N} = \frac{S}{N} + 45.9 + 4 \log n - 10 \log f_m$$

$$- 10 \log \left(\frac{B}{f_m}\right) - 20 \log \left(\frac{B}{f_m} - 2\right) \qquad (34)$$

where C/N and S/N are now expressed in dB. The same noise objectives as before will be used and therefore:

$$\frac{S}{N} = 52.4 \text{ dB unweighted.}$$

$$\therefore \quad \frac{C}{N} = 98.3 + 4 \log n - 10 \log f_m$$

$$- 10 \log \left(\frac{B}{f_m}\right) - 20 \log \left(\frac{B}{f_m} - 2\right). \qquad (35)$$

For small capacity satellite systems, it will be more accurate to use the actual top baseband frequency f_m for the capacity concerned rather than an approximate algebraic function such as equation (25). The values of f_m are tabulated in Table 8-8 up to systems with 252 channels. The 252-channel system is actually a conventional 240-channel system plus 12 channels in the 12 KHz through 60 KHz baseband spectrum that is not normally occupied.

Table 8-8

n (channels)	f_m (kHz)
12	60
24	108
36	156
48	204
60	252
132	552
252	1052

Using the values in Table 8-8, equation (35) may now be used to obtain values of C/N versus rf bandwidth B, for each system capacity. These are tabulated in Table 8-9 and curves are drawn as shown in Figure 8-9. These curves will be used in subsequent sections of this study.

Table 8-9

B/f_m	12 channels f_m=60 kHz		24 channels f_m=108 kHz		36 channels f_m=156 kHz		48 channels f_m=204 kHz		60 channels f_m=252 kHz		132 channels f_m=552 kHz		252 channels f_m=1052 kHz	
	B (MHz)	C/N (dB)	B (MHz)	C/N (dB)	B (MHz)	C/N (dB)	B (MHz)	C/N (dB)	B (MHz)	C/N (dB)	B (MHz)	C/N (dB)	B (MHz)	C/N (dB)
3	.180	50.0	.324	48.7	.468	47.8	.612	47.1	.756	46.6	1.66	44.5	.16	49.9
4	.240	42.8	.432	41.5	.624	40.6	.816	39.9	1.008	39.4	2.21	37.3	4.21	35.7
5	.300	38.3	.540	37.0	.780	36.1	1.020	35.4	1.260	34.9	2.76	32.8	5.26	31.2
6	.360	35.0	.648	33.7	.936	32.8	1.224	32.1	1.512	31.6	3.31	29.5	6.32	27.9
8	.480	30.2	.864	28.9	1.248	28.0	1.632	27.3	2.016	26.8	4.42	24.7	8.42	23.1
10	.600	26.8	1.080	25.5	1.560	24.6	2.040	23.9	2.520	23.4	5.52	21.3	10.52	19.7
15	.900	20.8	1.620	19.5	2.340	18.6	3.060	17.9	3.780	17.4	8.30	15.3	15.80	13.7
20	1.200	16.7	2.160	15.4	3.120	14.5	4.080	13.8	5.040	13.6	11.05	11.2	20.12	9.6
25	1.500	13.3	2.700	12.3	3.900	11.4	5.100	10.7	6.300	10.2	13.80	8.1	-	-
30	1.800	11.1	3.240	9.8	4.680	8.9	6.120	8.2	7.560	7.7	-	-	-	-
40	2.400	7.2	4.320	-	6.240	-	8.160	-	-	-	-	-	-	-
60	3.600	-	6.480	-	9.360	-	12.240	-	-	-	-	-	-	-

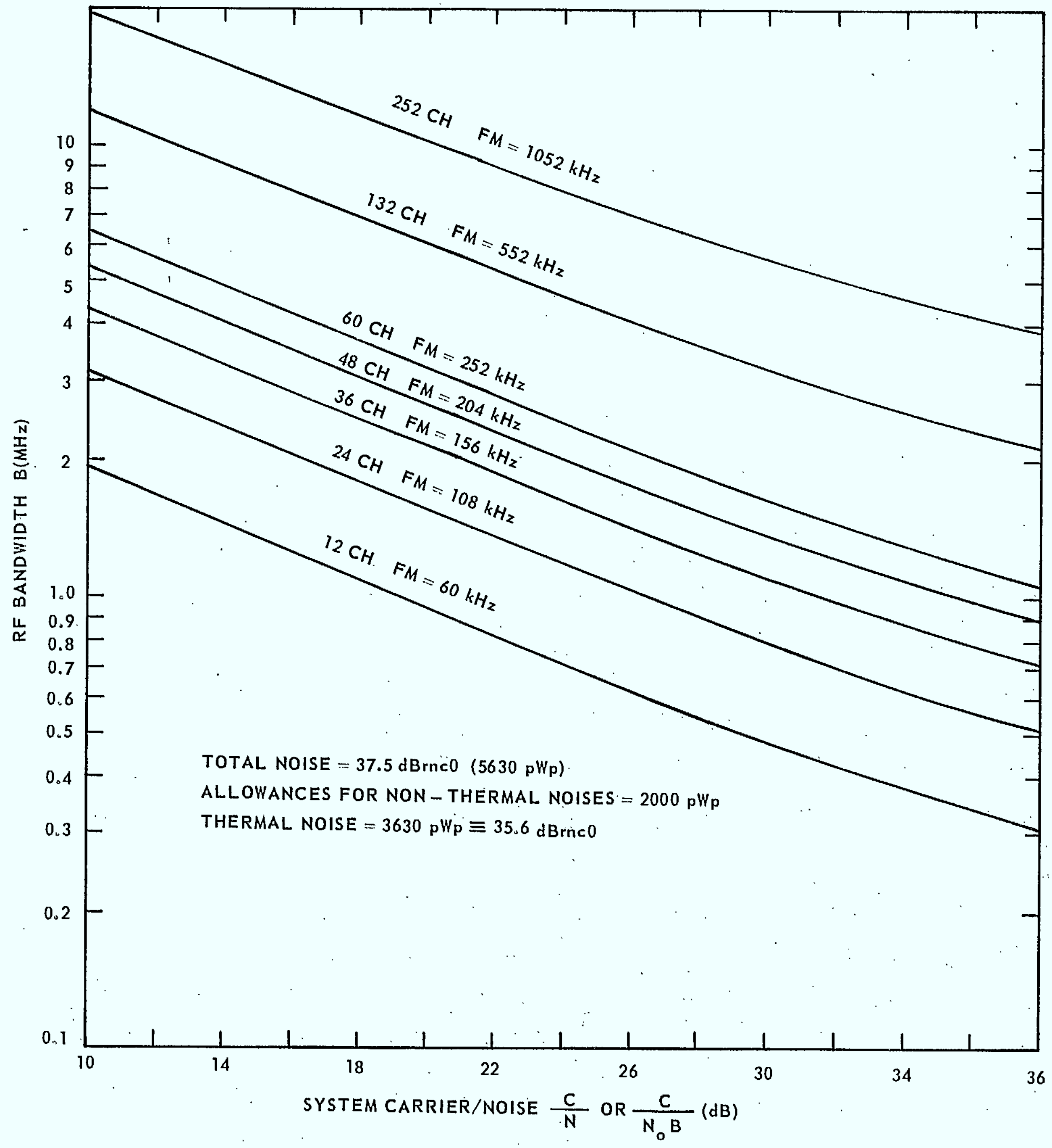


Figure 8-9 FDM-FM Satellite System:
Capacity ≤ 12 + 240 Channels per Carrier

8.3.3.3 SYSTEMS MODELING MAP FOR MAJOR TRAFFIC COMMUNICATIONS

The system modeling map for major traffic communications using FDM-FM-FDMA is derived. A working system may be chosen within the bounded area of the map.

This subsection will develop the system modeling map for major traffic communications.

It is assumed, as before, that the propagation reliability desired is 99.99 percent. In chapter 5 it is shown that for the FDM-FM-FDMA system in which the transponder is backed off to the linear mode, the system margin necessary is 9.7 dB for a network with uncooled paramps. With this large margin, click noise is not a problem under no-fade conditions.

It is assumed that threshold extension demodulators are used, since calculations (not presented here) have shown that the transponder power required is excessive if conventional demodulators are employed. It is assumed that for the average carrier capacity used, the threshold carrier-to-noise ratio is 6.5 dB.

From the above therefore, the operational carrier-to-noise ratio under no-fade condition should be 16.2 dB.

For multiple carrier operation, the optimum operating point for any number of accesses can be found from the output back-off and intermodulation characteristics of typical TWT amplifiers. It has been shown[8.9] that the carrier-to-intermodulation ratio for products falling in the center carrier of 16 equally-spaced carriers is only about 1 dB less than the extreme case of an infinite number of carriers. The 16-carrier access would therefore represent a typical system with a large number of accesses. This number of accesses will be used as the system model.

An outline of the system optimization process is presented in Appendix B. For any desired operational carrier-to-noise ratio, there is an optimum carrier-to-down-path thermal-noise ratio and carrier-to-intermodulation-noise ratio. For a 16-carrier case, with the desired operational carrier-to-noise of 16.2 dB, the optimum parameters are found to be as follows:

Carrier-to-noise (total $(C/N)_T = 16.2$ dB

Carrier-to-noise (down-link) $(C/N)_D = 19.2$ dB

Carrier-to-noise (up-link) $(C/N)_u = 29.2$ dB

Carrier-to-noise (intermod) $(C/N)_I = 19.8$ dB

Output back-off of transponder $B_o = 7.8$ dB

The down-link equation for each accessing carrier is given as follows:

$$(C/N)_D = (EIRP_s - B_o - 10 \log 16) - L_p + G/T - k - 10 \log B/16 \quad (36)$$

where $EIRP_s$ = single carrier saturated transponder EIRP

B_o = output back-off relative to EIRPs

L_p = path loss (206.8 dB)

G/T = earth station G/T

k = Boltzman's constant (-228.6 dBW/°K)

B = total usable bandwidth of transponder.

(It is considered that no guard band is necessary between the carriers[8.10].)

Substituting the values of $(C/N)_D$, B_o, L_p and k into equation (36) gives:

$$EIRPs = 5.2 + 10 \log (B) - G/T. \quad (37)$$

Equation (37) is the desired expression for plotting the system modeling map. This map, is presented as Figure 8-10. Any point on this map gives the transponder total rf bandwidth, the satellite single carrier saturated EIRP, and the earth station G/T. However, one vital piece of information is missing and this is the relationship between rf bandwidth and transponder channel capacity. This relationship depends on whether the system is used for single access or for multiple access, and is presented in Figure 8-11 for both these cases. The derivation of the curves in this figure is as follows:

(a) Curve for 16 Accesses

The operational carrier-to-noise ratio of each carrier is 16.2 dB. For multiple access it is reasonable to assume that each carrier will have a capacity less than 240 channels. Therefore the data of Figure 8-9 apply. Using Figure 8-9, the channel capacities and rf bandwidths required for this fixed C/N can be obtained. These values are plotted as the 16-access curve in Figure 8-11.

(b) Curve for Single Access

The system modeling map of Figure 8-10 is derived for a network optimized for 16-carrier accesses. However, such a satellite system may be used for single access if desired, although it would not remain optimum for this case. For multiple access, the carrier-to-noise ratio is 16.2 dB. For single access it is necessary first to determine the corresponding operational carrier-to-noise ratio. With single access no output back-off is necessary. There is therefore an immediate gain of 7.8 dB. Further, there is no multi-carrier intermodulation product. This gives an additional improvement of 2.6 dB. Therefore the total increase in C/N is 10.4 dB. Hence, the operational C/N for the single access system is 16.2 + 10.4 = 26.6 dB. For the single access case, it is reasonable to assume that the capacity is greater than 240 channels and therefore the FDM-FM curve of Figure 8-4 for capacities larger than 240 channels is applicable. From Figure 8-4, at a fixed C/N of 26.6 dB, the parameter n/B is given as 36. That is to say, the number of channels per MHz rf bandwidth is a constant 36. This is plotted as the single access capacity curve in Figure 8-11.

It is of interest to note from Figure 8-11 that the lower the transponder rf bandwidth, the lower is the ratio of the total capacity of the multiple access system to the single access system. FDM-FM-FDMA systems therefore should have as large a transponder rf bandwidth as practical. It should be noted that in a practical network, the single access system is not likely to be used as this calls for a large number of transponders. The purpose of consideration of the single access system above is to provide a datum against which the efficiency of the multi-access system can be measured.

In Figure 8-10 it can be seen that the system boundaries are somewhat different from those of the PCM-CPSK-TDMA system. The boundaries for the FDM-FM-FDMA system are discussed below:

(1) Boundary Set by Largest Practical Antenna

The largest practical earth station antenna with satellite tracking, as before, is about 58 feet. A system with non-tracking earth station antenna would be limited to about 17 feet.

(2) Boundary Set by Radio-frequency Filter Hardware

This is the same as in the other systems; that is, the lower limit of transponder bandwidth is about 15 MHz.

(3) Boundary Set by Largest System Capacity

As stated earlier, in the FDM-FM-FDMA system, a larger transponder bandwidth gives a lower channel capacity loss penalty compared to the single access case. Therefore a fairly large transponder bandwidth is desirable. The practical bandwidth limit will not be set by FM requirements, but rather by power and bandwidth of available TWT amplifiers. In Figure 8-10 the transponder bandwidth limit is arbitrarily chosen to be 100 MHz, which gives a system capacity of about 1600 channels.

(4) Boundary Set by Smallest Antenna and Inter-satellite Interference

In chapter 7, inter-satellite interference considerations set the smallest earth station antenna to about 17 feet.

(5) Boundary Set by Earth Station Transmitter Power

It can be easily shown that for an earth station network with uncooled paramps and 8 KW transmitters, the maximum down-link EIRP is given by:

$$(\mathrm{EIRP})_{\mathrm{Sat}} = 47.8 + B_o + 10 \log 16$$

$$= 67.6 \text{ dBW (in which } B_o = 7.8 \text{ dB).}$$

This limit is very high and will not constitute a real constraint in our system design.

(6) Area Enclosed by System Boundaries

The area enclosed by the system boundaries in Figure 8-10 would be the area within which a practical system may be selected. A point within this area would represent a system optimized for multiple access.

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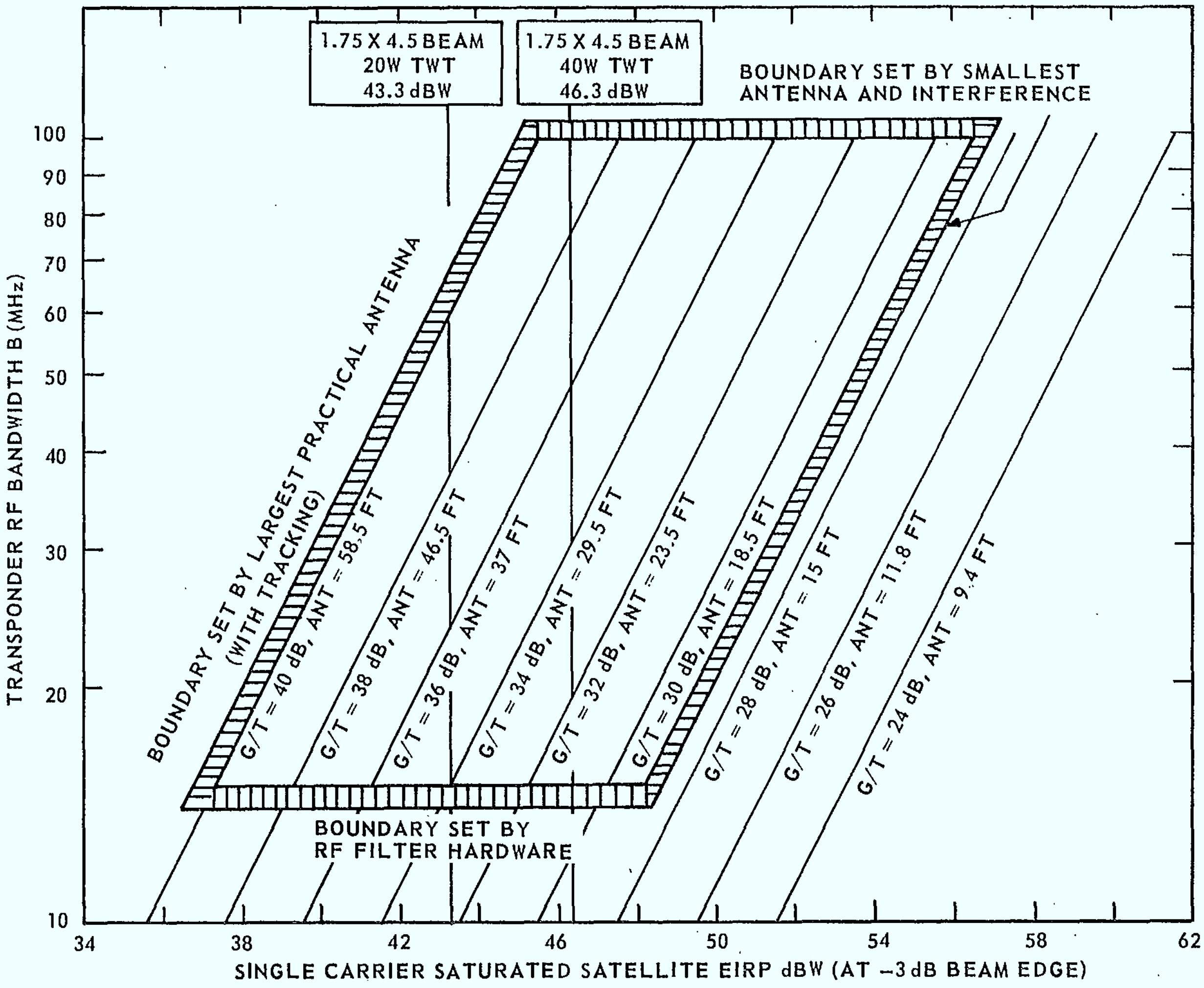

SYSTEM MARGIN = 9.7 dB (99.99 % RELIABILITY)
FM THRESHOLD = 6.5 dB (T.E D.)
OPERATIONAL $(C/N)_T$ = 16.2 dB (TOTAL)
OPERATIONAL $(C/N)_D$ = 19.2 dB (DOWN-LINK)
SATELLITE OUTPUT BACK-OFF = 7.8 dB
LOW NOISE RECEIVER = UNCOOLED PARAMP

Figure 8-10 Major Traffic Communications: System Modeling Map for FDM-FM-FDMA System with 16 Equal-Capacity and Equally-Spaced Carriers (Threshold Extension Demodulators)

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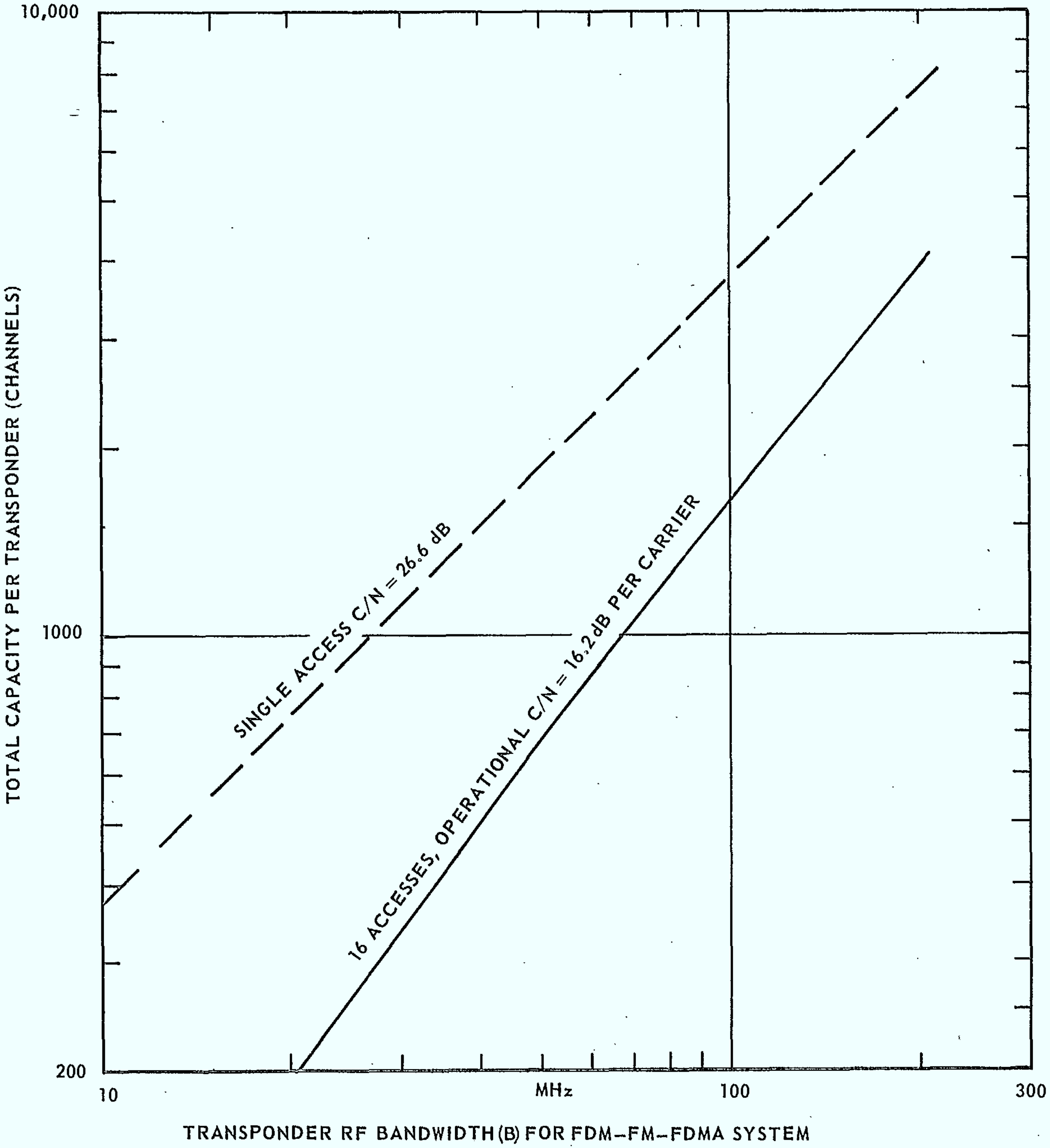

Figure 8-11 Major Traffic Communications: FDM-FM-FDMA System with Threshold Extension Demod. Total Transponder Capacity vs Bandwidth

8.3.3.4 SYSTEM MODELING MAP FOR REMOTE COMMUNICATIONS

The system modeling map for remote communications using FDM-FM-FDMA is presented. A working system may be selected within the area enclosed by the system boundaries.

This subsection will derive the system modeling map and system capacity for remote communications.

The propagation reliability is assumed to be 99.9 percent as in the PCM-CPSK case. The majority of the earth stations is assumed to be in that belt of Canada where the satellite elevation angle is around 10 through 20 degrees, and it is assumed that communications is mainly between North and South. In chapter 5, the margin required for such a network is given as 4.7 dB*. With this margin, click noise should not be a problem under no-fade conditions.

A network with threshold extension demodulators is considered. The threshold C/N of a threshold extension demodulator may be taken as 6.5 dB. The operational carrier-to-noise ratio is therefore 11.2 dB.

From Appendix B, the system optimization for a desired operational carrier-to-noise ratio of 11.2 dB gives the following:

Carrier-to-noise (total)	$(C/N)_T = 11.2$ dB
Carrier-to-noise (down-link)	$(C/N)_D = 14.5$ dB
Carrier-to-noise (up-link)	$(C/N)_u = 24.5$ dB
Carrier-to-noise (intermod)	$(C/N)_I = 15.1$ dB
Output back-off of TWT	$B_o = 4.4$ dB.

Using equation (36) and substituting the appropriate values above, gives:

$$EIRP_S = -2.9 + 10 \log (B) - G/T. \qquad (38)$$

This is the equation to plot the system modeling map for FDM-FM-FDMA remote communications with threshold extension demodulators. This map is presented in Figure 8-12.

NOTE: * Approximately the same margin is applicable for North-to-North links.

Figure 8-13 gives the relationship between total transponder channel capacity versus rf bandwidth of the transponder. The cases for the single-access and 16-access are presented.

The system boundaries of Figure 8-12 are essentially similar to those of Figure 8-10, except that the smallest antenna from inter-satellite interference considerations has now moved to about 9.5 feet. If a system were to have non-tracking earth station antennas, the maximum antenna size should not exceed about 17 feet.

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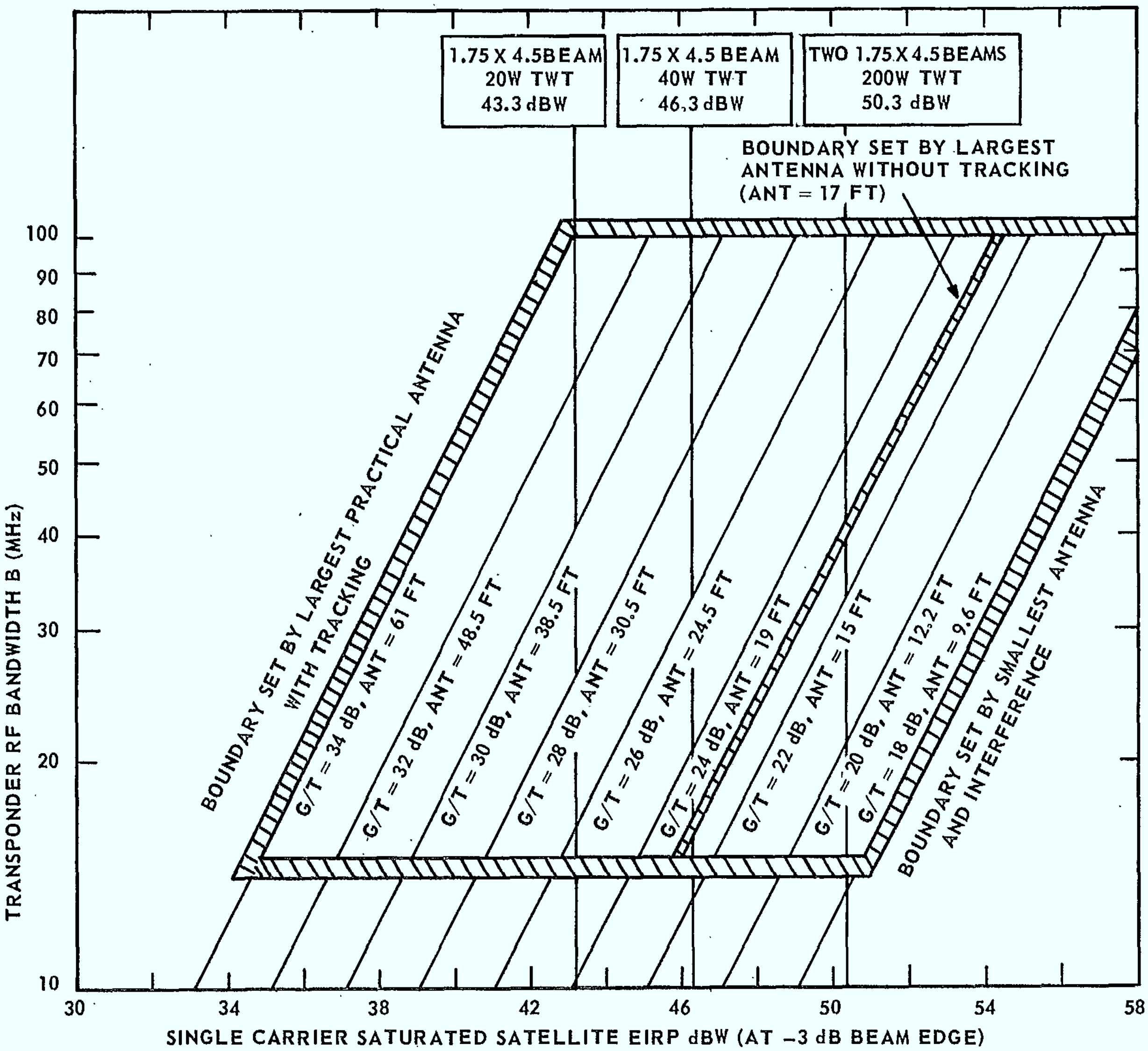

SYSTEM MARGIN = 4.7 dB (99.9 % RELIABILITY)
FM THRESHOLD = 6.5 dB

OPERATIONAL $(C/N)_T$ = 11.2 dB TOTAL)
OPERATIONAL $(C/N)_D$ = 14.5 dB (DOWN-LINK)
SATELLITE OUTPUT BACK-OFF = 4.4 dB
LOW NOISE RECEIVER = TUNNEL DIODE AMPLIFIER

Figure 8-12 Remote Communications: System Modeling Map for FDM-FM-FDMA System with 16 Carriers and Threshold Extension Demodulators

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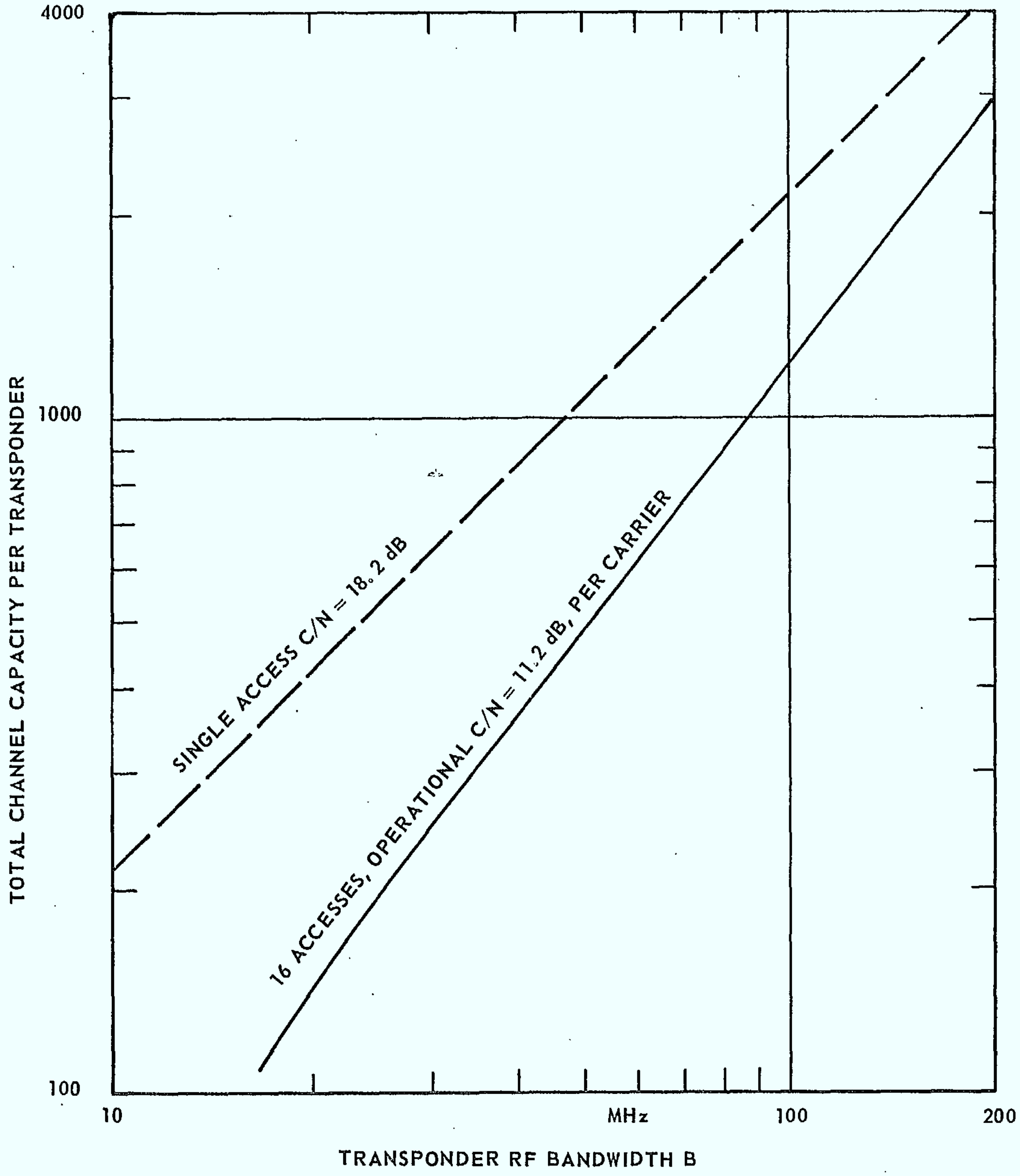

Figure 8-13 Remote Communications: FDM-FM-FDMA System with Threshold Extension Demod. Total Transponder Capacity vs Bandwidth

8.3.4 COMPARISONS BETWEEN PCM-CPSK-TDMA AND FDM-FM-FDMA SYSTEMS

For major traffic communications, PCM-CPSK appears to be significantly superior to FDM-FM-FDMA. For remote communications in which capacity is low, FM may be viable on account of low transmit power at earth stations.

Previous subsections have derived representative system modeling maps for PCM-CPSK-TDMA and FDM-FM-FDMA systems. This subsection will now compare the effectiveness of these modulation techniques in:

(a) Major Traffic Communications

(b) Remote Communications

The system effectiveness is measured in terms of bandwidth and power utilization as a function of transponder channel capacity.

* * *

8.3.4.1 MAJOR TRAFFIC COMMUNICATIONS

FM uses both more power and more bandwidth than the PCM-CPSK systems.

Figures 8-14 and 8-15 give a direct comparison of the effectiveness in the utilization of transponder rf bandwidth and power respectively. The systems compared are:

FDM-FM-FDMA (16 accesses)

PCM-4ϕ CPSK-TDMA

PCM-8ϕ CPSK-TDMA

The data for plotting these curves are obtained directly from Figures 8-5, 8-6, 8-10 and 8-11. Although the FDM-FM-FDMA system is worked out on a specific example of 16 accesses (as explained in 8.3.3.3), in general, the results apply to any system with a large number of accesses. The digital system is not very sensitive to the number of accesses and therefore the results also apply to any system with a large number of accesses.

It is quite clear from Figures 8-14 and 8-15 that for any transponder capacity, the FDM-FM-FDMA system uses more power and more bandwidth than either the 4-phase or 8-phase digital system. Between the 4-phase and the 8-phase systems, for any given channel capacity, the 4-phase system uses 1.5 times the bandwidth of the 8-phase system but uses 2.5 times less power. Whether the 4-phase or 8-phase system is to be preferred depends on whether bandwidth or power is the more costly commodity. These will be evaluated in another chapter of this report.

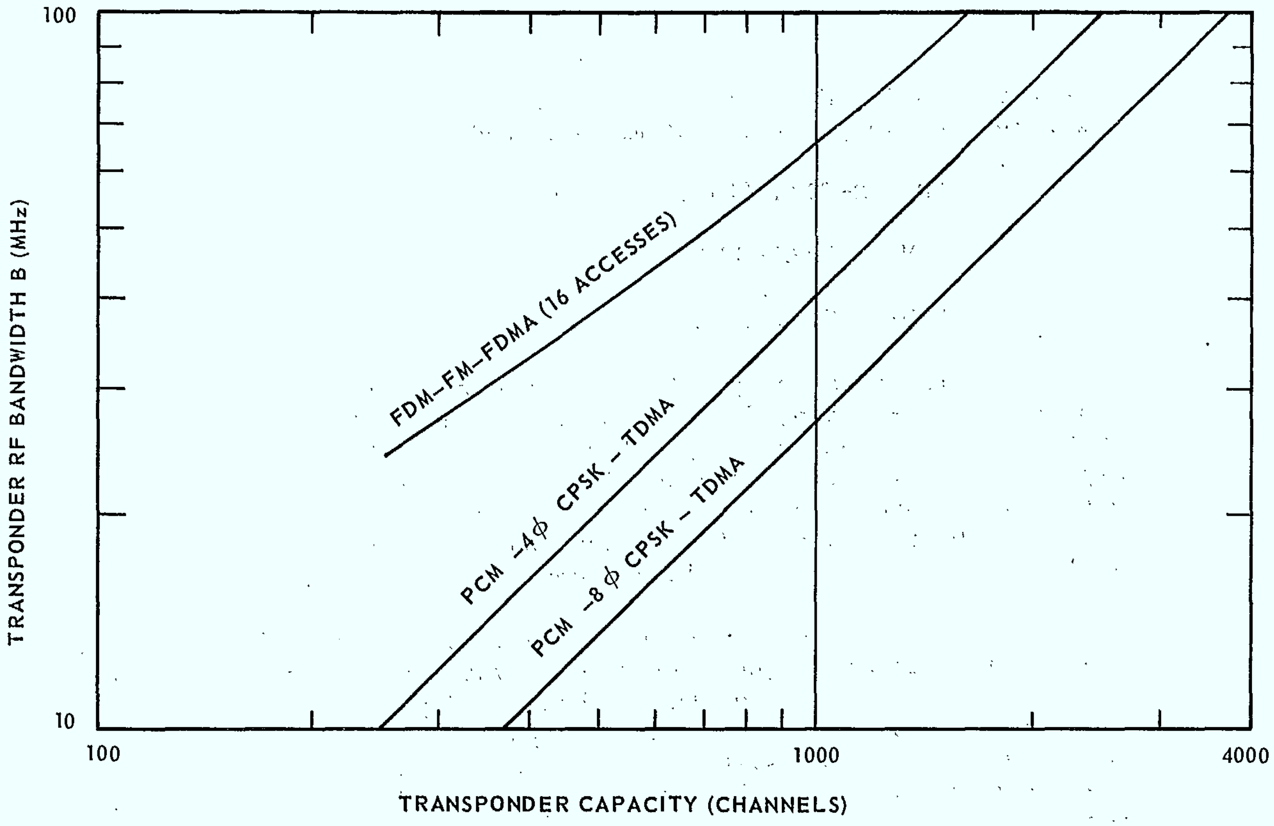

Figure 8-14 Major Traffic Communications: Comparison of Effective RF Bandwidth Utilization between Various Systems

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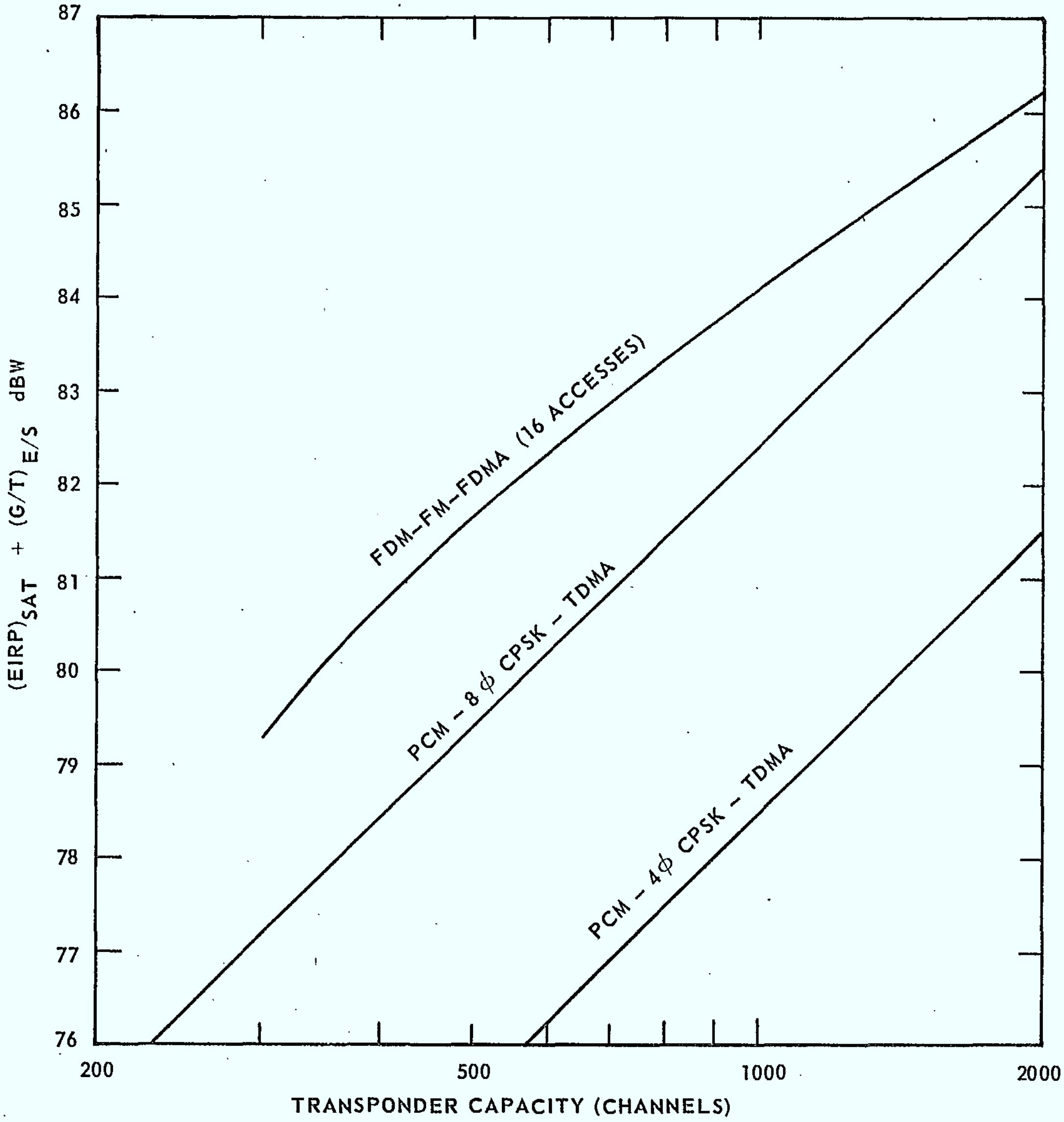

Figure 8-15 Major Traffic Communications: Comparison of Effective Power Utilization between Various Systems

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8.3.4.2 REMOTE COMMUNICATIONS

FM uses more power and bandwidth but may prove to be cheaper because of up-link power. The economics will be analyzed in chapter 9.

Figures 8-16 and 8-17 give a direct comparison in the effective bandwidth and power utilization of the following systems:

FDM-FM-FDMA (16 accesses)

PCM-2ϕ CPSK-TDMA

PCM-4ϕ CPSK-TDMA

The curves in these figures are derived from data presented in Figures 8-7, 8-8, 8-12 and 8-13. Again both the analogue and digital systems may be taken as representative of any system with a large number of accesses.

From Figure 8-16 it is quite clear that the FDM-FM-FDMA uses more bandwidth than either the 2-phase or the 4-phase digital system. However, at a large transponder capacity, the effectiveness of the FM system approaches that of the 2-phase system.

Figure 8-17 gives the comparison of power utilization. The FDM-FM-FDMA system uses much more down-link power than either the 2-phase or 4-phase digital systems. However, for small capacity systems such as a few channels per carrier as might be the case in remote communications, there is one important factor in favour of the FDM-FM-FDMA system over the PCM-CPSK-TDMA system, and this factor is the up-link transmit power. In the FDM-FM-FDMA case, the earth station transmit power is directly proportional to the channel capacity of the carrier. Therefore, for small capacity systems, the up-link power required is small. On the other hand, in a PCM-CPSK-TDMA system an earth station participating in a network must transmit at full power during the allocated time slot to saturate the transponder irrespective of the channel capacity of the station. For small capacity stations this power requirement becomes disproportionally large.

Between the 2-phase and 4-phase digital systems, for any given channel capacity, the 4-phase system uses half the rf bandwidth but only slightly more down-link power than the 2-phase system. The 4-phase system is therefore more efficient in the overall sense.

The choice of any particular modulation technique will be left to a later chapter after the economic and other aspects common to all the other services have been examined.

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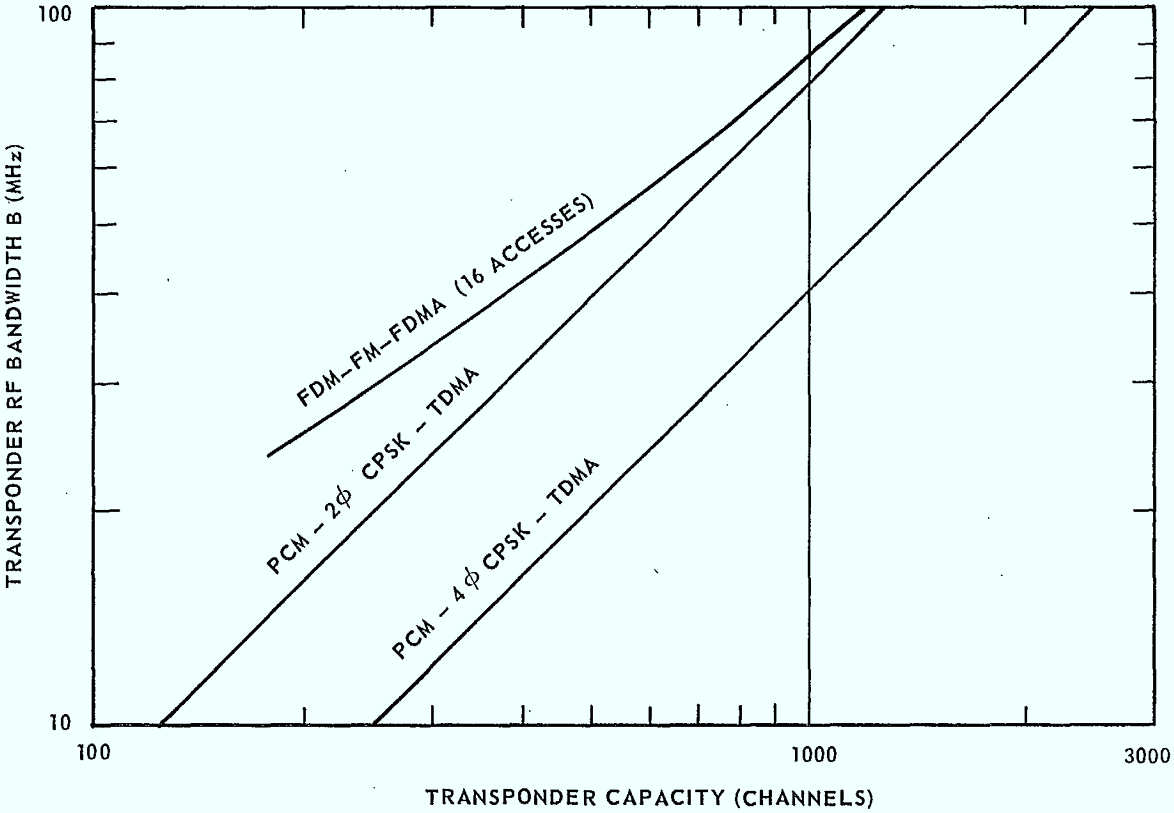


Figure 8-16 Remote Communications: Comparison of Effective RF Bandwidth Utilization between Various Systems

* * *

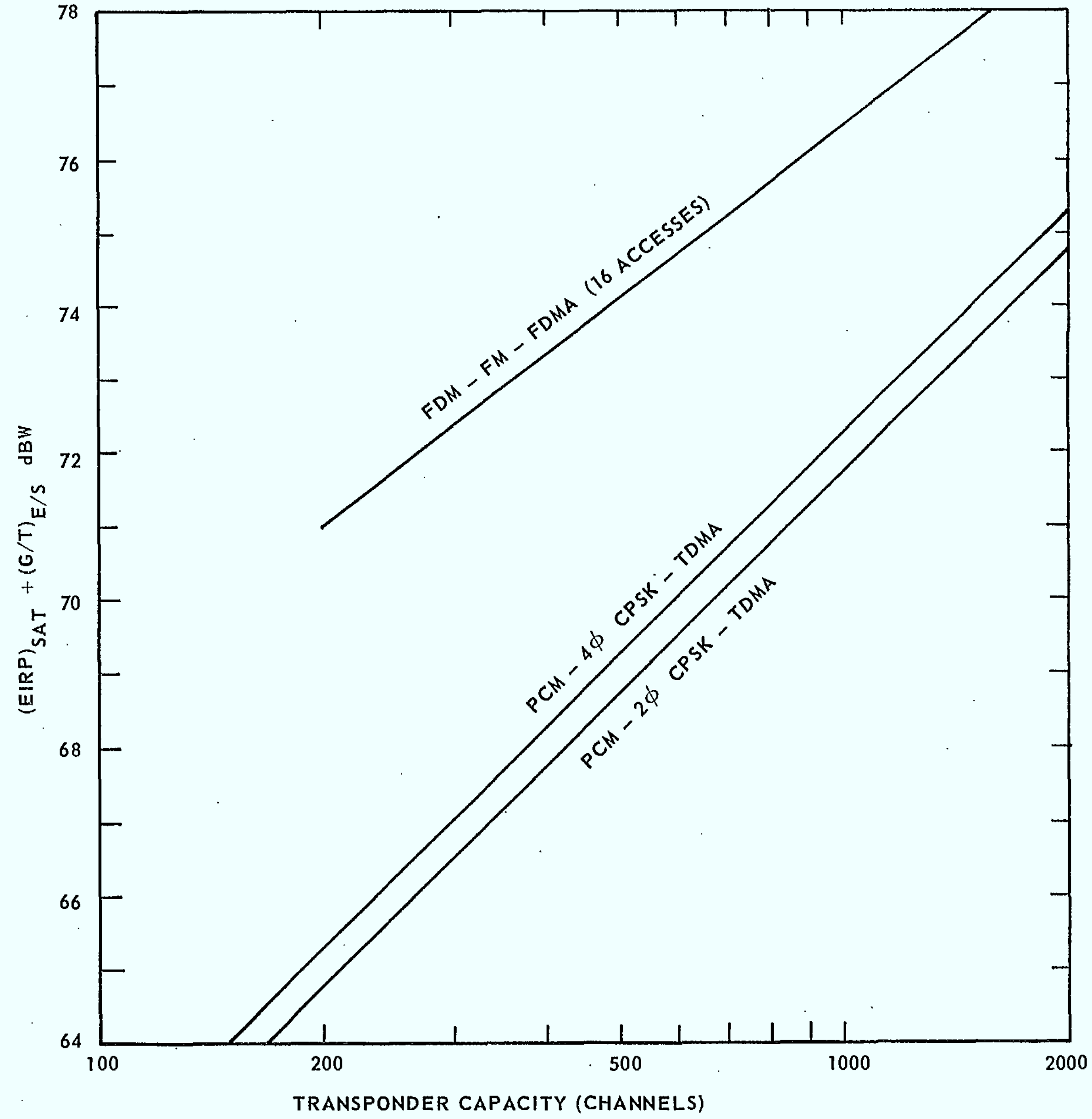


Figure 8-17 Remote Communications: Comparison of Effective Power Utilization between Various Systems

8.4 SINGLE CHANNEL PER CARRIER TELEPHONY SYSTEM

The technical parameters of a satellite system for single channel per carrier telephony are considered.

This subsection will consider the single channel per carrier telephony system for remote communications. The system modeling maps will be developed and system boundaries will be discussed.

*　*　*

8.4.1 NETWORK FEATURES

The network for the single channel per carrier system is assumed to have the following features:

(a) The system is homogeneous, that is, all earth stations are of the same size and have the same G/T values.

(b) Frequency division multiple access (FDMA) will be used rather than time division multiple access (TDMA). The use of FDMA very much simplifies equipment and control techniques at the earth stations. The carriers will be uniformally spaced.

(c) The modulation will be FM. It has been shown[8.10,8.11] that with syllabic compandors together with pre-emphasis, FM is superior to PCM-CPSK. Further, FM equipment is simple and easy to maintain.

(d) Voice activation will be used, that is, the carrier will be turned on only during the speech bursts (and of course during signaling to set up a call connection).

(e) The carriers or channels will be pre-assigned. The system is adaptable to demand assigned working, but discussions of demand assignment application will not be presented.

* * *

8.4.2 SINGLE CHANNEL PER CARRIER FM EQUATION

The relationship between the desired signal-to-noise ratio of the voice channel, the rf bandwidth and the carrier-to-noise ratio is developed.

This subsection presents the systems equation for single channel FM and states the assumptions made.

The well known FM equation for a single channel system is as follows:

$$S/N = 3\ C/N\ (\delta f_{rms}/f_m)^2\ B_x/f_m \text{ (unweighted)} \qquad (39)$$

where S/N = test tone to noise ratio (unweighted)

C/N = carrier-to-noise ratio

f_m = maximum baseband frequency (4 kHz)

B_x = radio-frequency bandwidth

δf_{rms} = rms test tone deviation

From Carson's Rule:

$$B_x = 2(p\delta f_{rms} + f_m) \qquad (40)$$

where p = peak factor of the voice signal above test tone.

From equations (39) and (40), it is easy to show that:

$$S/N = 3\ \frac{C}{N} \cdot \frac{1}{4p^2} \cdot \quad (B_x/f_m - 2)^2 \quad B_x/f_m \text{ (unweighted)}$$

Expressing all the parameters in dB, the above becomes:

$$S/N = C/N - 1.2 - 20 \log p + 10 \log (B_x/f_m \ - 2)^2 \ B_x/f_m \ \text{dB}$$

$$\ldots \quad \text{(unweighted)} \qquad (41)$$

For a system with syllabic compandors and pre-emphasis, assume:

Pre-emphasis advantage = 4 dB

Compandor advantage = 15 dB

Peak factor 20 log p = 3 dB

Also, for an effective voice band of 3.1 kHz, the bandwidth reduction factor from 4 kHz is 1.1 dB.

Applying these correction factors to equation (41), for a system with compandors and pre-emphasis:

$$S/N = C/N + 15.9 + 10 \log (B_x/f_m \ - 2 \ )^2 \ B_x/f_m$$

$$\text{(unweighted) dB} \qquad (42)$$

This is the equation required to calculate the rf bandwidth when S/N and C/N are defined.

8.4.3 SYSTEMS MARGIN

The systems margin determines the operational carrier-to-noise ratios for a system with conventional demodulators and a system with threshold extension demodulators.

It is assumed that a service reliability of 99.9 percent due to propagation effects would be acceptable. This is the same as the multi-channel remote communications system discussed in 8.3.3.4. It is expected that earth stations would be spread out in all parts of Canada. For the northern locations where the satellite elevation angles would be low (say below 20°), the tropospheric fading effects would be significant. While it is possible for any station to link with any other station it is assumed that a majority of the links would be in the North-South direction in which case, as shown in chapter 5, the system margin required is 4.7 dB*.

The threshold carrier-to-noise ratios of conventional and threshold extension demodulators are assumed to be 10 dB and 6 dB respectively. In view of the extremely narrow band system proposed and the problems of frequency stability (discussed later), the predetection noise band filters may have to be somewhat wider than that given by Carson's rule. Therefore an additional allowance of 1 dB will be made. Hence, the operational carrier-to-noise ratios (referred to Carson's bandwidth) are:

(a) For conventional demod system: C/N = 15.7 dB.

(b) For threshold extension demod systems: C/N = 11.7 dB.

NOTE:

* Approximately the same margin applies for North-to-North links.

* * *

8.4.4 RADIO FREQUENCY BANDWIDTH PER CHANNEL

The rf bandwidth per channel is derived, inclusive of guardband between the carriers. From this, the number of channels per MHz rf bandwidth (*n*/B) is obtained.

The rf bandwidth required to support a voice channel of a specified quality is derived. The system noise objective has been defined in chapter 4 as 44 dBrnc0. This corresponds to:

$$S/N = 88 - 44 = 44 \text{ dB (unweighted)}.$$

Using equation (42) and the operational carrier-to-noise ratios defined in 8.4.3, the required rf bandwidth can be shown to be as follows:

(a) For conventional demod system: $B_x = 16.3$ kHz.

(b) For threshold extensional demod system: $B_x = 20$ kHz.

The above are the "effective" bandwidths as given by Carson's Rule. For narrow band systems such as these it is essential to provide adequate guardbands between channels. The guardband required is dictated by the stabilities of the various oscillators. At 12 through 14 GHz, local oscillator stabilities in the transmitters and receivers are the critical elements. To partially overcome the problem, it is assumed that the receiver would be frequency locked to the transmit carrier through some means; e.g. like the SPADE system. The frequency drift problem would therefore be confined to the transmit end only. The transmitter frequency drift is estimated to be about ±8.0 kHz made up as follows:

Up-converter	±7.0 kHz due to crystal stability of ±5 parts in 10^7
Modulator	±1.0 kHz at i-f of 70 MHz.

Therefore, inclusive of the guardband the rf bandwidth required per carrier is KB_x where:

(a) For conventional demod system, $K = \frac{16 + 16.3}{16.3} = 2.0$ (43)

(b) For threshold extension demod system, $K = \frac{16 + 20}{20} = 1.8$ (44)

The number of channels per MHz rf bandwidth (n/B) is therefore given as follows:

(a) For conventional demod system,

$$(n/B) = \frac{10^6}{KB_x} = \frac{10^6}{2 \times 16.3 \times 10^3} = 31$$

(b) For threshold extension demod system,

$$(n/B) = \frac{10^6}{KB_x} = \frac{10^6}{1.8 \times 20 \times 10^3} = 27.8$$

For any specified system channel capacity, the transponder bandwidth required is obtained by simply dividing the number of channels by 31 or 27.8 as appropriate.

8.4.5 SYSTEM OPTIMIZATION

The optimum operational parameters to give the desired operational carrier-to-noise ratios are presented.

In an FDMA system, for each value of operational carrier-to-noise ratio there is an optimum point in the transponder output back-off which gives the maximum systems capacity. The technique in the optimization is well documented. Using the method and data presented in Ref 8.11, the optimum operating parameters are found to be as follows:

	CONVENTIONAL DEMOD SYSTEM	THRESHOLD EXTENSION DEMOD SYSTEM
Transponder Input Back-off	12 dB	8.4
Transponder Output Back-off (B_o)	5.6 dB	3.3
C/I	20.2 dB	16.1
(C/N) thermal	17.6 dB	13.7
(C/N) total	15.7 dB	11.7

* * *

8.4.6 SYSTEM MODELING MAPS

System modeling maps for a system with conventional demodulator and a system with threshold extension demodulator are derived.

With the results obtained in the previous subsections it is now possible to proceed to derive the system modeling maps.

The system down-link equation can be written as follows:

$$\begin{aligned}(C/N)_D &= (C/T)_D - k - 10 \log B_x \\ &= [EIRP_S - B_o - 10 \log n - 10 \log 0.4] \\ &\qquad - L_p + G/T - k - 10 \log B/nK \qquad (45)\end{aligned}$$

where $(C/N)_D$ = carrier-to-noise ratio (down-link)

$(C/T)_D$ = carrier-to-noise temperature ratio (down-link)

k = Boltzman's constant (-228.6 dBW/°K)

B_x = radio-frequency bandwidth per carrier = B/nK

B = total transponder rf bandwidth

n = total number of channels (active and inactive)

K = radio-frequency bandwidth expansion factor to account for the inclusion of channel guardband. Values of K are given in equations (43) and (44).

$EIRP_S$ = single carrier saturated transponder EIRP

B_o = transponder output back-off

0.4 = 40 percent channel activity factor (assumed)

L_p = propagation loss (206.8 dB)

G/T = earth station G/T.

Rearranging equation (45) and substituting the numerical constants, this equation becomes:

$$EIRP_S = (C/N)_D + B_o - G/T + 10 \log B - 10 \log K - 25.8 \text{ dBW} \qquad (46)$$

This is the basic equation needed to derive the equations for the system modeling maps, two cases of which will be presented below; that is, a system with conventional demodulators and one with threshold extension demodulators. In both cases, it is assumed that the up-link carrier-to-noise ratio is 6 dB higher than the down-link carrier-to-noise ratio. A slightly higher up-link noise contribution than that of the previously considered multi-channel systems is allowed here on account of the large number of earth station transmitters involved (about 200). The value of up-link noise chosen would degrade the down-link thermal noise by 1 dB and this is not excessive.

(a) System with Conventional Demodulator

In this system the appropriate parameters are:

(C/N) thermal = 17.6 dB (from 8.4.5)

The up-link contributes 1 dB degradation.

$\therefore$ $(C/N)_D = 17.6 + 1.0 = 18.6$ dB.

Output back-off $B_o = 5.6$ dB (from 8.4.5)

From equation (43), factor K = 2.0

$\therefore$ Equation (46) gives:

$$EIRP_S = -4.6 - G/T + 10 \log B \qquad (47)$$

This is the equation for plotting the system modeling map which is presented as Figure 8-18.

(b) System with Threshold Extension Demodulator (TED)

In this system the parameters are:

(C/N) thermal = 13.7 dB (from 8.4.5)

The up-link contributed 1 dB gradation.

$\therefore \quad (C/N)_D = 13.7 + 1.0 = 14.7$ dB.

Output back-off $B_o = 3.3$ dB

From equation (44) factor K = 1.8.

$\therefore$ Equation (46) gives:

$$EIRP_S = -10.3 - G/T + 10 \log B. \qquad (48)$$

This equation is used to plot the system modeling map of Figure 8-19.

* * *

8.4.7 SYSTEM BOUNDARIES

Constraints on the single channel per carrier system are discussed.

The systems boundaries indicated in Figures 8-18 and 8-19 are very much the same as those previously discussed in the system modeling maps of the other services, except for the boundary set by the earth station transmitter power. This latter boundary will be explained below.

The up-link and down-link carrier-to-noise temperature ratios and the inter-relationship between these two parameters are set out as follows:

$$(C/T)_U = (C/T)_D + X \text{ (dB)} \tag{49}$$

$$(C/T)_U = (G_t + P_t - L) - L_U + (G/T)_{sat} \tag{50}$$

$$(C/T)_D = (EIRP_S - B_o - 10 \log n - 10 \log 0.4) - L_D + G_R - T_S \tag{51}$$

where $(C/T)_U$ = up-link carrier/noise temperature

$(C/T)_D$ = down-link carrier/noise temperature

X = difference (dB) between $(C/T)_U$ and $(C/T)_D$ = 6 dB.

G_t = earth station transmit antenna gain

P_t = earth station transmitter power

L = earth station transmit waveguide losses

L_U = up-path loss

$(G/T)_{Sat}$ = satellite G/T

L_D = down-path loss

G_R = earth station receive antenna gain

T_S = earth station receive system noise temperature = = 30.7 dB/°K for TDA

$EIRP_S$ = single carrier saturated transponder EIRP

B_O = satellite transponder output back-off relative to $EIRP_S$

n = number of voice channels

0.4 = 40 percent activity factor.

Manipulating the above equations and substituting the appropriate numerical values where stated, it can be shown that:

$$EIRP_S = P_t + B_O + 10 \log n + 15. \tag{52}$$

In view of the very large number of earth station transmitters involved, it is desirable to keep the transmitter power as low as possible. Most of the earth stations are expected to be in remote areas and transmitter reliability and prime power requirements are important. Hence it is considered appropriate that earth station transmitters should not exceed 5 watt or 7 dBW. Setting P_t = 7 dBW, therefore:

$$EIRP_S = 22 + B_O + 10 \log n. \tag{53}$$

Now, B_O and n obtained from 8.4.4 and 8.4.5 are as below:

(a) Conventional demod system:

$B_O = 5.6$ dB

$n = 31 \times B$ (MHz).

(b) TED system:

$B_O = 3.3$ dB

$n = 27.8 \times B$ (MHz).

Therefore, the largest saturated satellite EIRP is given as follows:

(a) Conventional demod system:

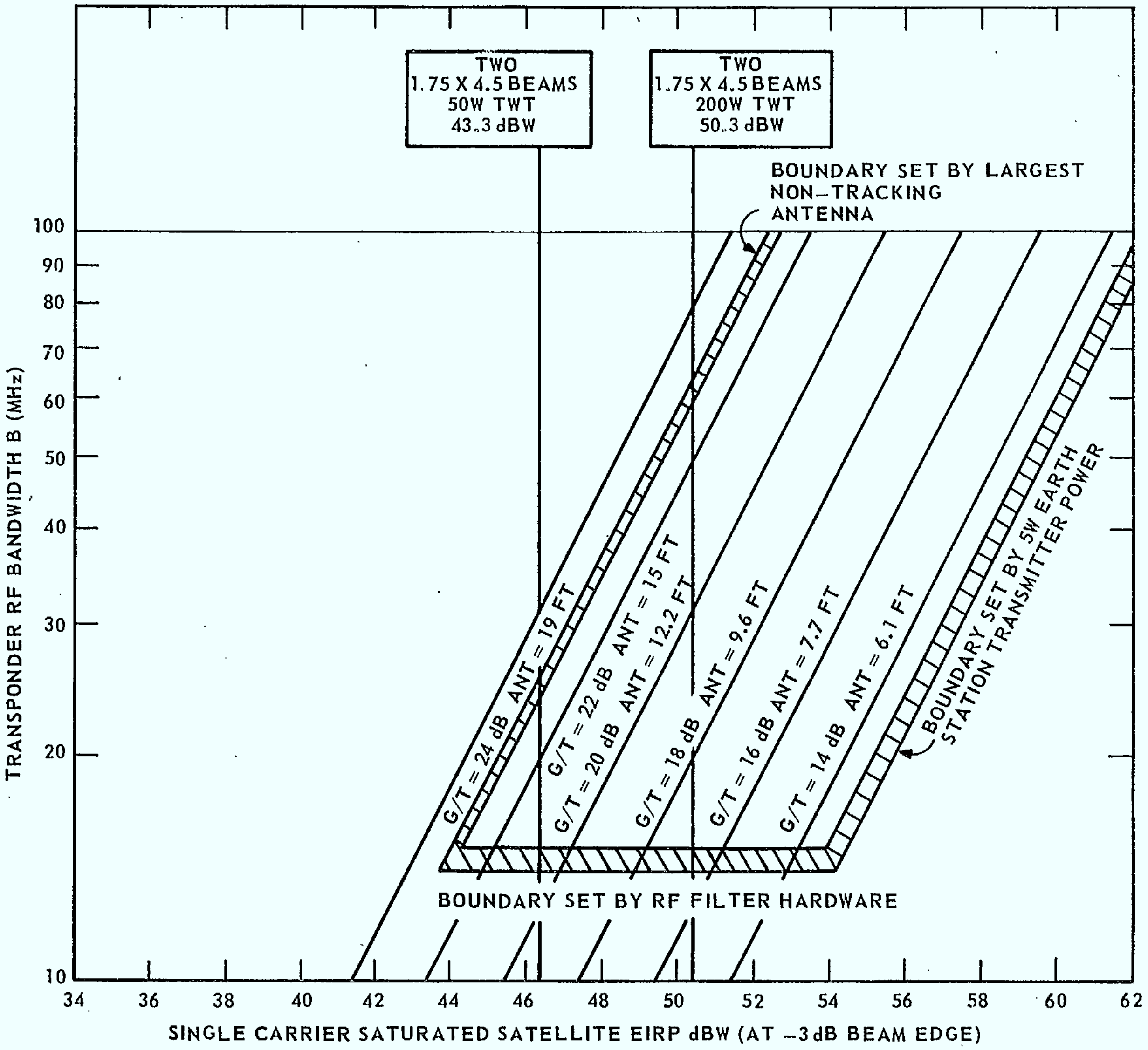
$$EIRP_S = 42.5 + 10 \log B \text{ (MHz)}.$$

(b) TED system:

$$EIRP_S = 39.8 + 10 \log B \text{ (MHz)}.$$

Each of the above equations give the boundary for the satellite single carrier saturated EIRP corresponding to 5 watts of earth station transmitter power.

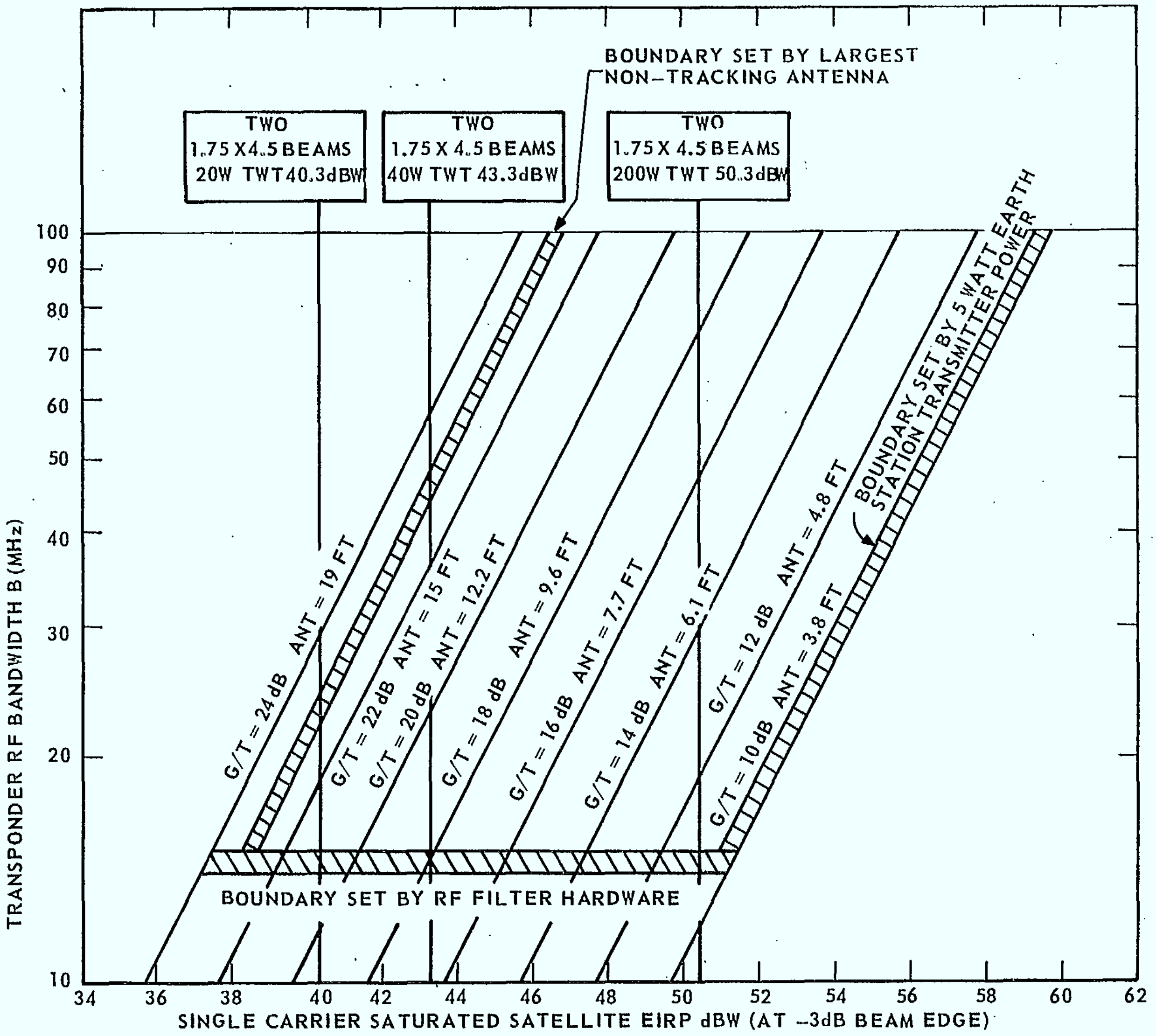
Just as in the case of the other system models discussed earlier, any point on the map gives a system choice. The choice of an optimum system will be left to chapters 9 and 10 where the economic and other aspects common to all the other services will be considered.



1) FM-FDMA, Equally Spaced Pre-Assigned Carriers
2) Voice Activation
3) Compandors and Pre-Emphasis
4) Noise Objective 44 dBrncO
5) Fade Margin 4.7 dB (Service Availability 99.9%)
6) Channel Capacity, n = 31 × B (MHz) Channels
7) Low Noise Receiver = TDA.

Figure 8-18 Single Channel per Carrier Telephony: Conventional Demod; 6 dB Difference in Up-link/Down-link Carrier-to-Noise Ratio

* * *



1) FM-FDMA, Equally Spaced Pre-Assigned Carriers

2) Voice Activation

3) Compandors and Pre-Emphasis

4) Noise Objective 44 dBrnc0

5) Fade Margin 4.7 dB (Service Availability 99.9%)

6) Channel Capacity n = 27.8 × B (MHz) Channels

7) Low Noise Receiver = TDA

Figure 8-19 Single Channel per Carrier Telephony: Threshold Extension Demod; 6 dB Difference in Up-link/Down-link Carrier-to-Noise Ratio

8.5 REFERENCES

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9. System Economics

9.1 GENERAL DISCUSSION

In the context of the major objective of any system design being to provide service at minimum cost, the most realistic approach is to synthesize the satellite system on a minimum annual charges basis within the economic and technical constraints imposed.

The major, and often determining factor, to be considered in designing any system is the cost to the user of the service provided. Although there are technical trade-offs which can and must be performed and technical and other constraints which limit the system choices, an economic optimization is vital in the choice of the correct mix of interrelated systems parameters. For the purposes of this study the satellite system is taken to consist of a space segment comprising one or more satellites in orbit and an earth segment embracing a number of different types of earth stations. Because of the technical trade-off of power and bandwidth, satellite EIRP and earth station G/T are interrelated by a factor which is dependent upon the service quality. Because the space segment cost increases as satellite EIRP increases and earth segment cost increases as earth station G/T increases, it follows that the sum of the space segment and earth segment costs will have a minimum at some particular value of G/T (or EIRP). The object of the economic trade-off is to locate this minimum cost within the technical constraints imposed. While the systems capital costs are of interest, it is the annual charges which determine the ultimate economy of the system and the trade-offs will be performed on this basis, as agreed with the Design Authority. In actual fact the annual revenue requirements would be a more realistic parameter but, as this approach would entail making assumptions about operating policies, interest rates and income taxes, the annual charges only will be considered. As will become evident in chapter 10, a profit before taxes of up to approximately 20 percent on investment will not result in the optimum mix, of the space segment and earth segment technical parameters, to change by more than approximately 1 dB. Annual charges are discussed in 9.4.1.

The trade-off method employed is to examine the total system annual charges required to meet each different service demand estimated earlier in this study. This is done by estimating the cost of sufficient space segment capacity in a multi-service satellite to meet the service demand and adding to this the cost of the associated earth segment. The total satellite cost is then the sum of the satellite costs for each of the services, and the total system cost is the sum of the total space segment and total earth segment costs.

A computer program was used to perform the calculations for the individual services. The method used, therefore, requires a calculation of the space segment cost as EIRP varies, and of the earth segment cost as earth station G/T varies. As the projection of costs six years ahead is difficult in itself the problem has been eased by giving all costs in 1971 dollars.

9.2.1 SATELLITE HARDWARE AND DEVELOPMENT COSTS

The total cost of a spacecraft is made up of repetitive hardware production costs and the amortization of development costs which include the development of the required technology, spacecraft engineering design and special development of engineering and prototype spacecraft models. For the class of satellite considered in the present study a figure of $10,000 per pound is realistic for satellite hardware costs; considering the anticipated state-of-the-art of the technology in the 12 through 15 GHz frequency bands a figure of $10M is realistic for development costs for a program to produce a small number of spacecraft for 1977 deployment.

As outlined in 6.2 a relationship between the weight of a satellite and its total transmitted rf power was required for the system optimization procedure. For the same reasons it is also necessary to establish a relationship between satellite weight and cost. The factors which must be taken into account are discussed below and a realistic satellite cost is established on a per pound basis for hardware costs. A first estimate of development costs is also made considering the expected status of the technology.

The design and manufacture of satellites consists of two major phases as outlined below:

(a) Development phase, which includes development of the required technology, engineering design of the spacecraft, development of engineering models, and development of prototype.

(b) Production phase, which is the production of a number of flight spacecraft to the engineering drawings and specifications resulting from the development phase.

Each phase would also include the necessary program direction and indirect overhead charges.

The costs of producing flight hardware being mainly the cost of manufacture to given engineering drawings would depend to a large extent on the manufacturing techniques employed and could reasonably be expected to remain fairly constant for satellites using similar technology. Any change in manufacturing requirements due for instance to a change in manufacturing tolerances may tend to increase the manufacturing costs. In order to establish reasonable estimates of hardware and development costs it would be appropriate to examine the program costs of a series of satellites using similar technology in the same frequency band.

As has been discussed in chapter 6, the satellite technology in the 12 through 15 GHz bands is expected to be at a stage of development equivalent to that which had been reached in the 4 GHz and 6 GHz bands about two years ago. That is, the technology for deployment in 1977, in the 12 through 15 GHz bands, will be advanced to the same stage as that in the 4 GHz and 6 GHz bands and currently in use for the Intelsat IV satellites. Because of this the Intelsat IV program can be considered as a good source of information regarding satellite costs. Information is available concerning the Intelsat IV program and the first four flight spacecraft cost approximately $12M each including maximum incentive payments. This cost is the cost of producing flight spacecraft and does not include development costs which will be discussed later. Another satellite which uses similar technology as Intelsat IV is that proposed by Hughes Aircraft Company for a United States domestic system. The total cost given for three such satellites is $21M or $7M per satellite. In the proposal for this satellite it is stated that a proportion of the development costs are included in the price. The weight in orbit of this satellite is about 550 pounds which gives hardware cost of $12.7k per pound. As this satellite is stated to be based upon a Hughes sponsored program of structure and associated development to be amortized over a number of systems and the associated specific design of the Anik satellite for the Canadian domestic system, it is reasonable to expect that the amount of development would be small because a significant amount of flight qualified hardware would be available and the basic satellite engineering design would have been completed. During discussions with NASA experts regarding development costs of satellites, a figure of $2.5k per pound of deployable spacecraft hardware was agreed as a realistic special development cost when a spacecraft is merely a reproduction of a previous design with minor modifications necessary due to the unique system requirements. This being so, the hardware costs of the Hughes satellite can be estimated at about $10k per pound. The hardware costs on a per pound basis for the Intelsat IV satellite are about $8k per pound using an in-orbit weight of approximately 1500 pounds.

More confidence can be placed in the Intelsat IV figure of $8k per pound than in the Hughes satellite figure of $10k per pound because it is known that the former includes no development charges while in the latter case the development charges can be only a close estimate. However, in addition it may be expected that, due to tighter manufacturing tolerances necessitated, and higher component densities possible, at frequencies in the 12 through 15 GHz bands compared with the 4 GHz and 6 GHz bands, the manufacturing costs may be slightly higher than the $8k derived from the Intelsat IV program. For these reasons a figure of $10k per pound is considered reasonable for the flight hardware costs of satellites in the weight range from about 500 pounds to 1500 pounds employing frequencies in the 12 through 15 GHz bands for deployment around 1977.

As regards the development costs for communications satellites these may be expected to vary considerably and depend to a large extent on the state of the required technology and on the availability of space-qualified components and subsystems at the time that a particular procurement is initiated. They will therefore also depend upon the previous experience of the particular manufacturer carrying out the development program. Another factor to be considered is the payment of any royalties, for example to Intelsat, if any Intelsat background or foreground information was used.

For the deployment of communications satellites in and around 1977 it is expected that much of the required technology and subsystems will have been developed in previous programs and will have been space proven in most cases in military, ATS, United States domestic satellites, and the CAS-C/CTS project.

The main areas of new technology which would be applicable to a satellite of the type considered in the present study are microwave communications in the 12 through 15 GHz bands including traveling wave tubes in the 5 through 10 watts and 15 through 20 watt ranges and shaped narrow-beam antennas, sun-oriented flexible solar arrays generating power in the 1 through 2 kilowatt range, hydrogen-oxygen fuel cells and body stabilization techniques.

In the microwave communications area much of the required technology is now under development for terrestrial microwave transmission systems. In addition communications satellite transponders in the frequency bands above 10 GHz are being developed at COMSAT Laboratories and in Japan. Much of the broad-band, medium and low power development carried out for the CAS-C/CTS project will also be relevant, and in addition the ATS-F satellite program will produce experimental results concerning propagation at millimeter wave-lengths. The ATS-H satellite to be deployed about 1976 will test the feasibility of shaped-beam and multiple-beam antennas. Some companies in the United States have proposed satellite designs for deployment within 2 to 3 years to provide service in the 12 through 15 GHz bands. The availability of traveling wave tubes has been discussed in 6.1.4.

Regarding flexible sun-oriented solar arrays these are currently under development by a number of companies in the United States as discussed in 6.1.3. These techniques have been under development since about 1966 and a 1000 watt array has recently been flight qualified. The flexible array development to be carried out for the CAS-C/CTS project will also be relevant. Hydrogen-oxygen rechargeable fuel cells are currently under development and are also discussed in 6.1.3. The development programs currently under way are expected to make such cells available for 1977 deployment.

Body stabilization techniques are currently under development and will be flight proven in the ATS-F and CAS-C/CTS programs. Some body stabilization systems have already been flight proven on a number of satellites discussed in 6.1.5.

It is therefore concluded that, because much of the basic technology development necessary for the deployment of a body-stabilized satellite of the weight class envisaged would have been done, the development costs associated with a program initiated in 1975 through 1976 would be somewhat less than those necessary to develop a spacecraft when the majority of the technology was not available and most of the techniques not flight qualified. The development costs of the Intelsat IV program were about $22M. It is believed that the basic technology required for deployment of a satellite in the 12 through 15 GHz bands about 1977 will be one stage ahead of that which existed in the 4 GHz and 6 GHz bands prior to the Intelsat IV development program.

There are two major strategies which may be considered in connection with a development program and although a discussion of the choice of the most appropriate strategy is outside the scope of this study, some brief comments are considered to be necessary. If a development program were to be set up to develop all the required technology anew it is estimated that the total development program costs would be in the same order as the Intelsat IV development costs, say $20M to $25M and this range has been confirmed as realistic by comparison with other independent estimates. The development program costs could increase by some 25 percent where the basic development and test facilities did not exist. The investment in development and test facilities and the establishment of development expertise in all areas of spacecraft development would imply a commitment to more than one program producing flight hardware for deployment by other countries.

If a development program were set up to develop only those areas unique to the specific system requirements and the remainder of the technology were obtained from elsewhere, so incurring royalty payments, the total development costs would be reduced. The specific development required would be concerned mainly with the communications subsystem which constitutes about 30 percent of the spacecraft weight and cost as has been shown in chapter 6. The remaining 70 percent of the spacecraft weight and cost is that imputed to the housekeeping and power subsystems and it would seem unnecessary to redevelop these subsystems including the satellite structure. It may therefore be assumed that 30 percent of the total spacecraft development costs could be imputed to the communications subsystem (including antennas) and in addition royalty payments of between 10 and 15 percent for the use of housekeeping subsystem technology might be appropriate. Also it would be necessary to include in the program the effort necessary to integrate the specific spacecraft; and this may be estimated to be in the range of 10 to 15 percent costs of development associated with the specific program. Under these conditions it may be expected that the development program would cost between 40 and 50 percent of a program to develop all the spacecraft subsystem from scratch such as was done in the Intelsat IV program which, as stated before, was about $22M. It is therefore believed that, if the second strategy were employed, the development program can realistically estimate to be in the order of $10M for the type of satellite considered in this study for deployment in or about 1977.

The development program costs may also be estimated by considering the basic development costs of $2.5k per pound of satellite hardware previously discussed for the case where a satellite is a repetition of a previous design with some additional development due to the unique mission requirements. For a program to produce three satellites a figure of $7.5k would therefore be appropriate and for satellites in the 1200-pound weight class this would lead to a development program cost of about $9M. Adding to this 10 to 15 percent in respect of royalty payments gives a total development program cost of about $10M.

As the development program costs constitute only about 10 percent of the total system costs the significance of any variations would be relatively small.

* * *

9.2.2 LAUNCH COSTS

Launch costs per pound for the 1977 through 1985 time period are derived from predictions of the maximum launch capability of suitable launch vehicles and estimates of the likely launch costs; a figure of $8,000 per pound has been used.

As regards the launching of synchronous satellites, the launch costs used are based upon information presented in Appendix C for the launch vehicles which could be considered suitable for use in 1977. Based upon the predicted maximum launch capability into synchronous orbit in 1977 and estimated launch costs for the vehicles, the launch costs per pound of satellite weight into synchronous orbit are as shown in the following table.

LAUNCH VEHICLE	PREDICTED CAPABILITY IN 1977	PREDICTED LAUNCH COSTS IN 1977	APPROX COST PER POUND IN ORBIT
Thor-Delta	1200	$ 7 - 8M	$7k
Atlas-Centaur	2000	$17 - 18M	$9k

A figure of $8,000 per pound of satellite weight into synchronous orbit has been used for launch costs in this study, and this is believed to be as close an estimate as possible considering the long-term predictions necessary. In the event, if the final choice of the design dictates the use of one or the other of these launch vehicles, a marginal adjustment to the launch costs can be made at the pen ultimate stage of system cost estimation, without invalidating the analysis to any significant degree.

* * *

9.2.3 TOTAL SPACE SEGMENT INVESTMENT COST

The total space segment cost is the sum of the satellite hardware cost and the appropriate launch costs, and a figure of $18,000 per pound has been used.

For operational satellite systems it is obviously necessary to provide system redundancy, and various methods of achieving this are possible. The method used in the system trade-offs is to assume that, in addition to providing redundant transponders in the satellite, two identical satellites would be launched and co-located. The space segment costs are therefore double the in-orbit costs of one satellite.

The total capital investment cost of the space segment is the sum of the satellite hardware cost and the launch costs. Based upon the previous discussions a figure of $18,000 per pound has been used. This cost excluding development represents the total cost of the satellite on a per-pound basis on station, in orbit at the beginning of life. Figure 9-1 shows the variation in satellite in-orbit costs on a per transponder basis as the transmitter saturated output power varies. Figures 9-2 and 9-3 show the variation of space segment capital costs with two satellites in orbit using antenna beamwidths of 1.75° by 4.5° and 1° by 2.5° respectively. The 1.75° × 4.5° antenna beams are used for the commercial television and major traffic communications services. The 1° × 2.5° beams are used for the educational television services for Quebec and Ontario and since this would represent service to a large majority of the population of Canada, this beam will be used as the typical example in the cost trade-off.

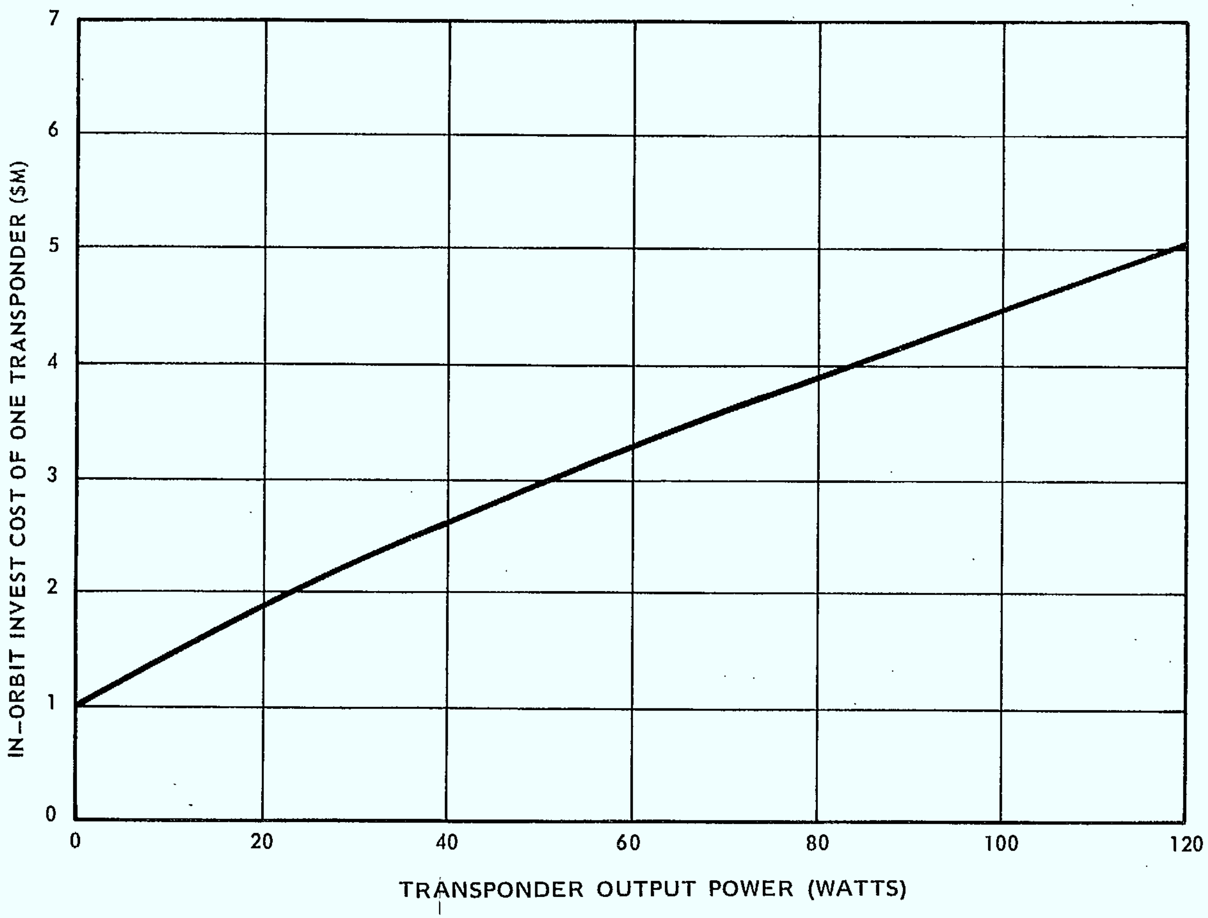

Figure 9-1 Transponder In-Orbit Cost
for Two Satellites in Orbit

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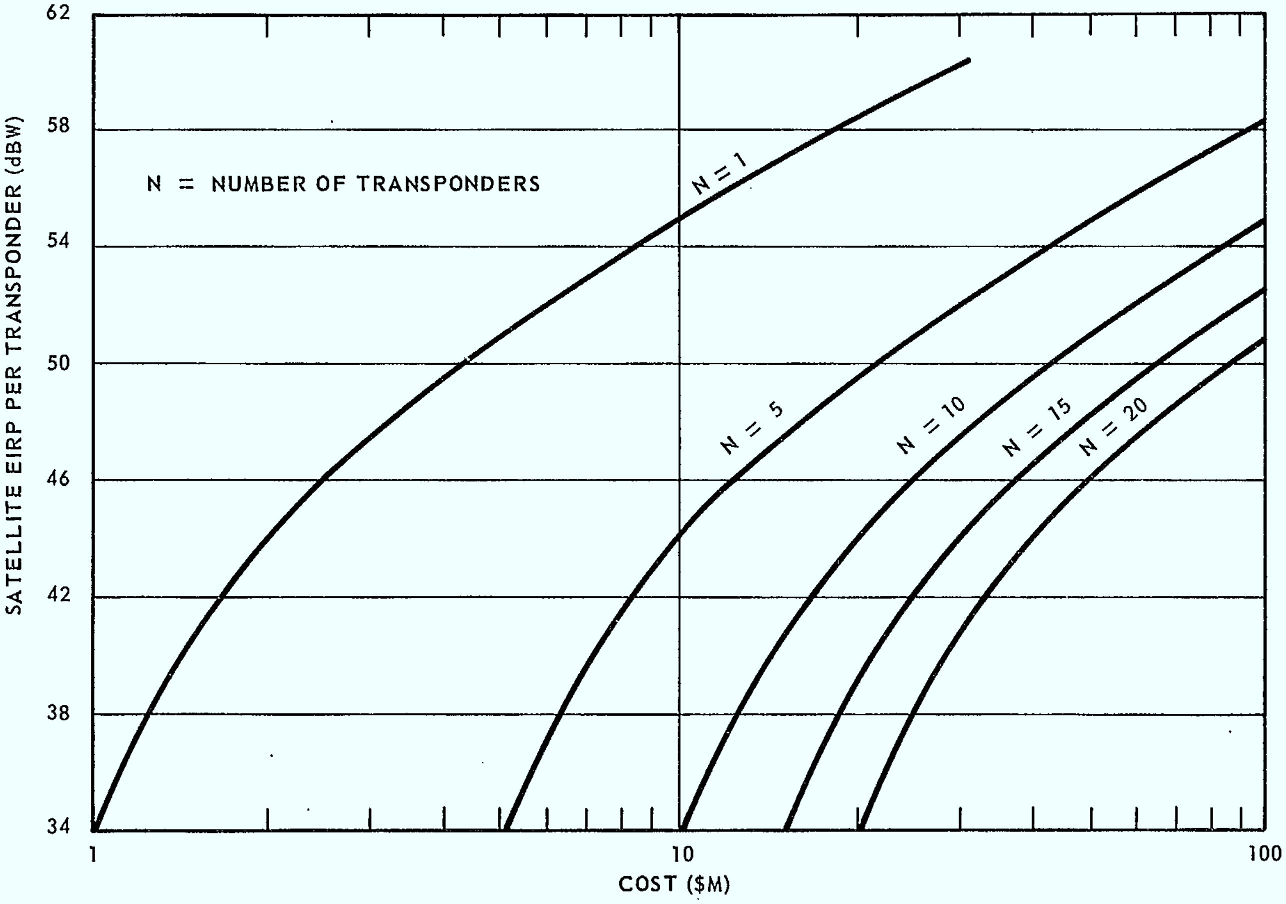

Figure 9-2 Total Satellite In-Orbit Costs
for Two Satellites (1.75° × 4.5° Beamwidth)

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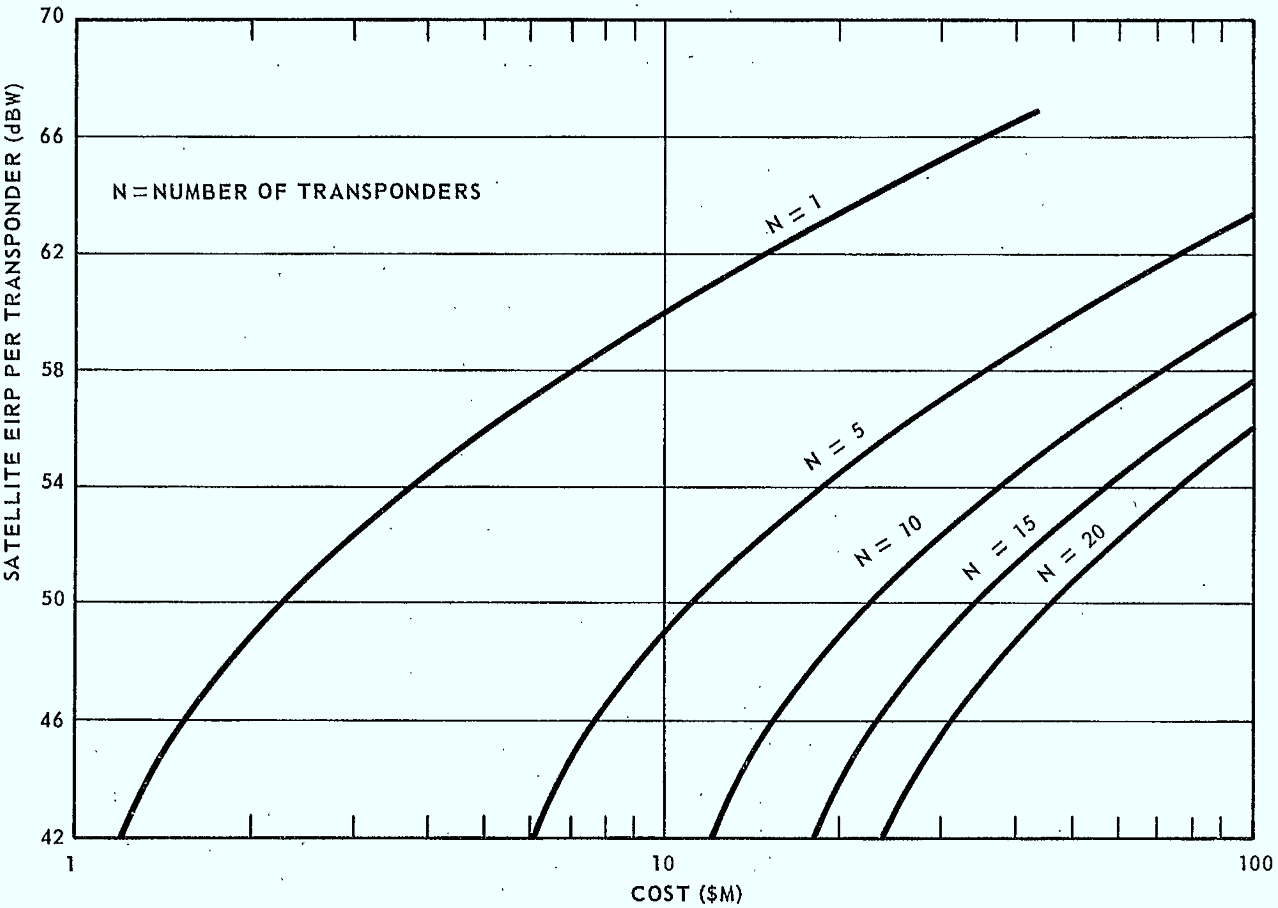

Figure 9-3 Total Satellite In-Orbit Costs for Two Satellites (1° × 2.5° Beamwidth)

9.3.1 EARTH STATION COST ESTIMATES

The capital costs of the earth stations have been estimated during discussion with various equipment manufacturers and it has been assumed that all earth station basic components and subsystems in the 12 through 15 GHz frequency band will be available in 1977.

The system modeling method employed in this study considered each type of service to be entirely independent, including the space segment of the system. The total system investment costs were therefore estimated individually for each category of services with similar modes of transmission. This enabled the requirement for the earth stations to be considered independently for each category. For each station, therefore, a station model was derived and the cost of each subsystem was estimated from past experience and by contact with various subsystem manufacturers. As the estimates are concerned with stations for implementation six years hence, they should be considered only as first estimates of costs. Where possible the cost estimates have been compared with the station costs proposed for certain of the U.S. domestic systems to check that they are in fact realistic.

For the trade-off analysis, it is required to show how the earth station costs vary with station G/T. As G/T can be varied by choosing different receiver systems and by changing antenna size, both of these factors have been taken into account where necessary. For those stations which have a transmit capability, any variation in antenna size will change the transmit power requirements and hence the cost of the transmit subsystem. This variation has also been taken into account in the station cost estimates. In order to show how the station costs vary with G/T, they are divided into a fixed and a variable portion, typically, according to the following breakdown:

(a) Fixed subsystems - Buildings and site
Power and utilities
Receive GCE
Transmit GCE
Monitor and control

(b) Variable subsystems - Receivers

Transmitters

Antennas

The detailed cost breakdown and estimates are presented for each type of earth station in the following sections of this chapter which deal with each type of service individually.

9.3.2 EARTH STATION VARIABLE SUBSYSTEM COSTS

The subsystems of the earth stations whose cost varies with station G/T are the antenna, receivers and transmitters. The first estimates of the costs of these subsystems are presented below.

(a) Antenna Cost Estimates

As discussed in 6.3.1 three types of earth station antenna are considered. Spun metal reflectors are used with no form of tracking up to 17 feet in diameter. First estimates of the cost of these antennas have been made during discussions with a number of manufacturers. For quantities up to about 50 the antenna cost may be approximated by the following equation which is valid over diameters from 6 feet to 17 feet:

$$C_a = 17.25D^{1.85} \text{ dollars}$$

where D is the reflector diameter in feet.

For diameters above 17 feet and up to the maximum of about 60 feet considered feasible in the 12 through 15 GHz frequency bands conventional fabrication techniques will be used. For antennas above 17 feet in diameter tracking will be required but between 17 feet and about 30 feet a simple step-track system would be adequate. The costs of this type of antenna have been estimated from information obtained during discussions with antenna manufacturers. Over the diameter range from 17 through 30 feet the first estimate of the costs of this type of antenna system may be approximated by the following equation:

$$C_a = 65{,}000 + 330\, D^{1.5} \text{ dollars}$$

where D is the reflector diameter in feet.

For reflector sizes above 30 feet precision tracking would be required and the first estimates of the cost of such antennas may be approximated by the following equation:

$$C_a = 200{,}000 + 670\ D^{1.53} \text{ dollars}$$

where D is the reflector diameter in feet.

(b) Receiver Cost Estimates

Three types of receiver have been considered in this study and each type was examined in conjunction with various antenna sizes to achieve the ranges of earth station G/T required for the system modeling. As discussed in chapter 6 it is expected that uncooled parametric amplifiers will be available off-the-shelf and a first estimate of the cost a non-redundant amplifier is estimated at $25k. Tunnel diode amplifiers are expected to cost in the region of $1,000 for deployment in 1977 and this has been used as a first estimate in this study. Mixer front ends were also considered as a possible receive system and the cost estimate used in this study is essentially that of a tunnel diode amplifier receiver system less the cost of the TDA.

(c) Transmitter Costs Estimates

Because the required earth station transmit power will vary with antenna size it is necessary to incorporate a variable transmit power cost in the trade-off calculations. As the power ranges of klystron power amplifiers are normally in incremental steps, the estimated costs were selected on this basis for use in the trade-off calculations. The first estimates of the costs of klystron power amplifiers were obtained during discussions with manufacturers and are tabulated below.

$C_T = 20{,}000$, $P < 20$ watts

$C_T = 40{,}000$, $20 < P < 300$ watts

$C_T = 70{,}000$, $300 < P < 1{,}000$ watts

$C_T = 90{,}000$, $P > 1{,}000$ watts

9.4 Total System Investment Cost and Annual Charges

9.4.1 ANNUAL CHARGES

The system annual charges have been estimated as a fixed percentage of the total capital investment. A figure of 18 percent of the total capital investment has been used for the space segment and 28 percent has been used for the earth segment.

It is general practice, based on economic reasoning, to use annual revenue requirements as the basis for investment decision in the deployment of Telecommunications facilities. Economic optimization, of the mix of technical parameters, which compares the relative economic merits of different mixes must also use a similar parameter. The parameter selected is that of annual charges, as agreed with the Design Authority. The only conceptual differences between annual revenue requirements and annual charges are that while the former considers the project capital as equity on which taxable profit is earned, the latter considers the project capital as debt capital on which interest has to be paid on the reducing balance after annual depreciation. As such, considerations of the acceptable rate of profit and the associated taxes are excluded from annual charges. Such rates are part of operating policy decisions on the one hand and Government tax-policy decisions on the other hand and are not within the scope of this study. The recovery of annual charges implies a no profit operation with debt capital borrowed at the associated interest rate. In this situation, the terms annual charges and annual costs would be synonymous. The rate of interest on borrowed capital (backed by government bond issue or similar guanantee) could be reasonably estimated to be 8 percent - a figure generally used and agreed to by the design authority. This interest rate of 8 percent has been used in the study.

In order to incorporate the annual charges into the system optimization procedure it is necessary to express them as a percentage of the system investment cost. In general, the annual charges are comprised of the amortization of the capital investment, operation and maintenance expenses, general and administrative expenses, local taxes and similar charges and the cost of money. The annual charges will depend upon the number of years over which the capital investment is to be amortized. As the space segment lifetime is likely to be shorter than that of the earth segment and the space segment can have no direct maintenance charges the amount of the total system annual charges imputed to the space and earth segments on a percentage basis will be different. This will effect the optimum choice of space segment and earth segment technical parameters and it is therefore necessary to establish separate annual charges for the earth and space segments.

(a) Space Segment Annual Charges

The amortization period of the space segment is taken to be 7 years in this study because of the following reasons:

i) The space segment has been sized to meet the expected service requirements between 1977 and 1985, a period of 7 to 8 years. After this period, the space segment will require replacement with larger capacity satellites or the launching of additional satellites of the same or similar design. Since the usefulness of the satellite beyond 1985 is unknown it is reasonable to amortize the space segment cost within the 7 year period in which the satellite is designed to operate.

ii) The 7 year amortization period is in line with recent U.S. Domestic satellite system proposals.

iii) Although technological advances would tend to increase the "design life" of satellites, experience in Intelsat has shown that the usefulness of the satellite is more dictated by obsolescence than by technical failure. It is therefore more realistic to tie the amortization period to the period of usefulness of the space segment rather than the technical "design life", whose major impact is to increase reliability.

(1)	Amortization over 7 years	14.0%
(2)	Cost of capital at 8 percent p.a. of outstanding balance, average over 7 years	4.5%
	TOTAL	18.5%

Examination of a number of United States Domestic Satellite System proposals shows that the space segment annual charges used (equivalent to those derived above) lie in the region of 16.5 percent to 20 percent of the total space segment investment. The figure of 18 percent is therefore judged to be realistic for use in the present study.

(b) Earth Segment Annual Charges

The amortization period for the earth segment has been taken as 14 years. Certain elements of the earth station costs such as buildings would have a much longer depreciation period (say 30 years); land would have no depreciation. A suitable depreciation period for all electrical and mechanical equipment is judged to be typically 14 years which is also used by AT&T in their United States Domestic Satellite System proposal. The earth segment annual charges will include maintenance of equipment, land and buildings and here again reference is made to the figures used by AT&T. As the maintenance of land and buildings would be small compared with that of the electrical and mechanical equipment they are taken to be included in the figure of 9 percent which appears to be reasonable for station operation and maintenance. General and administrative charges in the range 4.5 to 5 percent are also applicable and 5 percent has been taken as reasonable. The total earth segment annual charges are therefore computed as follows:

i)	Amortization over 14 years	7.2%
ii)	Cost of capital at 8 percent p.a. of annual outstanding balance, average over 14 years	4.5%
iii)	Operation and maintenance	9.0%
iv)	General and administrative charges	5.0%
v)	Land and local taxes	2.0%
	TOTAL	27.7%

Equivalent charges used in a number of the United States Domestic System proposals range between 26 and 31 percent. A figure of 28 percent would therefore appear justified for use in the present study.

* * *

9.4.2 TOTAL SYSTEM COST

The total system costs are obtained by calculating the space segment and earth segment costs independently for each service allowing the satellite EIRP and earth station G/T to vary over the ranges permitted within the technical constraints.

The approach taken for the estimation of the total system annual charges is to size the space segment for each service according to the specific service requirements established previously. The annual charges for the space segment are then calculated for a particular service over the appropriate range of EIRP and within the technical constraints imposed. After choosing a number of earth stations appropriate to the service requirements the system modeling map is used to find the required earth station G/T corresponding to the satellite EIRP values at a given system bandwidth. For a given bandwidth the total system cost is then plotted against satellite EIRP (or earth station G/T). Somewhere within the range of EIRP within the technical constraints the total system annual charges will have a minimum value and this represents the optimum mix of satellite EIRP and earth station G/T for the particular service requirements and system bandwidth chosen.

Depending upon the particular values chosen for the various system parameters the optimum point will lie within the boundaries set on the system modeling maps and under certain circumstances it could be coincident with one of these constraints. Also, as discussed in chapter 6 the minimum point could be located at one of the break points in the earth segment cost relationships. In the sections which follow, typical curves are presented and discussed for selected sizes of space and earth segments for the different types of service. Any change in the system sizing would require recalculation of the total system annual charges. The effect of any variations in space segment or earth segment costs would tend to effect the optimum mix of space segment and earth segment technical parameters but, as discussed in 9.1 any variations up to about 20 percent would have little significant effect.

* * *

9.4.3 EDUCATIONAL TELEVISION

For this service an earth segment consisting of three hundred stations was chosen for analysis and parametric trade-off curves are derived for various earth station costs and transponder bandwidths.

The first estimates of costs of the various fixed subsystems for the education television earth stations are summarized below:

TDA	-	\$ 1,000
Down Converter	-	\$ 3,000
IF and Baseband	-	\$ 6,000
TOTAL Fixed Costs		\$10,000

The fixed cost of a station with a mixer front end would essentially be the same as the above less the cost of the TDA. The antenna considered for this station is a spun reflector of less than 17 feet in diameter. No form of tracking is considered necessary and the antenna cost is therefore

$$C_a = 17.25\ D^{1.85}\ \text{dollars.}$$

The total station cost including installation in a suitable building is therefore

$$C_T = FE + 17.25\ D^{1.85}\ \text{dollars}$$

where FE is the fixed cost initially set at \$10,000. The results of the calculation of total system annual charges are plotted in Figure 9-4 for a typical selection of system parameters. Because the cost estimates for the earth stations may vary according to variations in station design, calculations were made using a range of values for the fixed portion (FE) of the earth station cost. The effect of this variation is shown in Figure 9-5 which shows the variation in total system annual charges due to variations in earth station fixed costs.

Figure 9-6 shows the variation in total system annual charges as the number of earth stations in the system varies. Because of the basic power - bandwidth trade-off employed in the system modeling - the total system annual charges vary with transponder bandwidth, and Figure 9-7 shows the total system annual charges for system bandwidths of 12, 14 and 16 MHz.

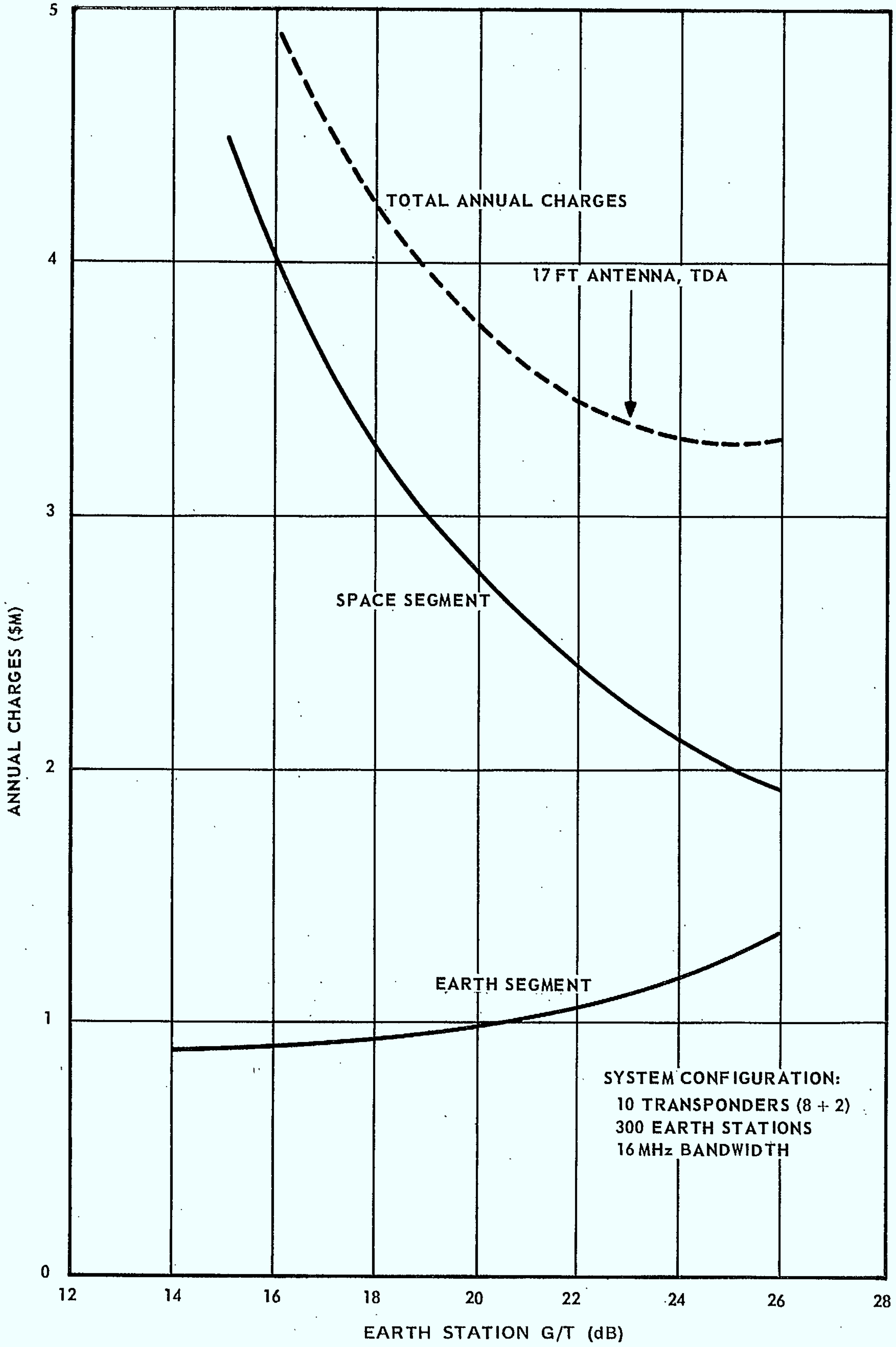

Figure 9-4 Educational Television Services - Annual Charges vs Earth Station G/T (16 MHz Bandwidth)

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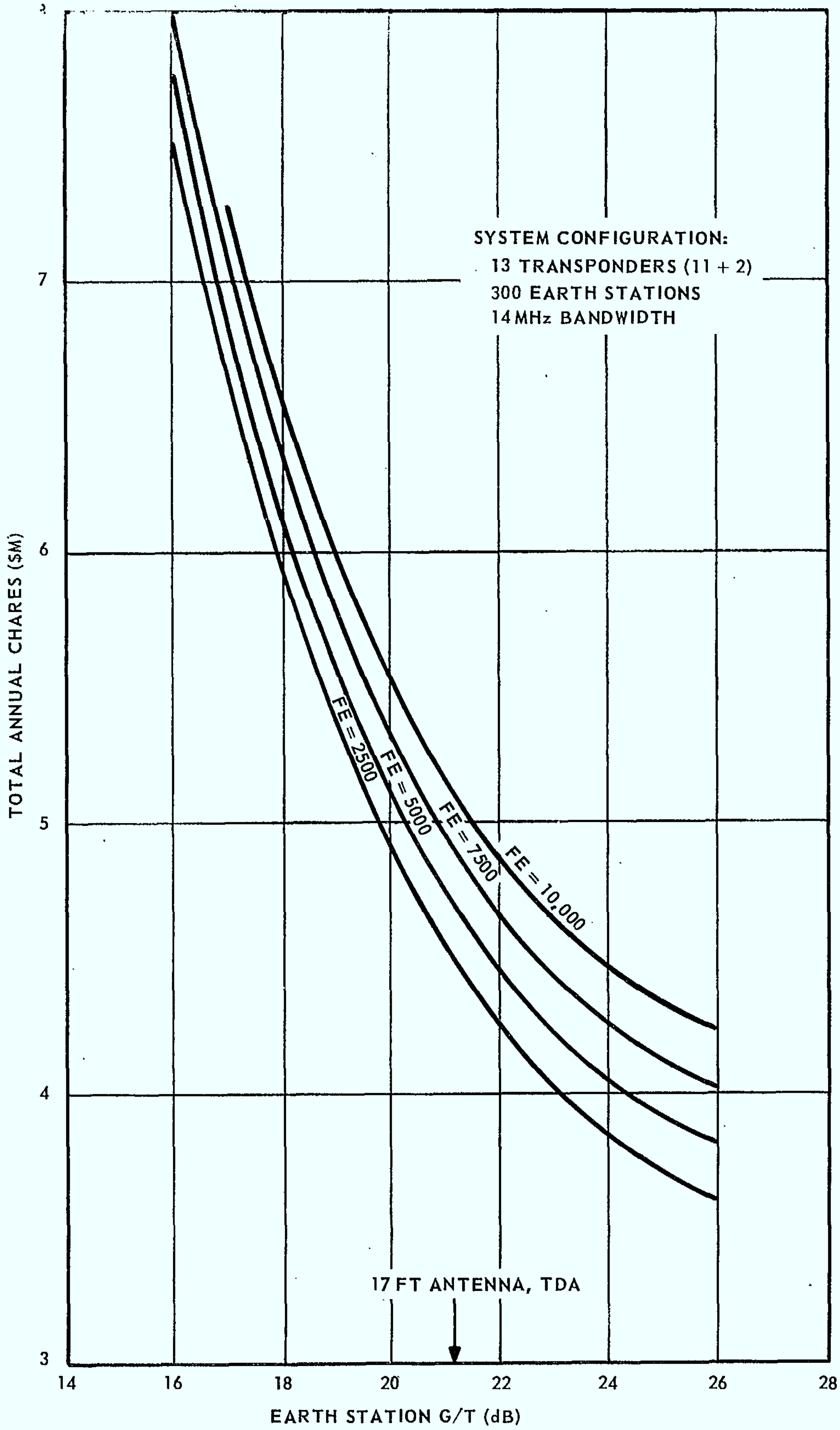

Figure 9-5 Educational Television Service - Total Annual Charges vs Earth Station G/T (14 MHz Bandwidth)

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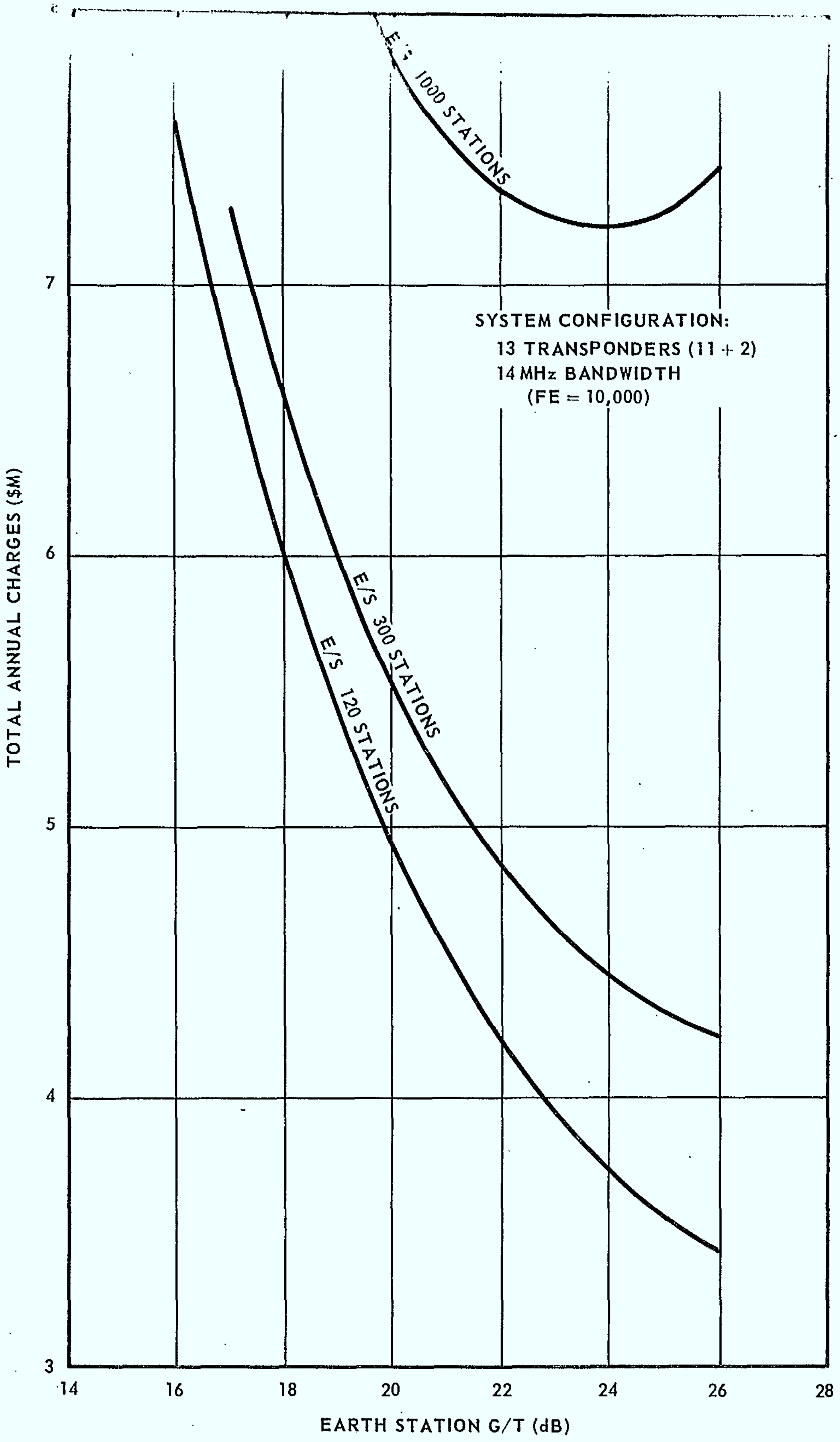

Figure 9-6 Educational Television Service: Total Annual Charges vs Earth Station G/T (14 MHz Bandwidth)

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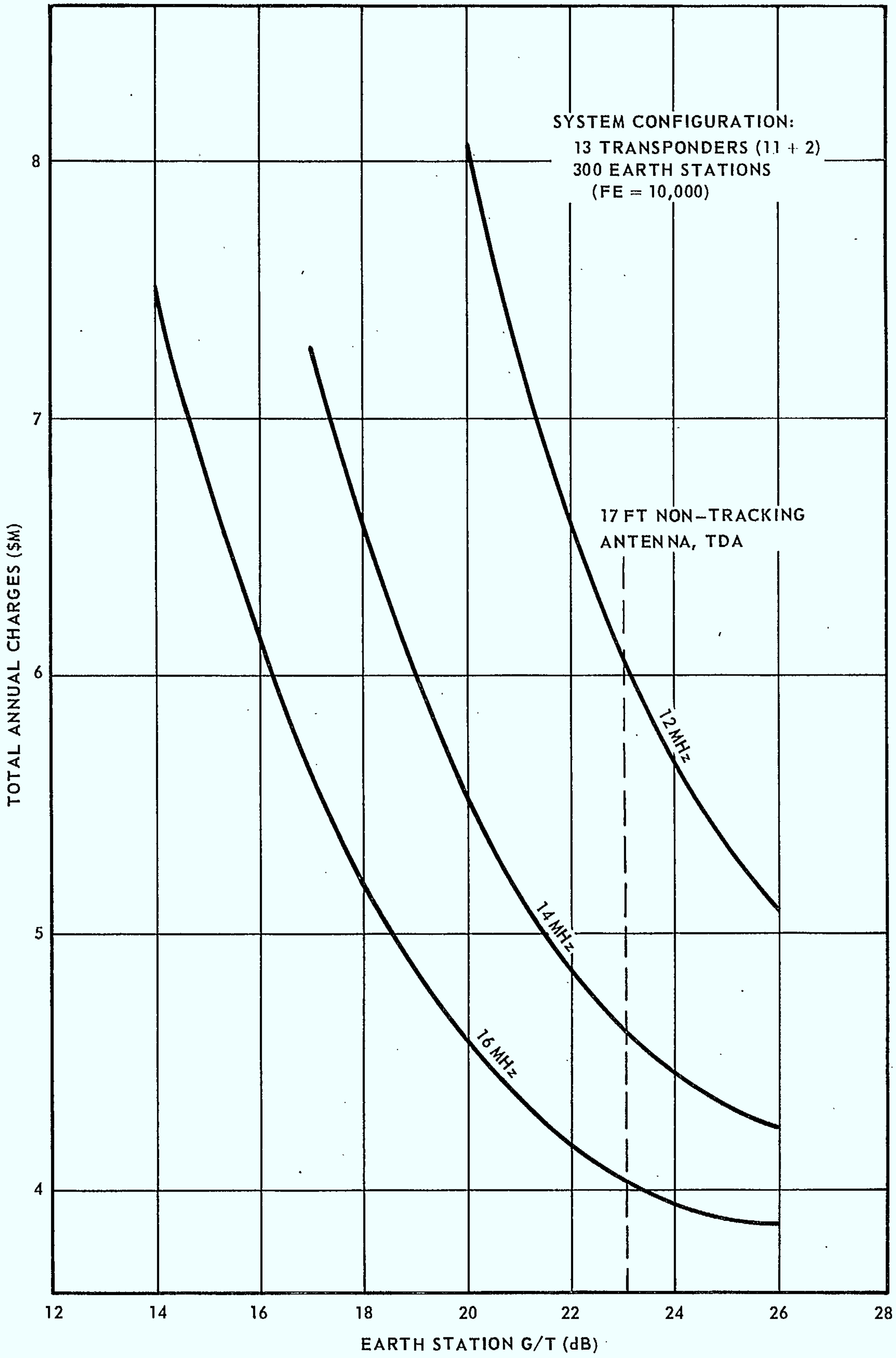

Figure 9-7 Educational Television Service: Total Annual Charges vs Earth Station G/T

9.4.4 COMMERCIAL TELEVISION SERVICE

The earth segment chosen for this service consists of fifty receive-only earth stations each having a capacity of two television channels; the space segment consists of four operational channels plus one spare.

The first estimates of the costs for the various fixed subsystems of the commercial television earth stations are summarized below:

		$k
Redundant uncooled paramps	-	50
Two receive chains	-	20
Redundant receive chain	-	10
Installation	-	10
Buildings, power and services	-	20
TOTAL Fixed Cost	-	110

The antenna considered for this station, as discussed previously, will be non-tracking for diameters less than 17 feet, will use step-tracking for diameters between 17 and 30 feet, and full-tracking beyond 30 feet. The computer program used for the system cost calculation selects the appropriate equation for the calculation of earth station costs. These equations are:

$$C = 110{,}000 + 17.25\ D^{1.85} \qquad D < 17$$

$$C = 110{,}000 + 65{,}000 + 330\ D^{1.5} \qquad 17 < D < 30$$

$$C = 110{,}000 + 200{,}000 + 670\ D^{1.53} \qquad D > 30$$

The results of the computation are shown in Figures 9-8 through 9-10 for an earth segment of 50 stations and a space segment of 4 operational and 1 spare transponder with bandwidths of 15, 27 and 30 MHz.

Any variations in system bandwidth will change the total system annual charges. Figure 9-11 shows how the annual charges vary with total system bandwidth for both educational and commercial television services.

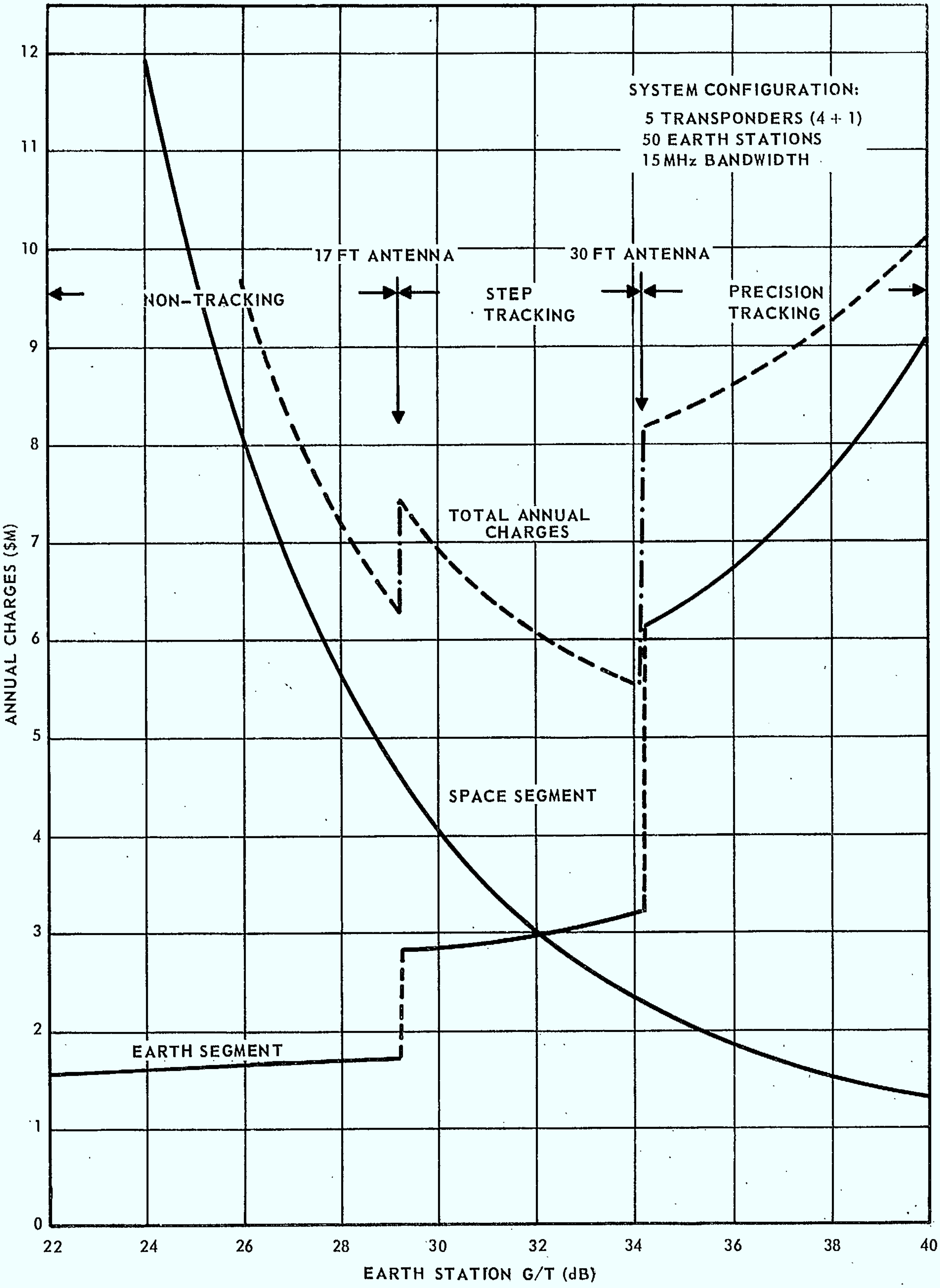

Figure 9-8 Commercial Television Services:
Annual Charges vs Earth Station G/T (15 MHz Bandwidth)

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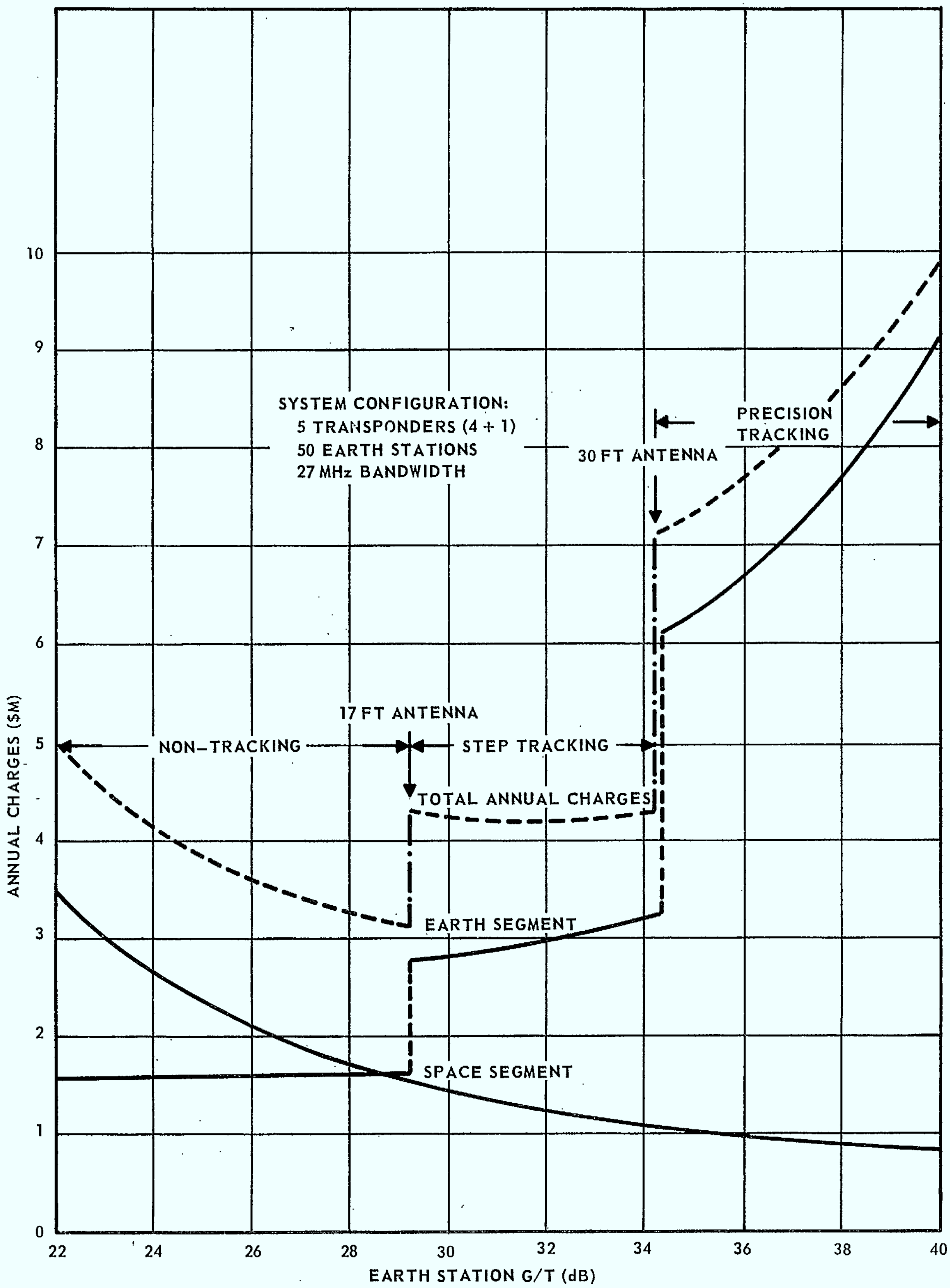

Figure 9-9 Commercial Television Service: Annual Charges vs Earth Station G/T (27 MHz Bandwidth)

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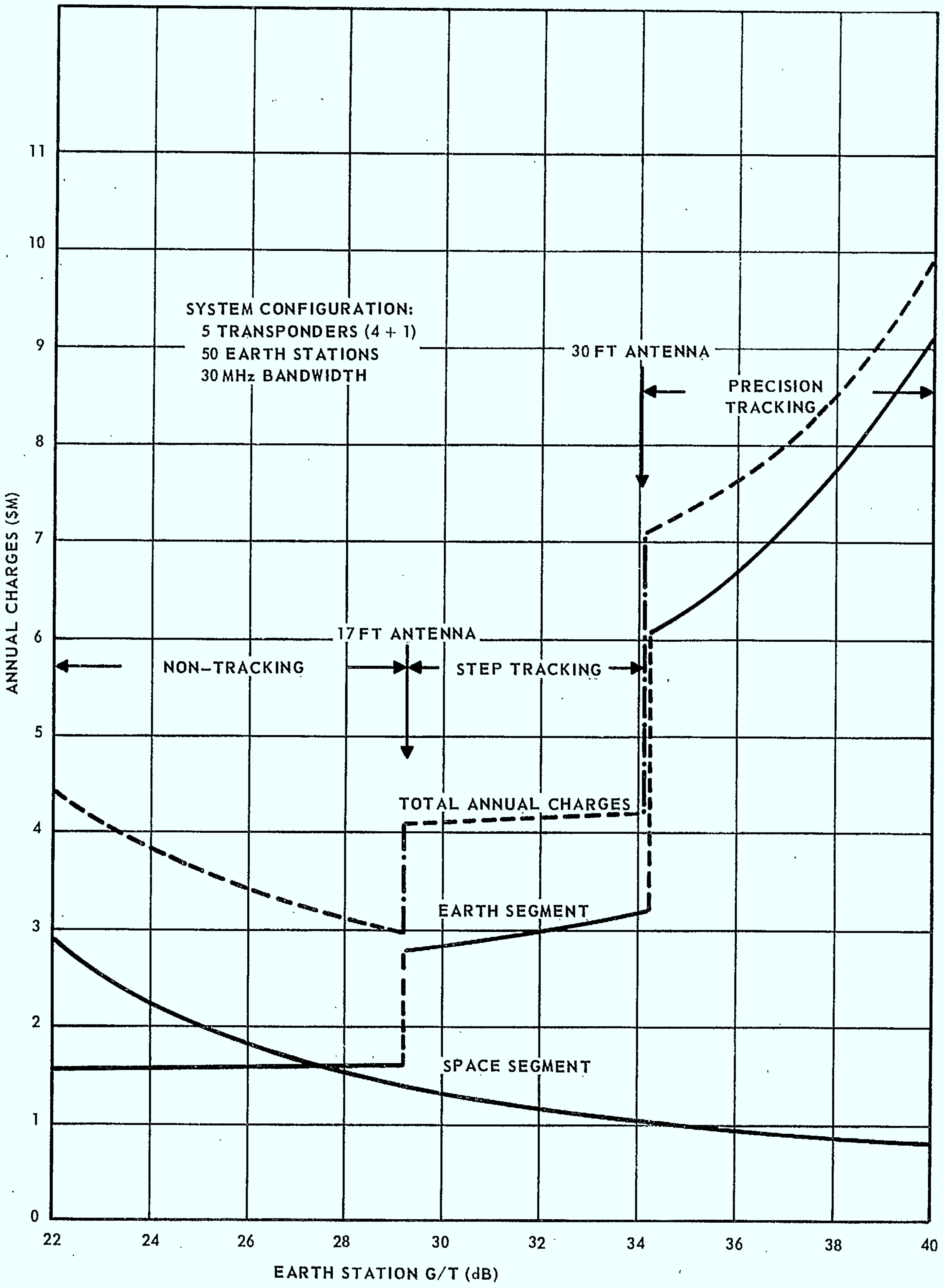

Figure 9-10 Commercial Television Service: Annual Charges vs Earth Station G/T (30 MHz Bandwidth)

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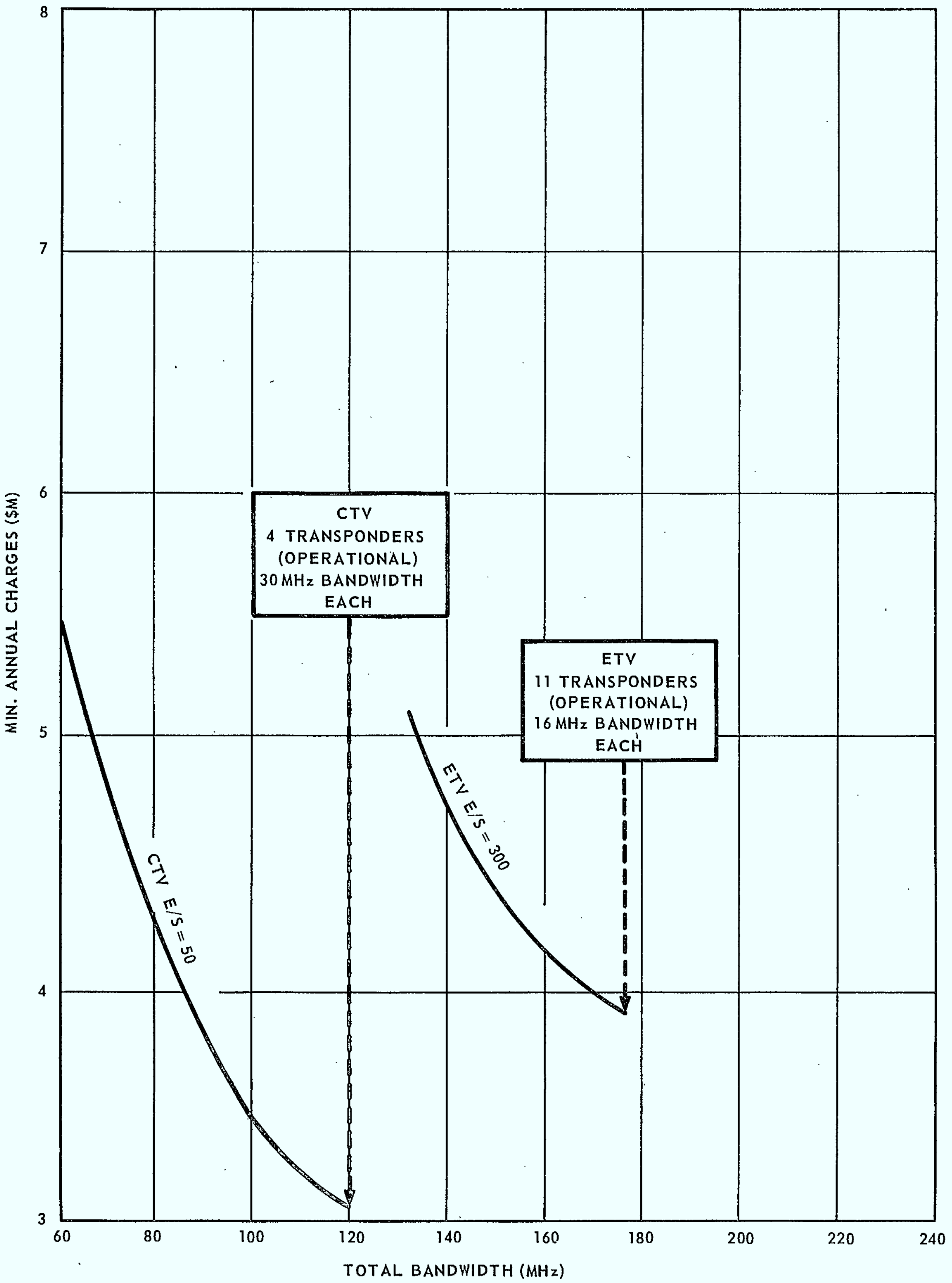

Figure 9-11 Commercial and Educational Television Service: Variation of Minimum Annual Charges with Total Bandwidth

9.4.5 MAJOR ROUTE MESSAGE SERVICE

In the case of message service for modestly high traffic capacity either analogue or digital modulation techniques are possible. Trade-off curves are presented for typical 4-phase and 8-phase CPSK-TDMA system models.

For the estimation of the costs of earth stations for this service it is assumed that the cost of an FM station will differ from that of a TDMA station but that the costs of TDMA stations do not vary with the level of modulation used. The fixed costs of the two types of station considered are summarized below:

(a) FM Stations

		$k
Redundant uncooled paramps and TWTA's	-	60
8 duplicated receive chains	-	200
2 duplicated transmit chains	-	60
Monitor and control	-	30
Power and utilities	-	50
Building and site	-	80
Installation, test equipment and spares	-	150
TOTAL Fixed Cost		630

(b) TDMA Stations

		$k
Redundant uncooled paramps	-	50
2 redundant up converters	-	20
2 redundant down converters	-	20
TDMA equipment	-	246
Power and utilities	-	50
Building and site	-	80
Installation, test equipment and spares	-	150
TOTAL Fixed Cost say		620

The variable costs of both types of station include the transmitters and antennas. The equations used for the antenna costs are the same as used in the commercial television service calculations. During the computation the earth station EIRP is calculated for each antenna size and the required transmitter power is calculated. The appropriate transmitter cost is then selected and added to the station cost. For powers up to 1k watt $70,000 is taken as being a realistic cost for a redundant klystron transmitter. For powers above 1k watt a figure of $90,000 is used.

The trade-off calculations were performed for both FM and digital systems. As will be shown in chapter 10, the FM system is discarded because it uses more bandwidth and satellite power and requires higher annual charges than the digital system.

Two sets of typical trade-off curves are presented in the systems models using digital modulation, one for 8-phase and one for 4-phase CPSK. These are given as Figure 9-12 and Figure 9-13 respectively and illustrate the earth and space segment and total system annual charges as functions of earth station G/T.

It should be noted that the 8-phase and 4-phase system configurations are not identical and are not intended to show the relative merits between these two systems. Comparison between these two modulation schemes is presented in chapter 10. The particular systems configurations are chosen as a matter of convenience because they correspond to the components of the final selected models given in chapter 10.

Figure 9-14 shows the effect on the minimum annual charges when the number of operational transponders is varied and the bandwidth per transponder is adjusted accordingly so as to give the same total system capacity. It can be seen that in general, a system with the least number of transponders but the widest possible bandwidth per transponder (subject to the constraints set in chapter 8 of course), gives the lowest annual charge. This is true for both the 8-phase and 4-phase systems and Figure 9-12 illustrates a typical 8-phase configuration.

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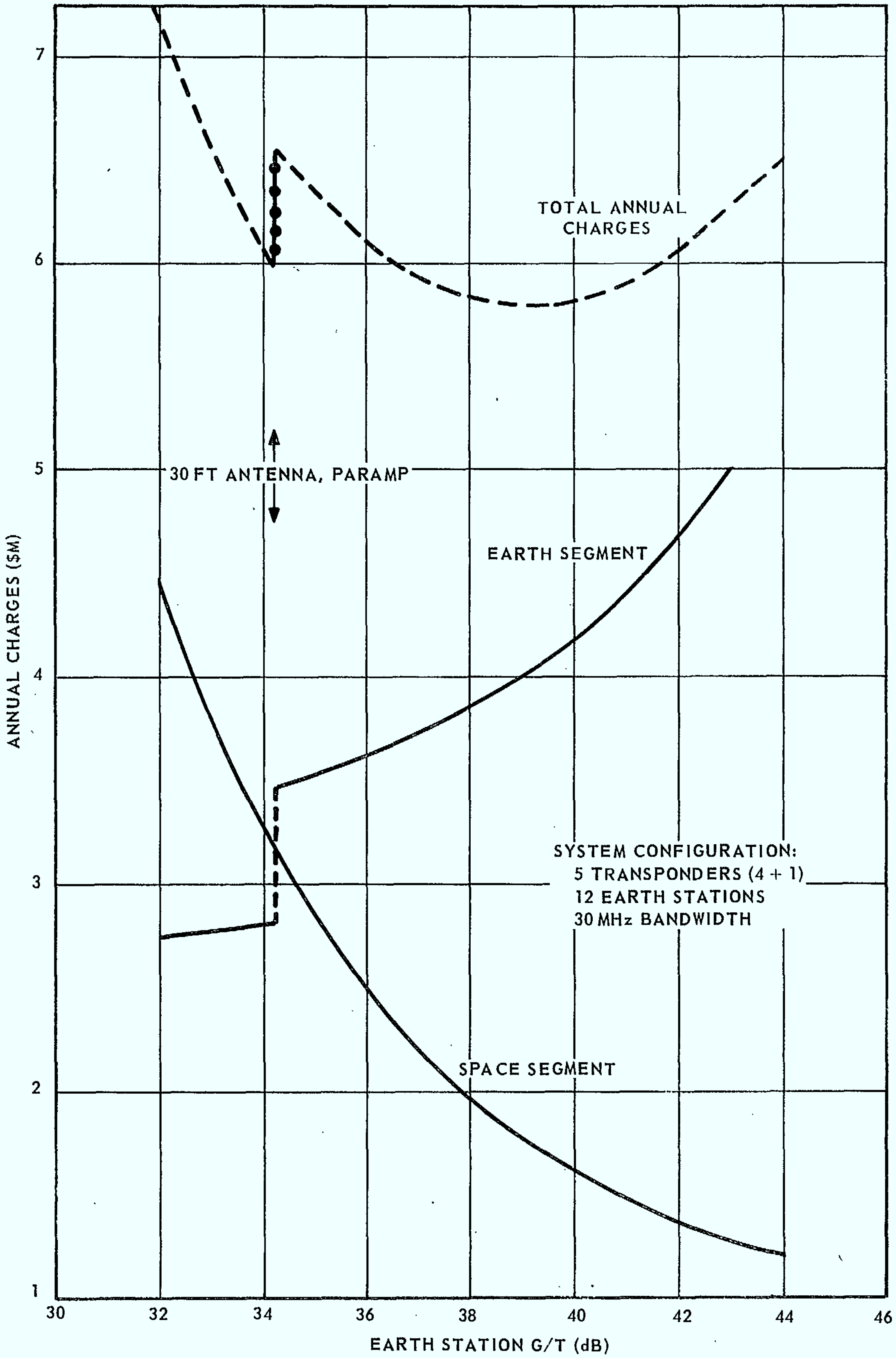

Figure 9-12 Major Traffic Communications for Multichannel Telephony and Digital Services, PCM-8ϕ CPSK-TDMA: Annual Charges vs Earth Station G/T

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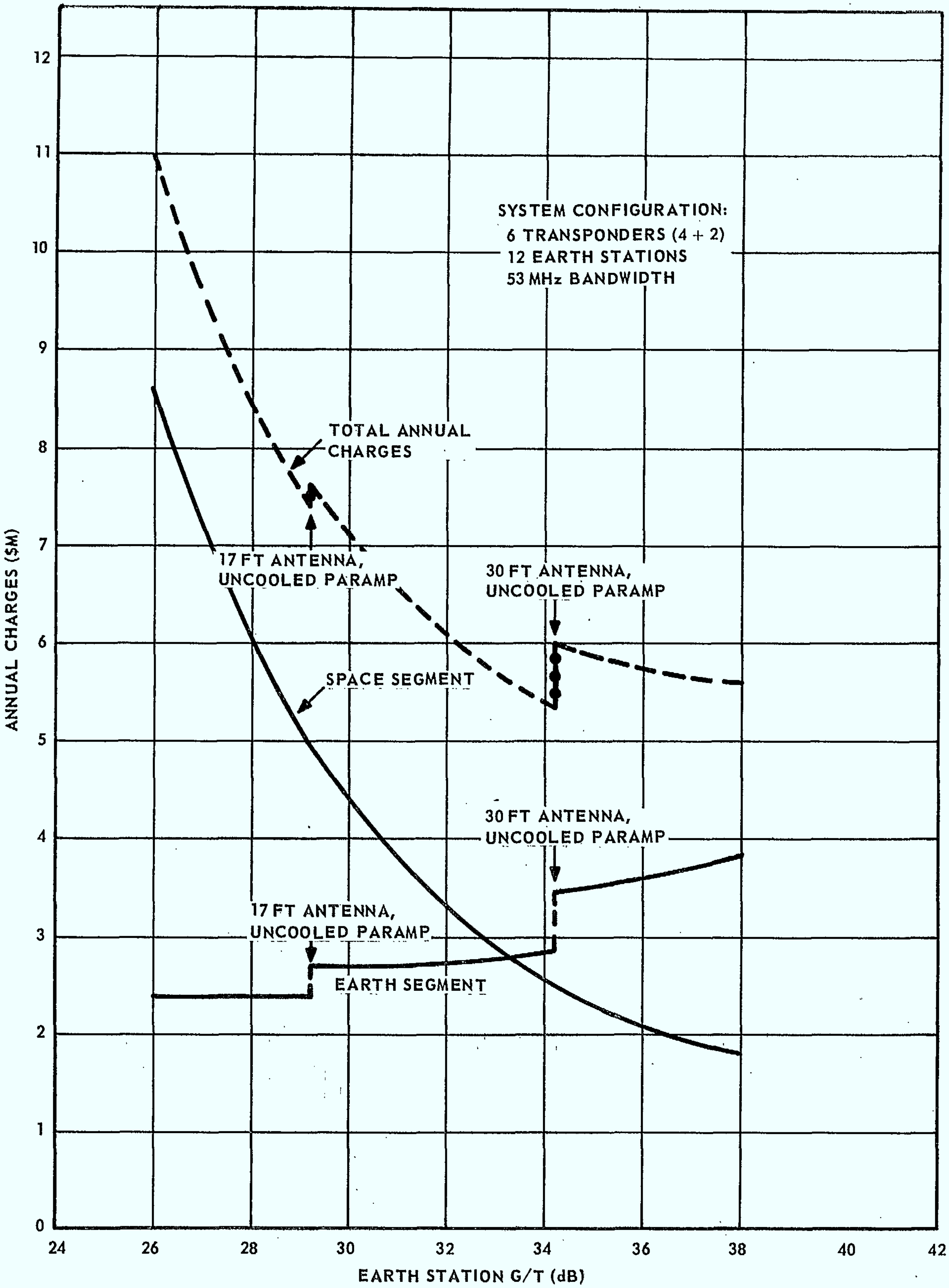

Figure 9-13 Major Traffic Communications for Multichannel Telephony and Digital Services, PCM-4ϕ CPSK-TDMA: Annual Charges vs Earth Station G/T

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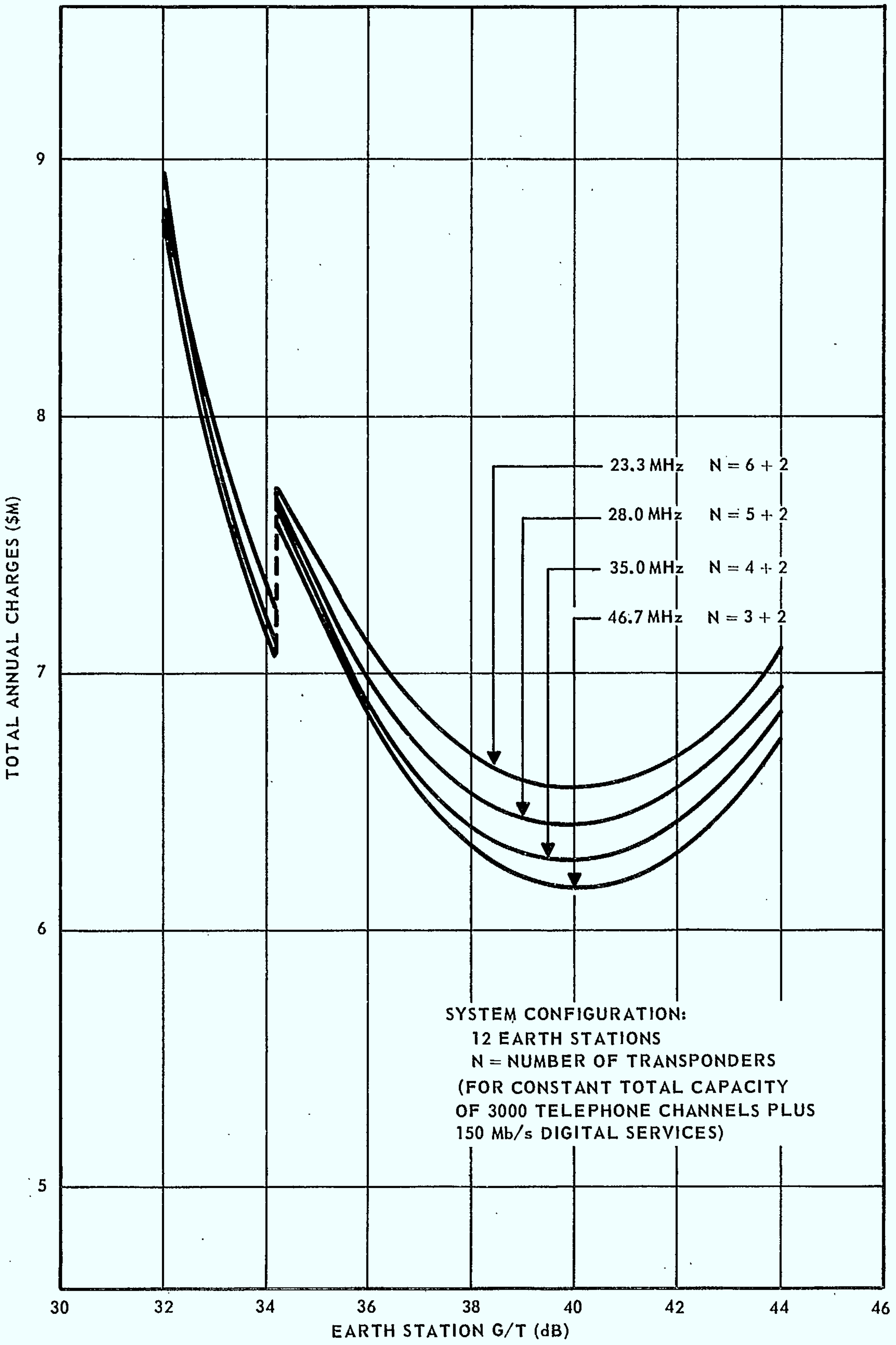

Figure 9-14 Major Traffic Communications for Multichannel Telephony and Digital Services, PCM-8ϕ CPSK-TDMA: Total Annual Charges vs Earth Station G/T

9.4.6 REMOTE COMMUNICATION SERVICE

One satellite transponder will provide sufficient capacity for this service and trade-off curves are presented for typical system models using frequency modulation and 4-phase CPSK modulation.

The first estimates of the station costs are presented below for both FM and TDMA modulation schemes:

(a) Frequency Modulation

		$k
Redundant tunnel diode amplifiers	-	2
3 operational receive chains	-	30
1 redundant receive chain	-	10
3 operational receive multiplex	-	18
1 redundant receive multiplex	-	6
1 transmit multiplex	-	6
1 redundant transmit chain	-	18
Power and utilities	-	16
Building and site	-	30
Installation, test equipment and spares	-	60
TOTAL Fixed Cost		196

(b) TDMA

		$k
Redundant tunnel diode amplifiers	-	2
Redundant up converters	-	10
Redundant down converters	-	10
Modems and TDMA equipment	-	230
Power and utilities	-	30
Building and site	-	40
Installation, spares and test equipment	-	100
TOTAL Fixed Cost		422

The variable antenna and transmitter costs were added to the fixed costs during the trade-off computations using the same data as was used in the major message service case.

Figure 9-15 shows the trade-off curves for a typical 4-phase CPSK system model having one operational and one spare transponder of 16 MHz bandwidth and 20 earth stations. The minimum annual charges occur at the break point corresponding to a 30-foot step-tracked antenna.

Figure 9-16 shows the trade-off curves for the FM case. The channel bandwidth here is 30 MHz and the optimum design point corresponds to a 30-foot step-tracking antenna.

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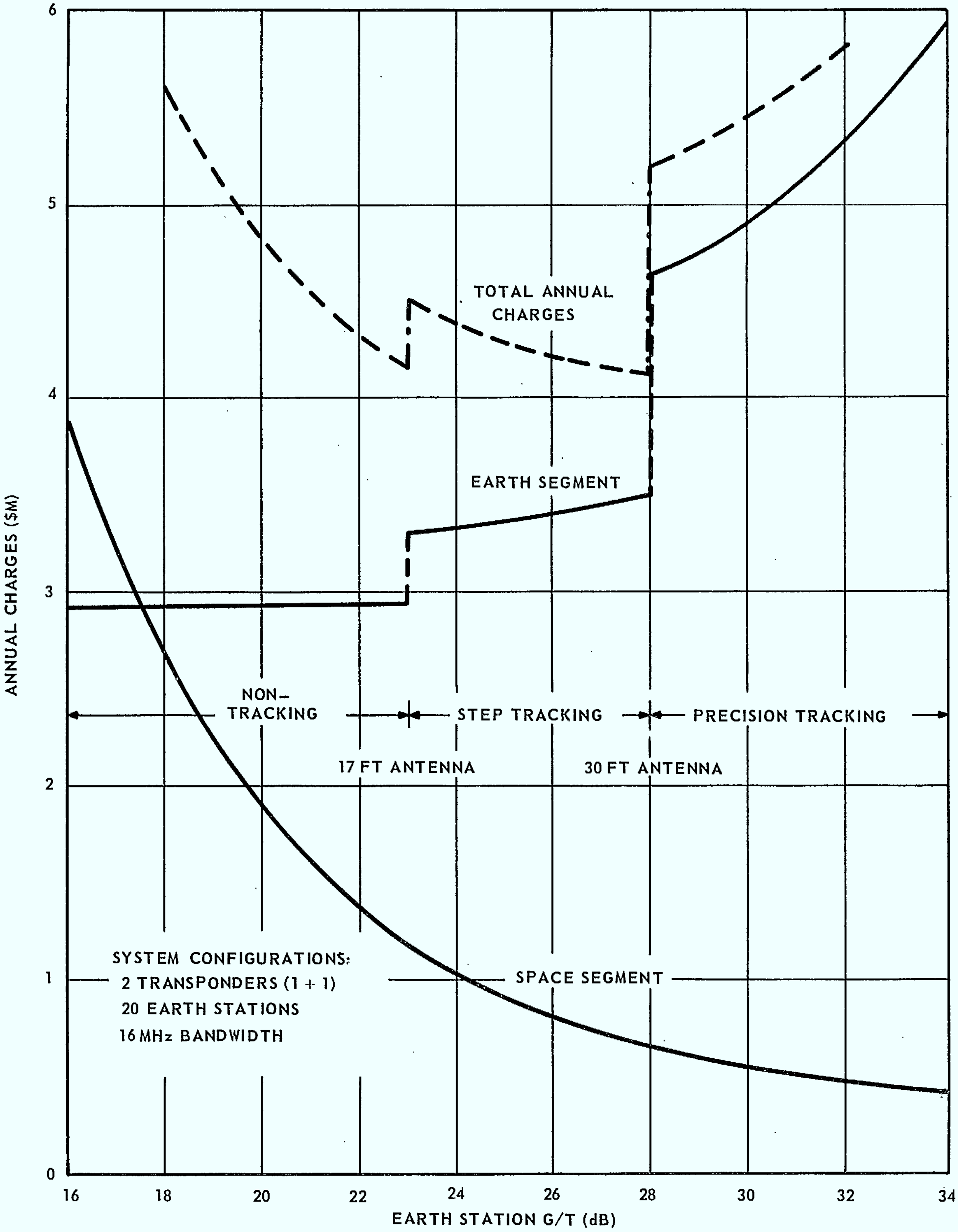

Figure 9-15 Remote Communications, PCM-4ϕ CPSK-TDMA: Annual Charges vs Earth Station G/T

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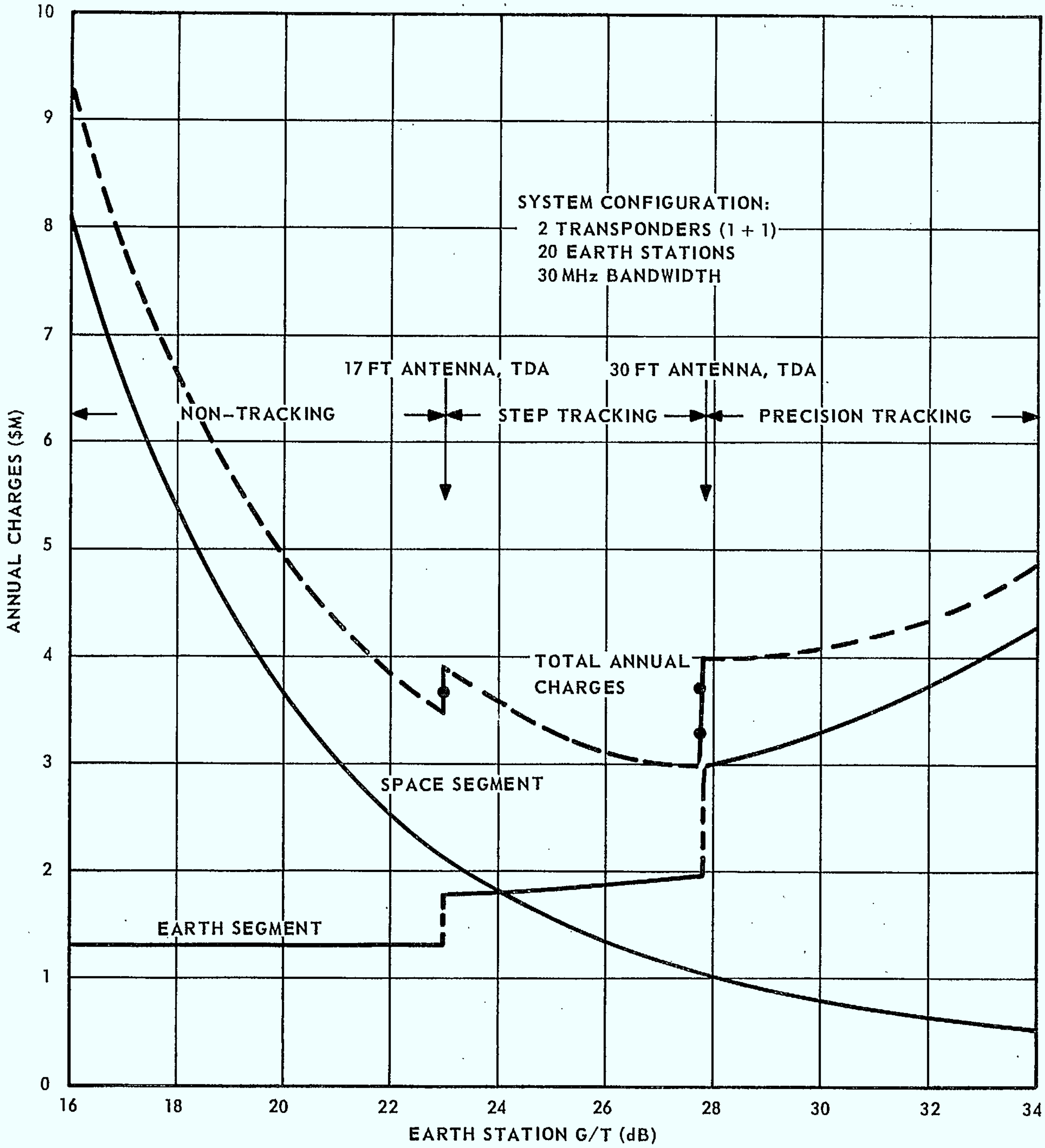

Figure 9-16 Remote Communications, FDM-FM-FDMA System: Annual Charges vs Earth Station G/T

9.4.7. SINGLE CHANNEL PER CARRIER SERVICE

For this service a single operating transponder is adequate. Trade-off curves are presented for the required rf bandwidth of 22 MHz and a typical earth segment comprised of 200 earth stations. The optimum antenna diameter is 17 feet and threshold extension demodulators are used.

The first estimate of costs for the fixed portion of the earth stations are summarized below:

	$
Echo suppressor	500
Compandor	300
Threshold Extension Demodulator	1,000
IF amplifier	200
Down converter and frequency lock	2,000
Modulator	500
Up converter	2,000
Klystron amplifier	2,000
TOTAL fixed cost per message channel	8,500
Total fixed cost for three message channels	25,500
Redundant TDA	2,000
TOTAL basic equipment	27,500
Station integration and assembly (say 25%)	7,000
Installation, test equipment and spares	10,000
TOTAL Installed Cost	44,500

The only type of antenna considered suitable for this service is the non-tracking type up to 17 feet in diameter. The total system annual charges were computed over this range of antenna size using the antenna cost equation previously established. The results of the computation are presented in Figure 9-17. The system modeled has a bandwidth of 22 MHz and provides up to 600 voice circuits. The number of earth stations chosen as typical is 200 and each station therefore provides 3 voice circuits. Any other mix of station capacities could be chosen, the earth station costs being approximately \$26.4k, \$37k and \$47.6k for one, two and three voice circuits respectively, at the optimum antenna size of 17 feet diameter.

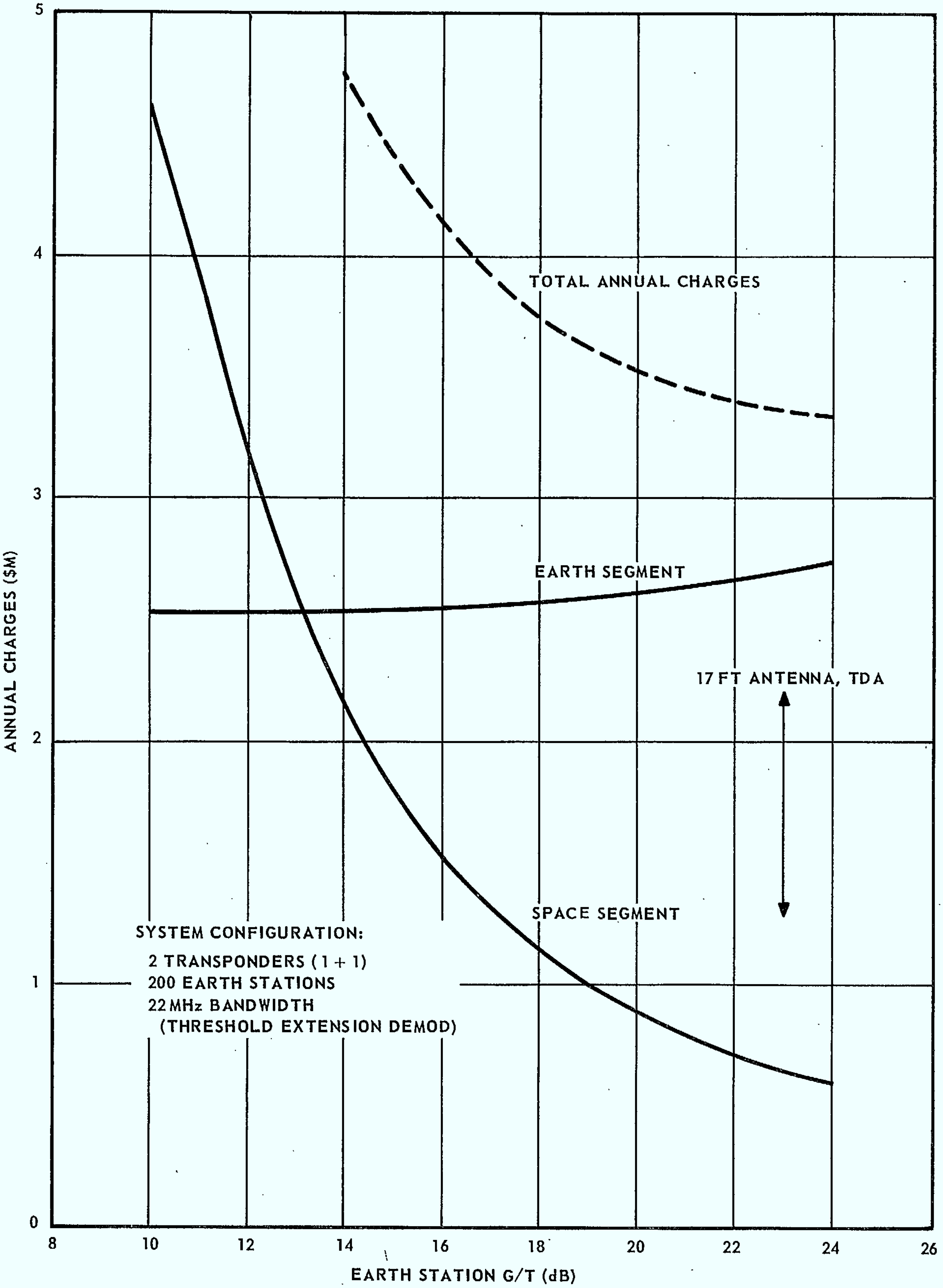

Figure 9-17 Single Channel per Carrier Telephony Service: Annual Charges vs Earth Station G/T (22 MHz Bandwidth)

10. Selected System Models

10.1 INTRODUCTION

Considerations of the forecast needs, the technical interrelationships and costs lead to selection of two satellite systems models in this chapter.

This chapter will consider the interaction between the needs as identified in chapter 2, the technical interrelationships and constraints as discussed in chapters 7 and 8, and the economic trade-offs as presented in chapter 9. A final decision on the modulation technique for the major traffic and remote communications will be made.

Out of these considerations will emerge two satellite system models designated as Satellite Systems Model 1 and Model 2.

Model 1 will be an absolute minimum annual charge system obtained by assembling the absolute minimum annual charge configurations for each of the services. In this context, at the risk of repetition, the reader is reminded that the minimum annual charge applies to deployed hardware excluding amortization of development costs. It will also fully meet the needs as defined in chapter 2. As might be expected, this would not necessarily result in an elegant model from the engineering and operational point of view. The model would also require more than 500 MHz rf bandwidth, nor would it be able to take advantage of the statistical variation of demand between different services due to its inherent inflexibility.

Model 2 would represent an effort to standardize as much as possible the technical parameters and to keep within a 500 MHz bandwidth. A slight increase in cost and a small reduction in capacity (within the variance of the needs as defined in chapter 2) would result, with the overriding advantage of flexibility.

* * *

10.2 FINAL CHOICE OF MODULATION TECHNIQUES FOR TELEPHONY SYSTEMS

Digital modulation technique is best suited for the major traffic system on all counts. For the small capacity remote communications system, FM is cheaper but uses more bandwidth than 4-phase PSK modulation.

In chapter 8, in considering major traffic and remote communications telephony systems, both FDM-FM-FDMA and PCM-CPSK-TDMA were dealt with extensively. However, no decision was taken in favour of one type of modulation or the other until the economic trade-offs have been done. The economic analyses have been carried out in chapter 9 and all the relevant data are now available to enable a rational decision to be taken.

Comparison of effectiveness between the two modulation techniques will be on the basis of rf bandwidth, rf power and minimum annual costs. The system capacity in each case will be the same, namely 3000 channels for the major traffic network with 12 accessing earth stations and 240 channels for the remote communications network with 20 earth stations. These figures correspond to the forecast needs of chapter 2.

Table 10-1 summarizes the direct comparison between the various modulation schemes.

For the major traffic telephony communications it is evident that FM uses more power, more bandwidth and more dollars than either the 4-phase or 8-phase digital system. The FDM-FM-FDMA scheme should therefore be rejected for any further consideration. Between the 4-phase and 8-phase systems, the 4-phase system is cheaper but uses more bandwidth. Hence where cost is important as in Model 1, the 4-phase system should be used. However, where bandwidth is at a premium as in Model 2, the 8-phase system should be selected.

With the abandonment of the analogue modulation technique, the major traffic telephony systems may now be combined with the digital services (wideband data, electronic mail, etc.) to share common facilities, thereby further reducing costs and increasing flexibility.

As for remote communications, it is clear that there is very little difference in power or cost between the 2-phase and 4-phase digital systems. However, the 2-phase system uses twice the bandwidth of the 4-phase system. Hence the 2-phase system is not attractive and may be discarded from further consideration. Between the 4-phase digital system and the FM analogue systems, FM is cheaper but uses more bandwidth than the 4-phase technique. Therefore FM will be used in Model 1 and 4-phase will be incorporated in Model 2.

Table 10-1 Comparison between Various Modulation Schemes

SERVICE	MODULATION	CAPACITY NEEDS (CHANNELS)	BANDWIDTH PER TRANSP. EXCLUDING GUARDBAND	NO. OF TRANSPONDERS	TOTAL BANDWIDTH	EIRP_s + G/T (dBW)	ANNUAL CHARGE (MIN.) ($M)
Major Traffic Telephony	FM	3000	95	2	190	85.2	5.8
	4ϕ	3000	60	2	120	80.2	4.2
	8ϕ	3000	40	2	80	84.1	5.2
Remote Comm. Telephony	FM	240	30	1	35	71.9	3.2
	2ϕ	240	20	1	25	65.7	4.1
	4ϕ	240	10	1	10	66.2	4.2

10.3 LOCI OF OPTIMUM CHOICE ON SYSTEM MODELING MAPS

On each system modeling map for any particular service, it is possible to determine and plot a locus of optimum choice of system parameters.

The earth segment annual charges, as functions of earth station G/T, and space segment annual charges, as functions of satellite EIRP, have been presented in chapter 9. The satellite EIRP and earth station G/T relationships for each service are coupled via the system modeling maps presented in chapter 8. For each service and at any rf bandwidth within the bounded area of the system modeling maps, an economic trade-off as given in chapter 9 may be carried out. The optimum G/T and EIRP may therefore be found for the bandwidth chosen. Repeating this process for other bandwidths within the constraints of the systems modeling map results in a number of similar optimum points for the particular service concerned. A locus joining these points may be called the "Optimum Choice Locus." Table 10-2 gives the optimum choice locus for each of the system configurations used in Model 1 and Model 2. These loci may be plotted into the appropriate systems modeling maps of chapter 8 if the reader so desires.

A point on the locus merely means that that point is optimum for that particular bandwidth. It does not give any information as to whether the optimum cost at one bandwidth is lower than that at another bandwidth. This latter information is now given qualitatively below.

In the case of the commercial and educational television services, since the quality and the imputed quantity of service per transponder are constant - as given by the performance objectives and the needs - the wider the rf bandwidth, the lower will be the systems cost. This is evident by reference to Figure 8-1 in which it can be seen that an increase in bandwidth can be accompanied by a decrease in systems carrier-to-noise temperature ratio (C/T), yet keeping the desired television signal-noise ratio constant. Since the C/T ratio is directly proportional to the quantity (satellite EIRP + earth station G/T), a decrease in C/T may be achieved by decreasing EIRP or G/T, or both. Whichever way this is done, it will result in lower costs. However, as has been shown in chapter 8, the maximum allowable bandwidth is constrained by the need to have some margin above threshold. In the commercial and educational television services, the largest permissible bandwidths are 30 MHz and 16 MHz respectively. Systems at these bandwidths therefore represent the absolute minimum cost systems practicable. Systems at lower bandwidths than these would cost more.

In the case of the telephony and digital systems, while the quality of service is defined, the quantity of service per transponder may be varied as a function of bandwidth within the constraints indicated on the systems modeling maps. For these systems therefore, an increase in bandwidth represents an increase in transponder capacity. Indeed, the capacity needs determine the exact bandwidths required for any given number of operational transponders. Within limits, the number of transponders can be varied and the bandwidth per transponder adjusted accordingly so as to satisfy the total needs. In general, a system with a fewer number of transponders and a wider bandwidth per transponder, yields a lower cost.

System cost trade-offs with various earth station front end receivers (including direct mixer for the ETV service) have been carried out. The front end receivers indicated in Table 10-2 represent the most cost effective choices.

It should be noticed from Table 10-2 that in all but one case the locus of optimum choice is constrained to lie along a line of fixed antenna size because of the large quantum change in cost when the antenna is forced to change from one mode of tracking (or non-tracking) to another. The exception is the 8-phase digital system. For this reason, and it has also been checked out in actual computation, the locus of optimum choice does not vary with uncertainties in earth and space segment costs, up to about ±25 percent of these costs. In specific cases, the tolerance to cost variance might be much higher. In the case of the 8-phase digital system in which the above tracking constraints do not apply (see chapter 9), variations of the earth and space segment costs by the above amount shifts the optimum choice locus to G/T of between 38 and 40 dB from its central position of 39 dB.

The conclusions to be drawn from the above is that, within the context of this study, the optimum choice of any system is likely to remain optimum despite any reasonable uncertainty in space and earth segment costs. The systems parameters arrived at for Model 1 and Model 2 are therefore expected to remain valid if there are cost variances within the limits indicated above.

Table 10-2 Optimum Choice Loci

SYSTEM MODELING MAP REFERENCE	SYSTEMS CONFIGURATION		RANGE OF BAND-WIDTH OVER WHICH LOCUS WAS COMPUTED (MHz)	OPTIMUM CHOICE	FACTORS CONSTRAINING LOCUS TO FIXED POSITION
	TRANSPONDERS +(SPARE)	EARTH STATIONS			
CTV (Fig. 8-2)	4 + (1)	50	20 - 30	Along Constant G/T = 29 dB	17 ft non-tracking antenna with uncooled paramp
ETV (Fig. 8-3)	11 + (3)	300	12 - 16	Along Constant G/T = 23 dB	17 ft non-tracking antenna with TDA
Major Traffic 8ϕ CPSK (Fig. 8-5)	6 + (1) to 3 + (1)	12	20 - 40	Along Constant G/T = 39 dB	--
Major Traffic 4ϕ CPSK (Fig. 8-6)	8 + (2) to 4 + (2)	12	26.2 - 53.0	Along Constant G/T = 34 dB	30 ft step-track antenna with uncooled paramp
Remote Comm. FM (Fig. 8-12)	1 + (1)	20	30 - 60	Along Constant G/T = 28 dB	30 ft step-track antenna with TDA
Remote Comm. 4ϕ CPSK (Fig. 8-7)	1 + (1)	20	10 - 40	Along Constant G/T = 28 dB	30 ft step-track antenna with TDA
Single Channel Per Carrier (Fig. 8-19)	1 + (1)	200	14 - 30	Along Constant G/T = 23 dB	17 ft non-tracking antenna with TDA

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10.4 SATELLITE SYSTEM MODEL 1

A complete satellite system catering to the needs of all the services and costing the absolute minimum is presented as Model 1.

Satellite System Model 1 is assembled based on the following objectives:

1) It is to be an absolute minimum annual charge system (excluding development cost and its associated amortization)

2) It should meet all the forecast needs for 1985, as defined in chapter 2.

3) It is permitted to exceed 500 MHz in total bandwidth, up to a maximum of 750 MHz.

Table 10-3 summarizes the salient features of Model 1. The absolute minimum annual charge requirement is ensured by picking the components of this model from the cheapest configurations for each of the services concerned. Comments on a service-by-service basis follow:

a) Educational Television Service (ETV)

The needs of chapter 2 indicate that in total 11 operational transponders will be required. Two additional transponders will be used as common back-up. The earth station network comprises 300 stations.

As indicated in 10-3, for the ETV service the absolute minimum cost system corresponds to the highest practical bandwidth of 16 MHz.

As indicated in chapter 8, this bandwidth is increased by about 6 percent to accommodate one sound subcarrier. The total occupied bandwidth is then 17 MHz. To this must be added the guardband between transponders. Bell Northern Research experts in filter designs indicate that a guardband of about 5 MHz is required, consistent with broad assumptions of filter weight and electrical characteristics (this 5 MHz guardband will be used for all the other transponders in this study). The total nominal band for the ETV transponder is therefore 22 MHz.

The other data on cost and technical parameters in Table 10-3 for the ETV service are easily obtained from the technical and cost relationships presented in chapters 7, 8 and 9.

b) Commercial Television Service (CTV)

The requirements for commercial television as detailed in chapter 2 comprise four channels in the space segment and a network of 50 earth stations. This calls for provision of four transponders in the satellite. An additional transponder will be provided in the system model as common back-up.

As shown in 10.3, the CTV system with the absolute minimum cost would be that corresponding to the largest allowable bandwidth of 30 MHz. When the allowances for sound subcarrier and guardband are added, the total nominal band of a CTV transponder is 37 MHz. The other parameters listed in Table 10-3 are calculated similar to the ETV case dealt with previously.

c) Major Traffic Communications (Telephony and Digital Services)

As explained in 10.2, the 4-phase modulation technique is chosen for Model 1, as this represents the lowest possible cost approach. In a digital communications system, the rf bandwidth requirement is determined by the capacity needs, which in this case are given in chapter 2 as 3000 telephone channels and 150 Mb/s of total digital facilities. For a 4-phase CPSK scheme, the total effective bandwidth required would then be 212 MHz. This bandwidth would have to be split into several transponders. Four operational transponders are used and the reasons are as follows:

i) Since two half-Canada coverage beams are used, one East, one West, the number of operational transponders must be even in order to be able to distribute the capacity uniformly.

ii) Computations indicate that the optimum annual charge is lower for a system with fewer transponders but a wider bandwidth per transponder, subject of course to the maximum bandwidth set by the boundary in the systems modeling map. In the 4-phase CPSK system, the upper bandwidth limit is 60 MHz.

iii) A four-transponder configuration, each with an effective bandwidth of 53 MHz seems to meet the requirements of i) and ii) above as close as it is possible and is therefore adopted. The total nominal bandwidth of the transponder is then 58 MHz.

The optimum G/T and satellite EIRP and other data presented in Table 10-3 for this network are easily calculated as in the previous cases.

d) Remote Communications

In 10.2 it was explained that multichannel FM was the lowest cost approach and will be adopted for Model 1. The capacity needs as detailed in chapter 2 are given as 240 channels for a network of about 20 stations. This channel capacity determines the required rf bandwidth to be 30 MHz (see Figure 8-13). Hence a transponder with this bandwidth will be selected. This transponder will be connected to the full Canada coverage beam, with another transponder as back-up.

From the economic trade-off curve of Figure 9-16 for a system with rf bandwidth of 30 MHz, the minimum annual cost occurs when the earth station G/T is 28 dB. Once this point is established, the other parameters in Table 10-3 relating to this service can be computed, as in the other services dealt with previously.

e) Single Channel Per Carrier Telephony

In chapter 2, the needs of this service are defined as 600 channels for a network of 200 earth stations. In chapter 8, for the single channel per carrier system, the analysis was carried out both for a system with conventional demodulator and a system with threshold extension demodulator. Economic computations (not presented) have shown that the system with conventional demodulation is more expensive (by about 20 percent) than the system with threshold extension demodulator. The system with threshold extension demodulator is therefore adopted. The total rf bandwidth required for this system is 22 MHz in order to provide 600 channels (see chapter 8). The nominal bandwidth of the transponder is therefore 27 MHz, inclusive of the 5 MHz guardband.

From the economic trade-off curve for this system, Figure 9-17, the annual charges decrease as G/T increases, at least up to a G/T of 23 dB and probably slightly beyond. At a G/T of 23 dB, the antenna size is 17 feet which is the largest practical antenna for a network without satellite tracking. As these stations are likely to be in far remote areas, the complexities of antenna tracking are considered to be unacceptable, quite apart from high costs. Hence a system with earth station G/T of 23 dB is to be adopted. The other data in Table 10-3 are obtained similar to the other services considered.

Returning now to general comments on Model 1, it can be seen that the total rf bandwidth required is 684 MHz. This exceeds the 500 MHz bandwidth in the 11.7 through 12.2 band in which there is no flux density limitation in the down-links. It is therefore necessary to use an additional spectrum in the down-link in the band

11.45 through 11.7 GHz (henceforth called the auxiliary band). Since the auxiliary band has a down-link flux density limitation[10.1] of:

$$\phi = -150 + \frac{\delta - 5}{2} \text{ dBW/m}^2/4\text{ kHz}$$

where δ = angles of arrival between 5° and 25°, it is therefore essential to assign to this band those services which are not likely to exceed this flux density. Computations indicate that the flux density for the 4-phase digital major traffic communications system is well below the above limit and since this service requires a total rf bandwidth of 232 MHz, it would be most logical to assign this service to the auxiliary band.

Model 1 represents the straightforward grouping of the lowest annual charge component systems for each of the services concerned. By hypothesis, this must represent the cheapest practical satellite system model (barring development costs), meeting all the specified needs. On purpose, no attention was paid to streamlining the systems parameters so as not to detract from the prime purpose of Model 1, which is to establish a reference in absolute minimum cost. It is therefore not surprising that Model 1 comprises a disorderly mixture of transponder powers and bandwidths. In Model 2 which is discussed next, some standardization will be applied.

Table 10-3 Satellite System Model 1

	G/T (dB)	ANT. DIAM. (ft)	LNA	TRANSPONDER POWER (W)	SATELLITE WEIGHT (lb)	Br.f. (MHz)	B (nominal) (MHz)	No. of TRANSPONDERS + (spare)	TOTAL B.W. (MHz)	CAPACITY	EARTH STATION TRANSMITTER	No. of EARTH STATIONS	ANNUAL CHARGE $ MILLION			CAPITAL COST $ MILLION		
													EARTH	SPACE	TOTAL	EARTH	SPACE	TOTAL
ETV	23	17	TDA	6	452	16 +6%	22	11 +(2)	242	11 CH	240* W	300	1.1	2.9	4.0	4.0	16.3	20.3
CTV	29	17	PAR #	11.7	312	30 +6%	37	4 +(1)	148	4 CH	1.8 kW	50	1.6	1.4	3.0	5.6	7.6	13.2
MAJOR TRAFFIC 4ϕ CPSK	34	30	PAR #	34.2	398	53	58	4 +(2)	232	3000 CH + 150 Mb/s	4.7 kW	12	2.8	2.6	5.4	10.0	14.4	24.4
REMOTE COMM. FM	28	30	TDA	45	154	30	35	1 +(1)	35	240 CH	17 W	20	2.0	1.0	3.0	7.1	5.5	12.6
SINGLE CH/ CARRIER	23	17	TDA	20	95	22	27	1 +(1)	27	600 CH	300 mW	200	2.7	0.6	3.3	9.6	3.4	13.0
TOTALS					1411 lb			21 + (7)	684 MHz				10.2 $M	8.5 $M	18.7 $M	36.3 $M	47.2 $M	83.5 $M

NOTES:

* Transmitted from Major Traffic Station Antenna.

\# PAR = PARAMP

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10.5 SATELLITE SYSTEM MODEL 2

A rationalized satellite system with reasonable commonality between the various transponders and occupying less than 500 MHz bandwidth is presented as Model 2.

As explained in 10.4, the purpose of Model 1 was to establish an absolute minimum cost reference. The result was that it was not an elegant model from the engineering and operational point of view, suffered from lack of flexibility and, prima facie, would require more development and engineering effort than a system with any degree of standardization. Model 2 will now be designed. It will have more streamlined features and will be based on the following objectives:

1) There should be the greatest possible commonality between the transponders.

2) Transponders connected to the same type of antenna coverage beams should be identical. This is to give future flexibility in transponder deployment and usage.

3) The total occupied rf bandwidth should not exceed 500 MHz.

4) The total in-orbit weight of the satellite should not exceed about 1100 pounds, which is the forecast maximum launch capability of the Thor-Delta vehicle in the time frame considered.

In meeting the above objectives, it is permissible that the system cost may rise a little and system capacity may be reduced within the limits of the variances of the needs as presented in chapter 2.

Applying the above objectives and critically examining all the services in an integrated manner, it is possible to arrive at a rationalized system designated Satellite System Model 2. The major parameters of this model are tabulated in Table 10-4. In lining up the various systems parameters so as to achieve the standardizations desired, it is not possible to detail here the many iterative processes that had to be gone through. However, broad logical sequences of the steps taken are given below.

The first factor to consider would be the 500 MHz total bandwidth. As explained earlier in this chapter, the total bandwidth required for the telephony and digital services, including the remote communications and single channel per carrier systems, is more or less fixed by the capacity needs. The only way to reduce bandwidth required for these services is really to cut the system capacity. On reviewing the needs of chapter 2, a great variance potentially exists in the digital services (video telephone, wide-band data, etc). A small variance may also exist in the telephone service. The capacity may therefore be somewhat reduced in the major traffic system. This is, in fact, done.

On examining the commercial and educational television services, it is possible to reduce bandwidth to some extent, but not to the amount to make it possible to pack all the services into the 500 MHz bandwidth. Moreover, attempting to reduce the television service bandwidths increases both costs (see Figure 9-11) and satellite weight rapidly. There is therefore no alternative but to cut back some capacity. In chapter 2, the ETV service is indicated to have a large potential variance. The final result is a reduction of the ETV service from 11 channels to 8 channels.

Table 10-4 is the end result of an iterative process, including removal of some redundant transponders, which is justified on account of the commonality now achieved. The parameters for all the services in Table 10-4 are selected along the "Optimum Choice Locus" except the 8-phase major traffic communications in which the G/T value chosen deviates from the optimum by 1 dB. It should also be noted that the transponder power for the remote communications 4-phase system can support a bandwidth of only 16 MHz and not the 20 MHz implied by the nominal transponder bandwidth of 25 MHz. However the 16 MHz bandwidth would yield a capacity of 400 channels which, in fact, exceeds the original needs.

The Satellite System Model 2 meets all the design objectives stated earlier. Specifically it has the following salient features:

a) It has only two types of transponder TWTs - 6 watts and 18 watts.

b) There are only three types of transponder bandwidths - 22, 25 and 34 MHz.

c) The CTV and major traffic communication transponders are identical and are connected to the half-Canada coverage antennas. Likewise, the remote communications and single channel per carrier telephony transponders are identical, sharing one common redundant transponder. These two transponders are connected to the full-Canada coverage antennas. The ETV transponders are connected to the various spot beams.

d) Total satellite in-orbit weight is 998 pounds.

e) Total rf bandwidth is 498 MHz which comes within the allocated 500 MHz by a margin of 2 MHz. This 2 MHz may be used for telemetry and command purposes.

f) Total system capital investment is $82.6 million (not including development costs). This in fact represents an increase of 6 percent over Model 1 if the capacities of Model 1 are normalized to those of Model 2.

g) The system capacity is somewhat reduced, as can be seen by comparing Tables 10-3 and 10-4. The reduction should be acceptable and is within the needs variances indicated in chapter 2.

In the light of Model 2, reference should be made to whether it was necessary in the first place to have chosen a 500 MHz band in which no power flux density limitation exists. Using the systems parameters in Model 2 and assuming that 1 MHz and 2 MHz peak-to-peak frequency dispersals are applied to the ETV and CTV carriers when no video modulation is present and digital energy dispersal is used for the major traffic and remote communications systems, the expected maximum power flux densities in Canada are as follows:

ETV	-141.8	$dBW/m^2/4$ kHz
CTV	-144.3	$dBW/m^2/4$ kHz
Major Traffic	-155.9	$dBW/m^2/4$ kHz
Remote Comm.	-156.3	$dBW/m^2/4$ kHz
Single Channel/Carrier	-156.1	$dBW/m^2/4$ kHz

From the above and with reference to CCIR recommendations[10.1] it can be seen that the ETV and CTV services would need to be within the frequency spectrem in which there is no power flux limitation. The other services may be located in other bands in which there is a flux density limitation.

In summary, Satellite System Model 2 should be considered an acceptable compromise between the two extremes of minimum cost and non-standardization on the one hand and high cost and complete standardization on the other hand.

Table 10-4 Satellite System Model 2

	G/T (dB)	ANT. DIAM. (ft)	LNA	TRANSPONDER POWER (W)	SATELLITE WEIGHT (lb)	Br.f. (MHz)	B (Nominal) (MHz)	No. of TRANSPONDER + (spare)	TOTAL B.W. (MHz)	CAPACITY	EARTH STATION TRANSMITTER	No. of EARTH STATIONS	ANNUAL CHARGE $ MILLION			CAPITAL COST $ MILLION		
													EARTH	SPACE	TOTAL	EARTH	SPACE	TOTAL
ETV	23	17	TDA	6	348	16+ 6%	22	8+ (2)	176	8 CH	60* W	300	1.1	2.2	3.3	4.0	12.5	16.5
CTV	29	17	PAR #	18	250	27+ 6%	34	4+ (1)	136	4 CH	2.8 kW	50	1.6	1.6	3.2	5.6	9.0	14.6
MAJOR TRAFFIC 8ϕ CPSK	40	58.7	PAR #	18	250	29	34	4+ (1)	136	2800 CH + 100 Mb/s	2.5 kW	12	4.2	1.6	5.8	15.0	9.0	24.0
REMOTE COMM. 4ϕ CPSK	28	30	TDA	18	75	16	25	1+ (½)	25	400 CH	280 W	20	3.5	0.5	4.0	12.5	2.7	15.2
SINGLE CH / CARRIER	23	17	TDA	18	75	20	25	1+ (½)	25	560 CH	300 mW	200	2.7	0.5	3.2	9.6	2.7	12.3
TOTALS					998 lb			18+ (5)	498 MHz				13.1 $M	6.4 $M	19.5 $M	46.7 $M	35.9 $M	82.6 $M

NOTES:

* Transmitted from Major Traffic Station Antenna

PAR = PARAMP

10.6 EFFECT OF DEVELOPMENT COSTS ON SYSTEMS CHOICE

Incorporation of development costs in the economic trade-off does not significantly affect the choice of optimum systems parameters.

In the economic analysis of chapter 9 and the choice of system models in earlier subsections of this chapter, development costs were not taken into account. This subsection will examine what effect, if any, there is on the systems choice if development costs were included.

In chapter 9, an estimate of the space segment development cost is presented. The earth segment development cost is given in Appendix A. In summary, these are:

a) Space Segment Development Cost is approximately 50 percent segment hardware cost (i.e. satellite costs, less launching).

b) Earth Segment Development Cost is approximately $3.0 million.

The manner in which these development costs may be taken into account depends very much on how development is to be financed and how the costs are to be amortized. In the space segment, the most severe case would be to amortize the development cost over the life of the first satellite. This of course would ignore the fact that satellites of the same or similar design may be sold to other nations or may be used in Canada in subsequent time frames. Even in this extremely unfavourable case in which the space segment development cost would amount to about 30 percent of the total space segment costs of the first system, computations have shown that inclusion of this development cost into the system optimization process does not significantly alter the "Optimum Choice Loci" given in 10.3. Consideration of the earth segment development cost results in the same conclusions. Indeed, the earth segment development cost is low in comparison and can be written off over the life of the earth station which may be approximately twice the life of the satellite. The effect of earth segment development cost is therefore small.

From the above, it is justifiable to keep development costs separate from the cost optimization process, at least in the context of this study. The development costs may then be added separately to the total system capital cost to obtain the gross total investment that is necessary to implement any system selected in this study. Likewise, depending on how the development costs may be amortized, the annual amortization may be added separately to the annual charges of the selected system model, to yield the total annual charges that are necessary (profits and taxes, etc, excluded).

10.7 TOTAL CAPITAL INVESTMENT

The total capital investment is estimated to be about $100.6 million.

In chapter 3, it is stated that the Design Authority had set a limit to the capital investment as not substantially above $100 million. In the study so far, all the system criteria have been met and the system designs have remained within the bounds of the systems constraints. One final constraint to be satisfied is total capital investment.

The capital costs for Model 1 and Model 2 are close together, being $83.5 million and $82.6 million respectively. It is expected that Model 2 would be the more acceptable model and hence will be assumed to be the selected system.

In either model, the up-link transmitting facilities for commercial and educational television were not included. A lump sum of $3 million capital cost for this transmitting equipment will be budgeted.

For the telemetry and command earth station, an allocation of $2 million will be made.

The total capital investment required therefore is as follows:

Capital Cost Model 2	$ 82.6 million
Capital Cost for Television Transmitting Equipment	3.0 million
Telemetry and Command Station	2.0 million
Space Segment Development	10.0 million
Earth Segment Development	3.0 million
TOTAL	$100.6 million

This total capital investment of $100.6 million satisfies the constraint laid down by the Design Authorities.

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10.8 SYSTEM BLOCK DIAGRAMS AND SYSTEMS OPERATION

System block diagrams for the communications portion of the satellite and earth stations are presented. A novel feature of TDMA operation is described.

The system block diagrams of the communications portion of the satellite and of the various types of earth stations are given in Figures 10-1 through 10-6. The systems parameters corresponding to Model 1 and Model 2 are also tabulated.

The systems operations are expected to be straightforward in most cases, except perhaps in the major traffic digital system for East-West communications. In a digital system using time division multiple access (TDMA), the transmitting station should generally be able to receive back its own time burst after looping around via the satellite. This is to enable extraction of timing and control signals so as to ensure that bursts from different stations do not overlap and cause interference. Since it is proposed to use two separate antenna beams to cover East and West Canada, the TDMA requirement described above would only be met for East-to-East communication and West-to-West communication. When it comes to communication between the eastern zone and the western zone, the transmitting station would in general not be able to see its own signal via the satellite. This problem can be overcome in the following way:

There should be only one reference earth station for both the eastern and western zone networks. This reference station would emit the two reference bursts for the two zones simultaneously. Thus, although each earth station in a zone would time its own burst relative to the reference burst of its zone, in so doing this earth station now has the information to time the burst destined for the other zone by virtue of the fact that the two reference bursts are simultaneous in time.

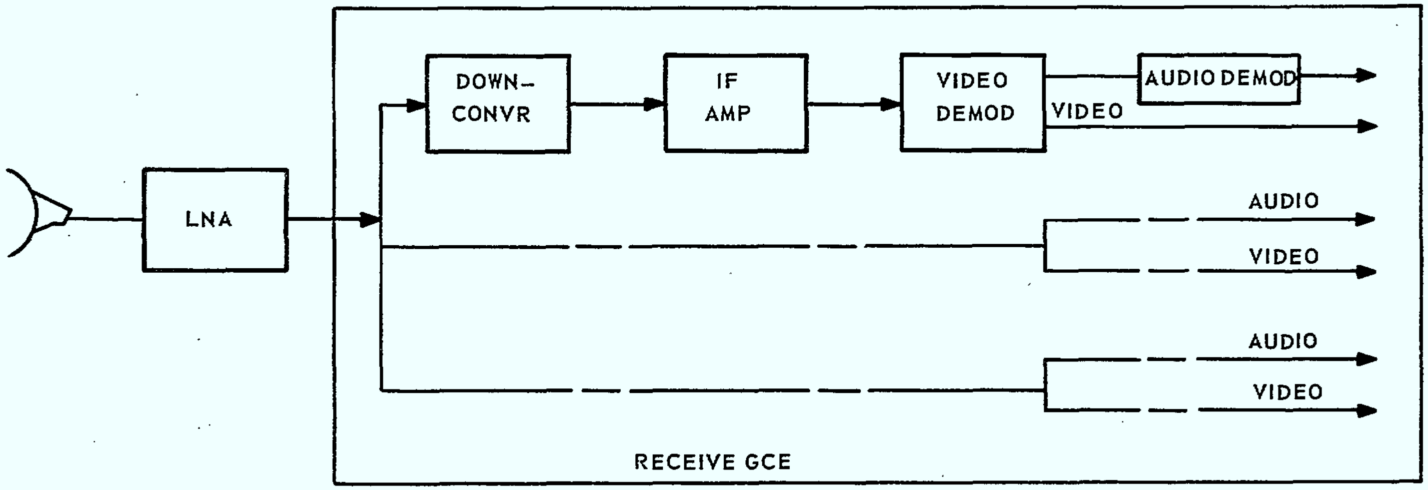
From the above it can be seen that an earth station must first have a burst (burst A) operating within its zone before it can time the burst (burst B) destined for the other zone. This means to say that each station for this mode of operation should have two transmit chains but may have only one receive chain to cover all parts of Canada. Since the stations concerned are major traffic type, and will need communications to all parts of Canada, it is likely there is sufficient volume of traffic to justify this.

While the above technique would be quite satisfactory, provision is made in the satellite design to leak back a low-level signal by cross-couplers at the satellite feed subsystem, to illuminate the zone in which the up-link is located. This leak-back signal (burst B) may be, say, -12 dB which will not cause any deterioration in EIRP in the forward direction but, under non-fade conditions (fade margin is 9.2 dB), may give acceptable error rate for the burst address unique code to be detected by its originating station for obtaining the proper timing. This will act as a back-up in case of failure of burst A.

By adopting the above techniques, and using half-Canada coverage beams, there is a 3 dB advantage in antenna gain. Put in a different way, there is a saving of 100 percent of the transponder power for the major traffic communications system and in terms of hard cash the saving is about $9 million in capital investment. This saving is significant.

It is believed that the solution proposed is novel and may lead to other TDMA techniques using spot beam satellite antennas.

* * *



NUMBER OF STATIONS = 300

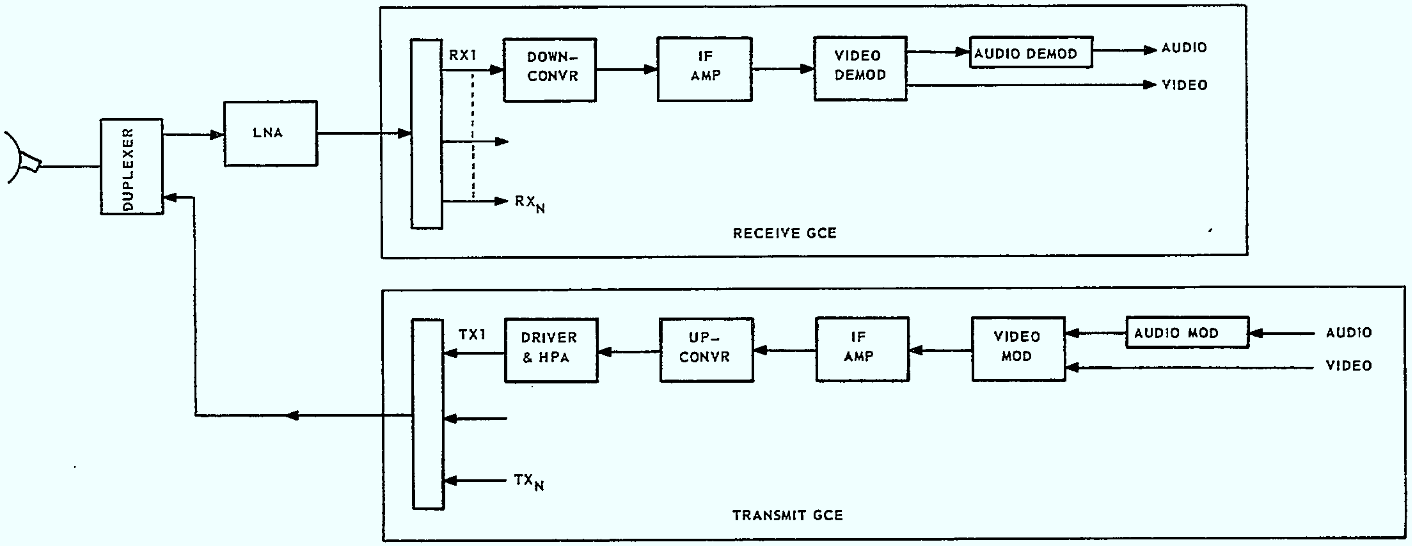
MODEL 1 & 2

PARAMETER	RECEIVER
ANTENNA (NON–TRACK.)	17 FT
TYPE OF LNA	TDA
STANDBY LNA	0
RECEIVER (G/T)	23.0 dB/°K
TYPE OF MODULATION	AUDIO – FM SUBCARRIER VIDEO – FM
RECEIVE RF BANDWIDTH	22 MHz
NUMBER OF OPERATING RX	1
NUMBER OF STANDBY RX	0
OUTPUT (S/N)*	VIDEO – 42.0dB–WEIGHTED AUDIO – 56.0dB–WEIGHTED
RECEIVE $(C/N)_T$ (MEDIAN)	14.6

$$*(S/N) \triangleq \left(\frac{\text{SYNC TIP TO PEAK WHITE VOLTAGE}}{\text{RMS WEIGHTED NOISE VOLTAGE}}\right)^2$$

Figure 10-1 ETV Receive Earth Station

* * *



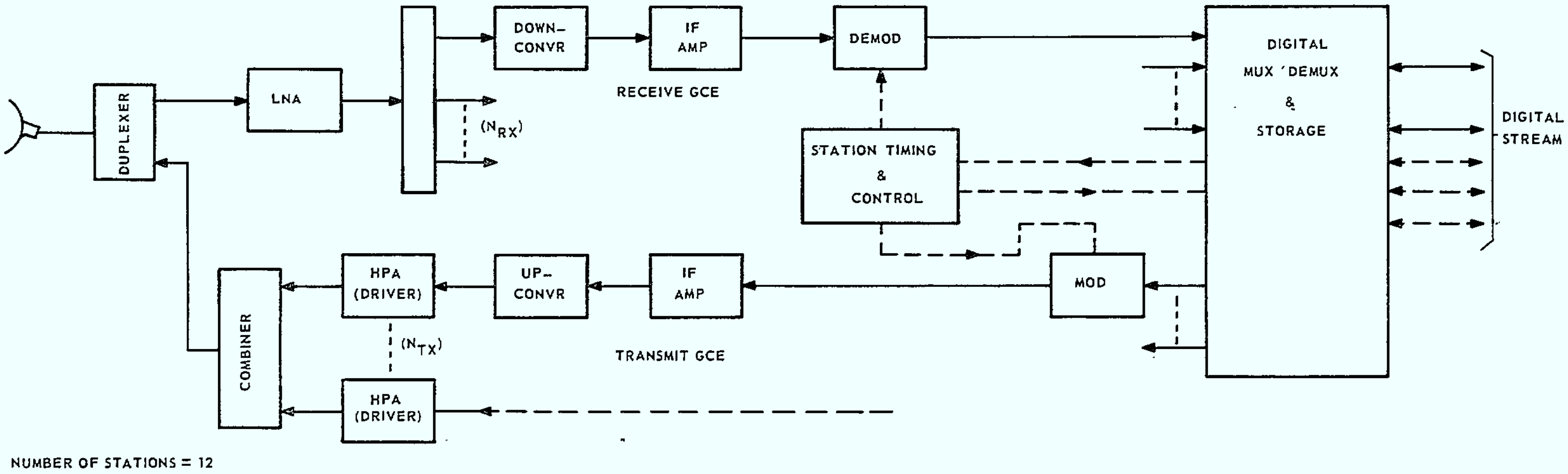
NUMBER OF STATIONS = 50

	MODEL 1		MODEL 2	
PARAMETER	TRANSMIT	RECEIVE	TRANSMIT	RECEIVE
ANTENNA (NON-TRACKING)	17 FT	17FT	17 FT	17 FT
ANTENNA GAIN	55 dB	53.6 dB	55 dB	53.6 dB
TYPE OF LNA		UNCOOLED PAR.		UNCOOLED PAR
STANDBY LNA		1		1
RECEIVE (G/T)		29 dB/°K		29 dB/°K
HPA OUTPUT POWER	1.8 kW		2.8 kW	
NUMBER OF CHAINS	0 OR 1	2	0 OR 1	2
NUMBER OF STANDBY'S	0 OR 1	1	0 OR 1	1
RF BANDWIDTH	37 MHz	37 MHz	34 MHz	34 MHz
TYPE OF MODULATION – AUDIO	FM SUBCARRIER		FM SUBCARRIER	
TYPE OF MODULATION – VIDEO	FM		FM	
RECEIVE (C/N) (MEDIAN)		15 dB		15 dB
TYPE OF DEMODULATOR		CONVENTIONAL		CONVENTIONAL
OUTPUT (S/N) AUDIO		56 dB WEIGHTED		56 dB WEIGHTED
OUTPUT (S/N) VIDEO*		57 dB WEIGHTED		57 dB WEIGHTED

$$^{*}(S/N) \triangleq \left(\frac{\text{SYNC TIP TO PEAK WHITE VOLTAGE}}{\text{RMS WEIGHTED NOISE VOLTAGE}}\right)^2$$

Figure 10-2 Commercial Television Earth Station

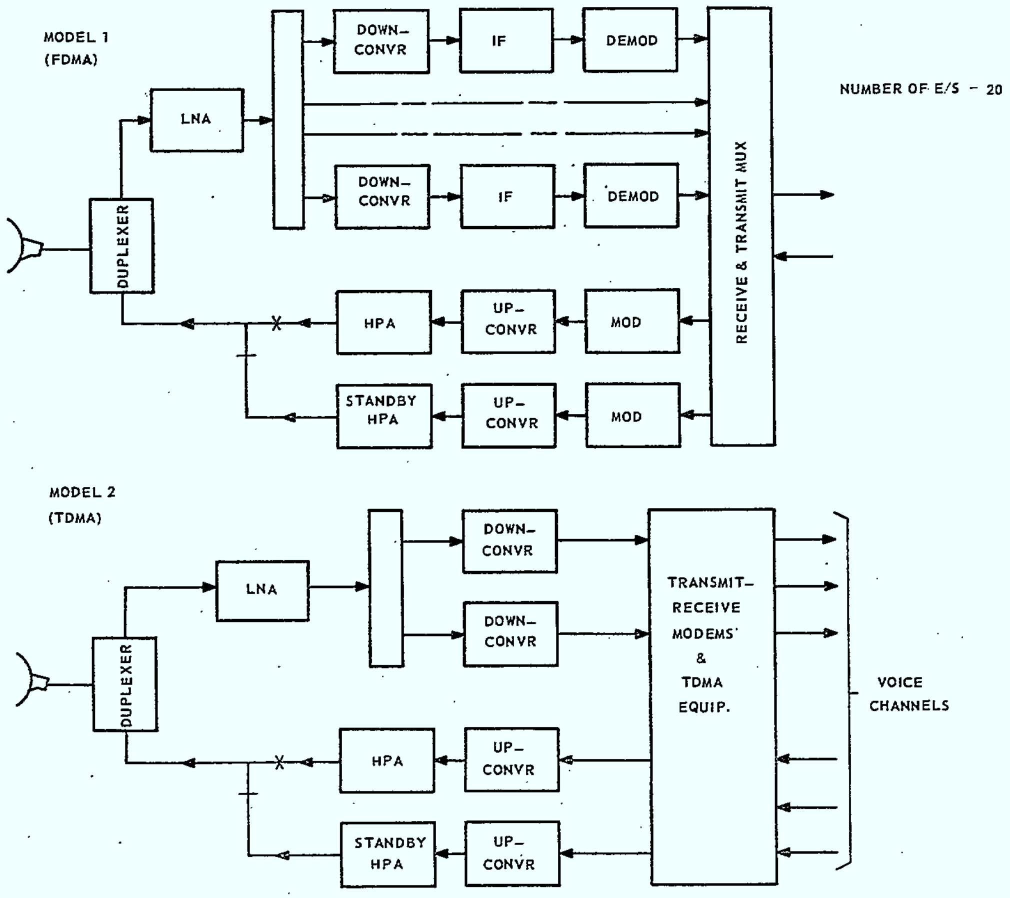
* * *



	MODEL 1		MODEL 2	
PARAMETER	TRANSMIT	RECEIVE	TRANSMIT	RECEIVE
ANTENNA (TRACKING)	30.0 FT	30.0 FT	58.7 FT	58.7 FT
ANTENNA GAIN	59.8 dB	58.5 dB	65.8 dB	64.5 dB
RECEIVE (G/T)		34 dB/°K		40.0 dB/°K
HPA OUTPUT POWER	4.7 kW		2.5 kW	
NO. OF OPERATING CHAINS	2	1 (2 ULTIMATE)	2	1 (2 ULTIMATE)
NO. OF STANDBY CHAINS	1	1	1	1
TYPE OF MODULATION	4φ CPSK	4φ CPSK	8φ CPSK	8φ CPSK
RF BANDWIDTH	58 MHz	58 MHz	34 MHz	34 MHz
TYPE OF LNA		UNCOOLED PAR		1-UNCOOLED PAR.
STANDBY LNA		1		1
TRANSMISSION CAPACITY/RF CHAIN	(88Mb/s) 1300 CH.	(88Mb/s) 1300 CH.	(72.5Mb/s) 1070 CH.	(72.5Mb/s) 1070 CH.
RECEIVE (C/N) (MEDIAN)		23.8 dB		29.5 dB

Figure 10-3 Major Message/Digital Traffic Earth Station

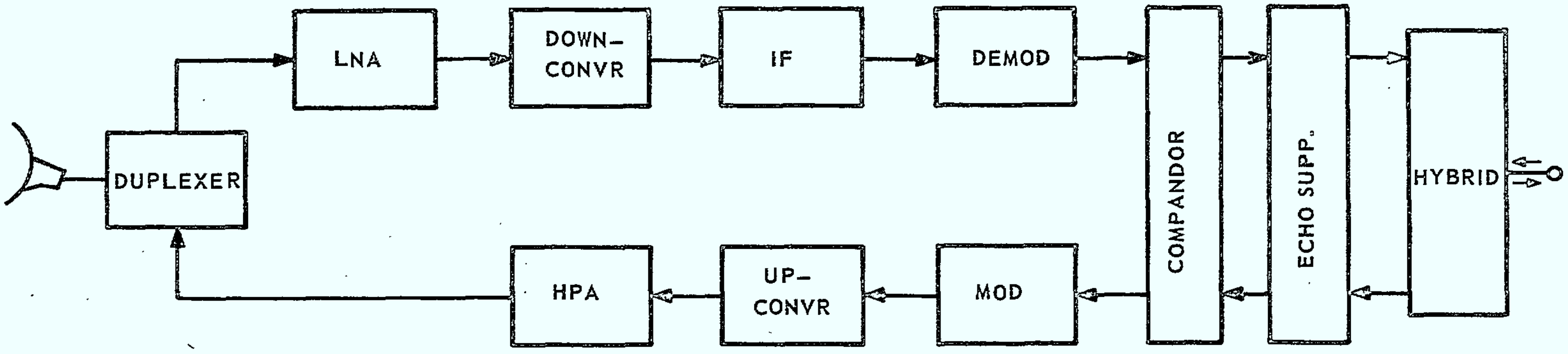
* * *



	MODEL 1		MODEL 2	
PARAMETER	TRANSMIT	RECEIVE	TRANSMIT	RECEIVE
ANTENNA (TRACKING)	30 FT	30 FT	30 FT	30 FT
ANTENNA GAIN	60 dB	57.5 dB	60 dB	57.5 dB
TYPE OF LNA		TDA		TDA
STANDBY LNA		1		1
RECEIVE (G/T)		28 dB		28 dB
NO. OF OPRG CHAINS	1	3	1	1
NO. OF STBY CHAINS	1	1	1	1
TYPE MODULATION	FM	FM	4φ CPSK	4φ CPSK
DEMODULATOR		TED		PSK
RF BANDWIDTH	30 MHz	30 MHz	16 MHz	16 MHz
HPA OUTPUT POWER	17W		280W	
RECEIVE $(C/N)_T$ (MEDIAN)		11.2 dB		17.6 dB

Figure 10-4 Remote Communications Earth Station

* * *



NUMBER OF E/S = 200.

MODEL 1 & 2

PARAMETER	TRANSMIT	RECEIVE
ANTENNA (NON-TRACK.)	17 FT	17 FT
ANTENNA GAIN	55 dB	53.6 dB
TYPE LNA		TDA
STBY LNA		1
RECEIVE G/T		23 dB/°K
NO. OF OPER. CHANS	3	3
NO. OF STBY CHAINS	1	1
TYPE MODULATION	FM	FM
DEMODULATOR		TED
RF BANDWIDTH	36 kHz	36 kHz
HPA OUTPUT POWER	300 MW	
RECEIVE $(S/N)_W$		46 dB
RECEIVE $(C/N)_T$ (MEDIAN)		11.7

Figure 10-5 Single Channel/Carrier Earth Station

SERVICE	SATELLITE PARAMETER	MODEL 1	MODEL 2
RECEIVER & COMMON AMP SECTION	RECEIVE ANTENNA	2-HALF-CANADA (CROSS-POLARIZED)	2-HALF-CANADA (CROSS-POLARIZED)
	RECEIVE (G/T)	-3.7 dB/°K	-3.7 dB/ °K
	RECEIVE BANDWIDTH	184 + 500 MHz	500 MHz
	RECEIVE FREQUENCY	12.5 - 12.75 & 14.0 - 14.5 GHz	14.0 - 14.5 GHz
	RECEIVER REDUNDANCY	1:1	1:1
ETV SERVICE	NO. OF OPERATING TRANSPONDERS	11	8
	NO. OF STANDBY TRANSPONDERS	2	2
	TWT OUTPUT POWER	6.0 WATTS	6.0 WATTS
	TRANSPONDER USABLE BANDWIDTH	17.0 MHz	17.0 MHz
	TRANSPONDER NOMINAL BANDWIDTH	22.0 MHz	22.0 MHz
	NO. OF TRANSMIT BEAMS	5	5
	MINIMUM ANTENNA GAIN	36 dB	36 dB
	MINIMUM TRANSMIT EIRP	42.8 dBW	42.8 dBW
MAJOR MESSAGE/DATA TRAFFIC	NO. OF OPERATING TRANSPONDERS	4	4
	NO. OF STANDBY TRANSPONDERS	2	1
	TWT OUTPUT POWER	34.2 WATTS	18 WATTS
	TRANSPONDER USABLE BANDWIDTH	53 MHz	29 MHz
	TRANSPONDER NOMINAL BANDWIDTH	58 MHz	34 MHz
	ANTENNA COVERAGE AREA	HALF-CANADA BEAMS	HALF-CANADA BEAMS
	MINIMUM ANTENNA GAIN	31.8 dB	31.8 dB
	MINIMUM TRANSMIT EIRP	46.1 dBW	43.3 dBW
COMMERCIAL TV	NO. OF OPERATING TRANSPONDERS	4	4
	NO. OF STANDBY TRANSPONDERS	1	1
	TWT OUTPUT POWER (SATURATION)	11.7 WATTS	18 WATTS
	TRANSPONDER USABLE BANDWIDTH	32 MHz	29 MHz
	TRANSPONDER NOMINAL BANDWIDTH	37 MHz	34 MHz
	NO. OF TRANSMIT ANTENNAS	HALF-CANADA BEAMS	HALF-CANADA BEAMS
	MINIMUM ANTENNA GAIN	31.8 dB	31.8 dB
	MINIMUM TRANSMIT EIRP	41.5 dBW	43.3 dBW
REMOTE COMMUNICATIONS	NO. OF OPERATING TRANSPONDERS	1	1
	NO. OF STANDBY TRANSPONDERS	1	1/2 (SHARED WITH SC/C TRANSPONDER)
	TWT OUTPUT POWER (SATURATION)	45 WATTS	18 WATTS
	TRANSPONDER USABLE BANDWIDTH	30 MHz	20 MHz
	TRANSPONDER NOMINAL BANDWIDTH	35 MHz	25 MHz
	GAIN OF TRANSMIT ANTENNA	28.8 dB	28.8 dB
	ANTENNA COVERAGE AREA	FULL-CANADA BEAMS	FULL-CANADA BEAM
	MINIMUM TRANSMIT EIRP	44.3 dBW	40.3 dBW
SINGLE CHANNEL PER CARRIER	NO. OF OPERATING TRANSPONDERS	1	1
	NO. OF STANDBY TRANSPONDERS	1	1/2 (SHARED WITH REMOTE COMM.)
	TWT OUTPUT POWER (SATURATION)	20 WATTS	18 WATTS
	TRANSPONDER USABLE BANDWIDTH	22 MHz	20 MHz
	TRANSPONDER NOMINAL BANDWIDTH	27 MHz	25MHz
	ANTENNA COVERAGE AREA	FULL-CANADA BEAM	FULL-CANADA BEAM
	MINIMUM ANTENNA GAIN	28.8 dB	28.8 dB
	MINIMUM TRANSMIT EIRP	40.8 dBW	40.3 dBW

Figure 10-6 Space Segment Communications

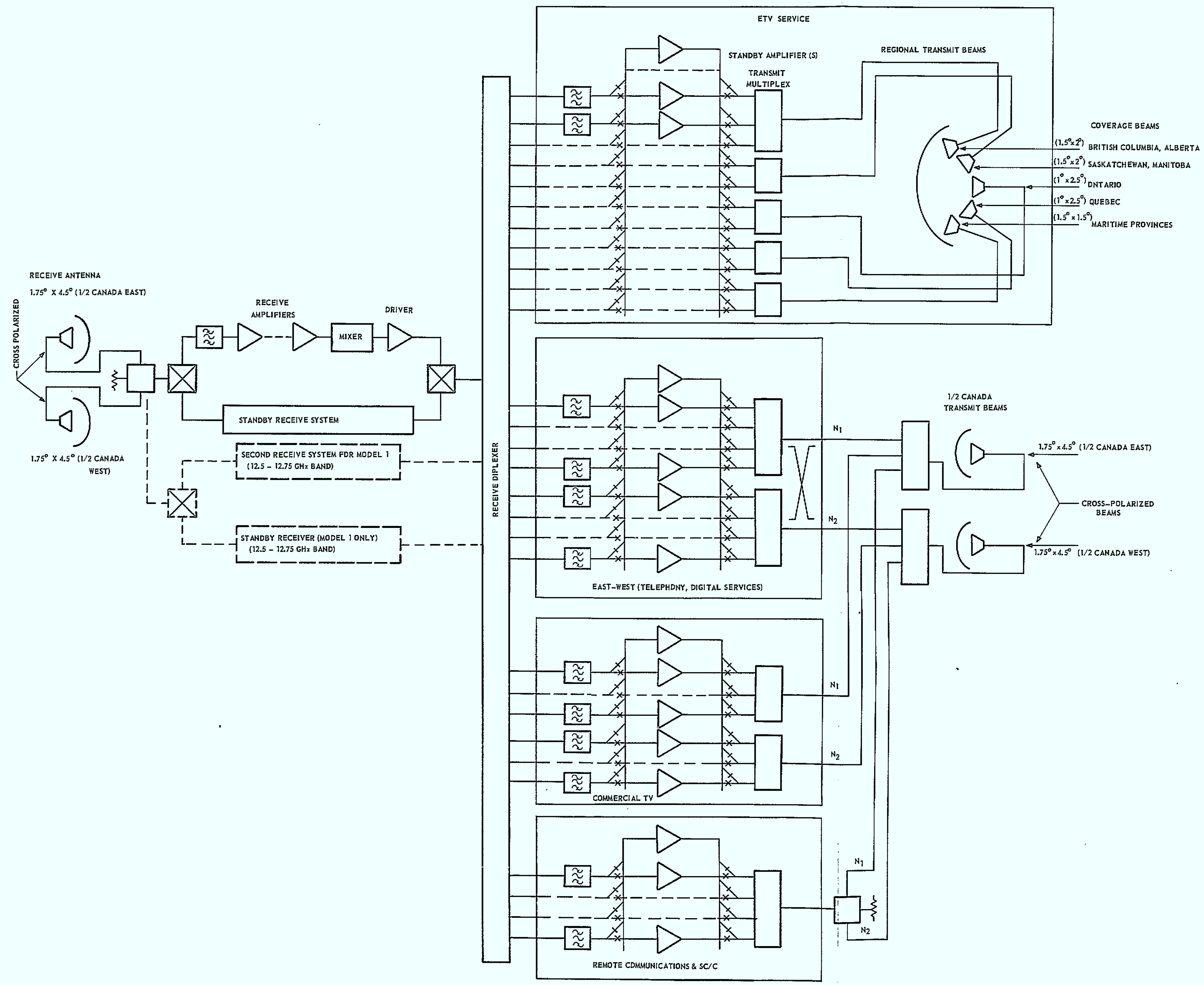


Figure 10-6 (continued)
Space Segment Communications

* * *

10.9 REFERENCES

10.1 World Administrative Radio Conference, Geneva 1971.

* * *

11. Conclusions and Recommendations

This chapter will present the conclusions of the study and make recommendations on follow-on study and development programs.

(a) Conclusions of Study

The objectives of the study, as defined in chapter 1, have all been met. Although the investigation has been limited by man-power resources, the study has been carried out with adequate thoroughness and in sufficient depth to enable valid conclusions to be drawn. The main conclusions are as follows:

i) The forecast demands for communications facilities in the time frame 1977 through 1985 justifies a satellite communications system additional to the satellite system in the 4 GHz and 6 GHz band provided by Telesat Canada. This additional satellite system would require approximately 500 MHz in rf bandwidths.

ii) A specific term of reference of the study is to synthesize a satellite system model to meet the forecast needs, using frequencies in the range 12 through 18 GHz. Model 2, presented in chapter 10, meets this objective. The optimum transponder TWT powers lie in the medium ranges of 6 to 18 watts; and total satellite in-orbit weight is around 1000 pounds. In the earth segment the largest non-tracking antenna of about 17 feet diameter is the most cost-effective choice for those services that have a large number of earth stations (e.g. commercial and educational television and single channel per carrier telephony). The frequency bands used are 14.0 through 14.5 GHz for up-links and 11.7 through 12.2 GHz for down-links. No investigation is made as to whether these frequency bands are optimum relative to other possible bands below or above the specified 12 through 18 GHz range, because a comparative study is outside the terms of reference.

iii) Analyses based on first estimates of costs indicate that the total capital investment for both the space and earth segments, inclusive of development costs, would be around $100 million (1971 dollars).

(b) Recommendations on Future Study and Development Programs

The satellite systems modeled in this study are predicated on certain advances in technology and techniques that are likely to take place between now and 1977. While it may be true that much of the system hardware, insofar as these may have a wide market internationally, would have been developed by private enterprises in the U.S.A., Canada and other countries, there will be segments of the system peculiar to the Canadian domestic environment, which must remain the system owner's responsibility to develop. These segments are discussed below.

The foremost item that needs study and development is the time division multiple access (TDMA) digital satellite system. While considerable work in TDMA development is going on in Intelsat and its member countries, notably Japan, U.S.A. and Germany, the Intelsat system is not expected to be suitable for Canadian domestic operation because of the vastly different environments. The Canadian operation will probably be characterized by East and West coverage beams or spot beams, and interface at earth stations would probably not be at voice channels but at the Bell Systems T1 and T2 PCM bit streams. Hence there is an urgent need to allocate resources to tackle this problem. Moreover, a Canadian TDMA study and development program would represent sound investment. The result of this work would be applicable to any domestic satellite network, be it the 12 through 14 GHz band or any other frequency band. There is therefore a certainty of useful application.

Next in priority is development of a single-channel-per-carrier telephony system, with voice activation and compandors. Special problems are foreseen in the generation and stabilization of rf frequencies in the transmitters and receivers at reasonably low costs. This system has potentials for communications in the Canadian far-North and in remote communities.

Other development areas are in the space segment. They are more specific and are associated with the particular satellite system configuration chosen. Examples of these are rf filters and combiners in the satellite and the satellite spot beam antennas.

Last, but not least, a first estimate of the development cost (see chapter 9 and Appendix A) is as follows:

i)	TDMA System	$ 2.5 million
ii)	Single Channel per Carrier	$ 0.5 million
iii)	Satellite Hardware	$10.0 million.

APPENDIX A

EARTH SEGMENT DEVELOPMENT

The satellite systems modeled in this study are predicated on certain advances in technology and techniques that are expected to take place between now and 1977. It is anticipated that much of the earth station hardware, insofar as these may have a reasonably wide market internationally, would have been developed by private enterprises in Canada and other countries. However, there will always be segments of the system which are peculiar to the Canadian environment and these must remain the system owners' responsibility to develop. This study has identified two such segments and they are:

(a) a time division multiple access (TDMA) system

(b) a single channel per carrier system with voice activation and compandors.

In the TDMA technology, development work is currently being carried out in Intelsat and its member countries, notably Japan, U.S.A. and Germany. While certain aspects of the Intelsat development may find application in the Canadian domestic system, by and large the system developed by Intelsat is not expected to be suitable because of the vastly different operational environments. The Canadian operation will most likely be characterized by East and West beams or spot beams, with its unique burst synchronization requirements (see chapter 10), and interface at earth stations would probably not be at voice channels but at the Bell System T1 and T2 PCM bit streams. Hence, there is a need to allocate resources to tackle this problem. The development fund required is estimated at $2.5 million.

The single channel per carrier telephony system with voice activation and syllabic compandors, holds great potentials for communications to the remote communities, especially in the North where transportation is a major problem. Although the system proposed uses FM which is well developed, the major problem areas are associated with operation, maintenance and reliability. Because of the very narrow bandwidth per channel (around 20 KHz) and the very high rf frequencies (12 through 14 GHz), special problems are foreseen in the generation and stabilization of the rf frequencies in the transmitters and receivers. The voice activation mode also presents problems with signaling. Solutions can be found and development cost involved is estimated to be about $0.5 million.

* * *

APPENDIX B

Some Technical Considerations of and Trends in Communications Satellite System Design

B.1 INTRODUCTION

This Appendix contains a discussion of multiple access techniques using frequency division and a report of the findings of Task B on the first phase of the study. The main objective in this task was to establish the current trends in communications satellite systems which would be used as a guide during the later phases of the study. The main effort consisted of a review of the trends established by the recent submissions to the FCC for the establishment of domestic satellite systems in the U.S.A. As the majority of these systems could feasibly be in operation by 1974 it was felt that the technology proposed for them would be an important factor in establishing the trends which would influence the design of a system for the 1977-1985 time frame.

During the performance of this task visits were made to COMSAT Laboratories and NASA Headquarters for discussions concerning current and future satellite systems technology. These visits are fully reported in Appendix D.

B.2 PROPOSED U.S. DOMESTIC SYSTEMS

B.2.1 General

At the March 15, 1971 deadline for submissions to the FCC for proposals for United States domestic satellite systems the following organizations had submitted proposals:

a) COMSAT
b) AT&T - COMSAT
c) Fairchild Hiller
d) MCI- Lockheed
e) Western Telecommunications
f) RCA Globom
g) GT&E - Hughes
h) Western Union
i) Tele-Prompter Corp.

Of these submissions only four proposed services are at frequencies above 10 GHz. In addition one proposal (AT&T-COMSAT) incorporates beacons for propagation experiments at these frequencies whilst another (COMSAT) proposes an experimental transponder at 12 through 13 GHz.

Fairchild Hiller, MCI-Lockheed, Western Telecommunications and RCA Globcom have proposed operational systems at frequencies other than the 4 GHz and 6 GHz bands. The RCA proposal has alternative systems in the 4 through 6 GHz band and in the 12 through 13 GHz band but the other three all offer service in the 4 through 6 GHz band and higher frequency bands in the same spacecraft.

Before discussing in detail the technical factors of each of these systems some general observations may be made:-

a) all the proposals (including those confined to the 4 through 6 GHz band) are multi-purpose,

b) all the satellites proposed have transponder bandwidths of the order of 40 MHz nominal spacing with usable bandwidths of about 36 MHz, in both the 4 through 6 GHz and 12 through 13 GHz bands,

c) all the satellites have area coverage antennas for the 48 contiguous states (CONUS) and a number of spot beam antennas for service to off-shore locations such as Hawaii, Alaska and Puerto Rico. One proposed satellite uses spot beams for point-to-point service in CONUS.

Many of the economic factors are presented for comparison in Table B-1. A comparison of various technical factors for the four systems is shown in Table B-2.

B.2.2 System Descriptions

A brief description of each of the proposals using frequency bands in addition to the 4 through 6 GHz band follows. Information is included concerning the services offered, the spacecraft and ground stations and the communications network provided by the system.

B.2.2.1 Fairchild Hiller

B.2.2.1.1 General

This proposal is for a system providing a wide range of services to all areas of the United States using initially two satellites in orbit plus one spare on the ground and six major earth stations (98 foot antennas) plus a number of smaller stations. The satellites are the most advanced of all those proposed and draw heavily on the experience gained by Fairchild Hiller in the ATS-F and G program. The majority of the transponders use solid state technology for the output amplifiers making possible the provision of 120 transponders of 36 MHz bandwidth plus other transponders for specialized services.

B.2.2.1.2 Services and Areas Covered

a) High-capacity point-to-point message service is provided by 96 transponders in the 4 through 6 GHz band using 6 spot beams for the interconnection of 6 major centers in CONUS:-

Table B-1 Comparison of Economic Factors

TOTAL SYSTEM		MCI LOCKHEED	FAIRCHILD HILLER	RCA GLOBCOM	WESTERN TELECOMMS
Total investment	($)	169.4 M	220.9 M	89.7 M	67.7 M
Total investment per satellite in orbit[1]	($)	84.7 M	110.5 M	44.8 M	33.8 M
Number of transponders per satellite		48	120	12	12
Total investment per transponder in orbit[2]	($)	1.75 M	0.92 M	3.73 M	2.82 M
Total annual revenue requirements	($)	68 M	70 M	40.2 M	22.3 M
Total annual revenue requirements per satellite in orbit	($)	34 M	35 M	20.1 M	11.2 M
Total annual revenue requirements per transponder in orbit	($)	710 k	290 k	1.68 M	960 k
Total annual revenue requirements as percentage of total investment	(%)	40	32	45	33
Rate of return	(%)	12	12	11	?

Table B-1 Comparison of Economic Factors (cont'd)

SPACE SEGMENT		MCI LOCKHEED	FAIRCHILD HILLER	RCA GLOBCOM	WESTERN TELECOMMS
Total investment	($)	138 M[3]	138 M[4]	52 M[5]	41 M[6]
Total investment per satellite in orbit	($)	69 M	69 M	26 M	20.5 M
Total investment per transponder in orbit	($)	1.44 M	570 k	2.17 M	1.7 M
Total annual revenue requirements	($)	55 M[8]	43.2 M	17.1 M	13.5 M[8]
Annual revenue requirements per satellite in orbit	($)	27.5 M	21.6 M	8.5 M	6.7 M
Annual revenue requirements per transponder in orbit	($)	570 k	180 k	710 k	560 k
Cost of one satellite[9]	($)	30.6 M	20.2 M	7.25 M	11.5 M
Satellite weight in orbit	(lb)	3910	2903	638	727
Satellite cost per lb	($)	7.8 k	7.0 k	11.4 k	15.8 k
Launch costs	($)	22.25 M	25.6 M	7.3 M	7.5 M
Launch costs per lb in orbit	($)	5.7 k	8.5 k	11.4 k	10.6 k
Total cost per lb in orbit	($)	13.5 k	15.5 k	22.8 k	26.4 k

Table B-1 Comparison of Economic Factors (cont'd)

EARTH SEGMENT	MCI LOCKHEED ($)	FAIRCHILD HILLER ($)	RCA GLOBCOM ($)	WESTERN TELECOMMS ($)
Total investment	31 M	56.6 M	37.7 M	26.7 M
Earth stations	21 M	32.7 M	37.7 M[12]	10.6 M
Connecting facilities	10 M[11]	17.8 M	—	16.1 M
Interest during const.	—	26.7 M	—	—
Earth station average cost				
2 × 98' 4/6 GHz	—	6.14 M	—	—
2 × 98', 2 × 35' 7/13 GHz	—	8.55 M	—	—
2 × 32' 4/6 GHz	868 k	—	—	—
1 × 32' 12/13 GHz	1.0 M	—	—	—
20' R/O 4 GHz	—	—	—	79 k
18' R/O 12 GHz	—	—	—	97 k
1 × 60', 2 × 45' 4/6, 12/13 GHz	—	—	—	2.5 M

NOTES:

1. Total initial investment divided by actual number of spacecraft in orbit.
2. Satellite cost divided by number of transponder per satellite.
3. Includes 3 flight spacecraft (2 in orbit, one space on ground) and 2 launches.
4. Includes 3 flight spacecraft (2 in orbit, one spare on ground) and 3 launches (one as backup for first two).
5. Includes 4 flight spacecraft (2 in orbit, one lost, and one spare on ground) and 3 launches.
6. Includes 2 flight spacecraft (2 in orbit) and 2 launches.
7. One additional s/c and one launch.
8. As percentage of total investment.
9. Including R&D costs pro rata.
10. Includes apogee motor (after firing).
11. Including multiplex.
12. Including connecting facilities.

Table B-2 Comparison of Technical Parameters

PARAMETER	MCI LOCKHEED	FAIRCHILD HILLER	RCA GLOBCOM	WESTERN TELECOMMS
Spacecraft - General				
In-orbit weight	3910 lb	2903 lb	638 lb	727 lb
Orbital positions	114°W, 119°W	104°W, 115°W	125°W, 121°W	113°W, 116°W
Number of spacecraft:				
- operational	1	1	1	1
- in-orbit spare	1	1	1	1
- on ground spare	1	1	1	—
Design lifetime	10 yrs	7 yrs	7 yrs	7 yrs
Launch vehicle	Titan IIID/ Agena	Titan IIIC	Thor-Delta	Thor-Delta
Stabilization	3-axis	3-axis	3-axis	Spin
Orbital position:				
- control	±0.1°	±0.1°	±0.1°	±0.1°
- method	Ion engine	Hydrazine	Hydrazine	Hydrazine
Attitude control (antenna pointing)	±0.14°	±0.1°	—	—
Conversion	Single (4/6) Double (12/13)	Single	Double	Single
- IF	1.3 GHz	—	2 GHz	—
Power Subsystems				
Type of array	2 panels sun-oriented	Half cylinder (2) sun-oriented	2 Panels sun-oriented	Cylinder spinning
Type of battery	Nicad	Nicad	Nicad	Nicad
- capacity	—	15 Ah	—	162 Wh
Array power				
- beginning of life	—	—	695W	—
- end of life	4400W	750W	610W	270W
- degradation	27%	—	12%	—
Array area	—	200 ft^2 21,400 N on P cells	—	—
Array weight	—	—	—	101 lb
Watts/lb				
- beginning of life	—	—	—	—
- end of life	—	—	—	2.75 W/lb

Table B-2 Comparison of Technical Parameters (cont'd)

PARAMETER	MCI LOCKHEED	FAIRCHILD HILLER	RCA GLOBCOM	WESTERN TELECOMMS
Power SS weight	1408 lb	572 lb	—	154 lb
Watts/lb total SS				
- beginning of life	—	—	—	—
- end of life	3.1 W/lb	1.3 W/lb	—	1.75 W/lb
Receive Subsystem				
Satellite G/T				
12/13 GHz	-3.0 dB/°K	1.4 dB/°K	1 dB/°K	—
4/6 GHz	-4.5 dB/°K	15.2 dB/°K	—	1.9 dB/°K
2.2/2.5 GHz	—	—	—	—
First stage type				
12/13 GHz	Paramp	Mixer	TDA	—
4/6 GHz	TDA	TDA	—	TDA
3.2/2.5 GHz	—	—	—	—
First stage NF				
12/13 GHz	—	—	—	—
4/6 GHz	—	5.5 dB	—	—
2.2/2.5 GHz	—	9 dB	—	—
Receiver Noise Temp.				
12/13 GHz	1200°K	2800°K	—	31.6 dB/°K
4/6 GHz	1595°K	—	—	30.6 dB/°K
2.2/2.5 GHz	—	—	—	—
Receiver Redundancy	1 for 1	1 for 1, 1 for 2	1 for 1	1 for 1
Transmit Subsystem				
Satellite EIRP				
12/13 GHz	46 dBW	—	42 dBW wide 40 dBW spots	— 41.6 dBW
7 GHz	—	35.2 dBW	—	—
4/6 GHz	37.5 dBW	36 dBW	—	38 dBW wide 26 dBW spot
2.2/2.5 GHz	—	31.3 dBW	—	—
2.55 GHz	—	54.8 dBW	—	—
PA Type & PWR				
12/13 GHz	+13 dBW TWT	—	+13 dB TWT	10 dBW TWT
7 GHz	—	3 W TWT	—	—
4/6 GHz	+9 dBW TWT	0.1 W Solid state	—	6 dBW TWT
2.2/2.5 GHz	—	0.05W Solid state	—	—
2.55 GHz	—	15W Solid state	—	—

Table B-2 Comparison of Technical Parameters (cont'd)

PARAMETER	MCI LOCKHEED	FAIRCHILD HILLER	RCA GLOBCOM	WESTERN TELECOMMS
Transmit redundancy	1 for 1	1 for 1	1 for 1	1 for 1
Station keeping & Propulsion				
Limits	±0.1°	±0.1°	±0.1°	±0.1°
Method	Ion engine	—	—	—
Fuel weight	—	—	—	—
Fuel type	—	Hydrazine	Hydrazine	Hydrazine
SS weight	180 lb	485 lb	—	—
Attitude Control				
Method	Momentum wheel	Momentum wheel	Momentum wheel	Spin
Accuracy	—	0.3° min all axes	—	—
SS weight	125 lb	266 lb	—	—

New York
Chicago
Atlanta
Dallas
Los Angeles
Seattle

and Alaska, Hawaii, Panama and Puerto Rico. For the network of six major stations in CONUS the average airline distance between the nodes is approximately 1,200 miles. For point-to-point coverage of the CONUS network 72 transponders have been allocated (12 per station). Of these, 8 per station are pre-assigned whilst the other four are connected via a switching matrix so that they may be used as required to deal with variable loads. The capability exists to increase the capacity of the New York and Los Angeles spot beams from 12 to 24 transponders by using cross polarization. Transponder allocations for offshore locations are as follows:-

Alaska	4
Hawaii	4
Panama	2
Puerto Rico	2

The offshore transponders are connected via the switching matrix.

Each transponder is said to have a capacity of 1200 one-way voice channels, equivalent to 1 television channel or up to 35 Mb/s. Based upon a 75 percent fill each spot beam will have a capacity of approximately 5,000 two-way circuits. The initial transponder usage is not stated explicitly but the initial provision of transmit and receive channels at the earth stations is as follows:-

	Transmit	Receive
New York and Los Angeles	24	24
Atlanta, Chicago, Dallas, Seattle	12	12
Alaska and Hawaii	4	6
Panama and Puerto Rico	2	6

The traffic requirements are based upon a report in the National Academy of Science series in which it is estimated that in 1975 the estimated U.S. domestic telephone traffic (public message plus private line) that is a candidate for satellite service will require 40,000 two-way circuits. This does not of course include TV or data traffic requirements.

b) Wide area television coverage of CONUS is provided by 24 transponders operating in the 13 GHz band (up-link) and the 7 GHz band (down-link). Transmission to the satellite takes place from two 13 GHz transmit stations in New York and Los Angeles and transmission from the satellite to numerous receive-only stations in the 7 GHz band.

c) Provision of random access telephone service to 400 remote communities in Alaska can be provided by 100 narrow band (80 KHz) transponders in the frequency band 2.15 through 2.20 GHz. A 1° beamwidth would be used for this service.

d) Direct to schoolhouse educational TV may also be provided at a frequency of approximately 2.5 GHz. This service would use two transponders and a 1° beam for coverage of Alaska, Hawaii, or any other area where a requirement exists.

B.2.2.1.3 Spacecraft and Earth Stations

The initial application is for two spacecraft in orbit at 104° West and 115° West with a spare on the ground. The satellites would be launched by a Titan IIIC vehicle, would use 3-axis stabilization and sun-oriented solar arrays. The antenna system consists of a 30-ft parabolic reflector with multiple beams and two 2.8 ft by 1.4 ft parabolic reflectors for area coverage services.

The initial application is for six major earth stations in CONUS for point-to-point service in the 4 through 6 GHz band. Their locations have been previously stated. Each station will have two antenna systems and the stations at Chicago and Dallas will have additional antennas for Texas Telephones and Communications (TT&C) and will be the system control centers. All the antenna systems will have autotrack facilities. In addition to these six stations a further four are planned for the offshore locations.

For the TV area coverage application two TV transmit stations using 35-ft antennas will be located at the New York and Los Angeles earth stations. Multiple receive-only stations using 25-ft antennas will be deployed throughout CONUS. These will be unattended stations. For the Alaska thin route message service earthstations using 12-ft antennas would be used, whilst for the direct-to-school ETV 7-ft antennas are envisaged.

The total initial investment in ground stations is summarized in the table below. Interest at 11 percent per annum on investment during the period to first launch (30 months) is included.

STATION	ATLANTA	L.A.	SEATTLE	N.Y.	DALLAS	CHICAGO
	($M)	($M)	($M)	($M)	($M)	($M)
Earth station	6.09	8.84	6.19	8.27	8.94	8.16
Connecting Links	1.750	5.38	2.47	0.72	6.4	1.1
No. of Antennas:						
98-ft	2	2	2	2	2	2
35-ft TV		2		2		
TT&C					1	1

The wide variance in the cost of connection facilities may be explained by the fact that the interconnection distances are a variant and also a varying proportion of interconnecting facilities will be leased. From the cost of the earth stations the following may be deduced:-

a) Average cost of earth station with two 98-ft antennas (4 through 6 GHz band) is $6.14 M.

b) Average cost of earth station with two 98-ft and two 35-ft antennas (7 through 13 GHz) is $8.55 M.

c) Average cost of earth station with two 98-ft antennas and one TT&C facility is $8.55 M.

d) Additional cost of station due to two 35-ft antennas in 7 through 13 GHz band is $2.41 M.

e) Additional cost of station due to one TT&C facility is also $2.41 M.

B.2.2.1.4 Overall System Availability

The concept of system reliability in this proposal is that the full communication capability of the spacecraft should be available for a seven-year period and the annual reliability is the percentage of the year that transmission objectives are not available on a given group of channels. This reliability objective is 0.01 percent (52.6 minutes per channel per year). The contribution of the various system elements is as follows:-

1) Sun outage - no contribution because of two satellites and dual earth station antennas.

2) Atmospheric effects (mainly rain) -0.002 percent (11 minutes) due to both up- and down-link.

3) Satellite transponder - negligible contribution due to redundancy. Design objective for solid state circuits will be 20 years.

4) Earth stations and terrestrial facilities - contribution is 0.0004 percent.

In addition to the outages due to rain the remaining time of 42 minutes is allocated to "human error at the earth stations".

B.2.2.2 MCI-Lockheed

B.2.2.2.1 General

This proposal considers the advantages of the 12 through 13 GHz band for point-to-point service whereby earth terminals may be installed in the centers of major urban areas, hence significantly reducing interconnecting facility costs. Half of the 48 transponders in each spacecraft are therefore in the 12 through 13 GHz band and the other half in the 4 through 6 GHz band. Two satellites would be launched initially. The proposer intends to pass on to the user the economic advantages to be gained from satellite systems by proposing distance-insensitive rates.

B.2.2.2.2 Services and Areas Covered

The coverage areas of the satellite will be CONUS in the 4 through 6 GHz band and CONUS, Alaska and Hawaii in the 12 through 13 GHz bands. In the 4 through 6 GHz band five major earth stations will be located close to the major traffic nodes:-

New York (TT&C)
Atlanta
Chicago
Dallas
Los Angeles (TT&C)

In addition it is proposed to install earth stations on existing buildings within urban areas in the following cities:-

Seattle
San Francisco
Los Angeles
Dallas
Denver
Kansas City
Chicago
New Orleans (2 stations for diversity)
Cincinnati
Detroit
Boston
New York
Washington
Atlanta
Miami (2 stations for diversity)

Stations will also be installed in selected locations in Alaska and Hawaii.

The proposed system will carry FDM-FM message, PCM-PSK digital data and FM television in any channel. The channel capacities working with 32-ft antennas in the 4 through 6 GHz band is:-

FDM-FM message - 800 one-way channels
PCM-4ϕ PSK digital - 50 Mb/s at 10^{-7} BER
FM Television - 1 channel at 56 dB S/N

The corresponding figures for the 12 through 13 GHz band are:-

FDM-FM Message - 600 one-way channels
PCM-4ϕ PSK digital - 50 Mb/s at 10^{-6} BER
FM Television - 1 channel at 54 dB S/N.

The system will simultaneously offer the following types of service:-

Leased Services (including data, voice and low-speed record).
TV and Radio program distribution
Cable TV Program distribution
Service to Alaska and Hawaii
Electronic Mail Delivery
Carrier Trunk Message
Educational Services

Customers may access the system through the MCI-Lockheed earth stations and interconnection links or may provide their own links. A summary of some of the service provisions is given below:-

a) Leased Services

Leased data transmission is said to be the most rapidly growing requirement. The use of these services has been constrained by high costs and limitations on flexibility and reliability. The growth rate for these services is expected to grow especially with the introduction of distance-insensitive rates. Based on a traffic study carried out by Booz, Allen and Hamilton the following predictions for long distance non-switched data traffic have been made:-

Year	Equivalent 4 KHz two-way circuits
1975	22,000
1980	40,000
1985	87,000

The largest proportion of this traffic will be for medium- and high-speed applications (150 b/s to 14,400 b/s and over 14,400 b/s). Also it is estimated that at least 20 percent of this traffic will be over distances greater than 1,000 miles. A high precentage of this is expected to be carried by satellite due to the distance-insensitive rates.

Leased voice circuits over 1,000 miles in length will amount to 20,000 two-way circuits in 1975. This figure is expected to increase due to the provision of distance-insensitive rates. In addition 2,000 equivalent 4 KHz circuits would be required by 1980 for low speed record services such as TWX and TELEX. For all these leased services MCI-Lockheed proposes part-time and shared use to provide maximum system efficiency and minimum costs to the user.

b) Television and Radio Program Distribution

This service will be offered in the 12 through 13 GHz band. Nine full-time channels are proposed plus an additional nine channels on Saturdays and Sundays. In addition to service to the 15 cities served by MCI-Lockheed, users can install their own earth stations in other locations.

c) Cable TV Services

Booz, Allen and Hamilton have concluded that duplication and distribution of video tapes is too expensive and inefficient for the large quantities of programming that will be required in the future. Service will be offered on an occasional use basis for individual programs or on a dedicated transponder basis for complete network service. The system offers direct transmission to urban areas using receive only stations owned by MCI-Lockheed, or otherwise.

d) Alaska and Hawaii

Four transponders are permanently dedicated to these two areas and additional transponders can be switched in if necessary.

e) Educational Services

For five years after the start of operation five transponders will be made available *free of charge* for educational use within the U.S.

B.2.2.2.3 Spacecraft and Earth Stations

The initial application is for two satellites located at 114° West (primary) and 119° West (spare) and an additional spare satellite on the ground. The satellites will be 3-axis stabilized and will have sun-oriented solar arrays. They will be launched by Tital IIID/Agena launch vahicles. The following communications antennas will be used on the spacecraft:-

4 through 6 GHz Band

Two transmit antennas with 30-inch by 60-inch elliptical reflectors, one vertically polarized and one horizontally polarized. The 3 dB beamwidth is 3.5 by 7.0°.

Two receive antennas with 20-inch by 40-inch elliptical reflectors, one vertically polarized and one horizontally polarized. The 3 dB beamwidth is 3.5 by 7.0°.

12 through 13 GHz Band

Receive: Two redundant antennas for CONUS coverage using 10-inch by 20-inch elliptical reflectors. (3.5 by 7.0° beamwidth).

One dual beam antenna for coverage of Hawaii and Alaska using a circular 18-inch reflector (3.5° beam).

Transmit: For CONUS coverage two dual-beam composite antennas are used where the Eastern beam is driven at a level 6 dB higher than the Western beam to overcome the higher rainfall in Eastern areas. A 30-inch circular reflector is used giving 2.5° beamwidth in each beam.

For Alaska and Hawaii a dual beam (3° beamwidth) antenna is used having a 24-inch circular reflector.

In the 4 through 6 GHz band five earth stations employing dual 32-ft antennas. The total cost for these stations is $4.344 M giving an average cost per station of $868 k. In the 12 through 13 GHz band, except for two stations which use space diversity, fifteen stations using single 32-ft antennas are proposed. These will be located on buildings in urban areas. The total cost for these stations is $16.65 M giving an average cost of $1.11 M per station. Considering only the thriteen stations which do not use space diversity the average cost per station is $1.006 M. This is 16 percent higher than the 4 through 6 GHz stations. The antennas at the 12 through 13 GHz stations have autotrack and limited motion capability.

B.2.2.2.4 Overall System Availability

The design lifetime of the space segment of this system is 10 years. The system operational availability model is based on the likelihood that the system performance will be available for 20 out of 24 transponders (in each band) for a period of one year and for 10 years. The system is fully redundant in that there are two in-orbit satellites working with separate antennas at each earth station.

The probability of success achieved in each band out of one and ten years (for 20 out of 24 transponders) is tabulated below:-

	4-6 GHz	12-13 GHz
One year	0.99969	0.9995
Ten years	0.97393	0.893

The figures for the 4 through 6 GHz system include contributions by the earth stations, satellites, and rain whilst those for the 12 through 13 GHz system include loss of service due to slewing during sun transit as only single-antenna earth stations are used.

B.2.2.3 RCA Globcom

B.2.2.3.1 General

The RCA proposal is for a system operating in the 4 through 6 GHz band, but proposes an alternate system entirely in the 12 through 13 GHz which will be substituted if frequency allocations become available. The system will include thirteen earth stations, seven of which will be in CONUS, five in Alaska and one in Hawaii. Initially two 12-channel satellites will be launched using Thor-Delta vehicles.

B.2.2.3.2 Services Provided and Areas Covered

The system will provide point-to-point message, data and TV service to major centers in CONUS, Hawaii, and Alaska. In the first phase of the system with two satellites in orbit the allocation of the 12 transponders in the primary satellite would be as follows:-

7 - analogue voice and data
3 - network TV
1 - Alaska ITV
1 - Alaska ITV or other use.

The second satellite would be reserved as an in-orbit spare but could be used for occasional TV and for experimental services.

The following is a listing of the services which would be provided:-

a) Voice and data within Alaska, between Alaska and CONUS and between Alaska and Hawaii,

b) Private line voice and data on an analogue basis within CONUS and between Hawaii and the major centers in CONUS. Available services would include photo transmission, facsimile, press networks, computer services. A wide range of bandwidths and speeds of transmission would be available to customers.

c) Digital data services within CONUS would be available on a full duplex basis providing end-to-end digital transmission.

d) Various types of Government private line services would be available at considerable cost savings. Secure voice transmission would be included.

e) Studio-to-studio television and radio program distribution would be available.

f) Two channels would be available at a reduced cost for public radio and television services such as ETV. Two channels would also be allocated for ITV in Alaska.

g) CATV services.

h) Motion picture distribution would be offered to the motion picture industry for transmission direct to cinemas over satellite and terrestrial systems.

The areas to be served are covered by three antenna beams. One elliptical beam covers CONUS and Alaska while two spot beams cover Hawaii and Puerto Rico.

Distance-insensitive rates are not proposed and typical private line rates for analogue service in CONUS are shown below for voice grade circuits:-

			$ Per Month
Chicago	-	New York	250
Seattle	-	Los Angeles	350
Denver	-	Seattle	550
Chicago	-	San Francisco	700
Washington	-	Los Angeles	1,000

B.2.2.3.3 Satellites and Earth Stations

The two initial satellite positions are 125° West and 121° West. The 4° spacing was chosen to allow the use of dual beam antennas at earth stations. Each satellite will have 12 identical transponder channels having usable bandwidths of 36 MHz. The satellite would use 3-axis stabilization and sun-oriented solar arrays. The launch vehicle would be an improved Thor- Delta.

The antenna system comprises a single 2.5 ft reflector producing two beams of 2.33° beamwidth for coverage of Hawaii and Puerto Rico. Two elliptical reflectors (2-ft by 9-inches) provide coverage of CONUS and Alaska. Very little technical detail concerning the satellite is given.

Thirteen earth stations are proposed initially and will be located as follows:-

CONUS	Alaska	Hawaii
New York	Anchorage	Honolulu
Washington	Juneau	
Chicago	Ketchikan	
Denver	Fairbanks	
Los Angeles	Prudhoe Bay	
San Francisco		
Seattle		

These earth stations would have antennas about 32 feet in diameter and would probably use cooled parametric amplifiers. It is stated that is is feasible to mount a 32-ft antenna on a tall building and that tracking would be required independent of building sway. Tracking would also be required for 15-ft antennas when mounted on very tall buildings.

No information is given concerning the costs of the earth stations but is is stated that antennas would be substantially more costly in the 12 through 13 GHz band because of the better pointing accuracies required and the tighter surface accuracies.

B.2.2.3.4 Overall System Availability

The overall system reliability for a seven year period is 99.97 percent. Typically, the contributions from the satellites and earth stations are as follows:-

1) Satellites - there would be a spare satellite in orbit and the likelihood of both of these failing simultaneously is negligible. However, if one failed the probability that the other would not fail during the estimated time to launch a new satellite (40 days) is 0.989. This is based upon a total satellite MTBF of ten years.

2) Earth stations - total earth station availability is calculated to be 99.95 percent. This is an approximate figure for illustrative purposes only.

B.2.2.4 Western Telecommunications

B.2.2.4.1 General

This proposal considers two satellites in orbit each with six transponders in the 4 through 6 GHz band and six in the 12 through 13 GHz band. The system will offer voice, data and TV services in both bands between major transmit-receive stations and to receive-only stations for TV distribution.

B.2.2.4.2 Services and Areas Covered

In the 4 through 6 GHz band the coverage area is CONUS, Hawaii and Alaska. In the 12 through 13 GHz band the coverage is of CONUS only. The system is designed for the transmission of voice, data and video services between major earth stations located as follows:-

New York — Chicago
Denver — Los Angeles

For network TV services 26 locations have been identified as possible choices for transmit-receive stations in the 4 through 6 GHz band. In addition, 127 receive-only station locations in the 4 GHz band have been listed. The use of transportable transmit-receive stations is also proposed.

Some of the services which will be offered by the system are listed below:-

a) Use of the satellite system to connect Western Telecommunications present regional microwave network into the four major centers - New York, Chicago, Los Angeles and Denver for data transmission.

b) Computer communication (video or high-speed data) with a limited speed return data link.

c) Tariffs for the lease of transponders (could be on a time-assignment basis).

d) Short term wide-band or video requirements (30 through 100 days). This market is virtually untapped. Transportable terminals would be offered for this service.

e) Network TV (studio-to-studio).

f) CATV.

g) Non-commercial TV and educational services with channels for the latter at no cost.

h) Transponders to be leased to common carriers such as GT&E and Western Union for a seven-year period at an annual rate of $750,000.

The initial earth stations will have the following capabilities:-

STATION	TYPE	CAPACITY	
		4-6 GHz	12-13 GHz
Los Angeles	T/R	8 TV 2 Mess.	6 TV
Las Vegas	R/O	4 TV	
Denver	T/R + TT&C	8 TV 2 Mess.	6 TV
Huron, S.D.	R/O		4 TV
Chicago	T/R	10 TV 2 Mess.	6 TV
New York	T/R + TT&C	8 TV 2 Mess.	6 TV

B.2.2.4.3 Satellites and Earth Stations

Two satellites are proposed initially to be located at 113° West and 116° West. Both satellites will be used for carrying traffic and no spare on the ground is proposed. The second in-orbit satellite would be used as a back-up for primary services in the first satellite in the event of failure. Each satellite will have six transponders in the 4 through 6 GHz band and six in the 12 through 13 GHz band. The satellites will be spin stabilized and will be launched by Thor-Delta vehicles.

The satellite antenna systems consist of a 100-inch by 60-inch elliptical reflector in the 4 through 6 GHz band using multiple feeds. In the 12 through 13 GHz band there are three transmit antennas and one receive antenna using 26-inch diameter shaped reflectors. The three transmit antennas are steerable in the E-W plane for five point adjustments. As there are only six 40 MHz transponders in each band on the satellite these are spaced 80 MHz apart, the channels on each of the two satellites being interleaved.

The main transmit-receive earth stations will have one 60-ft diameter antenna having dual beams in the 4 through 6 GHz band for communication simultaneously with both satellites. Each station will have two 45-ft diameter antennas for use in the 12 through 13 GHz band. The 60-ft antennas have initial limited adjustment capability. The 45-ft antennas have ±0.1° sidereal motion tracking by subreflector steering in addition to manual adjustment for initial alignment.

The costs of the various types of station are as follows:-

T/R station with TT&C	$2.718 M.
T/R station without TT&C	$2.468 M.
R/O station 4-6 GHz (20-ft)	$79 k.
R/O station 12-13 GHz (18-ft)	$97 k.

Comparing the costs of the receive-only station would indicate that the station operating in the 12 through 13 GHz band costs about 23 percent more than the station in the 4 through 6 GHz band for similar performance. However, this may not be a true indication of the cost difference between the bands because the station in the higher band has a dual-beam antenna.

B.2.2.5 Proposed ESRO System

B.2.2.5.1. General

This system is currently in the study phase and is planned for implementation about 1980.

B.2.2.5.2 Services and Areas Covered

The proposed system will carry telephone, data (narrow-band and wide-band) and TV distribution for the members of CEPT (European Conference of Post and Telecommunications Administration), including the European Broadcasting Union. It is proposed that three satellite channels be provided for TV distribution, each channel carrying up to 20 audio channels in addition to the TV program. Approximately 33 through 50 percent of projected telephone and data traffic is expected to be carried via the satellite system over distances greater than 480 miles. The number of voice circuits required during the lifetime of the satellite is estimated as follows:-

	33% - 50%
by 1980	4300 - 6450
by 1985	7800 - 11700
by 1990	14400 - 21600

The satellite will probably carry three transponders for telephone and data traffic each having 120 MHz bandwidth.

B.2.2.5.3 Satellites and Earth Stations

The proposed satellite will operate in the 11 through 13 GHz bands and its in-orbit weight is expected to be within the range 1500 through 1800 lbs. In addition to the TV transponders the desired capacity of the satellite is 12,000 telephone channels. This satellite capacity is in the same range as that of the COMSAT satellite which is in the same weight class. The satellite will have

3-axis stabilization and sun-oriented solar arrays.

It is expected that there will be about 20 ground stations for telephone, data and TV traffic and about 12 TV receive-only stations. Bit rates of 150 Mb/s with 4ϕ or 8ϕ modulation are being considered as well as TDMA and TASI techniques.

B.3 MULTIPLE ACCESS OPTIMIZATION

This appendix briefly outlines the method of optimizing the capacity for a frequency modulation/frequency division multiple access system (FM/FDMA) employed in a satellite communication system as presented in chapter 7.

For multi-channel telephony systems using FM, the general FM equation to obtain the unweighted signal/noise in a 3.1 KHz telephone channel is given by:

$$\frac{S}{N} = \frac{C}{N}\,\frac{B}{b}\,P\left(\frac{\delta f_{rms}}{f_m}\right)^2 \qquad \text{unweighted}$$

where:

$\frac{S}{N}$ = unweighted signal-to-noise

b = voice channel bandwidth (3.1 KHz)

f_m = top baseband channel frequency

B = RF bandwidth

C/N = Carrier-to-noise ratio

δf_{rms} = RMS test-tone deviation

P = pre-emphasis improvement factor (4 dB)

In the case of multiple-access FM, the system carrier-to-noise, (C/N), is comprised of the following components:

- Up-path termal
- Down-path thermal
- Satellite intermodulation

The tradeoff to obtain the optimum satellite link carrier/noise is performed between the up-path, down-path and satellite intermodulation noise contributions.

The intermodulation noise due to the non-linear characteristics of the satellite output amplifier (assumed to be a TWT in this analysis) is dependent upon the following system parameters:

- operating point which is determined by input drive power relative to saturation point (input or output back-off)
- number of carriers transmitted simultaneously through the amplifier and also the relative spacing and amplitudes of the respective carriers.

The cases considered assumes equal carrier accesses (equal amplitude and spacing) which will give the worst case intermodulation since the intermodulation products in this case fall in the same frequency slots as the wanted carriers compared to unequal or randomly spaced carriers. For this case Westcott* gives the carrier to total intermodulation ratio, C/n_I versus output backoff for four equal carriers as shown in Figure B-1.

To obtain the C/n_I ratio for 6 or more carriers, one can use the following relationship:

$$\frac{C}{n_I} = \left(\frac{C}{I}\right)_4 - 10 \log_{10} \frac{16}{n^2} \quad {}_rD_n$$

where $\frac{C}{I}_4$ = carrier-to-intermodulation ratio for four equal carriers

I = a single intermodulation product

${}_rD_n$ = distribution function of intermodulation products e.g. the number of intermodulation products of type $f_1 + f_2 - f_3$ of n carriers falling on the r^{th} carrier for equal spacing case.

This relationship is applicable for 6 or more carriers in which case the $f_1 + f_2 - f_3$ type product is the predominant intermodulation term. Figure B-1 shows the C/n_I versus output backoff for 4, 6, 10 and 16 equal accesses.

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* R.J. Westcott; "Investigation of Multiple FM/FDM Carriers through a Satellite TWT Operating Near to Saturation," Proc. of IEE, Vol. 114 No. 6 June 1967.

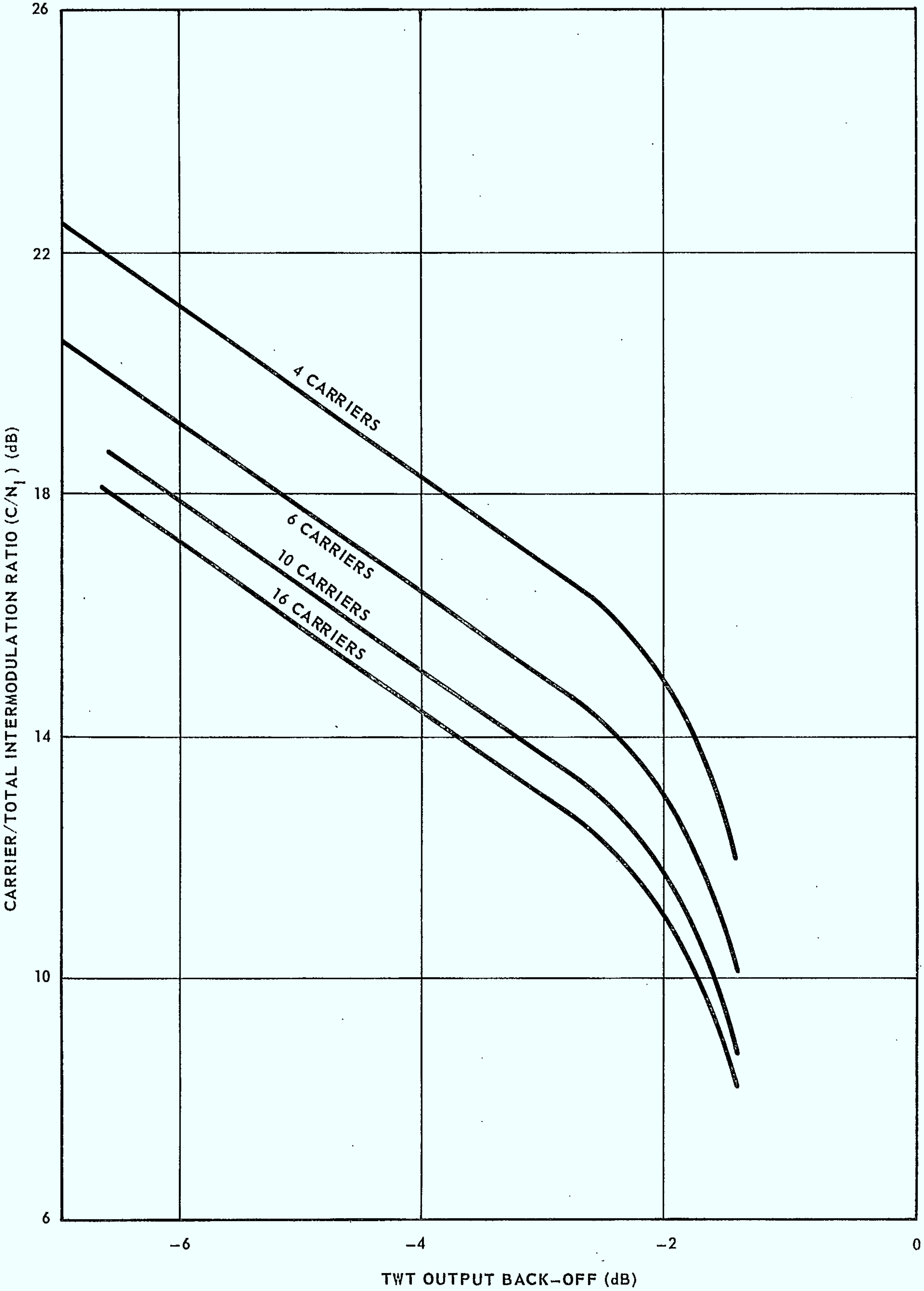

Figure B-1 Carrier/Total Intermodulation - Power Ratio as a Function of Output Back-off

Westcott has shown that the (C/I) for an infinite number of carriers is approximately 1 dB worse than the 16 access case. Thus with a small loss of accuracy, the C/I for more than 16 carriers will be taken the same as the 16 access case.

The total carrier/noise of the satellite link from thermal noise and intermodulation noise can be expressed as:

$$\left(\frac{C}{n_T}\right)^{-1} = \left(\frac{C}{n_U}\right)^{-1} + \left(\frac{C}{n_D}\right)^{-1} + \left(\frac{C}{n_I}\right)^{-1} \qquad \text{(ratios)}$$

where $\frac{C}{n_T}$ = carrier-to-noise (total)

$\frac{C}{n_U}$ = up-link carrier-to-noise

$\frac{C}{n_D}$ = down-link carrier-to-noise

$\frac{C}{n_I}$ = carrier-to-intermodulation ratio of satellite TWT.

The down-link carrier/noise can be expressed as follows:

$$\frac{C}{N_D} = EIRP_S + G/T - L_p - K - B - B_o$$

where $EIRP_S$ = satellite single carrier saturated radiated power (dBW)

G/T = Receive station figure of merit (dB/°K)

K = Boltzmann's Constant

L_p = Path loss at 12 GHz under fair weather conditions (206.8) dB)

B = Transponder RF bandwidth (MHz)

B_o = Output back-off of TWT relative to single carrier saturation

$$\therefore \quad \frac{C}{N_D} = EIRP_S + G/T - B - B_o + 21.8 \text{ dB}$$

The up-link carrier/noise is controlled by the earth station transmit EIRP plus the receive figure of merit of the satellite $(G/T)_{sat}$. It is often the practice in the design of FDM/FM/FDMA systems to make the up-path carrier/noise such that it will only produce a small degradation to the total carrier/noise of the link. In the optimization performed here, the up-link carrier/noise was set at ten dB higher than the down-link carrier/noise *at the system operating point* defined as the optimum satellite TWT back-off point.

The optimization procedure is also dependent upon the type of satellite transponder that is employed. (i.e. variable gain or fixed gain transponder). The variable gain transponder employs a variable attenuator prior to the input to the TWT to accomplish TWT back-off. By this method, the up-link carrier/noise is not effected by the satellite back-off. On the other hand with the fixed gain design, the satellite input TWT back-off is achieved by reducing the up-path transmit power which correspondingly reduces the up-link carrier/noise. Therefore the variable satellite transponder gain method is more efficient powerwise and hence this method has been assumed in the optimization process.

Since the carrier/intermodulation and the down-path carrier/noise are linear functions of output back-off for output back-off greater than 3 dB as shown in Figure 8-1, there is a fixed relationship between the carrier/intermodulation and down-path carrier/noise at the optimum operating point. This relationship is independent of satellite link parameters such as bandwidth, EIRP and earth station G/T and can be derived as follows.

The total carrier/noise of the satellite link is given by:

$$\left(\frac{c}{n}\right)_T = \frac{1}{\frac{1}{c/n_U} + \frac{1}{c/n_D} + \frac{1}{c/n_I}} = \frac{1}{\frac{1}{u} + \frac{1}{x} + \frac{1}{y}}$$

where $\left(\frac{c}{n}\right)_T$ = total carrier/noise of satellite link.

$\frac{c}{n_U}$ = up-path carrier/noise (=u).

$\frac{c}{n_D}$ = down-path carrier/noise (=x).

$\frac{c}{n_I}$ = carrier/intermodulation noise (=y).

Setting the up-path carrier/noise ten dB better than the down-path carrier/noise so as its contribution is small compared to the total (u = 10x)

$$\left(\frac{c}{n}\right)_T = \frac{1}{\frac{1.1}{x} + \frac{1}{y}} = \frac{xy}{1.1y + x} \qquad (1)$$

The down-path carrier/noise and carrier/intermodulation noise vary linearly with TWT output back-off as shown in figure B-3. This is valid for carrier/intermodulation for output back-off greater than 3 dB as indicated in figure B-1.

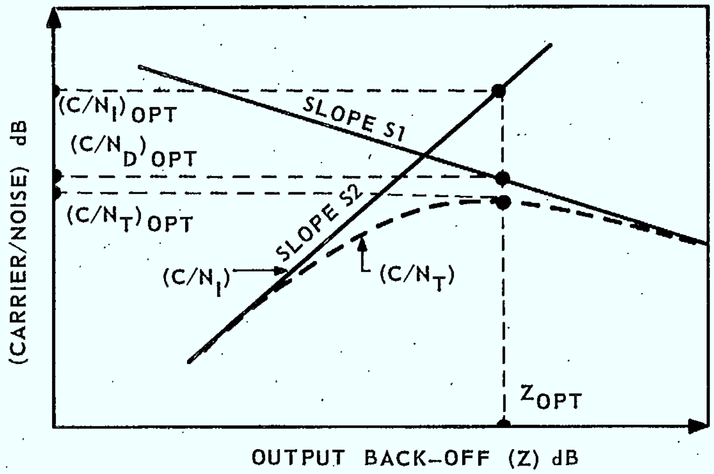

Figure B-2 Trade-off of Carrier/Intermodulation (Y) and Down-Path Carrier/Noise (X)

The down-path carrier/noise can be expressed as:

$$X = K_1 - S_1 Z \qquad \text{(dB)}$$

where S_1 = slope of X versus Z

K_1 = constant

Z = output back-off (dB)

or in ratio expression:-

$$x = k_1 z^{-S_1}. \tag{2}$$

The carrier/intermodulation noise, (Y), can be expressed as:

$$Y = K_2 + S_2 Z \quad \text{dB}$$

where K_2 = constant

S_2 = slope of Y versus Z

or in ratio expression :-

$$y = k_2 z^{S_2}. \tag{3}$$

Substituting equations (2) and (3) into equation (1) and simplifying one obtains:

$$\left(\frac{c}{n}\right)_T = k_1 k_2/(1.1\ k_2 z^{S_2} + k_1 z^{-S_1}) \tag{4}$$

Differentiating equation (4) w.r.t. output back-off, z, and setting the derivative equal to zero to obtain the optimum $(c/n)_T$ versus output back-off one obtains:

$$z_{OPT} = \left(\frac{k_1 S_2}{1.1\ k_2 S_1}\right)^{\frac{1}{S_1 + S_2}} \tag{5}$$

Substituting (5) into (2) and (3) to eliminate z,

$$\left.\begin{aligned} x_{OPT} &= k_1 \left(\frac{k_1 S_2}{1.1\ k_2 S_1}\right)^{-\frac{S_1}{S_1 + S_2}} \\ y_{OPT} &= k_2 \left(\frac{k_1 S_2}{1.1\ k_2 S_1}\right)^{\frac{S_2}{S_1 + S_2}} \end{aligned}\right\} \quad (6)$$

From equation (6), the ratio of y to x is then given by:

$$\left(\frac{c}{n_I}\right)_{OPT} \Big/ \left(\frac{c}{N_D}\right)_{OPT} \triangleq \frac{y_{OPT}}{x_{OPT}} = \frac{S_2}{1.1\ S_1} \quad (7)$$

Thus at the point of optimum $(c/n)_T$, the ratio of $(c/n)_D$ and $(c/n)_I$ is given by a fixed quantity dependent only on the slopes of the two curves.

For the case being considered, $S_1 = 1.0$ and S_2 from figure 1 is 1.4:1 for output back-off greater than 3 dB.

Thus

$$\frac{\left(\frac{c}{n_I}\right)_{OPT}}{\left(\frac{c}{n_D}\right)_{OPT}} = \frac{1.4}{1.1} = 1.27 \quad (8)$$

or

$$\left(\frac{c}{N_I}\right)_{OPT} \simeq \left(\frac{c}{N_D}\right)_{OPT} + 1.0 \text{ dB} \quad (Z > 3 \text{ dB})$$

Thus if one knows the desired $(c/N)_T$ for the satellite link, it is possible by using equations (1) and (8) to obtain the three link parameters for the optimum operating point, namely $(c/N)_U$, $(c/N)_D$ and $(c/N)_I$.

* * *

APPENDIX C

LAUNCH VEHICLES

C.1 THOR-DELTA RANGE

a) Nomenclature

The Delta range of launch vehicles is now identified by a three or four digit series of numbers. These numbers are generated as follows:

Three digit series:

3	-	-	Standard long-tank Thor with 3 to 9 Castor II strap-ons.
6	-	-	
9	-	-	
-	0	-	Second stage 65-inch fairing
-	-	0	No third stage
-	-	2	FW-4 motor third stage
-	-	3	TE-364-3 third stage
-	-	4	TE-364-4 third stage

Four digit series:

1	-	-	-	Extended long-tank Thor
2	-	-	-	Extended long-tank Thor (H-1 engine)
-	3	-	-	Number of Castor II strap-ons
-	6	-	-	
-	9	-	-	
-	-	0	-	Second stage 65-inch fairing
-	-	1	-	Second stage 8-foot fairing
-	-	-	0	As for 3-digit series
-	-	-	2	
-	-	-	3	
-	-	-	4	

b) Payload Capability

For payload injection into a 28.5° synchronous transfer orbit it is the intention to increase the capability of the Delta range of vehicles in accordance with the following table[1].

Recent discussions with NASA indicate that the 1977 estimate is somewhat conservative and an increase of 10 to 20 percent in this figure would not be unreasonable.

YEAR	USEFUL LOAD IN TRANSFER ORBIT (lb)
1970	1,000
1971	1,000
1972	1,400
1973	1,500
1974	1,700
1976	2,000
1977	2,000 (2,400)

Discussions with McDonnell-Douglas[2] indicate that the capability of the Thor-Delta vehicle may be increased up to at least 2,400 lb in transfer orbit with only a modest increase in vehicle costs.

This increase has not yet been funded and it would be unwise to assume its availability[3] although there appears to be no technical reason why this capability should not be attained by 1977. In addition to this capability for increasing the maximum payload, the capability will also be maintained to launch payloads at the lower end of the scale.

The current estimated cost for the launch of a Thor-Delta 2914 in the 1973 through 1974 time frame is $5.6M. This includes all services associated with the launch, but does not include range costs of approximately $1M. These range costs are presently being re-negotiated with the USAF and the outcome of these negotiations may be to slightly increase the launch costs. NASA expect that the total cost for the launch of the Delta 2914 would, in general, decrease with time so that by 1977 it is estimated at $5.0M. This decrease in costs is an attempt to compete with the space shuttle which will begin operational flights in 1978 through 1979.

To the above-mentioned launch costs must be added additional amounts to cover any special development required in connection with the integration of the spacecraft with the launch vehicle. For launches of the Delta 2914 in 1973 through 1974, total launch costs of $7.3M are typical. Based on the information currently available it appears reasonable to assumed a total launch cost of $7.5M in 1977 through 1978 as a basis for preliminary system design.

C.2 ATLAS-CENTAUR

At the present time this vehicle has the capability to launch into synchronous orbit payloads of the order of 1200 lb (Intelsat IV class). By 1974 the capability will have increased to 1600 lb and by 1977 to a maximum of 2100 lb, although 2000 lb is a reasonable upper limit[3]. The expected total launch costs in 1977 are expected to be in the order of $17M.

An increase in payload of about 200 lb could be achieved if the Titan III B was used as a first-stage instead of the Atlas. This would increase the launch cost somewhat and would probably not be an economic solution.

The Atlas-Centaur could be used to launch smaller payloads than the maximum, but the launch costs would not be reduced as there is no capability in this vehicle to obtain reduced performance for reduced cost as in the Thor-Delta range (strap-ons).

C.3 TITAN III C

The present capability of this vehicle is to launch payloads of the order of 2900 lb direct into synchronous orbit. This means that the spacecraft needs no apogee motor and the proportion of its weight normally taken up by this motor and its fuel is available for spacecraft hardware relevant to the communications mission. However, the estimated launch cost for this vehicle is about $25M.

C.4 OTHER VEHICLES

There are other feasible launch vehicle combinations which may become available and economic by 1977. One such possibility is the Atlas/TE 364-4 which is a combination of the Atlas first-stage with the third-stage normally used with the Delta series. NASA considers this to be a feasible launch vehicle providing capabilities equivalent to those of the Delta series. As yet it has not flown, nor are they able to estimate costs at this time.

C.5 SPACE SHUTTLE PROGRAM

There appear to be conflicting opinions concerning the usefulness of the space shuttle, but the current view indicates that an experimental vehicle will be flown in 1976 or 1977 and the first operational flight will probably be at the end of 1979. This vehicle, when operational, is intended to replace all launch vehicles larger than the Scout and smaller than the Saturn V. This view is shared by the U.S. Department of Defense which also intends to phase out other launch vehicles. In the early stages of the program the capability of the shuttle will be to carry 60,000 lb payload from an eastern test range on a due east launch into a 100 nautical mile circular orbit. Each vehicle is designed for 100 missions with some maintenance and refurbishing between flights. A fleet size of four vehicles is envisaged and the total number of flights per year would probably be in the range of 30 through 40. This would mean that launch capability would be available more or less on demand. The cost per flight is expected to lie in the range 3 through 9 million dollars with 5 million dollars as a current target. This would include between flight maintenance, crew and support costs. Each shuttle flight will carry a number of different payloads probably for different authorities and for different missions. This is expected to lead to problems in scheduling the different programs for the different missions. The costs of the flight would probably be prorated among the different payloads for the flight.

A study has been undertaken to assess the various requirements for the missions which would probably use the shuttle service. The conclusions of this study are that approximately 73 percent of the spacecraft to be launched by the shuttle would require additional stages to carry them from the final shuttle orbit to their final destination orbit. This applies particularly to communications satellites in synchronous orbits. In order to provide this added capability it is intended to develop a space tug which would be capable in the initial stages of the program of carrying approximately 10,000 lb payload from the initial shuttle parking orbit to synchronous orbit. This tug will also be capable of recovering payloads from synchronous orbit and returning them to the parking orbit.

Due to economic reasons the development of the tug has been dropped from the NASA program. It is proposed that some international cooperation will be possible in this area and it is likely that the tug development could be done outside the USA. The time taken to organize such a venture will mean that the tug program will be approximately 3 years behind the development of the shuttle itself and during this time it will be necessary to provide, for synchronous satellites, a means of propulsion from parking to synchronous orbit. Typically this could be the Centaur vehicle which would have to be carried in the shuttle, together with its payload, to parking orbit. Using this method the shuttle program will not be so cost effective in the early stages due to the fact that the extra booster required to achieve synchronous orbit will not be recoverable as would the tug which would be developed later. Also, the fact that additional boosters must be carried in the shuttle means that the available space of 60 feet by 15 feet would not be completely available for carrying useful payload.

It is expected that the shuttle program will have a number of effects on communication satellite technology. From the reliability point of view the shuttle environment will probably be more benign than conventional launch vehicles and, in particular, vibration levels would probably be relaxed. However, in the early stages of the operational program the acceleration levels will probably remain unchanged because the space tug will not be available and conventional vehicles such as the Centaur will be required to achieve synchronous orbit. However, the opinion has been expressed that money spent on reliability in spacecraft has always paid off in the long run. Eventually, when the space tug becomes available, it is not planned that people will be carried to synchronous orbit for the purpose of repairing satellites. It would therefore be necessary for units to be changed by tele-operated robots and the design of satellites to allow this to be possible would most likely increase their weight, cost and complexity.

Because the cost per pound of launching satellites will drop considerably, this would mean that weight restrictions on communication satellites could be relaxed. This would probably remove the requirement for satellite structures to be made from titanium or other lightweight materials. On the other hand, any relaxing of weight restrictions could allow more complex satellites. The overall view therefore is that the shuttle program will have little effect on satellite reliability, at least in the early stages.

With regard to launch costs by the shuttle, these are expected to fall to approximately one tenth of the current range in the early stages of the program. When the space tug becomes operational the cost per pound into synchronous orbit could fall as low as $100. These costs of course would depend upon the number of different missions carried in the shuttle and the way in which the launch costs would be prorated.

C.6 LAUNCH VEHICLE RELIABILITY

The record of launches successfully completed by NASA since 1960 is tabulated below:

YEAR	TOTAL LAUNCHES	SUCCESSES	FAILURES	% SUCCESS
1960	6	4	2	67
1961	9	5	4	56
1962	26	20	6	77
1963	17	13	4	77
1964	26	22	4	85
1965	20	18	2	90
1966	28	27	1	97
1967	32	29	3	91
1968	20	17	3	85
1969	18	16	2	89
1970	16	13	3	81

From these figures it would appear that an 80 percent success probability would be conservative and 90 percent would be somewhat optimistic. These figures are for all classes of vehicle, however, and may not be representative of the probabilities of individual vehicle types. For example, considering the Thor-Delta since the first launch in 1960, 78 successful launches have occurred out of a total of 84 attempts - a success of 93 percent.

In the four U.S. domestic system proposals considered, different approaches to the probability of launch success are evident. Some proposals set up a launch failure reserve (the estimated cost of insuring against launch vehicle failure) and some include the cost of a spare launch vehicle as a backup for the first two launches.

REFERENCES

1. McDonnell-Douglas Astronauts Company; Delta Launch History - 1960 through March 1971.

2. McDonnell-Douglas; Private Communication.

3. NASA; Private Communication.

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