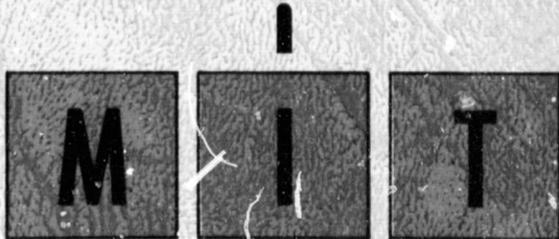# N O T I C E

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FUTURE LARGE BROADBAND
SWITCHED SATELLITE COMMUNICATIONS NETWORKS

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FUTURE LARGE BROADBAND

SWITCHED SATELLITE COMMUNICATIONS NETWORKS

FINAL TECHNICAL REPORT
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ABSTRACT

Future Large Broadband Switched Satellite Communications Networks

This report summarizes critical technical, market, and policy issues relevant to future large broadband switched satellite networks. Four market projections for the period 1980-2000 are compared; they yield estimates of $\sim$ 10-100 Gbps domestic satellite traffic for the United States. A new concept for clusters of switched satellites, in lieu of large platforms, etc., is shown to have some significant advantages. Analysis of an optimum terrestrial network architecture suggests the proper densities of ground stations and that link reliabilities $\gtrsim$ 99.99% may entail less than a 10 percent cost premium for diversity protection at 20/30 GHz, a result highly favorable to utilization of this band. These analyses also suggest that system costs increase as the $\sim$ 0.6 power of traffic, thus favoring consortia which obtain economies of scale. Cost estimates for nominal 20/30 GHz satellite and ground facilities based on projected 1985 technology suggest optimum system configurations might employ satellites with $\sim$ 285 beams, multiple TDMA bands each carrying $\sim$ 256 Mbps, and $\sim$ 16-ft ground station antennas. The resultant low systems costs favor significant use of satellites and the growth of new services such as full-motion video conferencing. A review of policy issues suggests that current changes in this area could impact the full benefits ultimately received from these new technologies. NASA's new initiatives in this area could be quite helpful and a nominal development program is outlined.

D. H. Staelin
R. L. Harvey
December, 1979

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PREFACE

This report summarizes the results of a study which began under NASA sponsorship in August, 1978. The purpose of the study was to explore alternate approaches to establishment of possible future large wideband satellite communications networks, and to identify technologies that may be critical and require additional development. The report is intended to support NASA's definition of its revitalized communications satellite research program.

Because development programs should reflect constraints imposed by the marketplace, technology, and issues of public policy, all three of these aspects were surveyed and integrated in this report. Although the wide scope of this effort did not permit complete discussions of most topics, we did touch upon several critical issues, a few of which are explored here in greater depth than is generally available elsewhere.

The market survey in Chapter 2 is unique primarily in its summary of several recent studies in the public domain, and in its projections of future domestic telecommunications and satellite traffic. Unfortunately certain other major surveys are not publicly available. The network issues described in Chapter 3 are intended primarily to stimulate further discussion and analyses; the optimum densities of ground stations, the proper market share for satellites, the true costs of site diversity to combat rain-induced outages at 20/30 GHz, and the advantages of clusters of switched satellites are examples of interesting questions considered here which deserve further attention.

In Chapters 4, 5, and 6 a particular 20/30 GHz satellite communications system is analyzed and the relevant technologies and costs are surveyed and extrapolated to the 1980-1990 time period. Although the report focuses on a particular "baseline" design, the analysis, with modest revisions, is relevant to a wide range of system variations. Chapter 7 summarizes the results of these baseline studies and shows how the baseline specifications could be altered slightly to further reduce and optimize system costs. Because these chapters present detailed costs, it should be possible for readers to alter various assumptions and to trace the consequences. Another result of interest is the "economy of scale" estimate derived from these analyses.

In Chapter 8 certain historical, economic, and regulatory issues are surveyed briefly, with emphasis on issues which impact technological change and satellite communications systems. Chapter 9 concludes the report by suggesting some of the technological challenges NASA might most usefully address.

For the most part, the principal author for Chapters 4 and 5 was Robert Harvey, and the principal author for the other chapters was David Staelin.

Because of the ambitiousness of this study, there are undoubtedly some errors, and some assumptions which could be revised. We would welcome correspondence and will attempt to incorporate any improvements in future reports on this subject.

In this effort we have been very fortunate in being able to draw upon the expertise of a large number of people -- too many to properly credit here. The most intense effort was contributed contractually by personnel at the M.I.T. Lincoln Laboratory, where the baseline spacecraft and ground station designs were analyzed. In addition to these contributors, acknowledged at the ends of Chapters 4 and 5, we should particularly like to thank Walter Morrow, Donald MacLellan, and Charles Niessen who were instrumental during the definition phases of the project.

The public policy questions are more intangible, and the guidance and critical comments of Ithiel Pool, Wilbur Davenport, John Harrington, Charles Jackson, Roger Noll, Delbert Smith, Edward Zajac, and Thomas Zimmer were particularly helpful. Because of the continual editorial process, the final version of the policy discussion was not fully reviewed, and the author (DHS) must take full responsibility for any remaining imperfections.

The market survey drew heavily from the parallel NASA contractual efforts undertaken by Western Union and the International Telephone and Telegraph Company. In addition, Michael Tyler provided further valuable information and useful appraisals and perspectives.

During the course of the study we also benefitted greatly from group discussions held at various locations. We particularly wish to thank the organizers of these sessions, including Donald Dement and John McElroy at

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December 12, 1979

CHAPTER 1

EXECUTIVE SUMMARY

1.1 INTRODUCTION

This report summarizes the results of a NASA-sponsored study of the critical technical, market, and policy issues relevant to the future development of large broadband switched satellite networks for domestic communications. The study was particularly intended to support the definition of appropriate NASA new-technology initiatives for its revitalized communications research program. Although a few issues were explored in some depth, the report is general and intended to serve as a useful reference for future workers who will be able to revise our various assumptions and test their impact on our conclusions. The arguments have been presented in sufficient detail that such revisions should be straightforward.

The report first surveys several market studies which suggest that during the period 1980-2000 domestic satellite capacity will grow to ~10-100 Gbps, and that voice will probably remain the dominant service. Consideration of general network architectural issues combined with an analysis of a particular baseline design for a 20/30 GHz satellite net-work led to cost estimates that are quite attractive for the expansion of new broadband services and satellite voice circuits. The same analysis suggests the character of nearly optimum network architectures in both the nascent and fully developed phases. A review of relevant national issues suggests that there are no intrinsic barriers to the establishment of such large systems, but that much may depend upon the outcome of current debates. It is clear that NASA's involvement could be very beneficial, and a normal spaceflight and technology development program is outlined.

1.2 MARKET ISSUES

Market studies by ITT, Western Union (WU), Xerox, and the Conference on European Posts and Telecommunications (CEPT) all suggest rapid growth in both broadband and satellite traffic. The ITT and WU studies suggest

growth in domestic satellite traffic capacity to ~25-125 Gbps by the year 2000; the Xerox study projects a growth in non-voice service to ~1.4 Gbps by 1990, which becomes 14 Gbps if the 66-kbps video circuits are replaced by 3-Mbps circuits; and the CEPT study suggests that video-conferences might substitute for ~1.7 to 10 percent of meetings requiring travel as the price varies from a couple of dollars per minute to negligible values, a range (in Gbps) which rivals voice traffic, even with video compression to 3 Mbps.

The ITT and WU studies projected the market share of long-lines traffic allocated to satellites on the basis of relative per-circuit-mile costs. This analysis was repeated here with the fixed and variable costs separately identified for each modality, an approach which suggests that satellites may also capture some shorter thin routes and lose to optical fibers or microwaves some long heavy routes.

The most controversial estimates involve videoconferences and related services, primarily because they are the most novel and involve the most uncertain technology and economics. The potentially low costs projected in this study for compressed full-motion video suggest that serious attention should be given to the possibility that video services could become areas of major growth in the late 1980's and perhaps eventually equal the total satellite bandwidth allocated to voice.

1.3 NETWORK ARCHITECTURE AND ECONOMICS

In optimizing the network architecture, attention was given to the efficiency with which each of the economic elements was utilized; these include the satellites, ground stations, transponders, subsystems comprising the satellite and ground stations, and the links connecting the ground stations to the users. For example, satellite efficiency can be maximized by launching several similar switched satellites sequentially into the same orbital slot as required to share the growing load. Thus, instead of large space platforms or a cluster of satellites served by a single switch, there would be a cluster of individually switched satellites which would share the total load and could communicate if necessary. Other virtues of this approach include improved reliability, ease of modernization, and ease of interconnectivity with multiple ownership.

Ground stations and user links are efficiently utilized if no terrestrial link connecting satellite traffic from one local hub to another is more expensive than the basic costs of a ground station which could alternatively serve the first hub. This implies that the optimum number of ground stations in a region is proportional to the 2/3 power of regional traffic, and that it also depends upon the minimum fixed cost of each ground station and the cost-per-circuit-mile of the terrestrial alternative. Typical cost and traffic estimates suggest that there should be ∿1000-2000 ground stations in the United States network, and that spacings between them might vary from ∿3 miles in large cities to ∿60 miles in typical rural areas; this is roughly comparable to the distribution of existing toll centers. The same analysis suggests that the additional cost of diversity protection to achieve 99.9% link reliability at 20/30 GHz should be less than ∿10 percent of the cost for the satellite/ground-station system, which is highly favorable for use of the 20/30 GHz bands for these purposes.

Because of the large number of ground stations it is economically desirable to have a large satellite antenna, which implies many beams. Because satellite transponders are expensive and few, it is necessary to efficiently distribute this communication capacity over the beams by flexible TDMA switching schemes, the two most promising of which are the switched-feed configuration proposed here (also Staelin and Harvey, 1979) and a similar segmented scanning array scheme proposed by Acampora et al. (1979); the former becomes increasingly attractive as the satellite capacity increases. Thus the satellite switching function would be split into an r.f. portion which couples the antenna to the transponders, and a baseband portion which interconnects the transponders.

In order to determine the appropriate tradeoffs between antenna gains, transmitter powers, data rates, etc. a baseline design was analyzed and costed, and the results were then used to determine a more nearly optimum system for handling ∿10-60 Gbps. Figure 1-1 characterizes the form of the optimized network and Table 1-1 summarizes the set of system parameters which appear to yield minimum total costs assuming 1985 technology were utilized. Because of the many assumptions necessary in such an analysis, the true optimum parameters may vary a factor of two from these, but deviations by more than a factor of three would be unexpected without a correspondingly significant change in network topology or assumptions.

SINGLE ORBITAL SLOT,
2-6 SATELLITES

PER 18/30 GHz SATELLITE:

- 25 × 2 TRANSPONDERS
  @ 256 Mbps = 12.8 Gbps

- 4-7 W TRANSMITTERS

- 2 4×6-M APERTURES,
  285 BEAMS TOTAL

- FAST BASEBAND SWITCH;
  NO MEMORY

TDMA IN 12 FDMA BANDS (2.6 GHz)
×2 POL. = 6 Gbps MAX PER BEAM

≤ 6 Gbps IN NEW YORK BEAM IMPLIES
≳ 60 Gbps FOR UNIFORM SYSTEM

LIMITED
COMMUNICATIONS

ACCESS
BLOCKS (16 Kb)

200-BIT
HEADERS

4.16
msec

80 CH. @ 3 Mbps
EQUIVALENT
PER BAND

COMMAND
& CONTROL

MICROWAVE
FIBERS
COAX
OPTICS
WIRES

TERRESTRIAL LONG-LINES NETWORK

GROUND STATIONS

~16 FT. ANTENNAS
7W FOR 1-2 BANDS IMPLIES ~ 10-15 dB RAIN MARGIN
CODING, CRYPTOGRAPHY, BANDWIDTH COMPRESSION
~1800 GROUND STATIONS, CARRIER OWNED AND OPERATED

USER FACILITIES

○ VIDEO
DATA
DOCUMENTS
FACSIMILE
VOICE

Figure 1-1. Nominal optimized network architecture assuming 30 Gbps
domestic traffic for the United States, 20/30 GHz links,
monolithic architecture, and 1985 technology.

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Table 1-1. Optimized System Parameters.

ASSUMPTIONS:

1. Satellite traffic of $\sim$ 30 Gbps; full U.S. coverage, all services.

2. 1985 technology; 20/30 GHz; monolithic architecture.

SYSTEM PARAMETERS:

1. 3-6 similar fully-switched satellites share one orbital slot.

2. $\sim$ 1500 ground stations, $\sim$ ½ rural, typically near existing toll centers.

3. Terrestrial links between ground stations provide diversity protection and 99.99% reliability.

4. Multiple FDMA TDMA bands, each at 256 Mbps, are synchronized and assigned so that memoryless digital switching occurs in space without inter-satellite traffic.

5. Bit-error-rate $\leq 10^{-7}$; QPSK/TFM modulation; 12 210-MHz bands in 2.6-GHz allocation, in each polarization; 240 TDMA cycles/sec.

6. Satellite has $\sim$ 4-7 watt transmitters, 800°K T_{sys} superheterodyne receivers, and a 285-beam antenna simultaneously activating $\sim$ 12-50 independent switched beams that address limited but overlapping service areas.

7. Ground stations typically have 16-ft antennas, 7-watt transmitters, 500°K T_{sys} receivers, dual-redundant 256-Mbps electronics, and assorted error-correction coding, crypto-graphic, and bandwidth-compression circuits.

8. Broadband user links of 256 kbps-128 Mbps capacity would be $\sim$ 0-7 miles long in cities and $\sim$ 0-30 miles in rural areas.

The total investment required (1979$) for the system described in Table 1-1 is suggested in Fig. 1-2. Since 1985 technology is assumed, there is no allowance for nonrecurring costs incurred prior to then, some of which would be borne by NASA.

Network Investment
(Revised Baseline System)
Total = $1.6B

Network plus User-Facilities
Investments
Total = $4.6B
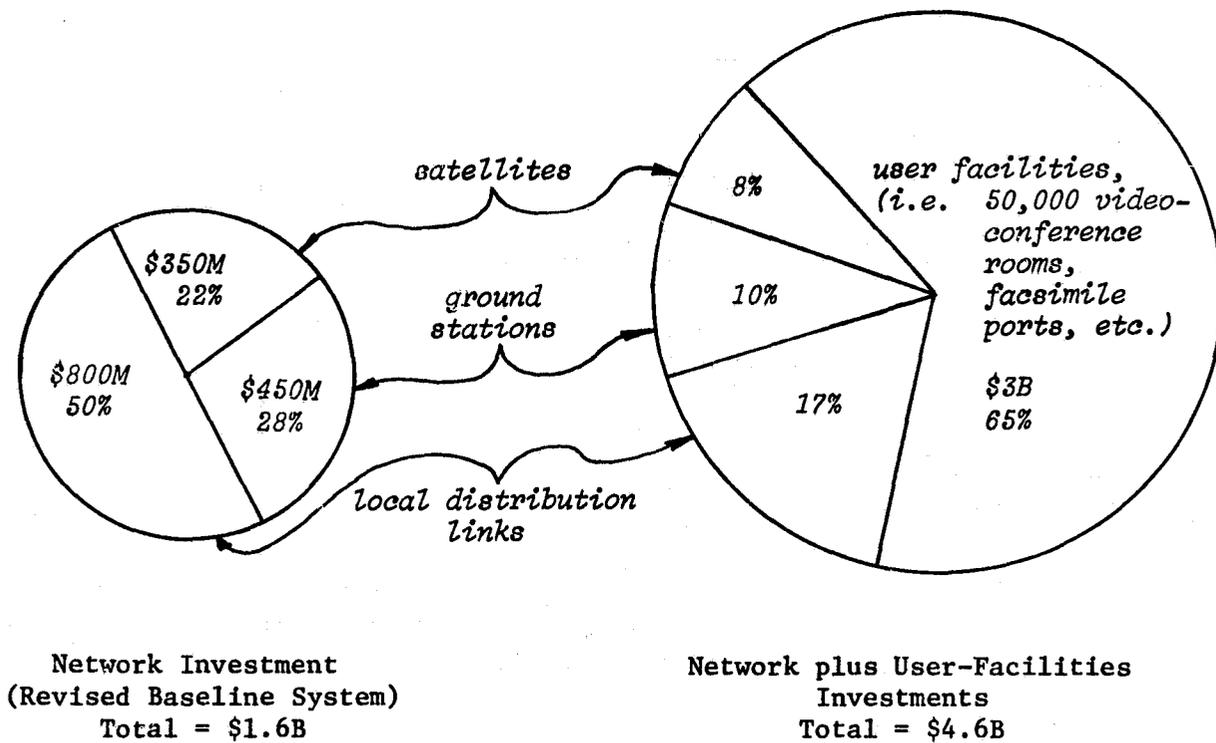
Figure 1-2. Allocation of system investments.

The important conclusion is that local links may dominate network costs, and that user facilities may dominate service costs. Although these estimates assumed video-conference and fast facsimile terminals dominated user facilities, even voice equipment capable of generating 30 Gbps would be expensive (perhaps 10 million telephones plus electronics).

Annual tariffs designed to cover these costs might be ∿$40,000 for a typical dedicated one-way 3-Mbps link user-to-user, and ∿$20,000 for a similar link which is nearly unused (half the investment is in user links). If multiplexing costs were zero, then a dedicated 60-kbps circuit might cost ∿$900 per year, depending largely upon the pricing of the particular local links serving the users. Non-dedicated links would be cheaper. The price for a one-way 3-Mbps video conference might be 63¢ per minute plus $2000 per month, which is sufficiently low to stimulate considerable usage. All these numbers are more than an order of magnitude less than present tariffs and almost certain to cause full-motion video to prevail over most freeze-frame services.

The above costs and tariffs are based on 30-Gbps system capacity, but other system sizes can be evaluated because total costs are approximately proportional to the 0.6 power of total traffic. This estimate, combined with the market-share calculations based upon the relative costs of terrestrial and satellite circuits, suggests that a system which would be profitable on a large scale should be even more profitable on a smaller scale because then the market is more nearly "cream," whereas the costs vary relatively slowly with size. This dependence of costs upon system size also provides an incentive for small competitors to jointly own or share certain network resources if they are to compete successfully or perhaps even survive; such sharing might involve ground stations and satellites, but need not include local links, user facilities, or other communications services, which together totally dominate costs.

1.4 POLICY ISSUES

Regulatory control in the telecommunications industry has been exercised to varying degrees over market entry, market exit, tariffs, corporate structure, and various other technical and market decisions. Such control originated because of the pervasive and essential role of telecommunications in our society and because of historical monopolistic tendencies in the industry arising partly from economies of scale and the need for interconnectivity in certain business segments.

Regulation in the United States has been guided largely by the Communications Act of 1934, which had antecedents in still simpler times, and which is now possibly being revised. The FCC has recently exercised its authority under that Act to introduce more competition into the industry. In a series of events, including the Carterphone, Execunet, and the Resale and Shared-Use decisions, the interconnect and private-line markets have become increasingly competitive, and this process is beginning to impact even standard MTS long-distance services.

Much of the effort to introduce competition has centered on reducing AT&T's ability to cross-subsidize or compete in certain markets. The acceptance of fully-distributed-cost (FDC) accounting principles, the early restrictions on AT&T's ownership of certain satellites and on the marketing of certain information services (under the 1956 Consent Decree), and the current debate concerning the possible forced restructuring of the company are characteristic of this controversy.

These debates will influence the growth of satellite communications in various ways. Although competition can stimulate the introduction of economic technologies such as communication satellites (which can be even more competitive with terrestrial links on long thin routes than on heavy ones, and can therefore appeal more to small carriers), the present regulatory and legal uncertainty in the marketplace has a depressing effect on such long-term investments by focusing attention on short-term returns on investment and on risk limitation.

Economic factors will almost certainly stimulate the use of large switched satellites singly and/or in clusters as traffic grows. Policy issues will be more critical, however, in determining whether various competitors will adopt efficient protocols for interconnecting these networks, perhaps through the sharing of switched-satellite clusters. Development of common protocols for efficient interconnection of networks and services will almost certainly be critically important to achievement of the full potential of modern telecommunications technology, but it is one of the most uncertain aspects of the present regulatory situation.

Although the system architect to date has principally been AT&T, there is no clear replacement emerging in the newly competitive markets, and the ability of hostile competitors to produce an efficient integrated architecture remains to be demonstrated, as does the ability of any government agent, such as the FCC, to accomplish the same objective. Such architectural issues arise, for example, in definition of protocols for TDMA signals, cryptography, command and control signals, video bandwidth compression, etc. If the evolving federal policies are to be maximally productive, they must provide a good solution to this problem. This problem is also manifest on an international scale, where the protocols and connectivity of domestic and international satellite systems are issues.

One of the most difficult policy issues is how the nascent broadband services will be tariffed; will prices tend to be somewhat independent of circuit bandwidth, or more nearly proportional to it? Technical arguments ultimately favor the former, and present policies favor the latter. The basic problem is that cheap broadband circuits could be multiplexed by competitors who might then underprice the narrowband tariffs. These narrowband tariffs must now support today's costs plus some operating costs and depreciation charges associated with certain obsolete equipment. Part

of the obsolete-equipment problem apparently arose because depreciation charges under regulation have tended to reflect the physical rather than the technological life of assets; some depressed tariffs earned previously should now be compensated by increases—will AT&T shareholders or the public pay? The issue is presently unresolved and may never be addressed directly. To summarize, the health of broadband services, particularly of full-motion video conferencing, will require low broadband tariffs, and many policy tools exist (such as market and tariff controls) to achieve them; the question is whether those tools will be used.

1.5 NASA PROGRAM OPTIONS

There clearly is an important future global role for large switched communications satellites of the type considered here, because the cost advantages of satellites for long-haul circuits are so significant. Because regulatory uncertainties and other factors have curtailed long-range high-risk investments necessary in this area, and because of the national benefits in proceeding expeditiously, several national groups have recommended NASA's re-entry into development of basic communications satellite technology.

The presently proposed 20/30 GHz technology program appears well conceived to achieve the major goals proposed by the various advisory groups, and the optimum system parameters proposed here should provide good guidelines for specification of that program. One additional architectural option which deserves attention is that of a pure FDM system designed to increase power efficiencies, and therefore reduce ground station costs to much lower levels. The technical challenge is significant, however.

Another area which may deserve increased emphasis is that of protocol compatibility. Some of the most profound decisions made in the establishment of pervasive new broadband services will be those which fix protocols for services such as inter-frame video bandwidth compression, facsimile, etc. In today's competitive environment a variety of technologies and options will emerge, and promotion and demonstration of technologies designed to enhance compatibility between present protocols and future improvements and requirements could constitute a major contribution to the ultimate public utility of these new developments.

To summarize, there is significant potential for major growth in satellite communications, and NASA's historic role in promoting the relevant technologies could be of critical national value.

Chapter 1   References

1. Acampora, A. S., C. Dragonne, and D. O. Reudink, A satellite system with limited-scan spot beams, IEEE Trans. Comm., COM-27, 10, pp. 1406-1415, 1979.

2. Staelin, D. H. and R. L. Harvey, Architectures and economics for pervasive broadband satellite networks, ICC'79 Conf. Rec., 2, June 1979 (79CH1435-7CSCB), pp. 35.4.1-35.4.7.

CHAPTER 2

FUTURE UNITED STATES MARKET FOR TELECOMMUNICATIONS SERVICES

2.1 INTRODUCTION

This chapter summarizes published estimates of the future growth in domestic long-distance telecommunications traffic together with estimates of that fraction which might be allocated to satellites. These projected demands for services are the primary design constraints which shape the architecture and economics of the advanced satellite communications systems analyzed later in this report.

In Section 2.2 various traffic projections are summarized, and in Section 2.3 the particular case of video services is examined further because of its uncertain but potentially large impact on traffic projections. Section 2.4 summarizes briefly the international market for communications satellites and international competition. The remainder of this introduction summarizes briefly some of the very important motives for continued expansion of telecommunications capabilities.

The two primary motives for significantly expanded communications capabilities are improved national productivity and improved quality of life.

The productivity of the 15-20 million information workers in the United States has been estimated to be reduced by as much as 30 percent due to missed information and inferior or needlessly duplicated solutions to problems. Instant business mail, convenient video-conferencing, and shared computers and data bases could all improve business productivity considerably. For example, personal travel and slow distribution of mail can introduce costly delays or inhibit desirable contacts. Perhaps more important is the extent to which even our present communications and productivity could be impaired by future energy shortages and diminished transportation. Since even a one percent change in national productivity represents billions of dollars, the incentives are enormous.

Improvements in the quality of life due to broadband communications would probably be greatest in rural areas; the result would be de-urbanization

and expansion of rural suburbs. Benefits could follow, for example, from increased use of teleconsultation in medicine, increased video-conference education and job training programs, improved contact between distant friends and relatives, and the increased rural distribution of information-intensive businesses and government organizations. The cultural importance of these changes could ultimately rival those of the automobile.

2.2 TRAFFIC PROJECTIONS

2.2.1 UPPER LIMITS TO TRAFFIC GROWTH

Before reviewing the estimates of traffic growth presented in Section 2.2.2, it is useful to estimate those upper limits on traffic placed by the finite intellectual capacity of a population to generate useful information. These simple limits also provide a more intuitive understanding of the relative traffic associated with the various services. The four general classes of service, in order of increasing traffic potential, are data, facsimile, voice, and video.

These upper bounds to United States long-distance (over $\sim$30 miles) traffic potential are summarized in Table 2-1. The data, voice, and facsimile services were assumed to involve most future information sector employees as potential generators of traffic, approximately 50 million people.

Table 2-1. Assumed Upper Bounds to United States
Long-Distance Telecommunications Traffic

Service	Assumed Limits	Bits/year	Peak rate (Gbps)
Data	50×10^6 employees 50 pages/day @ 5×10^4 bits/page peak rate = 2.5 x 40 hr/wk average	2×10^{16}	7
Facsimile	50×10^6 employees 50 pages/day @ 10^6 bits/page peak rate = average rate	5×10^{17}	15
Long-distance Voice	50×10^6 employees 8 hr/wk @ 30 kbps peak rate = 2.5 x 40 hr/wk average	2×10^{18}*	700
Video	10×10^6 employees 1 hr/wk @ 3 Mbps peak rate = 2.5 x 40 hr/wk average	5×10^{18}	1900

*This is $\sim$10 times the actual 1978 equivalent traffic (30 kbps circuits).

An average of only one long-distance recipient is assumed, although local distribution of traffic could increase the number of message recipients. Video is assumed to involve fewer people, perhaps 10 million. The data rates of 30 kbps and 3 Mbps assumed for voice and video services reflect a modest amount of compression, appropriate for large traffic levels. Facsimile is assumed to be a deferred service for which the peak transmission rate approximates the average rate, whereas the other three services are assumed to occur predominately during a 40-hour work week, with a peak rate arbitrarily equal to 2.5 times the average rate during that 40-hour period. Although these approximations are crude, they do suggest the relative traffic potential of the various services if price or availability were not factors.

The principal conclusion is that data and facsimile communications involving people or text are comparable with each other, but are dwarfed by voice, particularly since present voice traffic is already within an order of magnitude of its limit. The only service capable of surpassing voice is video, but this would require extensive acceptance of video by most organizations now possessing telephones. As discussed later, these upper limits for voice and video could be fully accommodated by satellites only with very great difficulty; terrestrial links would be required for much of it, although satellites could easily handle the maximum level of data and facsimile traffic.

One other service deserves notice, computer-to-computer data traffic. It is sufficiently unpredictable that it is not considered here. It is unlikely to surpass the other services, however, because economics would tend to encourage duplication and one-time transmission of data or software instead of repeated computer access from distant locations. Since most software and data bases are compatible with human intellect, the data and facsimile limits are appropriate.

2.2.2 SURVEY OF TRAFFIC PROJECTIONS

2.2.2.1 Western Union Projections

In the summer of 1979 Western Union (1979) presented the results of a demand assessment study they performed under contract to the National Aeronautics and Space Administration as part of the NASA satellite communications program in the Office of Applications. In this section some of the

relevant highlights of that study are summarized. They first developed
estimates for total long-distance terrestrial and satellite traffic for
voice, data, and video services, where data includes facsimile, etc. These
estimates are primarily extrapolations of present growth trends. One set
of estimates was intended to be conservative, the "baseline market forecast",
and the second set, the "impacted baseline forecast", required speculation
about the uncertain effects of regulation, competition, price elasticity,
technology, etc. These are presented in Table 2-2.

Table 2-2. Western Union Traffic Forecasts

Services	Units of Volume	Baseline Market Forecast			Impacted Baseline Forecast		
		1980	1990	2000	1980	1990	2000
Voice	Half circuits (thousands)	3063	7661	10990	3068	8050	20371
Data	Terabits/year (10^{12} bpy)	1670	8883	34813	1678	10559	42834
Video	Wideband channels	176	267	341	176	294	458

They further divided these projections by service classification. In
1990 they anticipate that voice services will be comprised 38, 32, 29, and
1 percent by private line, public MTS, business MTS and miscellaneous ser-
vices, respectively. Data would be divided 69, 25, 3, and 2 percent for
data transmission, electronic mail, electronic funds transfer and point of
sale services, and miscellaneous, respectively. The video channels would be
allocated 35, 31, 18, and 16 percent to video conferences, CATV, network,
and occasional services, with video conferences dominating by the year 2000.
They also estimated the distance distribution of traffic demand for voice
and data, as summarized in Table 2-3.

Table 2-3. Distance Distribution Function for Traffic Demand, 1990

Mileage Band	Percent Traffic in Mileage Band	
	Voice Services	Data Services
41- 150	11.4	7.8
151- 500	28.8	26.9
501-1000	25.7	29.6
1001-2100	24.2	26.0
2101-2700	9.9	9.7
Totals	100%	100%

According to the table, slightly more than one-third the traffic occurs on circuits in the range 1000-2700 miles; this traffic is the set most likely to be transferred to satellite circuits, as discussed in greater detail in Section 3.2.2.

The study then assumed annual costs of approximately $10 per voice-circuit-mile and derived breakpoint distances (see Section 3.2.1) of ∿600 miles for satellite versus terrestrial least-cost routing. The costs per satellite voice circuit were assumed to be ∿$7000, based in part upon parallel NASA studies performed by Ford Aerospace Corporation (1979) and the Hughes Aircraft Company (1979). Such market-share computations were then combined with the previous market estimates for each category of service to yield the total market estimates for satellite communications service, as presented in Figure 2-1. This market is estimated to grow from ∿3 Gbps in 1980 to ∿40 Gbps in the year 2000.

2.2.2.2 ITT U.S. Telephone and Telegraph Corporation Projections

The ITT (1979) Service Demand Assessment, performed for the NASA Lewis Research Center in parallel with the Western Union, Ford and Hughes studies, projected the demands summarized in Table 2-4. The reason their data traffic estimates (Gbps) are so large relative to the other services is that the CPU-to-CPU links are assumed to be utilized inefficiently, which they may be if the cost of communications is small compared to that of computation; computer time typically costs several dollars per minute. Because of this service category the ITT estimates for data traffic are more than ten times those of Western Union. The two video and voice traffic estimates are more nearly comparable, differing by less than a factor of ∿3.

The estimated distance distribution function for traffic demand is listed in Table 2-5.

On the basis of traffic allocation procedures similar to those used by Western Union the amount of traffic which satellites would carry was projected for the 1976-2000 time period, as summarized in Fig. 2-2.
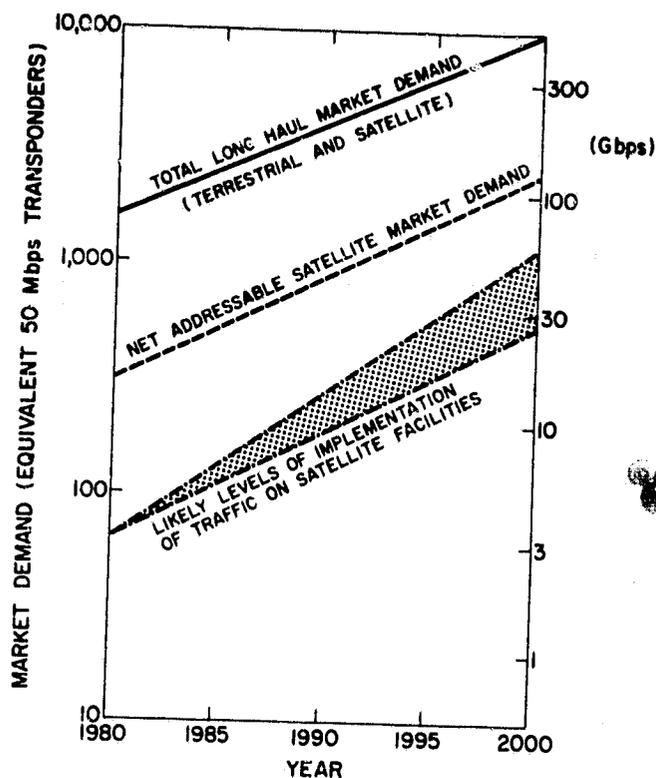
Figure 2-1. Projected demand for satellite capacity to serve the domestic United States market, as estimated by Western Union (1979).
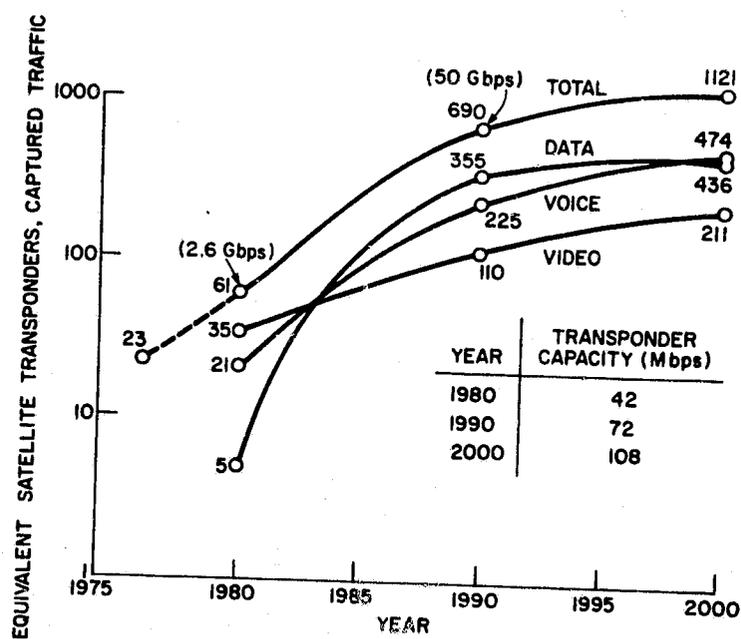
Figure 2-2. Projected demand for satellite capacity to serve the domestic United States market, as estimated by ITT (1979).

Table 2-4.   ITT Traffic Forecasts for Circuits over 200 Miles

Service	Annual Traffic (10^{15} bits)			Peak Demand (Gbps)		
	1980	1990	2000	1980	1990	2000
Voice						
Private Lines	230	605	1440	7	19	46
MTS	169	428	879	14	36	77
WATS	160	369	572	23	53	82
Total Voice	559	1402	2891	44	108	205
Data						
Terminal to CPU	110	265	389	*	*	*
CPU-to-CPU	1.2	7.1	35	21	50	77
Electronic Mail	0	5.8	6.7	*	*	*
Freeze-frame TV	0	0.6	1.9	0	0.2	0.7
Other	0.8	2.5	4.8	0	0.6	1.5
Total Data	112	281	437	21	51	79
Video						
Video Conference	3	84	268	0.4	10	33
Education	20	36	110	0.6	1.1	3.5
CATV	46	33	26	1.5	1.0	0.8
Network	13	16	11	0.4	0.5	0.3
Health and Public Safety	0	2	2	0	0.2	0.2
Total Video	82	171	417	2.9	13	38
TOTAL, ALL SERVICES	753	1854	3745	68	172	322
*Message services are combined here in "other" category.						

Note that the projected voice traffic for the year 2000 slightly exceeds the postulated limits postulated in Table 2-1, although the peak data rate is lower by a factor of 3; the lower peak rate arises from the ITT assumption that traffic is more uniformly distributed over the 168-hour week.

Table 2-5. ITT Estimated Distance Distribution
Function for Traffic Demand, 1990

Mileage Band	Percent Traffic in Mileage Band
51- 100	1
101- 150	14
151- 200	6
201- 250	8
251- 300	6
301- 500	15
501-1000	20
1000+	30

2.2.2.3 Xerox Corporation Traffic Projections

In November, 1978 the Xerox Corporation (1978) filed a Petition for
Rule Making with the FCC; they proposed the establishment of a new common
carrier Electronic Message Service in the band 10.55-10.68 GHz. As part
of that petition they presented a market survey to support their proposals.
Although they did not include voice services in their study, they did treat
data, document, and teleconferencing services. They too began by estimating
the total United States market, and then factored in the share of market
that the proposed system, XTEN, might capture.

On the basis of various arguments they estimated that the average
employee might handle a total of 12 pages per day, transmitted plus re-
ceived, which could be compressed to an average of 200,000 bits per page.
They projected data demand by using AT&T's projections through 1985, and
then assumed 10 percent per year growth subsequently. Their teleconferenc-
ing estimates were based upon SRI's estimate that 8% of U.S. air travel
could be substituted by an effective audio/graphic service; this, combined
with the projected number of passenger emplanements and the presumed 66-
kbps data rate required, led to their final projections for the potential
market. They further assumed that teleconference services would achieve a
maximum of only 10% of the SRI potential value, and that growth would
follow a Gompertz curve with an inflection point in 1990.

These projections are summarized in Table 2-6. The annual traffic is
reduced by the percent of market penetration and the assumed peaking factors
to yield the estimated peak communications capacity required; the market
penetration estimated for the entire United States in 1990 appears in the
rightmost column of the table.

Table 2-6. Xerox Traffic Projections

Service	Annual Potential Traffic (10^{15} bits per year)				Peak Capacity (Mbps)			Percent Market Penetration
	1975	1980	1985	1990	1980	1985	1990	1990
Document Distribution	10	13	16	18	1	182	657	8
Data Transmission	0.8	1.6	2.7	4.4	1	212	506	25
Teleconferencing (66 kbps)	10	12	16	20	0.6	51	282	3
Teleconferencing (3 Mbps)*	454	545	727	909	27	2318	12800	3

*Modification of Xerox projections if all 66 kbps circuits become 3 Mbps.

The Xerox estimates for teleconferencing assumed a freeze-frame format
for video services, but if the user equipment costs dominate the transmis-
sion costs, which is suggested by the present study in Section 7.4.2, then
compressed full video services may prevail and thus make greater demands
upon the network, as discussed in Section 7.4.3. In this case the data
rates could be increased by the ratio of 66 kbps to ∿3 Mbps, which is a
reasonable rate for interframe video compression algorithms. This possi-
bility is suggested on the last line of Table 2-6 for the assumed market
penetration of 3 percent. This traffic would completely dominate the Xerox
estimates, particularly if the penetration grows to 10 percent or more.

The Xerox study noted at length that the present high cost and slow
delivery of documents offers an important new area for growth of high-data
rate network capacity. Their estimated peak capacity refers only to traffic
handled by the XTEN class of satellite communications system.

2.2.3 PRESENT PRICES FOR TRANSMISSION SERVICES

Typical current monthly tariffs for end-to-end services were tabulated in an Aerospace Corporation Report (1978) prepared for the NASA Goddard Space Flight Center in July, 1978. These tariffs appear here in Table 2-7. The least expensive service is a single dedicated 4-kHz voice circuit which costs only $8880 per year for a New York to Los Angeles link and $4980 between Atlanta and Chicago (based on a quotation from American Satellite Corporation). For 56 kbps data the tariff is more than ten times as high, and color video costs are more than thirty times as high.

Table 2-7. Typical Monthly Tariff for End-to-End Service

Service Type	Situation	Monthly Tariff ($)
Single Circuit Via Satellite (4 kHz)	Atlanta - Chicago New York City - Los Angeles	415 740
Radio Broadcast Via Satellite (8 kHz)	Atlanta - Chicago New York City - Los Angeles	830 1480
Data 56 kbps, 2 stations	$1.8K/mo for fractional transponder. 84% are station costs for dedicated earth stations	10,000
56 kbps, 3 stations	78% are station costs	16,200
112 kbps, 2 stations	85% are station costs	12,400
224 kbps, 2 stations	87% are station costs	17,200
TV distribution, color or monochrome (uplink and satellite transmission only)	Before 5 PM EST After 5 PM EST Assumes 8 hours/day, 365 d/yr. (100 $60K receiving stations amortized over 3-7 years + 20% maintenance would quadruple costs)	32,600 71,800

Present terrestrial costs are not low, either. One recent quotation (1977) for a few two-way video channels prepared by an AT&T affiliated company suggests that the costs for a particular suburban 10-mile link are approximately $90,000 plus $5000 per two-way channel, plus a monthly charge of $6000 for 1-3 channels. These charges include cable facilities and terminal equipment for standard analog video signals. Such charges would presumably vary considerably depending upon the location.

2.3   THE MARKET FOR VIDEO CONFERENCING AND VIDEO-PHONES

Examination of the three estimates by Western Union, ITT, and Xerox
(Section 2.2) of the demand for video conference services suggests the great
uncertainty in these projections. The estimates for video capacity in 1990
were ∿100 wideband channels, 10 Gbps, and 282 Mbps, respectively. These
numbers can be better compared if the widths of all video channels are
assumed to be approximately 3 Mbps; then the data rates are 300 Mbps, 10
Gbps, and 12.8 Gbps. Because these estimates were based upon cost, per-
formance, and availability assumptions that varied widely, it is informa-
tive to review a more detailed study of person-to-person business communica-
tions conducted by a working group of the Conference of European Posts and
Telecommunications (CEPT). This recent study (Tyler, 1977) was quite exten-
sive and involved several consultants and approximately 30 PTT staff members
from seven PTT administrations, each of which conducted an extensive survey
within its own country of meetings which had required travel. Together they
surveyed 26,000 meetings in over 1000 establishments. Their conclusions
suggest the degree to which video-conferences supplemented by facsimile
might substitute for travel.

The CEPT analysis revealed that most meetings requiring travel involved
small groups (fewer than five people participated in 71-90% of the meetings),
lasted less than one hour (62-87%), and involved participants from only two
locations. About half the meetings were arranged a day or more in advance
and 40-60% involved visual aids or documents. Most of the documents were
less than five pages long and were not distributed in advance. About half
the meetings were for purposes of information exchange and problem solving;
only a small fraction involved conflicts or interpersonal relations that
are known to be less suitable for teleconferencing.

On the basis of these data the CEPT team developed mathematical market
models which led them to the following conclusions. First, the maximum
potential market share (ignoring costs) of teleconference systems in support-
ing business meetings now involving travel is ∿50%. One-fifth of these
teleconferences would require video and about half would require graphics
communications; the remainder could be served by purely audio systems. It
was estimated that the fraction of meetings that would employ video would
drop approximately a factor of 6, from 10% to 1.7%, if costs of a few dollars
per minute were assumed.

They further estimated that the European demand for desk-top audio-only conference systems would be roughly one meeting per year per person, e.g., equivalent to 250 million meetings per year in the United States. This implies an average of approximately 60,000 simultaneous one-half-hour teleconference meetings in the United States during working hours, and perhaps 12,000 simultaneous two-way video conversations, if those meetings requiring video employed it.

These results suggest that the largest network the United States might employ for video-conferencing would be one in which ~60,000 duplex video channels would typically be active, assuming maximum substitution of tele-conferencing for travel and use of video services in preference to audio; this implies video costs and convenience must not be problems. The CEPT data also suggest that if the costs are a more reasonable ~$0.50 - $2.00 per minute, then the total traffic might be ~4000-24,000 active one-way channels. These estimates could rise if the quality of the service stimula-ted an increase in the total number of meetings or a substitution of video for audio services or for meetings not requiring travel. The demand could be less if there were poor system characteristics, regulatory restrictions, or inhibitory prices due to technical or other factors.

A very important unknown is the final market acceptance of the service. Although the CEPT study was conducted very carefully, the actual choices made by people would depend on several elusive factors; therefore the per-formance of user evaluations in realistic circumstances is very important. Hough et al. (1977) reviewed several video-conferencing experiments, but the results are ambiguous because most of the various facilities involved a variety of shortcomings such as limited accessibility and quality, lack of simplicity and complete human factors design, expense of operation, lack of adequate graphics capability, and their temporary and sparse character. Although small scale experiments can be very informative, it is important to properly design, control, and analyze the results if they are to be applicable to the basic issue of video viability. These problems are dis-cussed at length in the book "Evaluating New Telecommunications Services," edited by Elton et al. (1978).

Examples of recent tests include SBS's 1977-1978 satellite communica-tions market test, Project Prelude, which involved testing teleconferencing, document distribution, and data processing at Montgomery Ward; Rockwell International, Texaco, and Aetna Life and Casualty; the test employed the

NASA 12/14 GHz Communications Technology Satellite for a few weeks at each of several corporate locations. The FCC also recently approved a limited test of satellite video conferencing by AT&T and GTE. It will last at least one year and will be offered at the same tariff rates as terrestrial land-line video service.

An example of one of the phenomena difficult to address by small experiments is the reality of the "threshold of utility", which is the hypothesized minimum size system necessary to maintain user interest in network capabilities; the probability that any desired party can be reached must be acceptably high (Staelin, 1979). If the purpose of a network is to provide intra-organizational communications, then the threshold number of terminals would be approximately the number of facilities which that organization wished to link. Because this number is typically modest, most existing video-conference networks are of this type. Communications between organizations, or communications within very large organizations such as the federal govern-ment, would require much larger systems.

Network size depends in part on the number of terminals, which depends in turn upon the degree to which they can be accessed and shared by the users. In general, terminals should be within reasonable walking distance of a majority of the users because most professional workers are accustomed to walking to conference rooms, computer terminals, or duplicating machines, but tend to resist travel to other buildings or across town. It is reason-able to assume that one terminal per 200-1000 employees would define an acceptable walking radius for most people; such groups typically might each generate revenues of $\sim$\$10-50 million dollars. The two-trillion-dollar gross national product for the United States might include 40,000-200,000 such average units, half of which would perhaps involve information workers.

Although some segments of the economy would not require so many termi-nals, others, such as law firms and similar professional organizations, might require more. If five percent of the information workers each used these terminals two hours per month, the terminals would be occupied $\sim$12-60 percent of the working day for 100,000 and 20,000 units, respectively, and approximately 12,000 one-way video channels would typically be active. In the "new rural society" this number would be many times larger.

The threshold of utility for an interorganizational video-conference system might be that network size for which only half of all desired conference partners have access to terminals. At this threshold, two-party meetings are constrained; and three-party conferences are very difficult. The probability that a desired conference partner has access to a terminal is plotted in Figure 2-3 under various assumptions as a function of the number of active one-way channels in a national network serving the United States. The first assumption is that the average person is willing to walk within the confines of 10-million or 50-million dollar entities; both cases are presented in the figure. Two alternative assumptions are then made concerning the use of the terminals. In Case A we assume that each terminal is used half the time regardless of the total number of terminals in the system, and in Case B we assume that this 50 percent utilization is multiplied by the fraction of entities that have terminals; for example, if only 40 percent of all entities had terminals, then their utilization would be 50 percent in Case A and 20 percent in Case B. Under these assumptions the threshold of utility for an inter-organizational network requires at least 2,500 to 25,000 active one-way video-conference channels, as indicated in the figure. Although this simple model overlooks threshold reductions arising from the fact that the most important communications centers will be the first to have them, the threshold would, on the other hand, be increased if some groups monopolize portions of the system capacity.

Thus it appears likely that a basic national inter-organizational fully-switched broadband communications network would need 2,500-50,000 one-way broadband channels, with 10,000 being a more realistic estimate. These might be nominal 3-30 Mbps channels capable of handling video-conferences, facsimile, and other services. The number of user-terminals required for each service might be on the order of 20,000-100,000. Later in this report it is assumed that 50,000 user terminals would comprise the baseline system analyzed in Chapters 4-7.

This analysis of the baseline system suggests that the costs of video-phone and videoconferencing services would be largely controlled by the costs of those facilities on the customer's premises if they exceed ∿$50,000. This threshold, where user equipment costs dominate, is related to the assumed bandwidth of ∿3 Mbps, which could probably convey acceptable quality full motion color video with inter-frame compression. If the images were
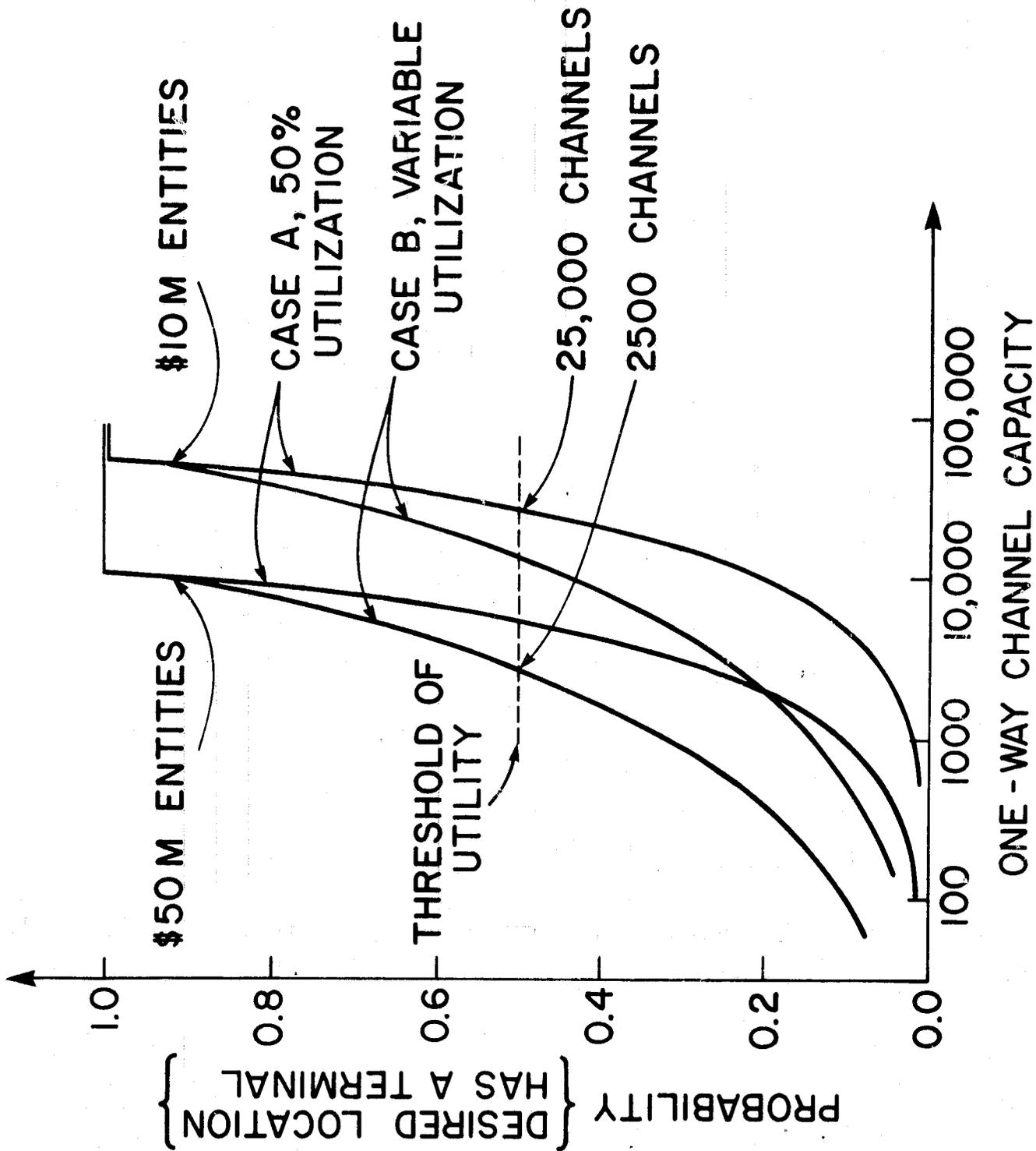
Figure 2-3. Probability that a desired callee has access to a terminal, as a function of the total system channel capacity and the utilization and distribution of terminals.

slightly blurred, jerky, or noisy in the presence of modest motion, then
256 kbps might even suffice, and the threshold cost for video equipment would
drop correspondingly. The lowest cost option in Table 6-1 was priced at
$25,000 and incorporated three cheap cameras and monitors. A unit which
physically resembled Picturephone, which is a desktop unit containing a
small camera and screen, should be manufacturable for less than $10,000,
even with the inter-frame compression equipment included (Inter-frame
compression and A/D equipment costs,~$3K, are estimated in Table 5-1.)

Thus, if a $60K facility corresponds to 3 Mbps, then $25K might corre-
spond to 1.5 Mbps, and less than $10K might correspond to 256 kbps. The
tariffs achievable with the favorable projected economics of the baseline
system, summarized in Table 7-1, might be as low as 65, 30, and 15 cents
per minute for 3, 1.5, and 0.5 Mbps, respectively, plus monthly charges of
$2000, $1000, and $400. If the customer purchased or leased the video
terminal separately, the monthly charge could be nearly eliminated.

Since these marginal costs per minute approximate present long-distance
telephone tariffs, significant use of such capabilities could be envisioned
if the service quality were preferable to regular telephones. In other
words, if a few key members of an organization believe that the initial ex-
pense of such a system is justified by their use alone, then the very low
anticipated marginal costs of everyone else's use could easily result in
the facility being over-utilized. This situation could conceivably prevail
even if the costs were doubled. Although technology may permit such low
tariffs, issues of national policy and corporate strategy might intervene
to prevent them, as discussed in Chapter 8.

In summary, although there is insufficient data on user behavior and
system economics to draw any safe conclusions, serious attention should be
given to the possibility that inter-frame-compressed full motion video in
the 256-3000 kbps range could become a major new service, perhaps rivaling
voice, with the growth of efficient broadband network capabilities.

2.4   THE INTERNATIONAL MARKET

The first launching and use of synchronous satellites was in 1963 when
NASA successfully transmitted television signals through the SYNCOM II
satellite, built by Hughes Aircraft Corporation. In 1962 Congress author-
ized the formation of Communications Satellite Corporation (Comsat) to

represent the United States in the International Telecommunications Satellite Organization (INTELSAT), which was formed in 1964 and has grown from the original 11 countries to more than 102 members today. Its growth in international traffic is now 20 percent per year. The system comprises more than 220 ground stations and approximately 5 active satellites and 5 spares operating around the globe.

Intelsat I was placed in service in 1965 with 240 voice circuits or one TV channel. The Intelsat V, being developed by Ford Aerospace Corporation, will have 12,000 voice circuits and 2 TV channels.

The first domestic satellite communications system using dedicated geostationary satellites was that of Telesat which became operational in Canada in 1972; it has grown significantly since then. More than five other such domestic systems have become operational, and the trend will continue. The United Kingdom flew the 7/8 GHz Skynet Satellite, France and West Germany provided the 4/6 GHz Symphonie with 90 MHz transponders in 1974 and 1975, Italy launched Sirio in 1977 for 11/17 GHz TV and telephone experiments, Japan has several satellites, including the CS satellite which provides 6 20/30 GHz channels and 2 4/6 GHz channels of 200 MHz each, the Soviet Union has several satellites, and the United States has several domestic satellite systems. In addition, many countries are now subscribing to Intelsat satellites to meet their domestic requirements and are also forming regional groups to develop special systems. Examples of regional activities include the Nordsat and Arabsat systems now being developed. Other national systems under development include those by France, West Germany, India, and others. The biggest users of the Intelsat domestic services are countries like Nigeria, with 19 ground stations, Algeria, etc.

Although most of the early communications satellites were developed by United States firms, this leadership position is rapidly and significantly eroding due to technologically aggressive developments in Europe, Japan, and elsewhere. For example, Thomson CSF (France), AEG Telefunken and Siemens (West Germany), and NEC (Japan) all are competing successfully with Hughes, Litton, Varian, etc. in the United States for high performance microwave power tubes, and similar competition is increasingly faced in other technologies as well.

Japan is perhaps the most aggressive in advanced telecommunications. Their Nippon Telegraph and Telephone Public Corporation (NTT) has developed a series of 5-year plans which grew from approximately one billion dollars in 1953-1957 to 26 billion in 1973-1977, and the pace is continuing. During the last period they added more than 22 million telephones to their system. Their first applications satellite (JETS-1) was launched in September, 1975. Their engineering test satellite, ETS-II, performed simple propagation tests with beacons at 1.7, 11, and 34 GHz. Just 9 months later they launched in December 1977 their "Medium Capacity Communications Satellite (CS)" with 1.6 GHz total bandwidth divided among 6 transponders. This capacity significantly exceeds that of most other existing satellites. Although CS was developed with considerable U.S. assistance, the Japanese capabilities are increasing at a very significant pace.

An example of their export posture is NEC's installations of terrestrial radio and transhorizon equipment. They placed 732 stations for NTT, 793 stations for other Japanese customers, and 2384 stations overseas; the numbers are significant. Other areas of technical strength include high-power solid-state microwave devices, low-noise microwave amplifiers, high-power microwave tubes, high-data-rate optical fibers, other digital equipment including inter-frame video bandwidth compression systems, and a wide variety of very low cost video cameras and monitors, a market they largely dominate today.

The United States has at least four domestic common-carrier satellite communications systems. RCA operates 20 medium and heavy route earth stations and 100 small ones in Alaska, plus 7 major stations in the 48 states. Western Union has at least 8 stations; GTE and AT&T operate 6 major facilities, and American Satellite has more than 5. In addition there are approximately 2000 receive-only stations for CATV video distribution, plus another large number of stations for other customer-premises applications. All the domestic U.S. satellites together have a capacity of ∿7 GHz, which should be compared to the 1.6 GHz capacity of the first Japanese CS satellite. The Canadian Anik series of satellites is also impressive.

Chapter 2 References

1. Elton, C. J., W. A. Lucas, and D. W. Conrath, Eds., Evaluating new telecommunications services, Plenum Press, New York, 1978.

2. Ford Aerospace and Communications Corp., Concepts for 18 and 30 GHz satellite communications system study, NASA Rept. No. NASA-CR159625, Nov. 1, 1979.

3. Hough, R. W., Teleconferencing systems: A state of the art survey and preliminary analysis. Final report for the National Science Foundation, May 1976. Grant No. SSH 74-22611.

4. Hughes Aircraft Corp., 18 and 30 GHz fixed service communications satellite system study, NASA Rept. No. NASA-CR159627, Sept., 1979.

5. ITT U.S. Telephone and Telegraph Corp., 30/20 GHz fixed communications systems service demand assessment, NASA Rept. No. NASA-CR159620, August 1979.

6. Tyler, M., Ed., Final report of the business communications studies on demand for new person-to-person communications systems, 1977. Available via Brian Cartwright, Rapporteur for demand for new services, Long Range Studies Division, Post Office Telecommunications, 88 Hills Road, Cambridge, CBT 1PE, England. Also see M. Tyler, B. Cartwright, and H. A. Collins, Long-Range Intelligence Bulletin 9, Interaction between telecommunications and face-to-face contact: prospects for teleconference services, Reference LRIB 009/ITF; Post Office Telecommunications Hdqtrs, England, May 1977.

7. Western Union Telegraph Co., 18/30 GHz fixed communications systems service demand assessment, NASA Contractor Rept. No. NASA-CR159547, July 1979.

8. Woodford, J. B., Ed., Communications satellite technology, Aerospace Corp. Rept. No. ATR-78(7735)-1, for NASA Contract NAS 5-24489, July 1978.

9. Xerox Corp., Petition for Rule Making, before the FCC, Wash.,D.C., Nov. 16, 1978; via R. E. Wiley, J. L. Bartlett, L. W. Secrest III, and D. E. Adams of Kirkland & Ellis, Washington, D.C.

CHAPTER 3

ARCHITECTURAL ISSUES: DEVELOPMENT OF A BASELINE DESIGN

3.1 INTRODUCTION

The market estimates summarized in Chapter 2 suggest that a pervasive domestic satellite communications system might reasonably have 10-60 Gbps capacity in the 1990's and could carry a significant fraction of all long-haul traffic, including voice. Such large-scale employment of satellites with their unique technical and economic characteristics raises important architectural issues not addressed previously. In this chapter several of these issues are identified and explored in sufficient detail to permit a baseline design to be defined. This baseline system includes the satellites, ground stations, local exchanges, and user facilities.

The purpose of the baseline design is to facilitate the system technology and cost estimates presented in Chapters 4-6, and to provide a starting point for the architectural tradeoff discussions and system optimization exercises presented in Chapter 7. The final result is a system design optimized for the various assumptions about future technology and economics. Since no such forecasts are perfect, the estimates and the conclusions which follow are presented in sufficient detail that readers may readily revise them and understand the consequences. In most cases revision of only one or two assumptions does not have a controlling influence on the outcome because the total system is so large and complex.

In Section 3.2 network architectural issues are discussed, with emphasis on the optimum distribution of traffic between satellites and terrestrial links and the resulting geographic distribution of ground stations. Interesting results include 1) the identification of satellite "markets" other than simple long-haul, 2) the dependence of ground-station density upon traffic density, 3) the costs of diversity protection, and 4) identification of other opportunities for optimization.

Section 3.3 reviews the architecture of the satellite system, with special emphasis on optimization of subsystem gain, switching architecture, and multibeam antenna design; the antenna discussion includes extensive computations of beam-crossover gains and sidelobes by T. Bigelow.

3.2 NETWORK ARCHITECTURE

3.2.1 RATIONALE FOR SATELLITES

The primary justification for communications satellites is economic, although issues of security, national policy, and communications flexibility may also intervene. In this section the principal cost advantage of satellites is discussed in terms of a greatly simplified cost model. This discussion continues in Section 3.2.2, where the model is extended to permit qualitative understanding of the proper division of communications traffic between space and terrestrial links.

Consider a cost model in which the transmission costs per circuit-mile-year are identical over the entire terrestrial telecommunications system. Then the cost of linking two stations ($/circuit year) is directly proportional to the length of that link, as illustrated in Fig. 3.2-1 for annual costs of one and ten dollars per voice-circuit mile. Although these costs are below those of the most expensive existing links, they are probably more nearly characteristic of that range spanning the present-average and present-marginal costs of the existing long lines network. Unfortunately the actual costs are generally unknown, unpublished, or controversial -- nonetheless the numbers used here are quite adequate to understand the general role of satellites in communications.

The division of traffic between terrestrial and space links will depend upon the relative costs. As noted above, it is reasonable to characterize terrestrial costs as proportional to the product of data rate and link length, whereas satellite costs depend only on data rate and not link length; once a satellite is invoked, it can communicate with any ground station within its field of view with almost equal ease.

In Fig. 3.2-1 two different costs per satellite circuit year are plotted: $250 and $2500. The smaller cost is approximately that projected per 64-kbps digital circuit for the baseline system analyzed later in this report (see Table 7-1). The higher cost is below present tariffs for existing voice links via satellite (see Table 2-7; costs are below tariffs for efficient use).

Since the satellite costs are independent of distance, there is some distance beyond which satellites are less expensive than the

- 31 -
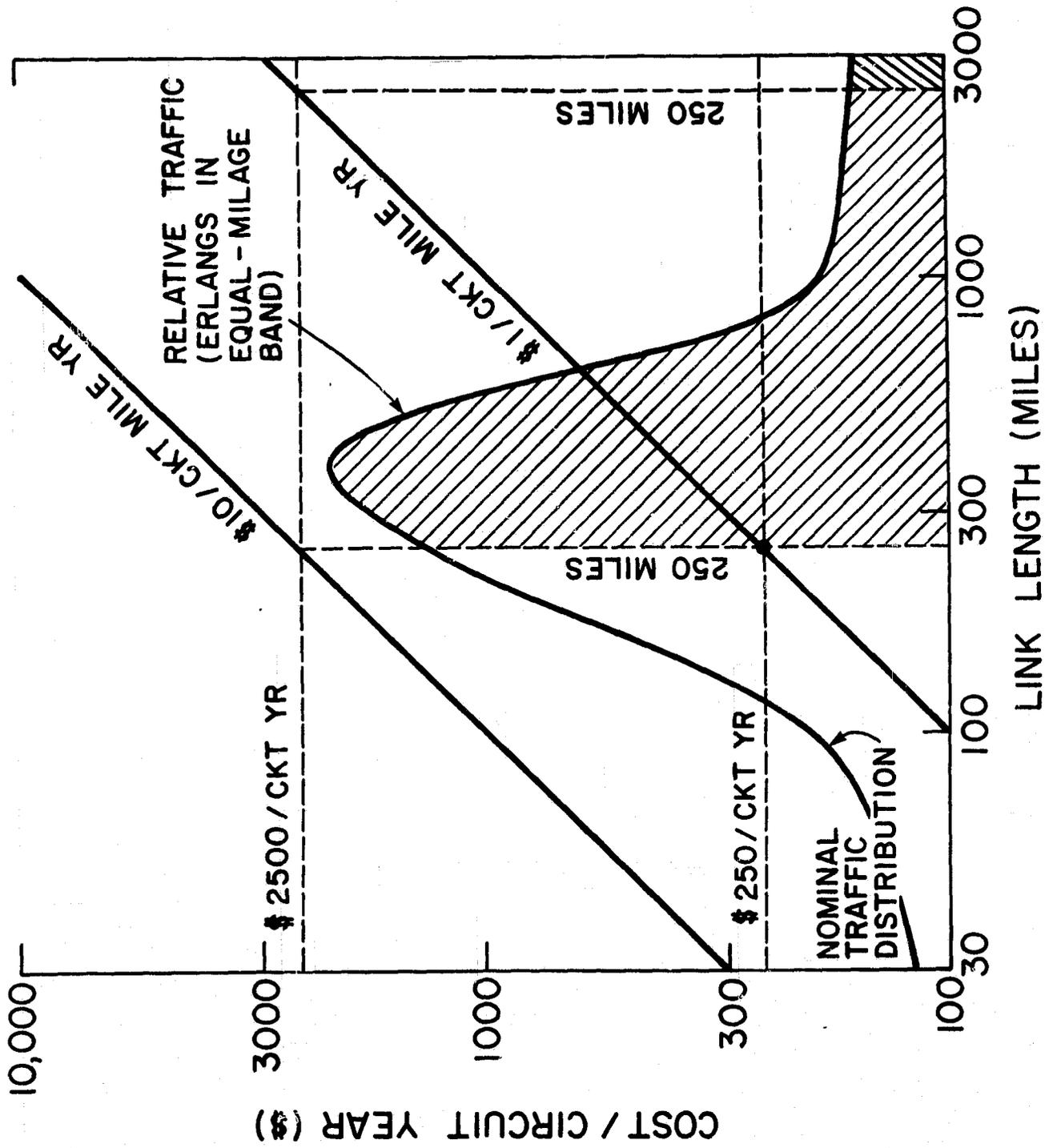
Figure 3.2-1. Relative costs of satellite and terrestrial circuits yield "breakpoint" distances beyond which satellites are cheaper; the breakpoint distance can be related to the nominal traffic distribution to yield estimates of market share.

distance-dependent terrestrial costs. If we compare the $250 per-satellite-circuit cost with the $1 per-terrestrial-circuit-mile cost, then it follows that for circuits over 250 miles long, satellite links are less expensive. Comparison of the $2500 satellite costs with the $1 terrestrial cost yields a breakpoint of 2500 miles, which would relegate satellite links primarily to transcontinental and intercontinental traffic.

Once the break-even distance is known, then the fraction of the total traffic that could be allocated to satellites can be roughly estimated. First consider the general shape of the traffic demand curve as a function of link length. If population were distributed uniformly, then the number of people per mile at any particular distance would be proportional to that distance L; the number of circuit miles would thus be proportional to L^2 if traffic were proportional to population alone. This growth with L must end when the boundaries of the total region are reached. For example, most of the eastern seaboard traffic occurs within distances characteristic of the Boston-Washington corridor, say 400 miles. Similar distances characterize the industrial midwest and the western seaboard. Thus the relative traffic for distances above $\sim$ 400 miles should drop to levels more characteristic of transcontinental distances. Such a curve appears in Fig. 3.2-1; it is qualitatively similar to one presented for a representative subset of large corporate customers of AT&T (Cochrane and Lawson, 1979). Actual traffic distributions also depend on tariffs and business practices, and these can move the peak of the distribution to distances of $\sim$ 100 miles for submarkets such as certain residential long distance calls, etc. (see Tables 2-3 and 2-5).

If we consider the 250-mile breakpoint in terms of this traffic distribution curve, then it is clear that satellites could carry well over half of all long-distance traffic. However, if the 2500-mile breakpoint is more appropriate to the actual costs, then satellites would best be used internationally, if at all. It is probably fair to say that present usage of satellites is more nearly characteristic of the 1500-mile breakpoint for conventional voice traffic, but that evolution toward increased use of satellites is likely. For distribution of wideband signals such as network television, it appears that the breakpoint

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distance is already approaching hundreds of miles, in view of the rapid growth of this service.

Some of these breakpoint arguments are somewhat artificial, however, because of regulatory and other considerations. For example, the cost of leasing AT&T terrestrial long-lines by a new communications vendor may be the tariff established to cover average AT&T system costs, rather than the marginal costs associated with his expansion of the total market. Thus the tendency for such new communications firms to employ satellites could be greater than that of AT&T, which faces a different tradeoff. These issues are discussed further in Chapter 8.

The other non-economic issues concerning the utilization of satellites include security, system flexibility, and national policy. Satellites enhance security because the only link elements readily vulnerable to natural or other hazards are at the ends of the link close to the users and within their more direct control. Although satellites face other hazards, they are statistically somewhat independent, and therefore increase the total security of the communications system. Security and economic advantages also follow from the flexibility inherent in satellite systems which link modest ground stations that can be installed, expanded, or removed relatively quickly and easily in response to rapidly changing needs. Both these virtues of satellites support national policy objectives. These objectives are also supported by the occupancy and utilization of orbital slots, the export of technology, equipment, and services, and the increase in national and international communications that can follow from the economies made possible by satellite technology.

3.2.2 DIVISION OF TRAFFIC BETWEEN SPACE AND TERRESTRIAL ELEMENTS

The rationale for allocating traffic to satellites was discussed in the previous section. Depending on the assumed costs per circuit, the fraction of long-distance traffic allocated to satellites could vary from a negligible fraction to a significant majority, with satellite links generally being dominant for circuits longer than some breakpoint distance. However, the basic assumption made in the preceding analysis was that terrestrial costs are proportional only to circuit miles. It is more accurate to consider a cost which is proportional to circuit

miles plus a second component which is a fixed cost proportional only to miles. These fixed costs include the costs of burying conduit, building microwave towers, right-of-way costs, etc. The costs proportional to the number of circuits or to bandwidth are associated with electronics and the costs of the transmission medium, e.g., optical fibers. The simplified analysis of the preceding section, based upon constant costs per terrestrial circuit mile, breaks down seriously if technological advances can reduce the variable electronics costs to levels significantly below the fixed costs per mile, or if traffic is sufficiently low that terrestrial fixed costs dominate.

To better understand the issue, consider the simplified cost equations below, which divide both the terrestrial and satellite costs for a particular circuit route into a constant term plus a variable component.

$$\text{Satellite Cost} \quad C_s = k_{s_o} + k_s t \quad (\text{dollars/route year})$$

$$\text{Terrestrial cost} \; C_t = k_{t_o} m + k_t tm \;(\text{dollars/route year}) \tag{3.2-1}$$

where the k's are constants, t is traffic (equivalent circuits), and m is the circuit length (miles). Whether any particular route should be handled by satellite or by terrestrial systems depends (in this simplified analysis) only upon which costs less. This decision thus depends only upon the variables t and m, once the constants k are fixed. This decision rule is represented graphically in Fig. 3.2-2, where the axes are m and t. Although several curve forms are possible, only a few are illustrated. Table 3.2-1 presents the values assumed for the constants used in the figure.

Table 3.2-1. Assumed Cost Constants for Terrestrial and Satellite Circuits.

Case	k_{s_o} ($/route)	k_{t_o} ($/mile)	k_s ($/circuit)	k_t ($/circuit mile)	Asymptotes High t k_s/k_t	Low t k_{s_o}/k_{t_o}	Cross-over k_{t_o}/k_s
A: Non-aggregated long lines	10^6	10^4	10^3	1	10^3	100	10
B: Aggregated long lines	$4 \cdot 10^5$	10^3	400	1	400	400	2.5
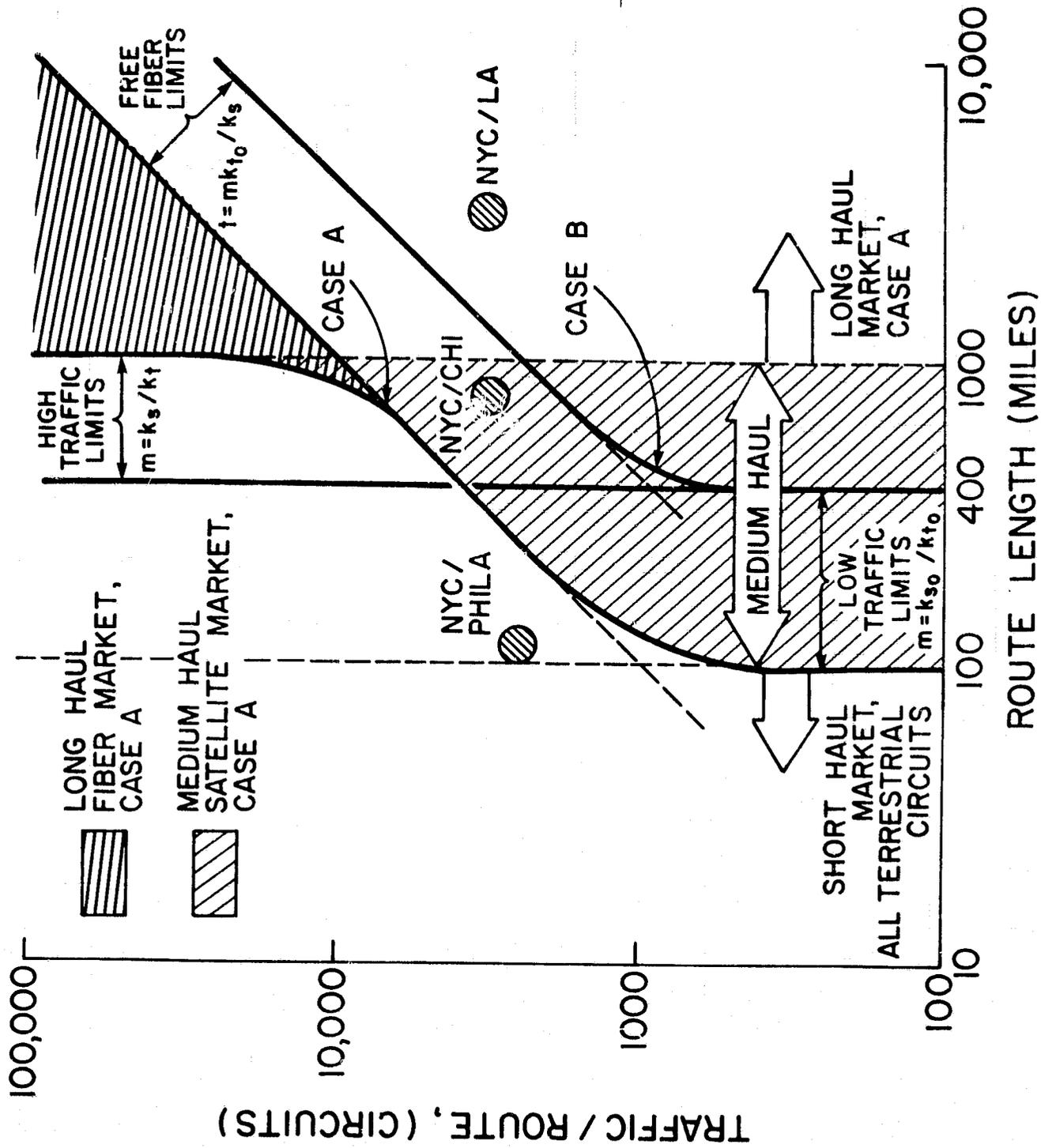
Figure 3.2-2. Decision diagram, satellites versus terrestrial circuits, as a function of route length and traffic.

Consider first Case A, as defined in the table and figure. The constants correspond to the case where the fixed cost of a link is allocated to that link alone and not shared by foreign traffic; the fixed cost per terrestrial link, k_t, is assumed here for illustrative purposes to be \$10,000 per mile. Consideration of Eq. (3.2-1) reveals that there are two major asymptotes of interest, the high and low traffic limits. In the high-traffic limit the variable terms proportional to t dominate; in the other limit the fixed terms are largest. The breakpoint mileages for these two limits are k_s/k_t and k_{s_o}/k_{t_o}, respectively; for Case A they are 1000 and 100 miles, respectively. There is also a transition region between the two limits defined by the equation $t = k_{t_o}/k_s$, if k_t is sufficiently small. Other values of constants give somewhat different curves and limits.

The high-traffic limit case is the same as that considered in the previous section, Section 3.2.1. In this limit the constant cost components are negligible compared to the variable terms $k_t$tm and k_st. This breakpoint, at 1000 miles here, defines the satellite market discussed in the previous section; in the figure it is designated the long-haul market and is best satisfied by satellites. If the breakpoint mileage for the low-traffic limit is less than the high-traffic breakpoint, then there may be a very important additional satellite market which is the low-traffic portion of the medium-haul market, also defined in the figure. In this medium-haul market satellites are competing primarily against the fixed per-mile costs of terrestrial links and not against their traffic dependent costs. The route between New York and Chicago may even fall into this medium-haul satellite market, whereas it is outside the long-haul satellite category. In fact many routes would fall in the satellite portion of the medium-haul market, but not very heavy short routes such as New York/Philadelphia. Different cost assumptions produce different decision rules, such as Case B.

In Case B the major change in assumptions is the reduction of the fixed terrestrial costs per mile by a factor of ten; such reductions could be appropriate for incremental additions to existing routes which already carry significant traffic. In Case B the high and low traffic limits are coincidentally both 400 miles, and thus there is only a

long-haul satellite market and a short-haul terrestrial market; the medium-haul market does not exist.

With future improvements in technology it will be possible for terrestrial links to regain a portion of the long-haul market. The possibility of this happening before the end of the century is non-negligible; already single optical fibers have been demonstrated to be capable of carrying 1.2 Gbps with repeater spacings of 23 km (Yamada et al., 1979). Thus a few fibers could carry a large fraction of all national traffic. The costs of fibers and repeaters are dropping rapidly, and they could become negligible expenses in the near future.

In the event the traffic-dependent cost term, k_t, goes to zero, the decision curves in Fig. 3.2-2 approach the free-fiber limits. The cross-hatched region in the figure that defines the long-haul fiber market for Case A does not include any routes with less than 10,000 circuits, and thus this market has little economic significance under these cost assumptions. However, under Case B this market could include the important New York/Chicago route and perhaps others like it. Thus the long-haul market could also be split, with the heaviest routes remaining or reverting to terrestrial services.

In the event that the fixed costs per mile dominate, then the number of miles required to connect major switching centers becomes of interest. In Fig. 3.2-3 the 50 largest U.S. metropolitan areas are shown; the five largest are marked by filled circles (New York, Los Angeles, Chicago, Detroit, and Philadelphia). If one were to connect these 50 areas by terrestrial links, only 8000 air miles would be required, as suggested by the solid lines in the figure. This network has no redundancy; any two nodes could be separated by a single break. Additional lines (30% of the total) could provide dual redundancy, as indicated by the dashed lines; any two nodes could then be isolated only if there were two separate line failures. If only the five largest areas were connected, then 4000 miles would suffice.

Consider the lines connecting the five largest cities, and suppose that they had a fixed cost of $20,000 per mile. The total cost for 4000 miles would be only eighty million dollars, and yet it might carry several percent of all long-distance traffic. Once such a line were established,
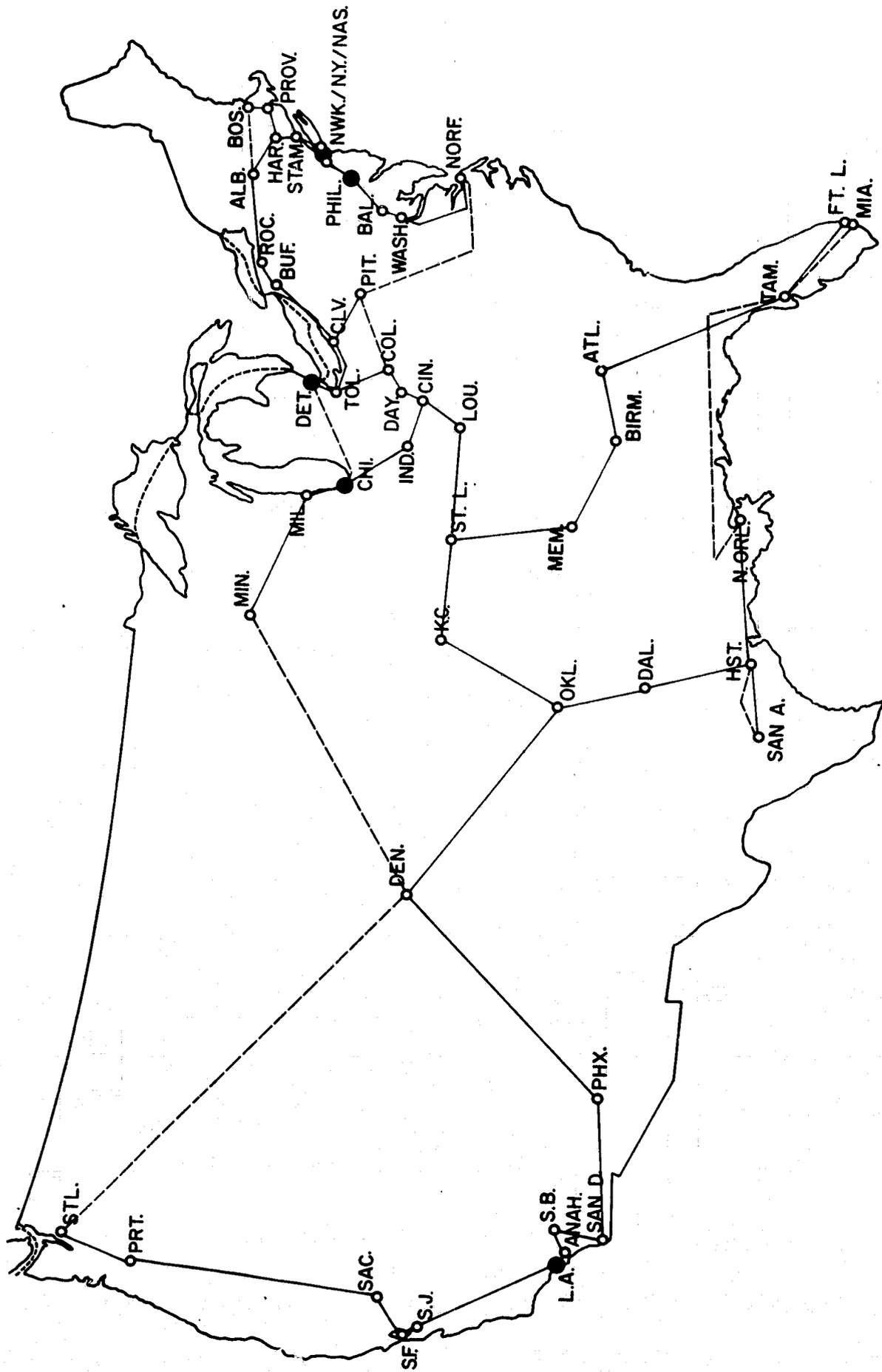
Figure 3.2-3. The five (solid circles) and fifty (open circles) largest U.S. metropolitan areas, plus one possible tree network connecting them (solid lines) and additional lines (dashed) that provide dual redundancy.

the marginal costs of adding traffic from nearby nodes, such as Toledo, could be small, so there would be a "halo" market as well. Nonetheless, satellites could probably retain a very firm grip on the low-traffic end of both the long-haul and medium-haul markets.

The market division between terrestrial and satellite links might be differentiated further by the quality of service desired. Such differences include the quarter-second delay incurred for single satel- lite hops and any differences in the statistical distribution of system failures and blocking. With the coexistence of both a satellite and a terrestrial network, as envisioned here, the traffic could divide between the two modalities in response to both tariffs and service, with the higher terrestrial tariffs being associated with the longer, thinner routes. Many regulatory and pricing options exist, and would complicate the simplicity of the preceding discussion.

Before concluding this section it is interesting to estimate the actual breakpoint distance for present AT&T or independent company deci- sions. Typical satellites cost $20M-$30M for 10^4 circuits (e.g., Intelsat V) and requirements for backup capacity, launch-failure allow- ances, loading efficiencies, etc. might increase this to $\sim$ $80M for 10,000 circuits, or $\sim$ $1200 per circuit year for a seven-year satellite lifetime. Inclusion of ground station depreciation, and labor costs might increase this total to $2000 per circuit year today.

These numbers represent estimates by this writer only and not the results of published analyses. Actual costs would also vary consider- ably with scale and specifications. Smaller systems providing digital switching services would be more expensive than large inflexible trunking systems.

Costs per incremental terrestrial circuit mile year now average $\sim$ $1-5. If we assume a 15-year life for the systems costed in Fig. 6-1 then the present capital costs might be $\sim$ $2, and labor costs could increase it further. The capital costs are projected to decrease significantly with technological improvements.

The ratio of these two variable costs, $2000 per circuit year and $4 per circuit mile year, yields a high-traffic-limit breakpoint distance of $\sim$ 500 miles. The fixed costs which determine the other breakpoints are

more difficult to estimate, and will generally be different for AT&T and its competitors.

The biggest fixed costs for microwave links are those for microwave towers, real estate, access roads, etc. and the associated development and maintenance. A tower costing $200,000-$300,000 and lasting 20 years might be costed at $20,000 per year plus maintenance costs of $\sim$ $20,000 (author's guess). A 20-mile link would thus have fixed costs of $2000 per mile per year. Since AT&T Long Lines already owns a large network of towers, cable routes, etc., its fixed costs for marginal increase in plant could be much less. They would consist primarily of the fixed costs of the electronics alone plus the marginal costs of maintenance (site visits are presumably already made regularly). Thus the fixed costs for marginal increases of existing links could approach the fixed electronics costs alone, which can be less than $1000 per mile per year. A very large ratio also exists between the fixed cost of new buried conduit versus cable additions to existing conduit. For k_{t_o} = $4K, k_{s_o} = $40K, and k_s = $4K, the low-traffic limit is 10 miles and the cross-over is 1, thus extending the medium-haul market to shorter, but thinner routes than suggested by Case A.

3.2.3 DISTRIBUTION OF SATELLITE GROUND STATIONS

In this section, as in the preceding ones, simple cost models are developed which illuminate the principal issues. The question of ground station density hinges on the relative costs of basic satellite ground stations on the one hand, and those of inter-node terrestrial links on the other.

First, it is important to note that in most cases it would be more economic to aggregate traffic from many users into one hub served by a single ground station, instead of providing each user with his own station. This conclusion follows easily from comparison of ground station costs of hundreds of thousands of dollars versus terrestrial link costs of thousands, or even tens of thousands of dollars, per mile. Only seriously isolated or very heavy users would normally find it cheaper to have a private station. Since these large satellite systems should be hub-centered, and since such hubs with convenient and economical rights-of-way, facilities, etc. already exist in most cities, the question of optimum inter-hub distances will, in practice, generally be a matter of deciding whether a particular existing hub should have its own ground station or whether it should route its traffic to a neighboring one.

This question is posed schematically in Fig. 3.2-4 where these options are cartooned. The costs of the two options are S dollars per year for the satellite ground station versus ktm dollars per year for the equivalent inter-node link, where t is satellite traffic, m is inter-hub miles, and k is a constant. The cost S represents only the fixed traffic-independent portion of ground station costs, because the traffic-dependent parts are the same independent of the number of ground stations. The breakpoint distance m_b beyond which two hubs should have separate ground stations is easily calculated by equating the two costs and solving:

$$m_b = S/kt \qquad (3.2-2)$$

The solutions to this equation are plotted in Figure 3.2-5 for several different cost assumptions listed in Table 3.2-2. Typical ground station separations might be on the order of 10 to 100 miles, with lesser separations in urban areas because of the greater traffic density there.

If we further assume that the peak satellite traffic t exported from a region is proportional to the population residing there, then the density of ground stations can be related to population density p (population mi^{-2}). The average traffic per capita is the total export satellite traffic T for regions of a given size, divided by the total population P. Combining these definitions with Eq. (3.2-2) and defining the region size as m_b^2, it follows that:

$$t = p(T/P) \ m_b^2 = S/k \ m_b \qquad (3.2-3)$$

$$m_b = [SP/kpT]^{1/3} \qquad (3.2-4)$$

Table 3.2-2. Assumed Costs for Terrestrial Links and Satellite Ground Stations: Definition of Cases.

k($/ckt.mi.) / S($/gnd.sta.)	1	4	16
50K	A	B	C
200K	D	E	F

BREAKPOINT MILEAGE $m_b = S/kt$
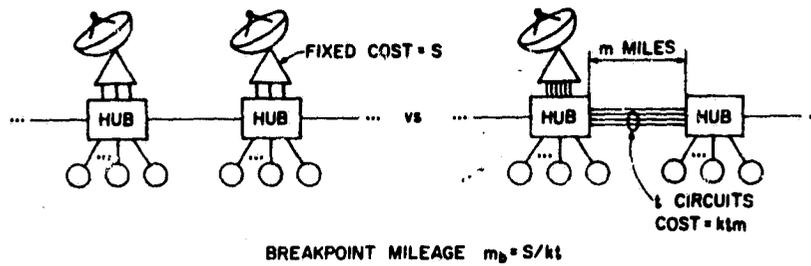
Figure 3.2-4. Configuration and cost alternatives; decision rule for determining separations between ground stations.
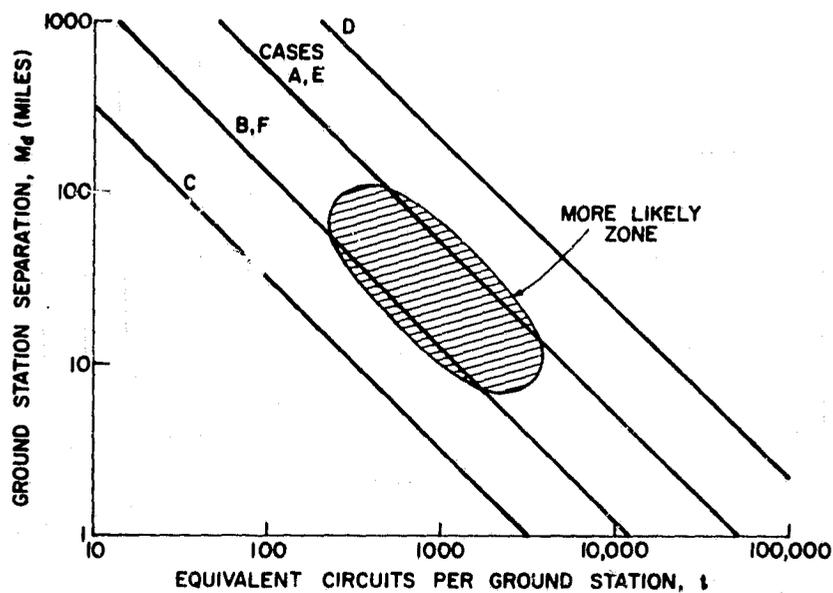
Figure 3.2-5. Nominal minimum-cost separations between ground stations as a function of the cost model and the peak circuit requirements per ground station.

If we assume a population of 300 million requires one million circuits, then the ground-station breakpoint distance ranges between 250 and 5 miles for cases A and E as the population density varies from 1 to 10^5 mi^{-2}; and 150-3 miles results for cases B and F.

It is also possible to estimate the total number of ground stations required for a given region. If the population and traffic densities were geographically uniform, then the number N of ground stations required would be:

$$N = A/m_b^2 = A(kpT/SP)^{2/3} \qquad (3.2-5)$$

where A is the total area of the region (mi^2). The number N can be bounded for the United States by assuming a population of 300 million is distributed uniformly over 3 million square miles; 1000-3000 ground stations would be required for cases A,E and B,F, respectively. If this same population were compressed into 3000 square miles at 10^5 people per square mile, then only 120-320 ground stations would be required for the same cases, respectively. A more realistic assumption is that perhaps 80% of the population resides on 5% of the land, and that the other 20% is distributed uniformly; this results in 700-1800 ground stations for the same two cost assumptions; about half would be rural stations. This number grows as the two-thirds power of 1) the total satellite system traffic T, and 2) the ratio of terrestrial-link to satellite-ground-station costs, k/S.

It is interesting to test Eq. (3.2-5) by computing the number of ground stations appropriate for present satellite traffic levels. If we assume the fixed cost per ground station is now $500,000 and the cost per circuit mile is $10, then the present United States satellite traffic capacity of $\sim$ 60 transponders, or $\sim 10^5$ voice circuits, would imply about 7 ground stations should serve this traffic; which is of the correct order for voice circuits.

3.2.4 IMPACT OF PROPAGATION STATISTICS ON NETWORK ECONOMICS AND ARCHITECTURE

It is very important to understand the impact of atmospheric propagation statistics on network economics because it is only the

increased susceptibility of the 12/14 GHz and 20/30 GHz bands to rain attenuation that ultimately will limit their utilization in preference to bands at lower frequencies. Otherwise, the far greater bandwidths and smaller antennas (late 1980's technology) required at these higher frequencies would make them clearly preferable, One of the most interesting and significant conclusions which can be drawn from the preceding simple cost models is that the propagation statistics for 20/30 GHz in the United States are sufficiently close to perfect that less than a ∿ 10% impact on network economics results from the inclusion of diversity protection adequate to ensure almost any reasonable level of link reliability. This result, explained below, applies for any reasonable level of satellite participation in the existing flow of traffic. The positive stimulus this conclusion could provide to the development of this band is clear.

The central technical fact is that if adequate space diversity is employed, then modest link margins of 10-15 dB are completely adequate to provide 99.99% reliability or more. Typical of the many studies of this phenomenon is the summary prepared by Ford Aerospace and Communications Corporation, one part of which is repeated in Table 3.2-3. This table lists the link fading margins required to ensure less than 0.1 and 0.01% link outage at 18 GHz for no diversity and for 8-km diversity. Without diversity a 12.4-dB margin is required in Houston to yield 0.1% performance, but with a second ground station only 8 km away this required margin drops to 4.7 dB for 0.01% performance. The attenuation in this frequency band is approximately proportional to the square of frequency (Wilson, 1969), so the required margin for Houston at 30 GHz would be ∿ 13 dB for 0.01% outage. This performance can easily be improved further by increasing the separation between the two independent ground stations or by using triple or higher order diversity.

The principal limit to the use of diversity is economics. Consider Fig. 3.2-1 which suggests that the peak of the traffic distribution curve corresponds to links several hundred miles long, and that terrestrial links are usually less expensive than satellite links for routes less than several hundred miles. The question now is: what percentage cost increase is associated with providing 8 km or more of permanent extra

Table 3.2-3. Rain Attenuation Statistics at 18 GHz.

Trunking Sites	Annual Rainfall (mm)	% Rain by Thunderstorm	Link Margins (dB)			
			No Diversity		8 km Diversity	
			0.1%	0.01%	0.1%	0.01%
New York	1021	14%	6.3	23.5	3.0	4.1
Chicago	875	20%	5.4	24.1	3.8	5.0
Los Angeles	294	6%	3.4	7.9	2.2	3.3
San Francisco	496	6%	4.5	9.6	2.5	3.5
Washington, D.C.	988	19%	6.2	26.9	3.0	4.2
Dallas	820	50%	7.3	38.1	3.2	4.5
Houston	1224	55%	12.4	45.2	3.7	4.7
Minneapolis	659	15%	4.5	15.9	2.5	3.9
Atlanta	1228	40%	9.5	41.5	3.4	4.6
Denver	394	18%	3.6	12.5	2.2	3.7

links between an originating hub and its nearest neighbor in order to provide this diversity protection? In the preceding section a typical inter-hub separation of 10 to 100 miles was derived, and if we compare this to the breakpoint distance of several hundred miles or more, then for the peak of the traffic distribution, the extra land links required would add typically less than ∿ 5% to the total link cost. The number 5% corresponds to an assumed 30-mile diversity link added to an assumed nominal 300-mile communications route (10%), reduced by a factor of two because two ground stations can share each such diversity link. These inter-hub diversity links would be a small part of the total terrestrial long-lines capacity unless satellite circuits totally dominate the long-lines installed plant. If these diversity links are a small part of the inter-hub communications plant, this implies that the costs of diversity could be reduced further. For example, if the rain outages systematically occur away from the peak hours, then there will always be adequate inter-hub plant sufficient to provide the desired diversity when required. The exact degree to which this effect could reduce diversity costs would depend upon the detailed statistics of local traffic and atmospheric propagation.

An alternative method for estimating diversity costs is to recall that ground stations are separated by distances such that the fixed ground station cost equals the cost of an inter-hub link adequate to handle the satellite traffic. To provide diversity this link is required anyway, and thus the fixed ground station costs are doubled; actually the fixed costs of only half the ground stations are doubled, because two stations could share each diversity link. Furthermore, the variable costs of each ground station should be increased by an amount adequate to handle the excess traffic from neighboring stations suffering rain attenuation. If the diversity links are rearranged so the ground stations are not connected in pairs but rather in a continuous mesh (this can be done without increasing the required number of diversity-circuit miles), then ground stations an arbitrary distance away can be employed to handle any rain-displaced traffic, and the excess required variable costs approximate zero. In this case, which is the configuration of choice, the cost of diversity is only half the fixed cost of the ground stations, as noted above. If the fixed ground

station cost were half the variable ground station cost, and if the total ground station cost equaled the space segment cost, the cost of full diversity would then be approximately 8% of the total satellite communications costs. This is comparable to the previous estimates. Therefore, if the cost savings of the 20/30 GHz bands exceed 5-10%, then these bands would be economically preferable.

Diversity costs become high only if a user who is totally reliant upon his own ground station and not connected with adequate back-up terrestrial plant insists upon receiving a very high degree of link reliability. In this case an extra ground station plus the connecting terrestrial link would be required, approximately doubling that user's terrestrial costs. This would obviously be an unusual situation. Such a user might alternatively segregate his traffic into high and low priority messages, with the high priority traffic enjoying the higher link reliability statistics afforded by whatever terrestrial circuits do exist.

3.2.5 MONOLITHIC VERSUS POLYCENTRIC ARCHITECTURES

Monolithic satellite networks are those with a single switching locus in space viewed by all ground stations; such a system could provide all communications services to all users. Monolithic networks need not be owned by only one entity, however. The switching locus could contain several interconnected satellites with diverse ownership, and the ground stations could also belong to a variety of organizations. Only the basic protocols and standards must be commonly accepted. The virtue of a monolithic architecture is its cost effectiveness and avoidance of long inter-satellite links or multiple hops with their attendant delays and costs. Within a monolithic system there could still be specialized satellite subsystems which, for example, might employ narrower bandwidths and greater power densities to communicate with very small and inexpensive ground stations.

Polycentric architectures can be broadly grouped in three classes: 1) multiple satellite systems, each providing some services to all users, 2) multiple satellite systems, each providing all services to some users, and 3) multiple systems, each providing some services to some users.

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Table 3.2-4 summarizes the main differential cost elements associated
with these various options. Unfortunately, the range of possible varia-
tions is so great that a simple comparative analysis of these options
is not practical.

Table 3.2-4. Differential Cost Elements for Alternative
Switched Satellite Network Configurations.

Configuration	Additional Cost Elements Required		
	Inter-Satellite Links	Multiple Ground Terminals for Each Hub	Multiple Satellites
Single satellite platform or cluster			
Multiple non-competing service-specific satellites		X	X
Multiple competing all-service satellites	X		X
Multiple competing partial-service satellites	X	X	X

3.2.6 FREQUENCY REUSE REQUIREMENTS

The degree of frequency reuse that is required depends upon the
available spectrum allocation, the efficiency of spectrum use, and the
desired levels of traffic. In the 20/30 GHz bands the spectrum alloca-
tion might be as much as two or three gigahertz; in this report we assume
2.6 GHz is available. The bit rate available for the tamed-FM (TFM) modu-
lation scheme discussed in Appendix A3.1.3.3 is 1.33 bits/Hz, which degrades
to $\sim$ 1.22 when allowances are made for gaps and system overhead functions.
If polarization diversity is employed, then these assumptions imply a total
capacity of $2.6 \times 1.22 \times 2 = 6.34$ Gbps per antenna beam. As discussed in
Chapter 2, the total domestic United States satellite traffic might fall
in the range 1-100 Gbps, which would require frequency reuse ranging from
1 to 32 times, which could be handled by 1 to 16 independent beams. If
the beams originate in one orbital slot, and if they are arranged in a
four-beam unit cell, then sidelobe characteristics such as those described
in Section 3.3.3 imply that from 1 to 64 beams would be required.

These estimates are appropriate if the traffic demand were distributed uniformly; however, as much as ten precent might originate in the New York City beam alone. In this event the system capacity might be limited to less than ten times the 6.34 Gbps beam capacity, if no region receives less than its per capita share of total capacity. If certain cities should saturate their capacity, then the total traffic could rise further. One mechanism for doing this is to handle a larger fraction of the traffic for saturated regions by terrestrial links. Another more general approach is to use terrestrial links in saturated zones only to link hubs outside the saturated beam, and then to allocate that traffic to satellites or to further terrestrial means on the basis of relative cost.

The length of a terrestrial link needed to offload traffic in a saturated beam can be estimated by assuming that the maximum number of beams discussed above, 64, are distributed uniformly over the $\sim 3 \times 10^6$ square miles of CONUS. This implies beam separations of 216 miles, thus links of 200 miles should normally suffice to transfer traffic to a non-adjacent non-interfering beam. Such a link could be heavily used, such that its cost per circuit could be quite low with high-technology optical fibers.

Alternatively, the need for such links crossing out of saturated zones could be avoided by making the beams smaller so as to resolve the high density areas. Resolving the New York area in a meaningful way would require beam diameters less than ~ 50 miles. Since the traffic already would be aggregated into a small number of hubs, to connect them to a high capacity link 200 miles long would probably be far cheaper than increasing the size of the satellite antenna by the required factor. This conclusion follows easily from the discussion in Section 3.2.2 and the cost analyses of Section 4.3.

We can now crudely estimate the required number of antenna beams in terms of the total traffic requirements. For uniform population distribution, 64 beams yield 100 Gbps capacity. If the beams are of equal size, and if the population resides uniformly over one-third of CONUS, then 192 beams would be required. Thus, crudely estimated, it appears that 200 antenna beams would have adequate frequency reuse

capability to provide 100 Gbps capacity for CONUS, if a few hundred miles of terrestrial links were used to disperse satellite traffic near saturated cities, and if 2.6 GHz were available.

To summarize, one beam could handle up to 6 Gbps, $\sim$ 200 beams could handle 100 Gbps, and intermediate loads would require an intermediate number of beams. Actually, as discussed in Section 3.3.2, the choice of antenna size and number of beams may be dominated by link margin requirements, and not purely by the issue of frequency reuse.

In the unrealistic limit of infinite traffic, a negligible portion could be handled by satellites. It is interesting to estimate the number of cable miles required to link CONUS customers without satellites. First divide metropolitan areas into 1) the 50 largest centers (populations above 770,000, or larger than Oklahoma City), 2) the next 200 centers (populations above 86,000, or Columbia, Missouri), and 3) the remainder of the population in suburban or rural areas; the total populations in these three classes are now $\sim$ 100, 56, and 55 millions respectively.

The miles of lines required to connect 50 population centers distributed uniformly over the United States' area of 3.6×10^6 square miles would be $\sim 50 \times (3.6 \times 10^6/50)^{\frac{1}{2}} = 14,000$ miles. This is comparable to the distances suggested by Fig. 3.2-3, which are 8000 miles for single links and 12,000 miles for dual redundancy. A similar geometric calculation for 200 additional centers yields 16,000 more miles of lines. Because population centers are clustered, fewer miles may suffice, but requirements for redundant lines and for circumventing geographic features partially compensate. Finally if we assume that user sites are distributed uniformly over one-tenth of CONUS, then $N(3.6 \times 10^5/N)^{\frac{1}{2}}$ miles might be required for additional local networks; this is 19,000, 60,000, and 190,000 cable miles for N equal to 1000, 10,000, and 100,000 user sites, respectively. Under these assumptions, the average length of a single link connecting any user to a nearest neighbor would be approximately 19, 6, and 1.9 miles, respectively. These mileages would all be reduced by a factor of 3.2 if the sites were distributed over only one percent of the land instead.

Although these numbers are crude estimates, it is clear that the miles required to link the 250 largest centers dominates until the number

of user sites exceeds some threshold, which appears to be on the order of 10,000. Subsequently the local lines would be of greater total length.

Thus, in the event the services spawned by inexpensive satellite communications outgrew the available spectrum resources, then the existing local distribution networks would already be so large that the cost of replacing the satellite long lines with terrestrial links would represent a small part of the total existing plant, provided that the fixed costs per mile then dominate the costs of long cables. It is fortunate that the level of traffic which would overwhelm the capacity of a satellite system would also move most intercity links above the free-fiber limit shown in Fig. 3.2-2; the conversion to terrestrial links might therefore occur for economic reasons in advance of total frequency saturation. Even if the reconversion to terrestrial links were motivated by saturation rather than economics, the cost penalty should be modest.

3.2.7 SIGNAL FORMS AND PROTOCOLS

Many of the questions concerning signal characteristics and protocols are not strongly dependent upon the topological form of the network. For example, although analog signals can be handled with considerable bandwidth efficiency, the need for such signals to pass through several switches, amplifiers, etc., and the requirements for system flexibility, cryptography, and bandwidth compression all strongly suggest that digital signals are best for large switched networks. The decreasing cost of digital circuits is rapidly making this alternative more attractive, even for video signals. For these reasons only digital systems are analyzed here.

One of the primary protocol issues concerns the method for handling the interface between satellite and terrestrial elements of an integrated wideband network. One approach would be to optimize the protocols and signal formats for the two elements separately, and then to provide whatever buffers are required to translate across the interface. For example, one system might employ packets and the other may rely on conventional switched circuits. Obviously each system must provide adequate command and control information to the common interface.

The amount of memory required at such interfaces between terrestrial and satellite elements, or between the users' terminals and the switched

network, would also depend upon the signal formats and protocols. In a wideband system the high data rate could lead to substantial memory requirements at switching nodes or system interfaces, so the use of small data packets and careful synchronization could be helpful. For example, a time-domain-multiplexed (TDM) satellite system which has its major switches in space could avoid most memory requirements if the up-link and down-link time-slot assignments were synchronized at the satellite.

3.3 SATELLITE SYSTEM ARCHITECTURE

3.3.1 INTRODUCTION

The satellite system comprises the satellite complex, the ground stations, and the associated command and control systems. In Section 3.3.2 those elements which impact the link margin are considered; they include the choice of modulation and data rate, antenna sizes, and transmitter powers. Although other factors such as receiver sensitivity are involved too, they generally have a less profound impact on the system. Section 3.3.3 discusses the architecture of the satellite switching system and its impact on system specifications and the efficiency with which the satellite transponders are utilized. The satellite antenna design enters this discussion, and this leads naturally to Section 3.3.4 which elaborates further on antenna design considerations. Section 3.3.5 combines the foregoing in a discussion of the total spacecraft communications system and the associated numbers of required components. The remainder of this section deals briefly with the subjects of command and control (Section 3.3.6), terrestrial signal processing equipment (Section 3.3.7), and the architecture of the satellite ground stations (Section 3.3.8).

3.3.2 SELECTION OF LINK PARAMETERS

3.3.2.1 Design Variables

The link parameters of interest here are those which determine the bit-error-rate (BER); they include the transmitted power P_T (watts), the gains of the transmitting and receiving antennas G_T and G_R, the path loss L, the receiving system noise power density N_o (W/Hz), and the link data rate R (bps). For reasons discussed in Section 3.2.7, only digital systems are considered here. The bit-error-rate depends upon the choice of modulation and the achieved ratio of bit energy E_B to noise power density N_o.

For a given type of modulation the bit-error-rate (BER) is a known function of E_B/N_o; this is discussed further in Appendix A3.1. This ratio is simply related to the ratio of received power P_R to noise N_o, as shown in Eq. (3.3-1), and is therefore related to the other link parameters:

$$P_R/N_o = R(E_B/N_o) = P_T G_T G_R L/N_o \qquad (3.3\text{-}1)$$

The path loss generally includes atmospheric attenuation as well as the more significant geometric losses, and the equipment attenuation losses can be included in the antenna gains G or listed separately.

The principal design variables of interest in Section 3.3.2 are R, P_T, G_T, G_R, and N_o. The satellite antenna gain is further expressed in terms of the number N of antenna beams it employs to cover Alaska, Hawaii, and the continental United States, the region of interest for the baseline design. There is essentially a one-to-one relation between the number of beams required and the satellite antenna gain because we assume that it is important to provide each state with approximately the same satellite performance. The number of antenna beams required is related to the peak beam gain. If we assume that the number of unique beams N is approxi-- mately equal to the total solid angle scanned by the satellite divided by the solid angle of a single beam (the angle inside the 3-dB contours), then, for example, 53-dB gain would correspond approximately to 100 beams, or in general:

$$G \overset{\sim}{=} 53 + 3 \log_2 (N/100) \qquad \text{(dB)} \qquad (3.3\text{-}2)$$

Although this relation is imprecise, it suffices for the following discussion.

3.3.2.2 Link Design Issues

The first issue is the choice of time-domain multiplexing (TDM) or frequency-domain multiplexing (FDM), in either case we have previously restricted ourselves to digital signals (Section 3.2.7). The importance of TDM results primarily from the requirements for significant switching in space. In Section 3.2.3 it was estimated that there should be hundreds of ground stations, each conveying traffic designated for any of the others. If single frequency bands were allocated to each of these station pairs, the number of bands could be 10^5-10^6, which could pose tremendous equipment problems. The fact that each of these bands would carry significantly different traffic loads seriously compounds the problem. Therefore the basic channel is assumed to be TDM within some fixed bandwidth. Ground stations with heavy traffic would employ several TDM

bands. Because the cost penalty for doing so appears modest, we further
assume that both the bands and time slots can be dynamically allocated,
and thus the result is a multiple-access FDMA/TDMA system.

Because the number of free parameters is large, it is conceptually
useful to regard the less variable ones as fixed so as to focus initial
attention on those which are more critical. These fixed variables can be
determined separately with little penalty. By simplifying the tradeoff
problems it is easier to understand the basic issues and to trace the
impacts of the various assumptions. Although computerized tradeoff
analyses employing large numbers of nonlinear cost equations are more
accurate in principle, the lack of understanding they convey makes them
less suitable for the present discussion.

Two variables which we initially regard as nearly fixed are the
receiver noise N_o and the ground station antenna diameter. The receiver
noise for the uplink includes perhaps 300°K of terrestrial blackbody
radiation, and economical uncooled superheterodyne mixers already have
nearly comparable noise temperatures. We assume a system noise tempera-
ture of 500°K, which would not vary much in any tradeoff analysis. The
nominal 8-ft antenna diameter for the ground stations can be varied
separately once the other variables and their costs are more nearly
determined. This issue is discussed further in Chapter 7.

We can now consider the basic tradeoff between data rate R, space-
craft transmitter power P_T, and the number of spacecraft antenna beams N.
We have assumed N_o is -201.6 dBW/Hz (for 500° system temperature), the
ground antenna gain as 52 dB (for an 8-ft aperture and 50% aperture
efficiency), E_B/N_o is 12.5 dB (for tamed f.m. modulation and a BER of
10^{-7}), and the satellite antenna gain G_T is $53 + 3 \log_2 (N/100)$ db
(coverage of United States). In addition we assume the path loss to
synchronous orbit is -211 dB, atmospheric and line losses are -3 dB, and
the margin for rain attenuation, etc. is 10 dB. With Eq. (3.3-1) these
assumptions permit the relationship between R, P_T, and N to be studied.

In Fig. 3.3-1 the data rate R is plotted as a function of the number
of antenna beams for transmitter powers of 10, 30, and 220 watts. To
begin, there are certain regions of the diagram which are undesirable.
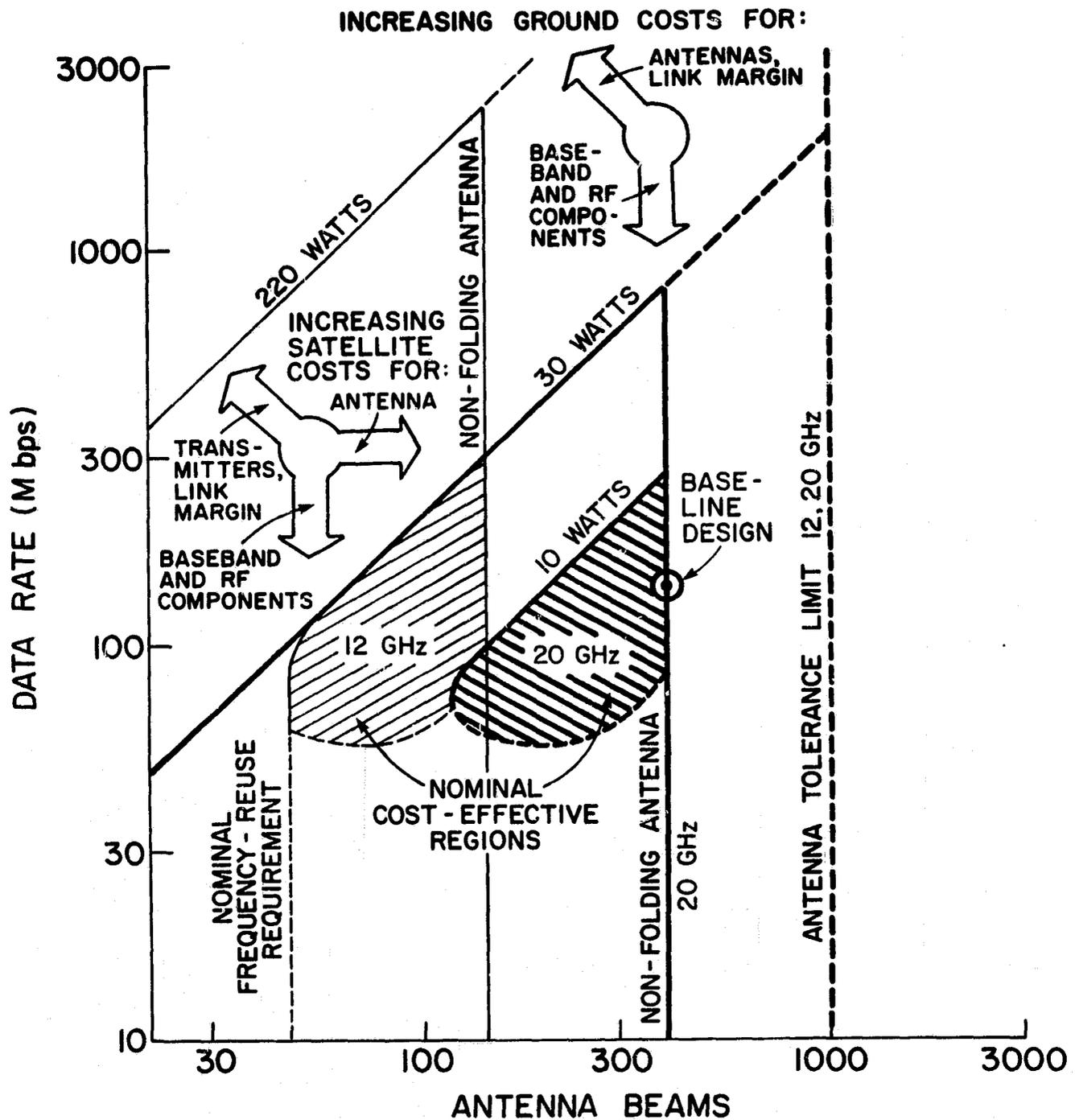
Figure 3.3-1. Cost-effective satellite specifications with respect to data rate and number of antenna beams, as bounded by maximum satellite antenna size, transmitter power, and component counts; 8-ft ground antennas were arbitrarily assumed, together with certain other system parameters.

For example, limits to the number of beams can be set by the maximum antenna size. In the figure there are bounds drawn for the 20 GHz band at 400 and 1000 beams. The bound at 400 beams corresponds to antenna apertures of 4 × 8 meters, approximately the largest size which can be launched by the space shuttle without folding the primary reflector. Use of larger folded reflectors at this frequency carries a significant cost penalty. The bound at 1000 beams is a soft one corresponding to readily available surface tolerances for folded 20 GHz antennas having standard surface deviations of 5×10^{-5} times the antenna diameter (Powell and Hibbs, 1977). In general the system parameters should be selected to the left of these bounds. A similar bound at 145 beams applies to non-folding antennas at 12 GHz.

The transmitter powers of 10, 30, and 220 watts correspond, respectively, to 1) a practical 20-GHz TWT expected to be available by 1985, 2) a near-maximum power 20-GHz helix TWT anticipated by the late 1980's (Frediani, 1978; Deml, 1978), and 3) the planned 220 watt H-SAT transmitter. To assume space transmitter powers above these could also entail significant cost increases, and so the preferred parameters lie to the lower right of these bounds.

Another bound can be set by frequency-reuse requirements. This constraint for the multi-gigabit systems hypothesized here lies in the range of tens of beams, although the bound can exceed 100 beams for the largest options over 30 Gbps.

Another bound consists of the data rate R desired for the most broadband service. If this service is full broadcast quality color video, then this lower bound might be ∿ 30-128 Mbps; 64 Mbps might represent a reasonable compromise. A softer but similar lower bound on data rate is set by the need to limit the number of separate r.f. sub-systems in the satellite. Each band requires receivers, transmitters, switch ports, etc., and similar costs occur on the ground.

These bounds together loosely define the desirable operating points for the communications space links. Motions in different directions on the chart incur different cost penalties, as suggested by the large arrows in the figure. The satellite costs are balanced between those

for the transmitters, antennas, and the other r.f. and baseband components. The ground costs are balanced between the necessary link margins and the r.f. and baseband component costs; they generally are reduced as the number of spacecraft antenna beams increases. The effect of this last observation is to favor larger spacecraft antennas as the traffic and therefore the number of ground stations increase.

3.3.2.3 Baseline Design and Options

Because a complete multidimensional non-linear minimum cost design would be prohibitively expensive and require an excessive number of arbitrary estimates, the baseline design parameters analyzed in the next chapters were selected to lie in the broadly defined "cost-effective regions" of Fig. 3.3-1. A further discussion of these design choices is contained in Chapter 7.

The number of antenna beams in the baseline design is 400, which is the maximum number that can be launched without folding the reflectors. The peak data rate R is 140 Mbps, or 128 Mbps average, which is adequate to handle one or two color broadcast video channels uncompressed. For most ground stations one such band would normally suffice; a 30-Gbps system with 1000 ground stations would average 30 Mbps per station. With such a large satellite antenna a 10-watt TWT transmitter yields a rain margin of 15 dB at 20 GHz, or a 4-watt solid state system could provide 11 dB margin. In general, the preferred range of specifications is ∿ 50-300 Mbps, 3-10 watts transmitter power at 20 GHz, and 100-400 antenna beams. With larger ground station antennas these ranges would shift correspondingly toward higher data rates, fewer beams, and weaker transmitters; the cost impact on the large anticipated number of ground stations suggests that little movement in this direction would be desirable, as discussed further in Chapter 7.

3.3.3 SATELLITE SWITCH ARCHITECTURE

3.3.3.1 Objectives

The primary objective of the satellite switch is to provide full connectivity for all ground stations, regardless of their shifting demands upon the system. To the extent practical the switch should also enable

all functioning transponders on the satellite to serve this varying load such that no link fails for lack of transponders unless all of the transponders are saturated. Since transponders account for much of the satellite costs, the efficiency with which they are utilized is an important consideration.

3.3.3.2 Switching at Radio Frequency

Any large multibeam satellite will generally have fewer transponders than antenna beams, and therefore one important reason to switch the signals at microwave frequencies is to efficiently share these transponders among the antenna beams. Efficiently sharing transponders can be important because the data rates of interest here are in the 50-300 Mbps range and the satellite capacities are in the 1-20 Gbps range (which implies ~ 10-100 transponders), whereas the number of beams is in the range 100-400, or several times larger. In addition, regardless of the number of antenna beams, microwave switches could be used simply to dispatch the traffic.

There are three r.f. switching schemes of interest here: the electrically scanned TDMA spot beam technique, the limited-range electrically scanned TDMA multiple spot beam technique, and the limited-range stepped TDMA multiple spot beam technique. The two former approaches have been described by Reudink (1978) and by Acampora et al. (1979); the latter is described here and by Staelin and Harvey (1979).

The scanning spot beam approach connects a single transponder to an electrically scanned phased array which has active elements associated with each array element. For example, in the scheme of Reudink et al. each transmitting antenna element has a separate small solid-state amplifier driven via an electrically switched phase delay. Because the many small transmitters are in phase for the desired beam, significant total transmitter powers can be achieved. The disadvantages are that use of more than one transponder requires the signals to be superimposed in each array element amplifier, which introduces serious intermodulation problems if more than a few transponders are employed. The need to employ few transponders also boosts the data rate, which can be partially compensated by the greater available space transmitter power, although

this does not help the uplink. The limited communications capacity of this approach suggests that it might be combined with several spot beams serving major traffic centers, as discussed by Reudink et al. (1978). The same research group subsequently showed that the transponder efficiencies would be low with this approach (Acampora and Davis, 1978; Acampora et al., 1979), and that multiple limited-range scanned beams were significantly more efficient. Another difficulty with the scanned beam approach is that for multiple transponders, one active device is required for each antenna array element, which generally equals or exceeds the number of available distinct antenna beams. Thus for large multibeam systems this could be a significant penalty, particularly if there are more than 100 beams.

The limited-range scanned TDMA multiple spot beam technique is a natural improvement of the previous scanning beam geometry. Rather than having multiple transponders each connected to all the antenna elements, the transponders would each serve their own separate subset. In the proposal of Acampora et al. (1979) there would be perhaps seven 500 Mbps transponders, each driving perhaps 20 phased array elements. These 20 elements would be arranged in a line, and the seven lines would be adjacent to one another; adjacent pairs would employ orthogonal polarizations. This configuration would thus incorporate 7 transponders and 140 transmitter phase shifters and antenna elements, and could handle 3.5 Gbps. If each transmitting antenna element were one watt, then each downlink would have 20 watts. If one of these 20 transmitters should fail, then that scanning beam would exhibit extra sidelobes of only 25 dB.

High transponder efficiency requires equal traffic in each strip; Acampora et al. show how this might be accomplished to first order by sizing the feed elements so that the strips are of different widths and are carefully placed across the service area. In addition, adjacent strips would overlap somewhat, although with degraded antenna gain, and one could therefore couple as many as three transponders to the same ground station. The difficulty with this approach is that there should be more than 10 transmitters per transponder if the failure of one is not to produce sidelobes over 20 dB. For satellite capacities of many gigabits per second this implies a great many transmitters and phase shifters, particularly if the data rate is a more modest 64–128 Mbps. For example, 12.8 Gbps at

128 Mbps per band implies as many as 1000 transmitter phase shifters and antenna elements.

The limited-range stepped TDMA multiple spot beam approach described by Staelin and Harvey (1979) is similar to the previously described limited-range scanned beam technique, except that each transponder would be connected to only one feed element at a time rather than to a set of several phased elements. These connections would be made via broadband low-loss ferrite or diode switch binary trees such that a typical transponder might serve 8-16 feeds. Furthermore, the switches would be configured so that each feed could be served by up to three alternative transponders. The geometry is shown in Fig. 3.3-2. The set of feeds normally serving each transponder would be arranged to yield approximately equal traffic loading on each transponder. This flexibility, plus that afforded by sharing traffic from one ground station on as many as 6 adjacent beams (albeit with reduced rain margins), should be more than adequate to ensure almost 100 percent transponder efficiency, even if one or more should fail.

The disadvantage of this approach is the relatively large number of ferrite or other switches required, approximately one per feed for the uplink, and the same for the downlink. Furthermore, placing feeds such that their beam cross-over points have reasonable antenna gain is difficult, as discussed and resolved in the next section; this problem is easier with phased-array feeds. Nonetheless, this is an extremely attractive approach to the problem of r.f. switching, particularly for satellites with very large capacities (above 5-10 Gbps), and is employed in the baseline design.

3.3.3.3 Switching at Baseband

The r.f. switches described in the previous section were used primarily to connect each ground station to one of perhaps two or three transponders allocated to that station. These input transponders must then be connected to the appropriate output transponders; this is most easily done at baseband or with demodulated digital signals. The receiving and transmitting portions of the transponders would thus perform the r.f.-baseband conversion for each band and would interface with the baseband switch, perhaps via modems; see Fig. 3.3-2.
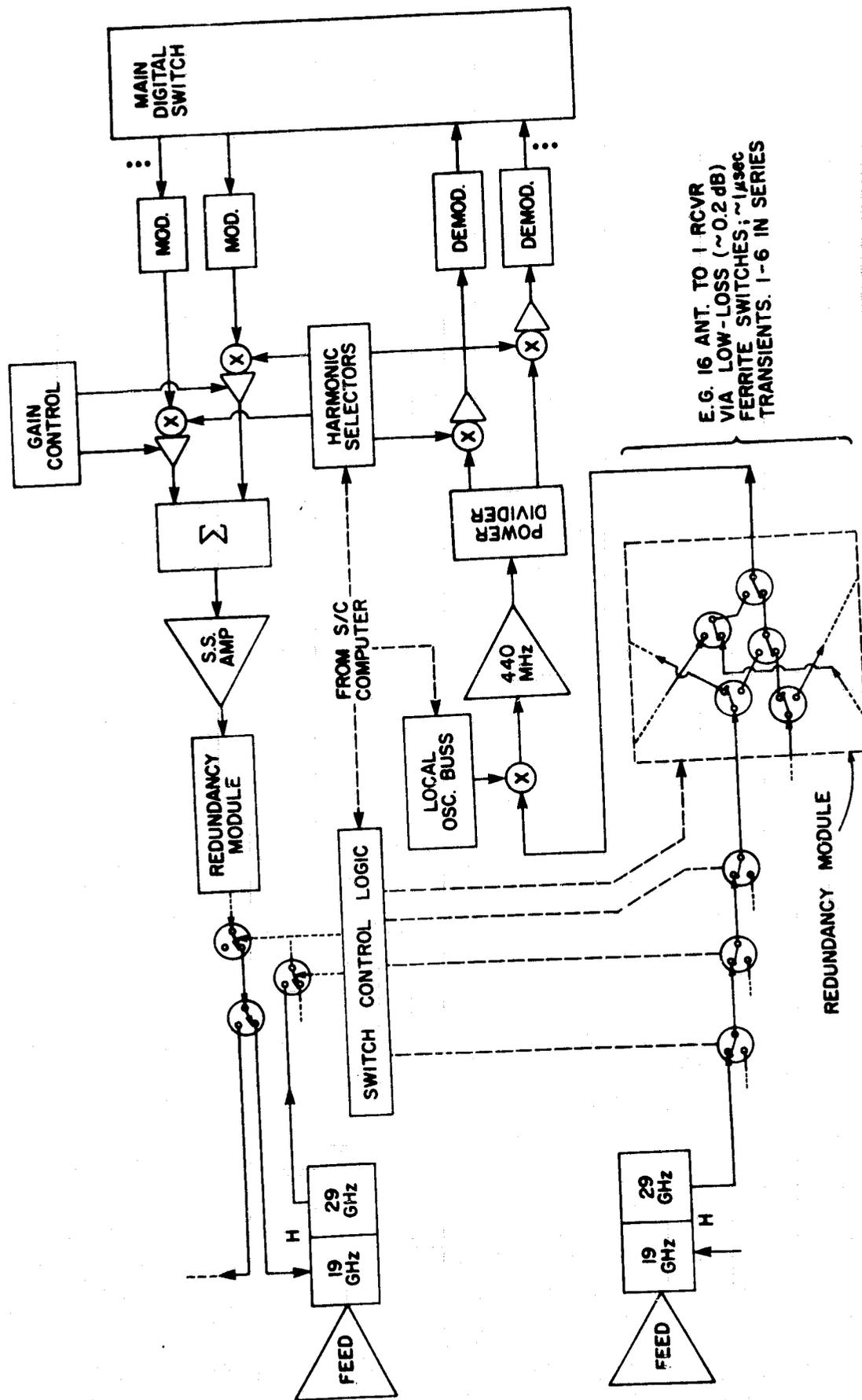
Figure 3.3-2. Satellite communications system. Binary trees of ferrite switches buffer feeds to r.f. circuits, and tunable translators and modems buffer r.f. circuits to the fast baseband digital switch which reconfigures many times per TDMA cycle.

During each TDMA time slot the switch would couple its input and output ports, and then would reconfigure between slots. If this switch were a digital logic switch operating at 140 Mbps, for example, then the switch could be reconfigured instantly without the need for any gaps. However, if memory is to be avoided on the spacecraft to perform time-slot translations, then the ability to reconfigure instantly will be limited by the duration of one bit compared to the timing tolerances which are achievable at the ground stations.

It is reasonable to synchronize the ground and space systems individually to within one bit, so that one might suppose that no data gap much larger than this would be needed to separate time slots. However, the inter-slot gaps should instead be established to permit the synchronization of the demodulators for each new TDM burst of data; this generally requires many bits. All ground stations would have to be separately synchronized to the spacecraft because they are separated by different distances. One-bit synchronization at 100 Mbps implies 10 nsec accuracy.

If M transponders are employed, then the switch should be M × M, which is straightforward if M is perhaps fewer than 10. However, a 10 Gbps system with 100 Mbps data rates would require a 100 × 100 switch, which is very large. As discussed in Appendix A4.4, one of the most efficient architectures is the rearrangeable Clos-type switch which requires approximately 12 M $\log_{10}$M elementary switches for M inputs and outputs; this number is 2400 for M equal to 100. With integrated GaAs switches, the switch power dissipation and size could be quite modest for operations on the order of hundreds of Mbps. Even silicon technology could probably be employed if necessary.

The switch could be driven by circulating memories which repetitively drive the switch in the desired sequence of patterns once per TDMA cycle. If the smallest burst contains approximately 1 kbit of data, then a 100 Mbps data rate and a 4-msec TDMA cycle (the baseline design) would imply 400 steps per cycle and a circulating memory of 400×2400 bits = 10^5 bits.

The design of the TDMA timing must also accommodate the requirement that each ground station may simultaneously have traffic destined for a

significant fraction of the other ground stations, and there should be sufficient time slots available to accommodate at least one packet for each such other station. A 30-Gbps system with 1000 ground stations would average 30 Mbps per station. If the smallest packet corresponds to a rate of 256 kbps, then 30 Mbps implies traffic is being sent to a maximum of 120 other ground stations, and thus 120 time slots would be adequate; the baseline design has 400 such slots per band.

A fundamental question is whether there exists a TDMA assignment for any given traffic matrix that ensures that all the transponders and TDMA time slots can be used efficiently. Fortunately this problem has been solved affirmatively and is discussed by Acampora et al. (1979).

3.3.3.4 Baseline Design

The baseline system incorporates both r.f. and baseband logic switches. The r.f. switches are binary trees of low-loss ferrite switches arranged as shown in Fig. 3.3-2. The bandwidths of these switches, many of which have flown in space, can be 1 GHz or more. The insertion loss can be 0.2 dB.

Because a single feed at a single frequency can be connected to only a single transponder at one instant, a high-traffic beam using several bands must either interleave the bursts at different frequencies so the transponder can be tuned to each frequency in sequence, or transponders in adjacent beams or satellites must be employed. Frequency multiplexers can alternatively interface one feed to several transponders at several different frequencies, but with an insertion loss of perhaps 1-3 dB. The baseline satellite might have one tenth of its 12.8 Gbps traffic originating in the New York beam, which would require 10 128-Mbps bands to handle it. With frequency diplexers on each beam, the New York beam and the seven overlapping beams around it could together accommodate 14 bands.

The use of redundancy modules in the ferrite switch matrix (Fig. 3.3-2) provides a degree of switching flexibility that should be more than adequate to handle varying loads and element failures with nearly 100 percent transponder efficiency, even on a single satellite.

The baseline design employs modems so that the baseband switch (Fig. 3.3-2) is a logic switch without any cross-talk problems. By

demodulating and remodulating, the link margins and beam cross-talk problems are also significantly reduced.

The baseband switch is assumed to be of the rearrangeable Clos type, or to have a similarly efficient architecture. Its state would be changed as often as once per basic packet, i.e., once per 9 microseconds.

The baseline TDMA timing diagram and some of its variations are illustrated in Fig. 3.3-3. The basic 4.16-msec TDMA cycle would be commensurate with typical television frame rates, so that four packets would accommodate one video half-frame. Periodic packets could accommodate data rates of 256 kbs to 32 Mbps or more. Each packet would have a 200-bit header for identification and control purposes, plus a preceding gap adequate to handle the satellite switching and modem synchronization requirements. The gaps necessary to accommodate the ferrite switch transients should be at least one microsecond long; they are specified here to be at least 5-microseconds, which enables 40 3-Mbps packets to be accommodated per cycle. Since the number 40 is larger than the maximum number of beams (36) accessible to any one baseline transponder, no beam should ever remain unserviced.

Each 4.16-msec TDMA cycle would be preceded by a 112-μsec access block containing space for 80 200-bit access and control words that could be used for communications with ground stations. Whether these slots alone are used for this purpose, or whether a single ground station aggregates all the commands would not impact the cost of the baseline system, and so this issue has not been examined.

3.3.4 ANTENNA DESIGN

3.3.4.1 Objectives

The spacecraft antenna has two important functions; it must be capable of the desired degree of frequency reuse and it must have sufficient gain to reduce the ground station antenna requirements to modest levels so as to minimize total system costs. Both these requirements become more severe as the total system traffic grows, although the dominant constraint initially is probably link margin requirements, as discussed in Section 3.2.2. That discussion led to estimates for an optimum 20/30 GHz system of

TIMING DIAGRAM FOR 105-MHz BAND

4.16 msec/cycle
(240 cycles/sec)

133 KBITS

952μs | 952μs | 952μs | 952μs | 952μs
112μs

80 200 BIT SLOTS

200-BIT HEADER
48-μsec GAPS

4 BLOCKS @ 133 KBITS,
133 KB/4.16 msec = 32 Mbps

ALSO POSSIBLE, FOR EXAMPLE

89μs

5-μsec GAPS
200-BIT HEADER

10 BLOCKS @ 12.4KB + 0.2KB
HEADER + 5μs GAP
12.4 KB/4.16 msec = 3 Mbps

1.4μ sec
7.3μs

0.2-μsec GAPS
200-BIT HEADER

10 BLOCKS @ 1.04 KB DATA
+ 0.2KB HEADER + 0.2μs GAP
1.05 KB/4.16 msec = 250 Kbps

4 32-Mbps CHANNELS

OR
40 3-Mbps CHANNELS

OR
400 250-Kbps CHANNELS

Figure 3.3-3. Baseline design TDMA timing diagram showing representative variations; mixed block sizes would be typical mode.

100-400 beams and many ten's of transponders. It also explored some of the relationships between the choice of antenna and the nature of the associated r.f. switching system.

The requirements for communications capacity led to a baseline design having 400 beams and 50 transponders, a ratio of 8 to 1. Each transponder handles two 105-MHz bands, so that a 2.6-GHz frequency allocation would require a minimum of four-times frequency reuse in a 12.8 Gbps satellite. A three-satellite system would have 12-times frequency reuse. An allocation of 450 MHz, such as might be obtained in the 12/14 GHz bands, would require frequency reuse of 24 times per satellite. The sidelobe level required for each beam must be such that the aggregate interference from all co-frequency beams is less than approximately 20 dB if link margin is not to be unduly penalized. Figure A3.1-8 presents the tradeoff curves for isolation versus loss of link margin, assuming TFM QPSK modulation.

The problem is made more severe by the nominal BER specification of 10^{-7}. One would like to assume that the interfering signals add incoherently, but in fact their oscillators will be synchronized to within the 0.5 percent implied by a baud length of 200 cycles (140 Mbps at 28 GHz). Such a frequency difference would correspond to being in the adjacent band, hence the synchronization. If we assume the relative phase of any oscillator is fixed within each baud, but otherwise random, and that two oscillators are "in phase" if they are within one radian, then the probability that n interfering sources are all in phase is only $(1/2\pi)^n$. This is less than the BER only if n is 9 or more. In fact, the envelope of the sum of single-frequency random-phase sinusoids is Rayleigh distributed, and the BER should be related to the sidelobe specifications on such a more complete basis.

In the absence of such a complete analysis, worst-case losses in link margin were plotted in Fig. A3.1-8, which assumes that all the co-channel interfering signals add in phase. If they are more nearly incoherent, then the sidelobe requirements are relaxed several dB. In the worst case one interfering signal 20 dB below the primary signal would result in the loss of approximately one decibel of link margin, and six such coherent signals would cost 8 dB of margin. If the six interfering signals were each reduced to 35 dB, then the margin loss would be only

1 dB. With the possible exception of the New York beams, one would normally not try to reuse frequencies in beams separated less than two or three beamwidths, so that the interfering signals would normally be seen in the second sidelobe or beyond. Additional isolation is provided by using polarization diversity for reuse within such a radius. A system requiring 12 times frequency reuse within CONUS is thus feasible if the higher order sidelobes approach 35 dB; in this case only 1 dB loss results. The sidelobe specifications might be relaxed to 8.5 dB and 24 dB if one or six interfering signals are accommodated, respectively, for a margin loss of 4 dB. Still other tradeoff possibilities can be obtained from the figure.

On the basis of typical system analyses, we may assume that the first antenna sidelobes should be no greater than $\sim$ 20 dB, and that they should fall away fairly rapidly to 30-35 dB or less. The polarization isolation should generally be at least 20 dB within a single beamwidth. More aggressive frequency reuse would require more stringent sidelobe specifications.

In addition to having a large number of beams and transponders, each with low sidelobes, there is a second important constraint on the antenna design. This is the requirement that the system provide sufficiently uniform coverage of the service area that no present or potential future ground station is burdened with excessive link margin requirements. In the present case, where there might be 1000 ground stations scattered across the United States every hundred miles or so, there is no good alternative to this policy. System economics suggests that a significant fraction of the ground stations should not be penalized with larger antennas, and related expenses. Requirements of system flexibility and political acceptability also make it undesirable to penalize any ground station more than a few dB because of its geography.

3.3.4.2 Coupled Feed Elements and Phased Arrays

Multibeam antennas incorporate many feed apertures; a single signal may pass through one, several, or all of these. In this section the last two alternatives are considered. In each case one of the major problems is resolution of the basic conflict between the requirements for low sidelobes and for uniform coverage. The problem is that two feeds can yield antenna beams which increasingly overlap as the feeds approach one another,

but once they touch, the feeds must be made smaller in order to approach further. As they become smaller, their diffraction beamwidth then increases at the expense of either spillover, sidelobe level, or dissipative losses.

One way to resolve that conflict is to couple adjacent feed apertures in small overlapping local clusters, as discussed for example by Ohm (1979). In this approach each feed connects to its designated electronics, but the same electronics is also weakly coupled to the immediately surrounding feed apertures with amplitudes and phases such that the local cluster serves as a hyper-feed with improved sidelobe characteristics. Since each feed may be part of several overlapping clusters, the hyper-feeds may overlap to any desired degree.

The principal difficulty with this approach is its complexity. If each hyper-feed consists of 7 feed apertures, then there must be 7-port hybrid networks for each aperture as well as an active element. The active elements are useful to compensate for the signal losses necessarily incurred in the hybrids. When the number of feed apertures increases beyond twenty or thirty, then this approach can become quite cumbersome and expensive; it clearly appears to be inappropriate if there are more than 100 overlapping beams.

Electrically phased arrays offer a more efficient method for obtaining many of the same objectives. In this case all or some subset of the feed apertures are each coupled to the same transponder by means of electrically controllable phase shifters. Reudink (1978) has discussed a system where all the apertures drive one transponder, and Acampora et al. (1979) present a configuration where linear subsets of the apertures drive each transponder.

For reasons discussed in Section 3.3.3.2, the configuration of Acampora et al. has advantages when several transponders are employed. The antenna concept is simple. Each transponder drives a set of electrically controlled phase shifters, amplitude modulators, and the associated feed apertures, which are arranged in a continuous straight line in the focal plane of the cylindrical primary aperture. The image on the ground is a single spot beam scanned linearly across a portion of the total service area. The optics can be folded if necessary.

The sidelobes can be controlled parallel to the linear array by means of controllable phase and amplitude tapers, and the sidelobes in the orthogonal plane can be controlled by the fixed feed excitation taper in that direction. In the case of the transmitter, it may be desirable to provide active elements for each feed aperture because many low-power solid-state amplifiers can thus be combined, as discussed briefly in Section 3.3.3.2. Fortunately only one receiver per transponder would be required if low-loss phase shifters are used. In general, the number of feed elements would equal or exceed the number of possible orthogonal beams. The sidelobe problem increases when one of these active elements fails, and can be serious if high-order frequency reuse is desired. If one of ten amplifiers in a line fails, then a new broad sidelobe of $\sim$ 20 dB is created and the on-axis gain drops $\sim$ 1 dB. The new sidelobe would not necessarily affect reuse by other parallel linear arrays a few beamdiwths away.

The same conflict between sidelobes and coverage arises in this configuration when adjacent linear arrays are positioned. The solution proposed by Acampora et al. is similar to that described by Staelin and Harvey (1979). By employing a polarization-diplexing subreflector (or primary reflector) it is possible to interlace the images of two cross-polarized sets of linear arrays. This effectively permits the line feed aperture to be doubled along the axis perpendicular to the scan axis, which is adequate to achieve an acceptable sidelobe-coverage compromise. The result is that there can be as many independently scanned spot beams on the ground as there are transponders. Each spot beam is constrained to scan a straight line, and an array of such lines covers the service area, with alternate beams in alternate polarizations. In general, one would probably employ two different primary reflectors, one for transmitting and one for receiving. Although they could be combined, it would be difficult. The satellite might resemble the baseline design illustrated in Fig. 3.3-11, except the feeds would be phased arrays instead of circular corrugated horns.

The most important virtues of this general class of antennas are 1) very low sidelobes can be achieved, so that they do not limit frequency reuse, 2) the number of independent solid-state amplifiers which can be

devoted to a single beam can range from one to the number of feed elements in a line array; ten or more per line are desirable if modest sidelobes are to result when one fails, and 3) the only electronics increasing with the number of feed elements are the phase-shifters required for both transmitting and receiving, and perhaps transmitter and receiver elements, unless low-loss phase-shifters operating at r.f. are used.

The disadvantages are 1) large numbers of transmitter and receiver elements (one per feed element) are required for high capacity satellites, unless the phase-shifters are at r.f., 2) either frequency multiplexers or more than several hundred beams are required if more than $\sim$?0 transponders are used; these multiplexers would interface the active elements with the antenna, and therefore might be required in very large numbers, and 3) in the desirable events that the phase shifters are broadband and at r.f., and that any multiplexers follow the phase-shifters, then there is only one excited beam per line, even though more than one transponder may serve that beam; for some traffic loading patterns this may be inefficient. If the multiplexers precede the phase-shifters, then very large numbers of multiplexers and phase-shifters are required. For these reasons the system described below becomes attractive when many beams and transponders are required.

3.3.4.3 Independent Feed Elements; Baseline Design

The offset Cassegrain reflector antenna has several well known advantages for multibeam antennas, including light weight, simplicity, broad bandwidth, and performance. In order to scan many beamwidths off-axis, it is necessary to increase the f/D ratio, however. For the systems of interest here the number of beams would be approximately $100(f/D)^4$, where f and D are the antenna focal length and diameter, respectively. Some of the issues have been discussed by Ruze (1965), Ohm (1974), and others.

Although a 400-beam antenna would require an f/D ratio greater than unity, the structure could be compact because hyperbolic subreflectors can magnify the effective ratio. Extensive computer computations are necessary to prove any given design, but there is no doubt that high-performance antennas with many hundreds of beams can be obtained.

Corrugated circular waveguide horns are excellent feeds for this type of antenna because of their very low sidelobes and smooth taper. Furthermore, the aperture field distribution can be made independent of frequency for up to octave bandwidths (Dragonne, 1977). This property aids in the equalization of ground patterns for a two-frequency system.

The basic problem is the conflict between sidelobes and the severity of the nulls between adjacent beams. To produce high beam-crossover gains, the angular separation between feeds should be minimized; hexagonal feed packing has advantages. Some additional spacing must be included to accommodate the feed wall thickness, which generally is $\sim \lambda/4$ for corrugations. This spacing can be reduced if the feed apertures are hexagonal and if the corrugations are omitted from the outer portions of the feeds where they touch. Such feeds can be made dual-frequency by employing one band of corrugations to detach one frequency from the horn wall, and then a second band tuned to the second frequency for the same purpose. In this fashion five frequencies were combined in a single horn in the SMMR microwave spectrometer flown on the Seasat and Nimbus-7 satellites in 1978 (Gloersen and Barath, 1977).

The best performance is obtained with the feeds packed tightly together; the other degree of freedom is the size of the primary aperture or, more precisely, the taper of the aperture excitation. If the image of a single feed cluster on the ground has unacceptably deep nulls for any taper, one approach is to superimpose the patterns for a completely different feed cluster, perhaps using a different primary reflector. Alternatively, two independent feed clusters could share one primary reflector if it or a subreflector had two different effective surfaces, one for each polarization. The baseline design incorporates two primary reflectors, each of which is polarization diplexed, so that the patterns of four independent clusters are superimposed. Ways in which such patterns can be superimposed for square and hexagonal clusters are illustrated in Fig. 3.3-4, and a sketch of such an antenna appears in Fig. 3.3-11.

The next several figures present the tradeoff curves relevant to the design of the baseline antenna. The patterns were computed assuming the corrugated feed supported only the dominant HE_{11} mode, which is reasonable
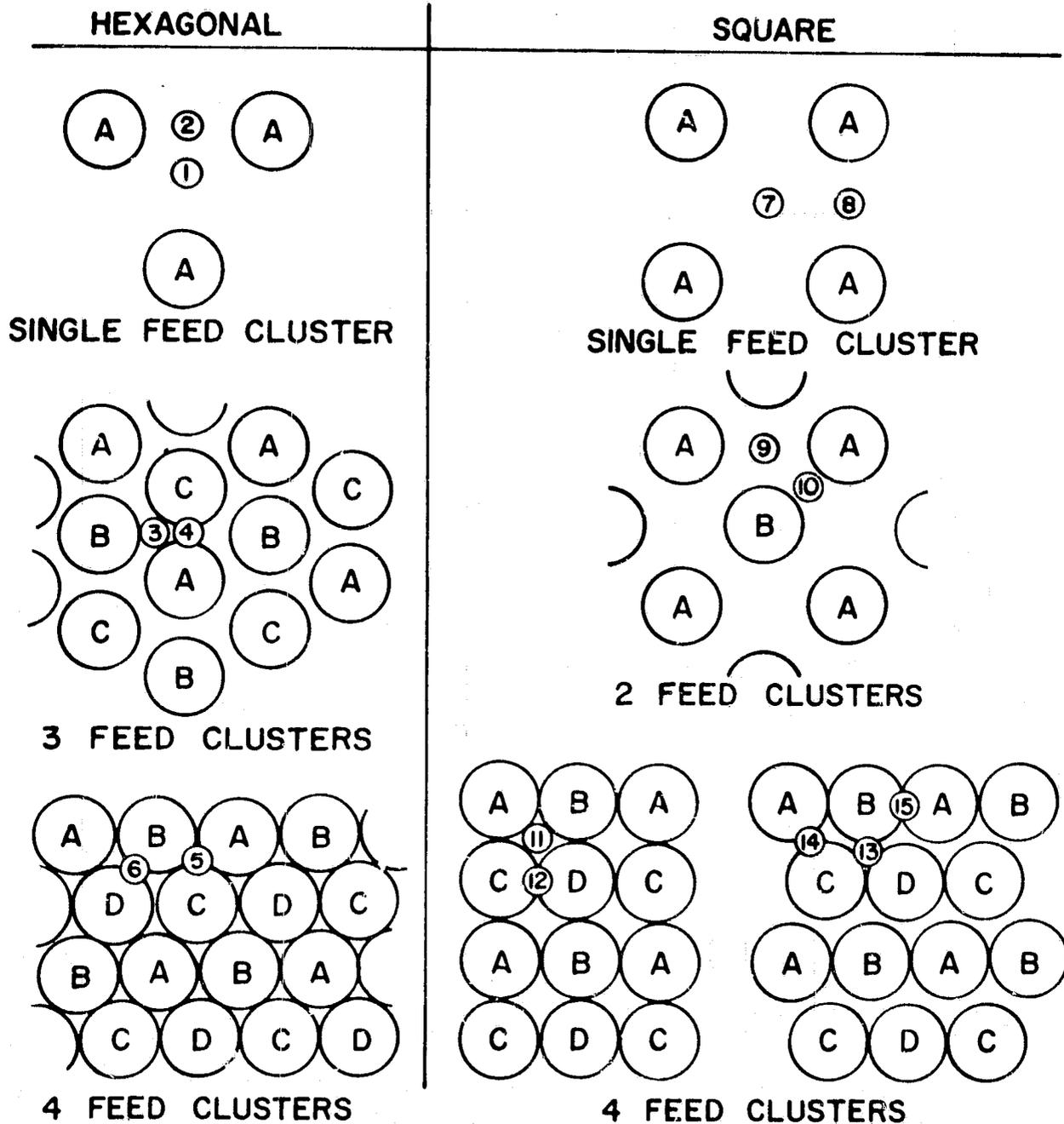
Figure 3.3-4. Alternative ways to overlap feed patterns A, B, C, D; numbers refer to points in Table 3.3-1, which lists null depths (dB).

if the feed is more than two wavelengths in diameter, and if the flare angle is small. The feed aperture fields were assumed to be:

$$\overline{E} = \hat{x} \, \overline{E}_o \, J_o \, (2.4048 \, \frac{r}{a})$$

where $\hat{x}$ is a unit vector, J_o is a Bessel function, a is the feed aperture radius, and r is a radius vector in the feed aperture. This feed excitation pattern is Fourier transformed to yield the pattern in the plane of the primary reflector. This field is assumed to have zero phase and is again Fourier transformed over the extent of the aperture to yield the far fields. Because the fields were represented by a finite grid, there are small computational errors in the far sidelobes.

Figure 3.3-5 shows how the two major gain-loss mechanisms depend upon the illumination taper for the primary reflector. Losses for 19 GHz were calculated assuming that the feed patterns were purely diffraction limited. The total loss relative to an ideal radiator refers to the degradation of on-axis gain by spillover losses at small tapers and by aperture illumination efficiency for large tapers. The additional gain reduction at points L and M results from the increasingly narrow character of the antenna patterns as the size of the primary reflector is increased in order to increase the reflector taper and reduce the associated side-lobes. It is clear from this figure that the gain advantage in the nulls is very significant for the 4-feed-cluster configuration, particularly at 29 GHz.

Figure 3.3-6 presents the antenna gain at the beam-crossover points relative to the on-axis gain which would result if the same primary aperture were illuminated with 100 percent efficiency and without spillover; the units are dB. Consider the worst null, which is point L at 29 GHz for a single feed cluster. The best performance is obtained at point 1 in the figure, which results in 8.5 dB loss for a 2-dB taper. This loss corresponds to an aperture efficiency of only 14 percent. The efficiency at 19 GHz is even less for this taper; a more optimum solution is point 3 in the figure, which yields 13 percent aperture efficiency at both frequencies for a taper at 29 GHz of 2.5 dB. The corresponding points on the figure for the four-feed-cluster configuration are labeled 2 and 4; they correspond to aperture efficiencies at the worst null of ∿ 37 percent for a
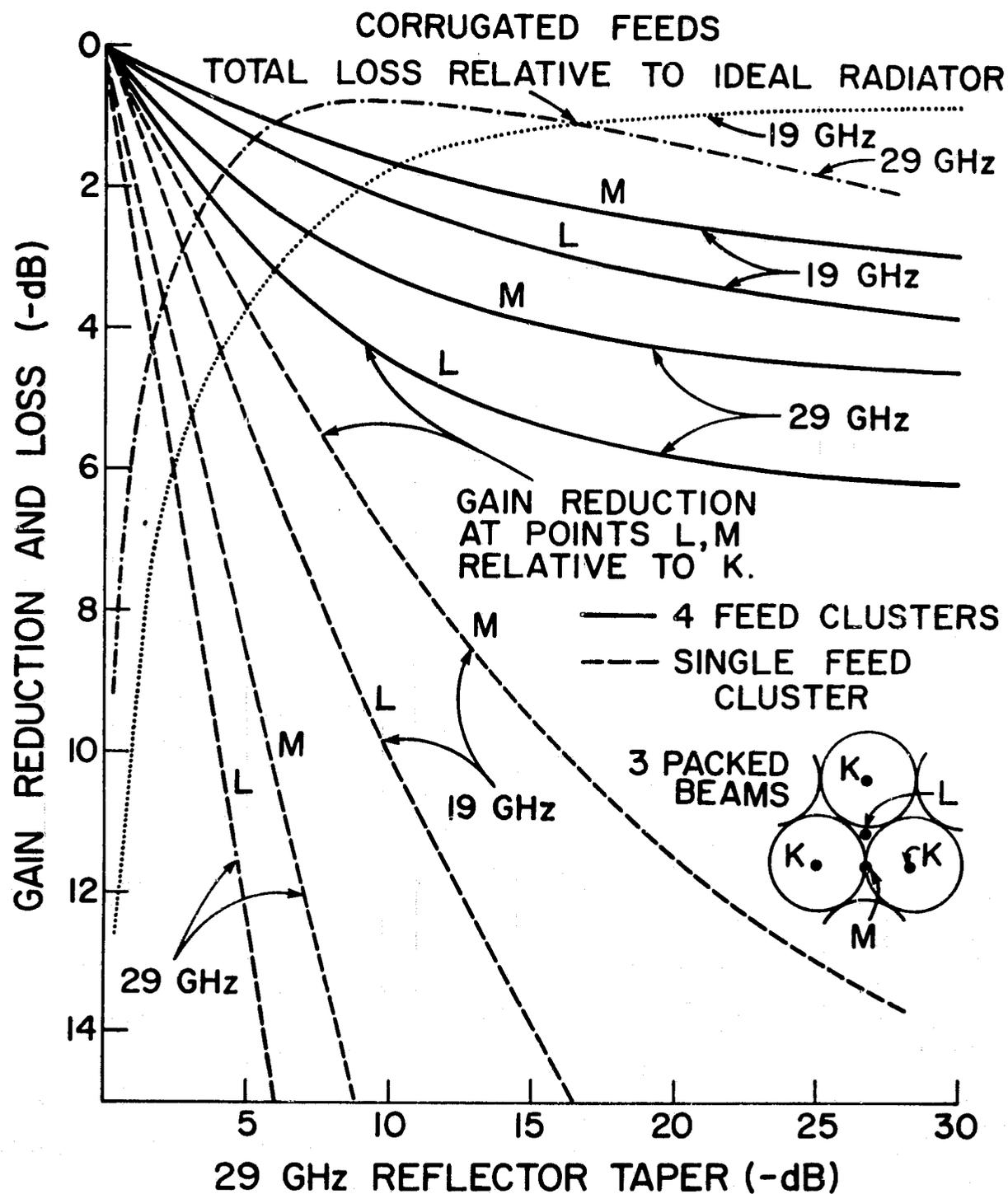
Figure 3.3-5. Antenna gain reductions due to spillover (particularly at low tapers) and to under-illumination (particularly at large tapers), for corrugated dual-frequency feeds at 20/30 GHz.
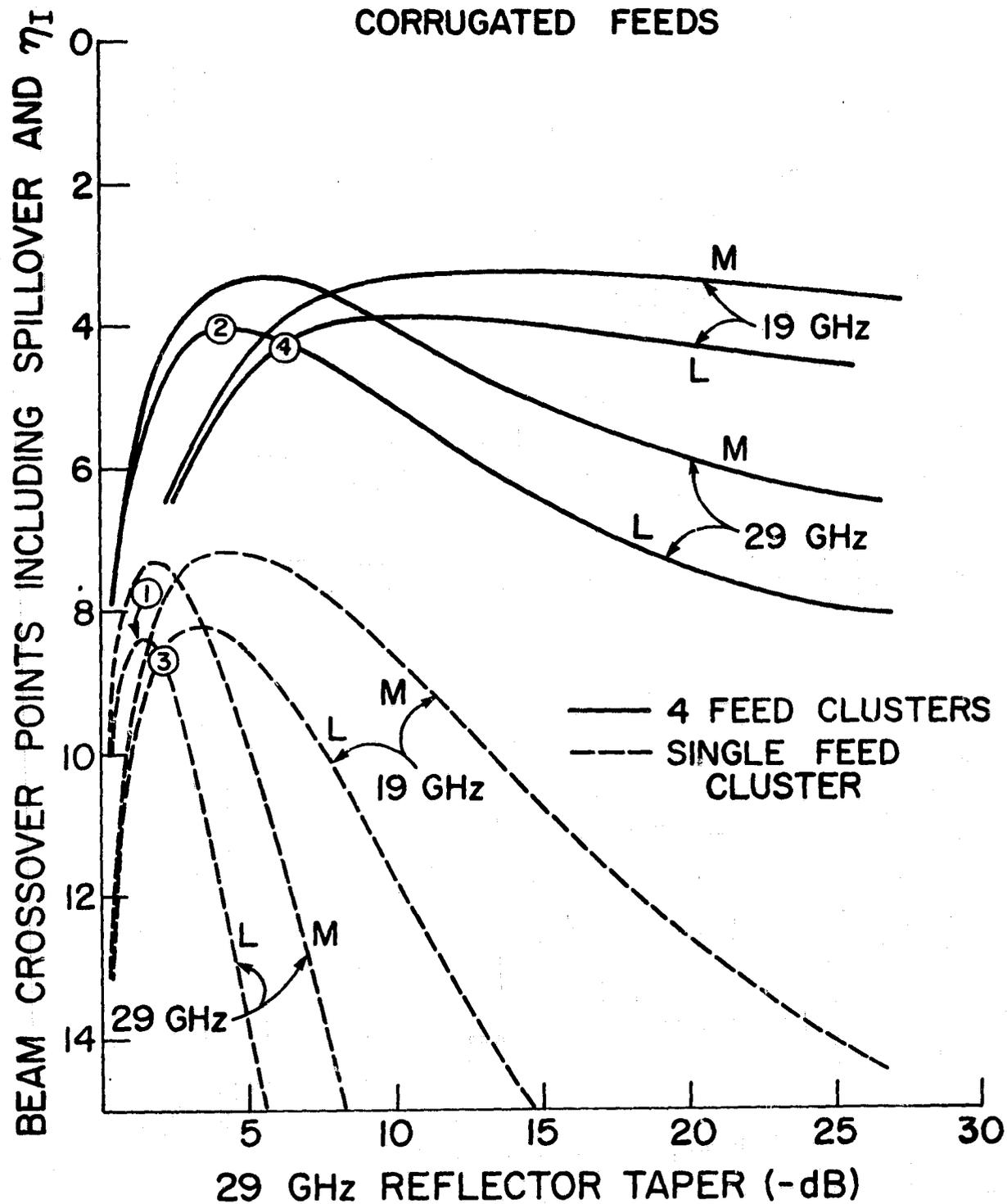
Figure 3.3-6. Gain at beam cross-over points relative to on-axis gain with 100% aperture efficiency. Points 1 and 2 are optimum for single frequencies, and points 3 and 4 are best for dual-frequency operation.

taper of ∿ 6 dB. The on-axis efficiencies for a 6-dB taper at 29 GHz would be approximately 48 and 79 percent for 19 and 29 GHz, respectively, neglecting other losses due to poor surface tolerances, etc. Thus the use of four feed clusters improves the gain in the nulls by approximately 4.5 dB.

The sidelobe levels are presented as a function of the 29 GHz taper in Figs. 3.3-7 and 3.3-8 for corrugated and non-corrugated feeds, respectively. Corrugated feeds have sidelobes which are approximately 1 dB less for tapers near 6 dB. The difference in sidelobe levels for corrugated and non-corrugated feeds may be even less than this because the points labeled 3 and 4 on Fig. 3.3-6 fall at larger tapers, 3 and 10 dB. Corrugated feeds also have very slightly larger efficiencies, 17 and 40 percent, at the beam-crossover points for single-cluster and four-cluster configurations. The question of corrugated versus non-corrugated feeds may ultimately depend on the specific cost situation.

The antenna patterns which result for a 6.4-dB taper at 29 GHz are plotted in Figs. 3.3-9 and 3.3-10 along the axis connecting adjacent feed centers. Even when the sidelobes are near 20 dB, there are sufficiently large solid angles in the nulls nearby where the gain is quite low enough to provide the protection necessary for significant frequency reuse.

A more complete comparison of the various feed configurations is contained in Table 3.3-1, where the optimal tapers, sidelobe levels, on-axis efficiencies (dB loss), and the null depths (dB relative to on-axis gain) are listed for the 15 different points identified in Fig. 3.3-4. The single-frequency part of the table presents the results if the design is optimized for 19 or 29 GHz alone, and the 2-frequency entries result when both frequencies share the same feeds and are optimized jointly. Corrugated feeds were assumed. The table entries relevant to the baseline design are points 5 and 6 for the 2-frequency case. This configuration seems to be nearly optimum for the present problem.

A view of the spacecraft illustrating the baseline antenna design is found in Fig. 3.3-11. The antenna employs two rigid mesh or solid surface reflectors, each of which drives a polarization-diplexing sub-reflector and two feed clusters. Thus the 400-beam baseline design has four clusters of 100 corrugated feeds each, arranged in hexagonal
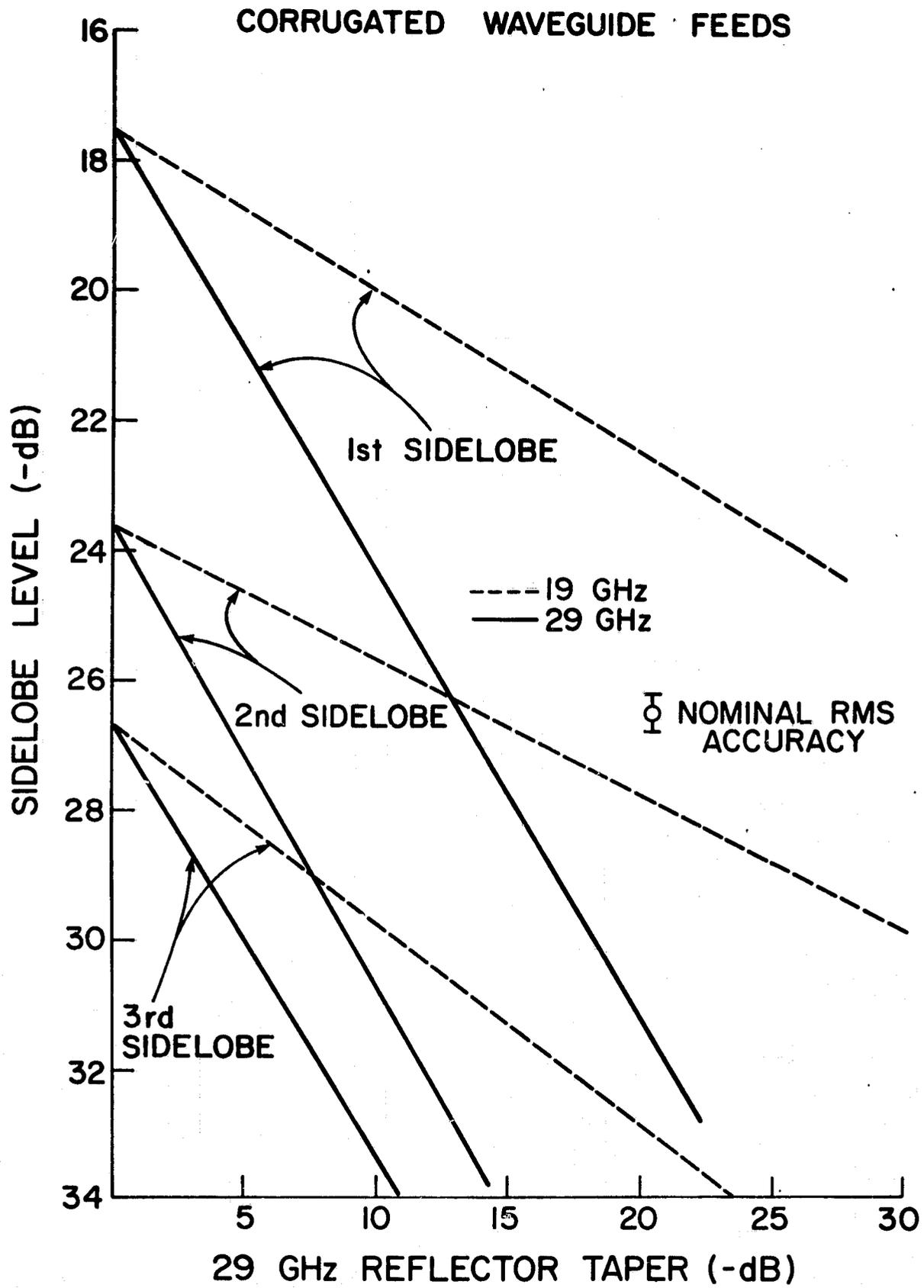
Figure 3.3-7. Sidelobe levels for circular corrugated dual-frequency waveguide feeds as a function of 29-GHz aperture excitation taper.
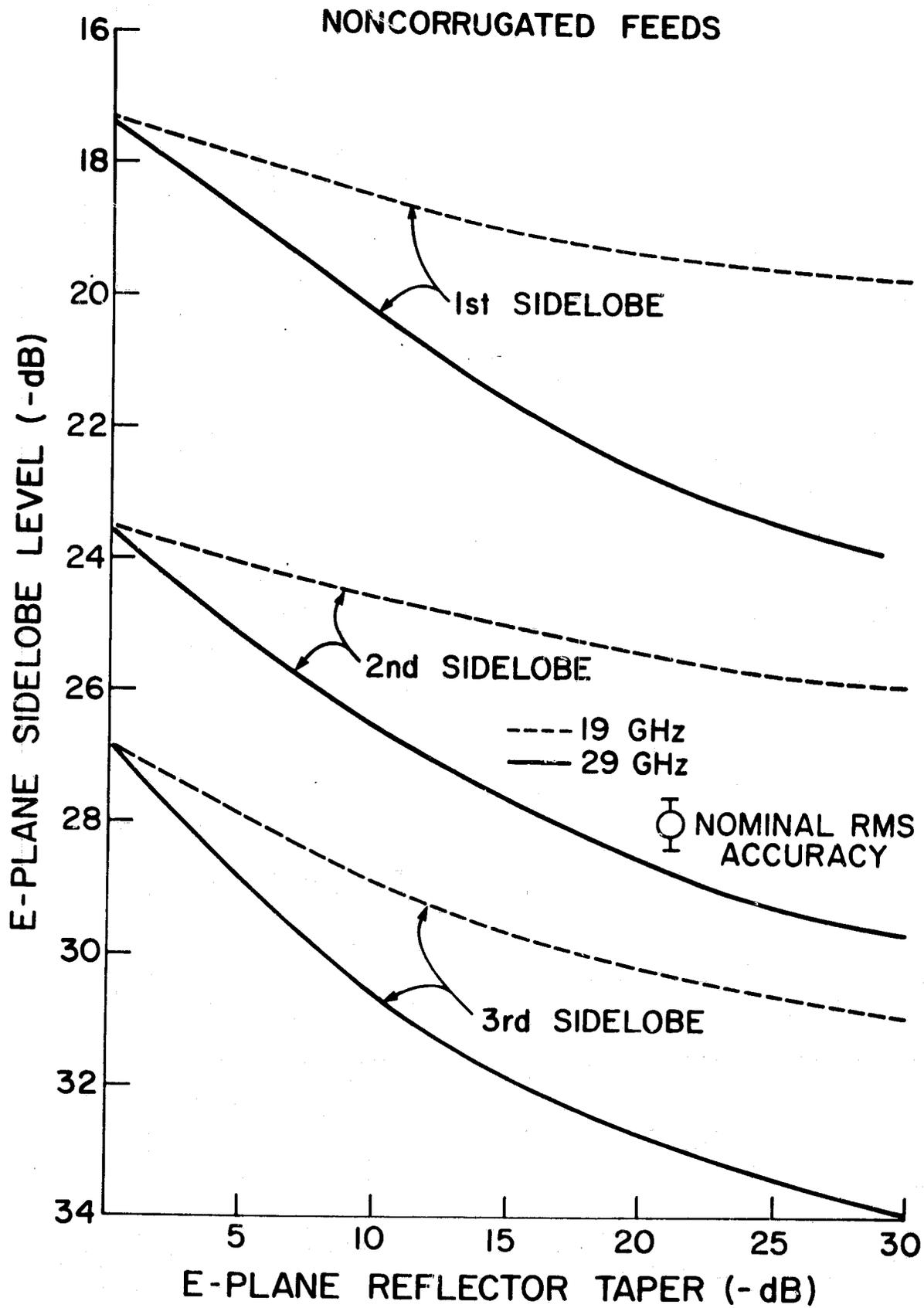
Figure 3.3-8. Sidelobe levels for circular noncorrugated dual-frequency waveguide feeds as a function of 29-GHz aperture excitation taper.
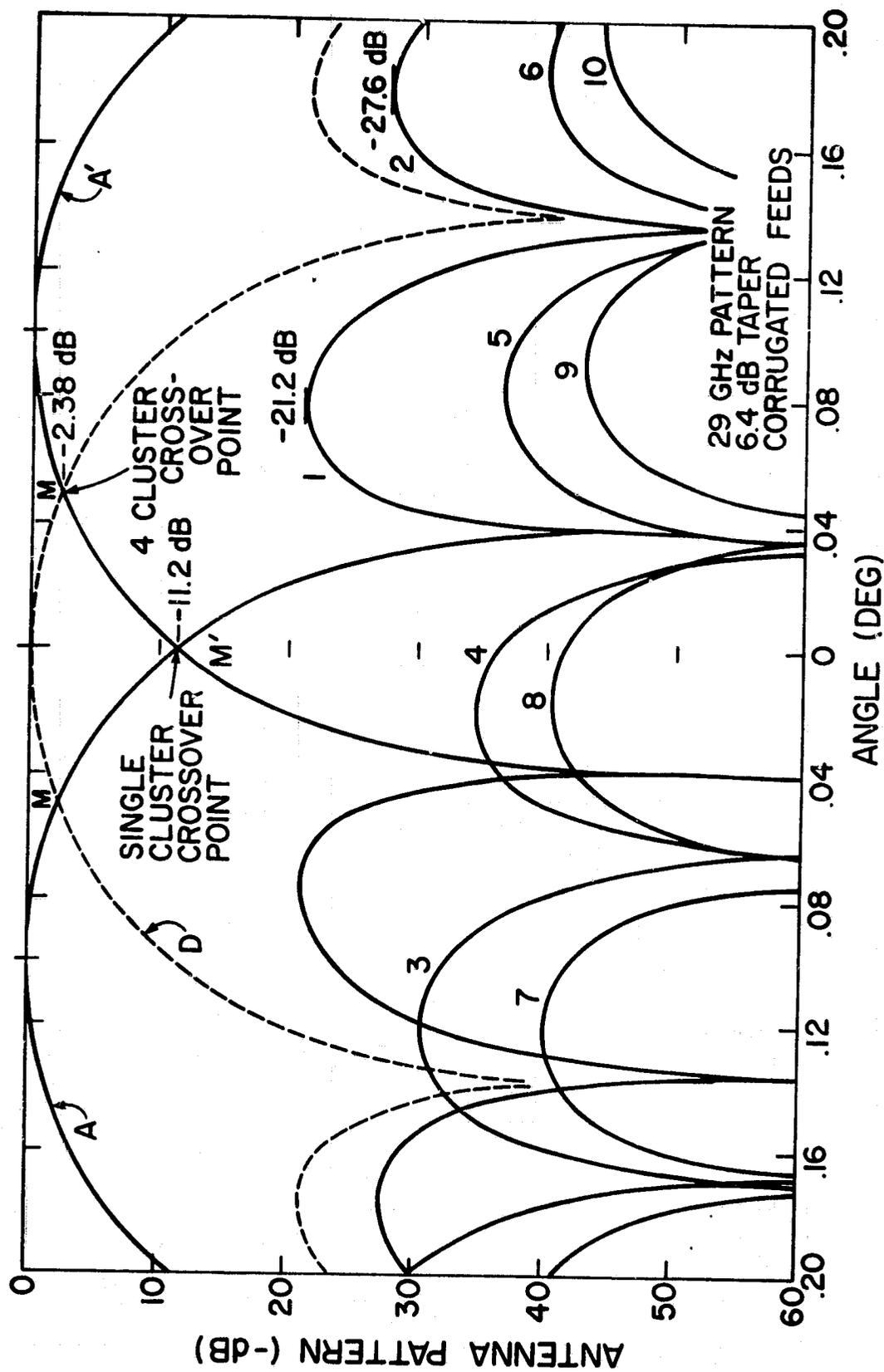
Figure 3.3-9. Antenna patterns for one and four packed clusters of corrugated feeds with a 6.4-dB taper at 29 GHz (the letters A and D represent clusters).
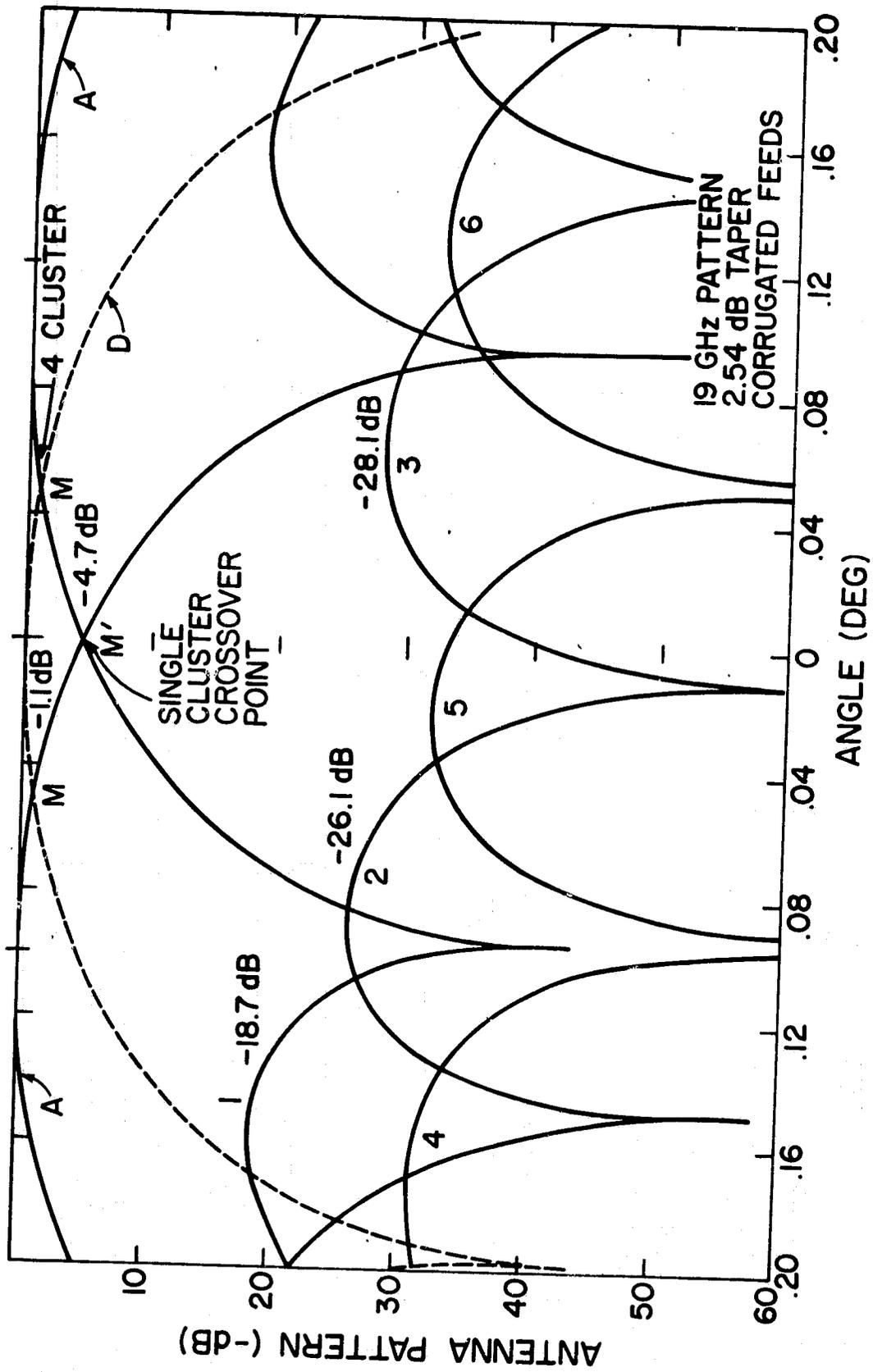
Figure 3.3-10.   Antenna patterns for one and four packed clusters of corrugated feeds with a 2.54-dB taper at 19 GHz (the letters A and D represent clusters).

GROUND ILLUMINATION PATTERN

400 BEAMS FROM
4 INDEPENDENT
CLUSTERS (A,B,C,D)

2×4 METER
SUB-REFLECTORS

MAINTENANCE
FEEDS

SOLID-SURFACE MIRROR
FOR VERTICAL POLARIZATION

HORIZONTAL POLARIZATION
MIRROR, TRANSPARENT TO
VERTICAL POLARIZATION

4 CLUSTERS, EACH
HAS 100 DUAL-FREQ.
CORRUGATED FEEDS
IN 1×2 METER ARRAY

400 SWITCHED ANTENNA BEAMS
19/29 GHz COMMUNICATIONS SYSTEM

SOLAR PANELS

4×8 METER
REFLECTORS,
OFF-AXIS.
$\theta_B \cong 8 \times 16$
ARC MIN.

H-POL
CLUSTERS

V-POL

Figure 3.3-11. Baseline spacecraft and multibeam antenna configuration.

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Table 3.3-1. Calculated Values of Optimal Taper and Pattern Characteristics for Cluster Arrangements Defined in Fig. 3.3-4.

	Single Frequency					2 Frequency				
Cluster	Optimal Taper	First Sidelobe	Total Loss on Axis	Point No.	Peak to Null at Crossover	29 GHz Optimal Taper	19 GHz First Sidelobe	29 GHz Loss on Axis	Point No.	29 GHz Peak to Null
1 hex	-1.6 dB	-18.6 dB	-4.2 dB	1	-4.2 dB	-2.1 dB	-18.0 dB	-3.5 dB	1	-5.5 dB
				2	-3.1				2	-4.0
3 hex	-3.1	-19.6	-2.4	3	-2.4	-5.5	-18.8	-1.2	3	-3.8
				4	-1.8				4	-2.9
4 hex	-3.6	-20.0	-2.0	5	-2.0	-6.4	-19.2	-1.0	5	-3.2
				6	-1.5				6	-2.5
1 square	-1.25	-18.3	-5.1	7	-5.1	-1.5	-17.8	-4.5	7	-6.3
				8	-2.3				8	-3.0
2 square	-2.0	-19.0	-3.8	9	-3.8	-2.5	-18.1	-3.0	9	-4.8
				10	-1.9				10	-2.3
4 square (A)	-3.0	-19.5	-2.6	11	-2.6	-5.3	-18.8	-1.3	11	-4.3
				12	-1.3				12	-2.1
4 square (B)	-3.6	-20.0	-2.2	13	-2.2	-6.8	-19.2	-0.9	13	-3.6
				14	-2.0				14	-3.3
				15	-1.5				15	-1.1

patterns. The feeds would be very thin metal, perhaps supported on a
rigid foam substrate. Each feed would incorporate a frequency diplexer,
which could be implemented instead as a polarization diplexer, because
polarization diversity within a single feed is not required here. Each
of the 800 antenna ports, 400 transmitting and 400 receiving, would be
connected to low-loss (0.2 dB) y-junction ferrite circulator switches,
as described earlier. Separate antenna feeds could be installed at the
subreflector facing the feed clusters for the purposes of system
monitoring and maintenance.

The baseline design uses primary reflectors 4 × 8 meters, which is
the aperture area required to yield ∿ 400 beams. The 4-meter dimension
is limited by the maximum width reflector the space shuttle can launch
without folding it. The 8-meter dimension is deployed such that the
patterns on the ground are more nearly circular than otherwise. The
fact that most major adjacent cities lie approximately north-south,
such as New York and Philadelphia, makes increased resolution in this
dimension more valuable for frequency reuse purposes as well. Such beam
distortion implies that the feed patterns must be comparably distorted,
but this should not pose a major problem. Figure 3.3-12 suggests how
the 400 beams would be distributed uniformly across the United States.

3.3.5 SPACECRAFT ARCHITECTURE AND COMPONENT REQUIREMENTS

The major architectural features of the baseline design have been
discussed in Sections 3.3.2, 3.3.3, and 3.3.4. Figure 4-4 is a summary
system diagram, and Fig. 3.3-2 shows the communications system architec-
ture in more detail. That figure illustrates how the 400 feeds would be
grouped in sets of 8, each of which drives one of 50 transponders. Each
receiver would have a bandwidth of ∿ 440 MHz, and would be followed by
two additional programmable frequency translators which drive baseband
demodulators capable of burst operation. Thus each transponder could
handle two tunable 128-Mbps bands, and 100 such digital bands would
enter the main digital switch. The 100 switch outputs (12.8 Gbps total
capacity) would drive modulators and programmable frequency translators.
These signals could be combined in pairs to drive a single 10-watt TWT
(as per the baseline cost analysis) or solid state amplifiers. Pro-
grammable gain controls on the two bands could allocate the bulk of the
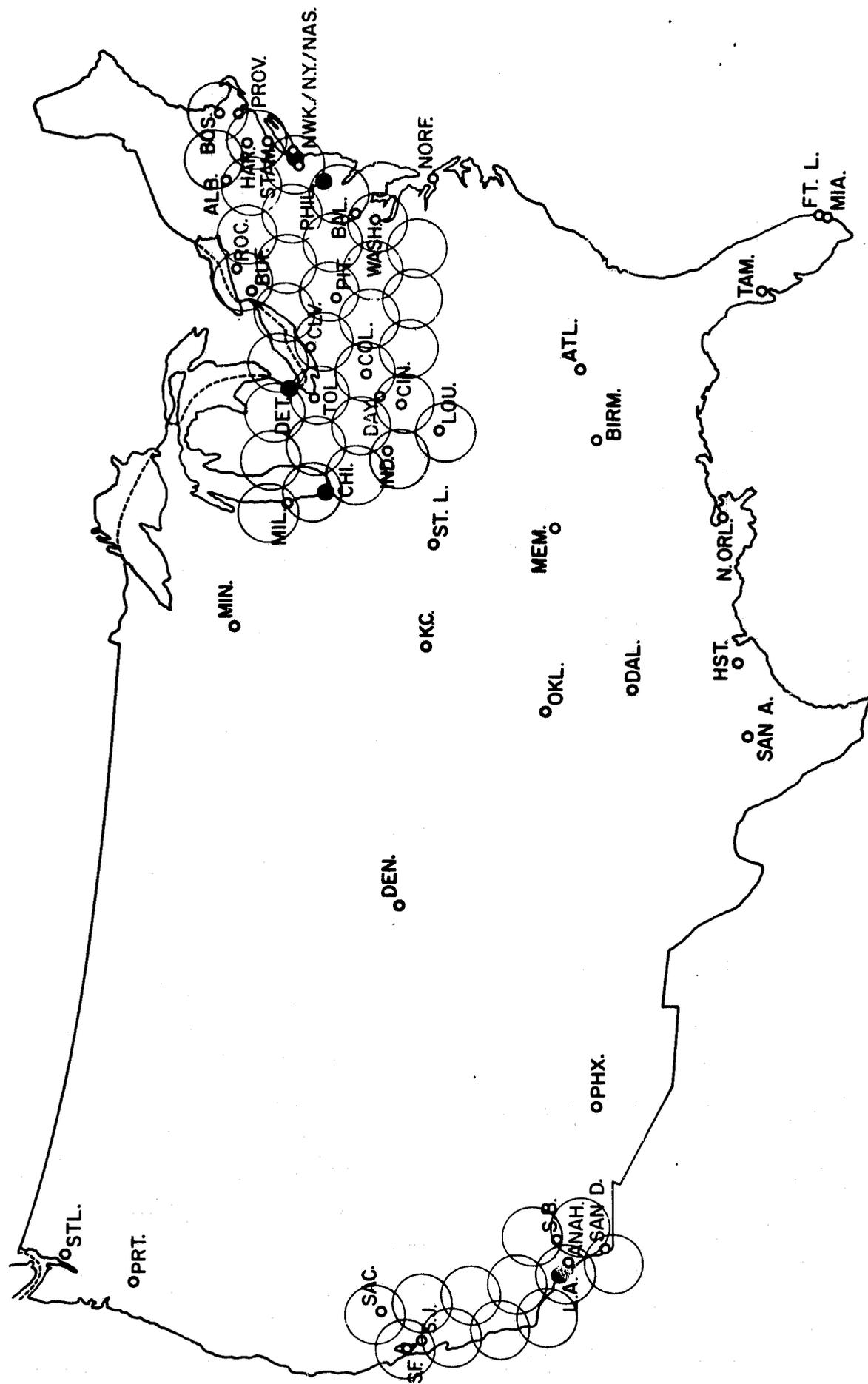
Figure 3.3-12. Representative placement of 3-dB contours for 400-beam antenna system providing full coverage for Conus.

transmitter power to one of the bands if it were affected by rain attenuation. A more economical approach would probably be to provide each of the 100 bands with its own ∿ 4-watt solid state amplifier.

The spatial distribution of the 8 feeds which are combined would be selected to maximize anticipated transponder efficiency. In general, beams serving areas like New York would be combined with beams serving rural areas like Nevada. Furthermore, beams in the same set should not be adjacent; this would maximize the ability of adjacent beams to share unexpectedly large traffic demands in one of them. Because alternate beams have alternate polarization, two-times frequency reuse should be possible everywhere, in addition to the reuse permitted by the specific sidelobe levels and link margin degradation.

In addition to the elements shown in Fig. 3.3-2, there would also be modems and TDMA buffers which could interface any of the signal streams to the main communications control computer. These lines would be dispatched by the main digital switch and would be used to handle all command and control signals communicated in the 200-bit headers on each TDMA burst and in the access block occurring once each TDMA cycle. Four such links would be sufficient. Additional lines could also interface the main digital switch with special purpose time-translation or format conversion equipment. Because several such baseline satellites would operate as an integrated unit in space, some of the 400 feeds, perhaps 4-8, would be directed along the synchronous orbit to provide inter-satellite communications. These circuits could be identical with those serving the ground, and the antenna gain could be much reduced. As discussed in Section 3.3.6, only a small fraction of the total communications capacity should normally be intersatellite.

The system architecture is summarized in Table 1-1, and the space link performance is summarized in Table A3.1-1.

The number of beams which would be required to serve local populations of various sizes is presented in Table 3.3-2. It shows that over half the satellite capacity would be serving beams with populations less than one million. Only 21 beams would normally require more than one 128-Mbps band, and even New York City would need fewer than 10. Since there are 7 beams which overlap New York, and since each transponder can

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Table 3.3-2. Components Requirements for
a Single 12-Gbps Spacecraft.

BEAM POPULA- TION	NO. BEAMS	AVG/MAX CAPACITY PER BEAM (Mbps)	TRANSMITTERS OR RECEIVERS			
			AMPS/ BEAM	TOTAL AMPS	NO. LINES†	FERRITE SWITCHES
>8M	3	512	2	6	12	12
>4M	5	256	1	5	10	10
>2M	13	128-256	1/2	6.5	13	32.5
>1M	22	64-256	1/4	5.5	11	38.5
>0.5M	38	32-256	1/8	4.8	9.6	52.8
>0.25M	65	16-256	1/16	4.1	8.2	77.9
>0.12M	74	16-256	1/16	4.6	9.2	87.4
>66K	46	16-256	1/16	2.8	5.6	53.2
>32K	30	16-256	1/16	1.8	3.6	34.2
>20K	25	16-256	1/16	1.6	3.2	30.4
<20K	80	16-256	1/16	5	10	95
MAINTENANCE FEEDS	(2)	128	2	(4)	(4)	(4)
TOTALS 220M	401	12 Gbps	-	52	96	524

†Numbers of: lines to switch, translators, and
modulators/demodulators.

( )Not included in total.

handle two such bands, there would be 14 128-Mbps bands available in the New York area per satellite. If this were not enough, it would be possible to add frequency multiplexers to the satellite so that more than one transponder might serve each of the relevant beams. The average and maximum capacities per beam listed in the table reflect the degree to which the dwell time of the ferrite switches might allocate transponders to those feeds. Because of the great flexibility of the architecture, the transponders would generally be available with 100 percent efficiency, even if some fail.

The 12.8 Gbps baseline satellite would carry a total of 100 primary amplifiers, 50 for transmission and 50 for reception. There would be a total of 1048 ferrite switches and there would be approximately 100 input and 100 output lines on the main digital switch.

3.3.6 COMMAND AND CONTROL; MULTIPLE SATELLITES

One significant economic problem in planning satellite communications systems is maximization of the average loading of the installed spacecraft. Often a satellite is placed in orbit such that the traffic grows linearly over its lifespan, and once it is saturated it may be replaced by a bigger unit and become a backup system. Approximately half of the Intelsat satellites now serve as spares. Suppose the load grows linearly over the life of a satellite, reaching maximum capacity on the last day; then the loading efficiency would be 50%. If two were in orbit, one as a spare, then the efficiency would be only 25%. The loading efficiencies of large satellite systems can become much larger if several satellites are used in a coordinated fashion, such as proposed here for the baseline system.

Since each baseline satellite is a completely self-contained redundant system which can tolerate a considerable number of component failures, and since many such satellites could operate in the same orbital slot without interfering, provided their frequency and time slot assignments did not conflict, such a multiple-satellite configuration should be practical. They could even be attached to a single platform. The advantages of multiple satellites sharing the same load would be 1) redundancy in the event one suffers a total failure, 2) efficient

redundancy since fewer than half the satellites need to be spares; one good satellite or a couple of obsolete systems would probably suffice, 3) flexible growth and higher average loading factors; new satellites would be launched to support load growth and technological improvements only as needed, and 4) separate carrier ownership and management of the various satellites is possible.

The improvement in loading efficiency can be understood in terms of a simple example. One satellite plus its spare would have an efficiency of 25 percent as the load grew to saturation, whereas a satellite one-third that size launched with a spare and then followed by two more units, when load growth requires, would result in a total loading efficiency of 50 percent over the same period for the same traffic. More frequent launches also permit more frequent upgrading of the technical specifications of the total system.

There are other economic consequences as well. Because the satellites are individually smaller, they are individually cheaper but slightly more expensive per Gbps capacity. The nonrecurring costs should also be less, but the reduced costs of individual launches may be more than offset by the increased number which are required.

Because any given link request could be handled by any of the satellites in a given cluster, there should be no requirements for inter-satellite communication. This would change if several carriers were involved and each wished, for example, to receive traffic from its own ground stations, or if one carrier used a peculiar space-link protocol which required it to handle all communications with its own ground stations. Such non-standard protocols would negate some of the economic and technical advantages of satellite clusters.

The problem of allocating traffic to multiple satellites is essentially the same as that for allocating traffic to multiple transponders and time/frequency slots on a single satellite. The only difficult allocation problems would be the political ones of allocating traffic among several cooperating satellites owned by separate entities, but these are not different in kind from the problems which now arise when revenues are distributed among several national or international carriers handling the same terrestrial communications traffic. Whether the

computer which executes the scheduling algorithm is on the ground or in space is not critical; although the benefits of making the difficult decisions on the ground are obvious.

Communications between carriers could be handled easily, as noted earlier, by simply placing a few of the antenna beams on the side of each spacecraft pointing in both directions along the synchronous orbit. Then as additional satellites were placed in the same slot to the left or right alongside existing ones, the flexible architecture of the baseline design could be used to transfer an appreciable fraction of the transponder capacity to the task of intersatellite communications, as necessary. As a matter of policy it may be desirable to require such intersatellite communications flexibility, as discussed further in Chapter 8.

3.3.7 TERRESTRIAL ELEMENTS

3.3.7.1 Introduction

The terrestrial elements include the ground stations, the local links, and the user facilities; these may be associated primarily with the satellite network, or they may simply be imbedded in the existing terrestrial telecommunications plant. A more detailed discussion of ground station design and economics appears in Chapter 5 and here in Table 3.3-3, and the local links and user facilities are discussed in Chapter 6. The relationship between the existing terrestrial system and satellite systems is discussed at length in Section 3.2. The design issues discussed here include those involving ground station costs, protocols, the distribution of signal processing capacity throughout the system, and the relationship between video bandwidth compression and system structure.

3.3.7.2 Ground Stations

For many existing satellite communications systems the majority of the cost is associated with the ground stations. Therefore the minimization of these costs is paramount here because of the very large number of such stations. A survey of basic ground-station equipment costs was presented in a recent Aerospace Corporation contract report (Woodford, 1978) and is summarized in Table 3.3-3.

Table 3.3-3. Basic Ground-Station Equipment Costs, 1978.

Ground Station Type	Approximate Cost
High performance INTELSAT standard station A	$1M or more
Advanced WESTAR, SBS (K_u band)	$345K
LES-8, LES-9 (4-ft antennas, 36-38 GHz)	$250K
MARISAT (4-ft antenna, L-band)	$63K
U.S. Army Manpack satellite terminal (225, 400 MHz; AN/PSAC-1)	$23K
Television receive-only ground stations	$10K - $22K

The general class of ground station appropriate to the baseline system design, i.e. an 8-foot K-band antenna with 10 watts transmitter power for one 128-Mbps TDMA band, is closest to those stations developed for the Lincoln Experimental Satellites LES-8 and LES-9, and for the Advanced WESTAR and SBS systems. The LES stations use r.f. technology that is relevant to the baseline 20/30 GHz systems, and the communications traffic of the Advanced WESTAR and SBS TDMA systems are also relevant. The SBS station has 18-25 ft antennas, 450 watts for 43 MHz, and 270°K system temperatures; these are more expensive than the baseline specifications. Approximately half the cost is for baseband and control electronics. Architectural features of the baseline system which can further reduce costs include 1) modest antenna diameters, near 8 feet, 2) modest transmitter powers, near 10 watts, 3) modest system noise temperatures, near 500°K, 4) use of non-tracking antenna mounts, and 5) maximum use of integrated circuit technology appropriate to the mid-1980's. Although it is conceivable that costs might approach those for MARISAT terminals, the differences in complexity and bandwidth are sufficiently great that the goal would be difficult to achieve. A detailed cost analysis of the baseline system appears in Chapter 5.

3.3.7.3 Locus for Signal Processing

The services of interest include voice, data, facsimile, and video; the bandwidths, protocols, and tariffs might vary within each of the service types. In general, most data must be converted to digital form, encrypted, encoded for error-correction, and buffered to the TDM modems.

Some data should also undergo bandwidth compression. The character and location of this equipment is the architectural issue of present interest.

Under the least-cost constraint, most multi-purpose equipment should be located in or near the ground stations so that it can be shared by the maximum number of users and most economically maintained. This would normally include all the processing equipment except perhaps that for A/D conversion, bandwidth compression, encryption, and error-correcting coding. The location of any encryption and error-correcting circuitry depends upon the tradeoff between circuit cost and the level of protection required. Economics suggests concentration at the ground stations or at the terminus where risk is first encountered, whereas the risk is probably least if this equipment is on the user's premises. With the rapidly decreasing cost of digital equipment, the dispersion of such equipment can be expected to increase; the baseline assumption, however, is that such equipment is part of the ground stations.

The best location for the A/D conversion and bandwidth compression equipment may depend largely on the tradeoff between efficiency of equipment utilization and the costs of local transmission for compressed and uncompressed signals. It is difficult to anticipate now how the local transmission costs will vary in coming years for broadband digital signals; the baseline assumption is that transmission costs will favor aggregation of video-compression equipment in the ground stations, and that facsimile compression equipment is cheaper and will be built into the user's equipment. In view of the relatively large costs for local digital links (discussed further in Chapter 6) compared to the costs for interframe video bandwidth compression circuits (estimated in Section 5.3.2.4), it is more likely that centralization of bandwidth compression in the ground stations will occur only if very short or low-cost links are available, perhaps analog links.

3.3.7.4 Protocols

We may consider the importance of these signal processing procedures to the various services. Voice traffic is increasingly being converted to digital form for long-lines transmission, and the obvious vulnerability of such traffic to interception is motivating increases in signal

security. The processing steps which are not required for voice include compression and error-correcting coding. In the future even compression may become increasingly attractive as the penetration of digital systems increases and the costs for compression decrease. None of the issues here change greatly if satellite links are involved in handling the traffic.

The services of greatest importance to facsimile and video are bandwidth compression. Selection of these protocols perhaps poses one of the greatest potential hazards to an efficient pervasive communications system. This is so because it is unlikely that two different compression algorithms would be compatible. One could imagine protocol conversion equipment being made available by the local carrier for a fee, but even this may not suffice because the best video compression algorithms take advantage of imperfections in the human visual system to discard irreversibly much of the data. If two compression algorithms are to be interfaced, and they discard information differently, then the cost and quality of such protocol conversion could be prohibitive. For the baseline system we assume these protocols were selected intelligently and no extra conversion equipment is required.

Although one could imagine prototol "wars" between vendors hoping to sell patented equipment or services, perhaps the greater problem is the conflict between protocols established initially and superior ones which may be discovered or become economic subsequently. The original controversial selection of a broadcast television protocol and the difficulty one would have changing it now are two examples of hazards to be avoided.

The only traffic for which error-correction coding is particularly desirable is data, such as involved in electronic funds transfers. This too is a problem in the present terrestrial network and is being addressed independently of satellite systems.

3.3.7.5 Video Bandwidth Compression

The importance of video bandwidth compression arises because of the potentially large fraction of satellite traffic that could be devoted to this service, perhaps as much as 50 percent (see the discussion in Chapter 2). The total cost of a video communications link will vary

almost inversely with compression ratio because most costs are bandwidth dependent rather than circuit dependent. If a good color video image is presumed to have 3×10^5 independent pels coded with 10-bit accuracy (2 bits for color) at a frame rate of 30/sec, then the data rate is 90 Mbps. By using intraframe coding techniques broadcast quality video has been reduced to 30 Mbps, and perhaps 20 Mbps may be achieved soon. Further significant reductions seems unlikely without picture degradation unless interframe compression techniques are used.

The most successful interframe compression techniques at present are those which employ selective replenishment schemes which code the replenishment information. Considerable savings are possible if only the image changes are transmitted, particularly if they are coded efficiently by sending, for example, only portions of Fourier transformed picture elements, or by sending velocity vectors for picture elements. A wide variety of schemes exist, and much work remains to be done. Nonetheless, there already is available from NEC an interframe compression unit that operates at a variety of compression ratios; for data rates of 6 Mbps the images are generally acceptable, and they deteriorate as picture motion increases or as the desired data rate decreases. With future improvements it seems reasonable that full color video motion adequate for video conferences should be available at a nominal 3-Mbps rate. Progress beyond 3 Mbps without noticeable degradation seems difficult to this writer, but good monochrome images at 1-2 Mbps have been claimed (Limb et al., 1974; Haskell and Schmidt, 1975; Wendt, 1977, and Burgmeier, 1977), and Musmann and Klie (1979) have claimed even 64 kbits can be achieved with only moderate degradation.

The importance of this is that tariffs for video conferences could be economically very attractive, as discussed further in Chapter 7, and that the total capacity of a 30-Gbps system is adequate to handle a pervasive national video-conference system operating near the threshold of utility, as defined in Chapter 2. A data rate of 30 Gbps could handle 10,000 one-way links at 3 Mbps.

Chapter 3   References

1. Acampora, A. S., C. Dragonne, and D. O. Reudink, A satellite system with limited-scan spot beams, IEEE Trans. Comm., COM-27, 10, pp. 1406-1415, 1979.

2. Acampora, A. S. and B. R. Davis, Efficient utilization of satellite transponders via time division multibeam scanning, Bell Sys. Tech. Journ., 57, 8, Oct. 1978.

3. Burgmeier, J., Dreidimensionale DPCM mit Entropiecodierung und adaptiven Filter, NTZ, 30, pp. 251-254, March 1977.

4. Cochrane, J. I. and J. C. Lawson, Architectures and economics for pervasive digital voice/data communications networks, ICC'79 Conf. Rec., 2, June 1979 (79CH1435-7CSCB), p. 35.3.1.

5. Dragonne, C., Characteristics of a broadband microwave corrugated feed ..., BSTJ, 56, 6, p. 869, July 1977.

6. Ford Aerospace and Communications Corp., Concepts for 18 and 30 GHz satellite communications system study, NASA Rept. No. NASA-CR159625, Nov. 1, 1979.

7. Frediani, D. J., Technology assessment for future MILSATCOM systems: the 30/20 GHz band, Project Rept. DCA-4, Lincoln Laboratory, M.I.T., August 1978.

8. Gloersen, P. and F. T. Barath, A scanning multichannel microwave radiometer for Nimbus-G and Seasat-A, IEEE J. of Oceanic Eng., OE-2, 2, pp. 172-178, 1977.

9. Haskell, B. G. and R. L. Schmidt, A low-bit-rate-interframe coder for videotelephone, BSTJ, 54, 1475-1495, Oct. 1975.

10. Limb, J. O., R. F. W. Pease, and K. A. Walsh, Combining intraframe and frame-to-frame coding for television, BSTJ, 53, pp. 1137-1173, August 1974.

11. Musmann, H. G. and J. Klie, TV-transmission using a 64 kbit/s transmission rate, ICC'79 Conf. Rec., 2, June 1979 (79CH1435-7CSCB), p. 23.3.1.

12. Ohm, E. A., A proposed multiple-beam microwave antenna for earth stations and satellites, BSTJ, 53, pp. 1657-1665, Oct. 1974.

13. Ohm, E. A., System aspects of a multibeam antenna for full U.S. coverage, ICC'79 Conf. Rec., 3, June 1979 (79CH1435-7CSCB), p. 49.2.1.

14. Powell, R. V. and A. R. Hibbs, An entree for large space antennas, Astronautics and Aeronautics, pp. 58-64, Dec. 1977.

15. Reudink, D. O., Spot beams promise satellite communications break-through, *IEEE Spectrum*, *15*, pp. 36-42, 1978. D. O. Reudink and Y. S. Yeh, A scanning spot-beam satellite system, *BSTJ*, pp. 1549-1560, Oct. 1977.

16. Reudink, D. O., A. S. Acampora, and Y. S. Yeh, Methods for achieving high capacity universal service satellites, Nat'l Telecomm. Conf., Birmingham, Ala., Dec. 1978.

17. Ruze, J., Lateral-feed displacement in a paraboloid, *IEEE Trans. Ant. and Prop.*, *AP-13*, pp. 660-665, Sept. 1965.

18. Staelin, D. H. and R. L. Harvey, Architectures and economics for pervasive broadband satellite networks, *ICC'79 Conf. Rec.*, *2*, June 1979 (79CH1435-7CSCB), pp. 35.4.1-35.4.7.

19. Wendt, K., Schmalband-Codierung, *NTZ*, *30*, pp. 251-254, March 1977.

20. Wilson, R., *BSTJ*, *48*, 5, p. 1383, 1969.

21. Woodford, J. B., Ed., Communications satellite technology, Aerospace Corp. Rept. No. ATR-78(7735)-1, for NASA Contract NAS 5-24489, July 1978.

22. Yamada, J-I., S. Machida, T. Kimura, Dispersion-free single-mode fibre transmission experiments up to 1.6 Gbits/s, *Electronics Letters*, *15*, 10, pp. 278-279, 1979.

CHAPTER 4

BASELINE SATELLITE DESIGN

4.1 INTRODUCTION

This section presents an estimate of the WIDENET satellite weight, power and cost assuming late 1980's technology. Many assumptions were needed to generate this estimate. It is believed that the most important assumptions have been explicitly stated in the following text. An effort has been made to be conservative regarding the system components. As will be seen in the discussions of individual systems, further weight and power reduction of 10% to 15% is possible with the assumed models if the most optimistic projections for the late 1980's are used. However, for purposes of exhibiting, hopefully, a credible design, the maximum use of projected late 1980's technology made by other workers in the field is avoided.

The baseline design is a big, complex satellite. The 12.8 Gbps version is approximately twice the weight of the recent FLTSATCOMs. Nevertheless, it appears to be feasible in the above time frame and it can be deployed by the Boeing IUS currently in development.

Section 4.2 gives the main conclusions of this analysis, including summary figures of weight, power and cost as a function of communication capacity. Section 4.3 gives a discussion of the major bus systems (4.3.1) and major communication systems (4.3.2). These two sections generate the inputs for estimating the total satellite weight and power. Section 4.3.3 outlines the weight and power algorithm. For comparison, application of this algorithm to the FLTSATCOM satellite is shown. Section 4.3.4 discusses costing algorithms for satellites. A simple algorithm based on BOM (beginning of mission) weight is applied. Final comments are in Section 4.4. The appendices contain the mathematical details. Appendix A4.1 reviews the launch capabilities of vehicles now under development. Appendix A4.2 reviews satellite attitude control systems and Appendix A4.3 surveys 20-GHz spaceborne transmitter technology. Models for the channel switching matrix and communication processor are given in Appendices A4.4 and A4.5, respectively. Finally, Appendix A4.6

estimates the 7-year East/West and North/South station-keeping require-
ments for a satellite over CONUS.

4.2 CONCLUSIONS

(1) Figure 4-1 shows the estimated BOM weight and power for WIDENET
satellites assuming late 1980's technology. The satellite BOM weight
and power for the baseline 12.8 Gbps satellite system is about 3,900
pounds and 4 kWatts.

(2) Figure 4-2 shows the (1979) nonrecurring and recurring costs based
on a DCA model after adjustment for inflation. The baseline 12.8 Gbps
channel satellite has a nonrecurring cost of $224M, a recurring cost of
$67M and a launch cost of $30M per satellite. The total space segment
cost, e.g., of two active satellites and one spare would be about $485M.
This system would have the capacity to handle 780 32 Mbps one-way chan-
nels or 7,800 3.2 Mbps one-way channels, or the equivalent, depending on
the sophistication of the ground terminal digital processing.

(3) Based on Appendix A4.1 and Fig. 4-10, a two-stage Boeing IUS can
deploy up to a 16.6 Gbps baseline satellite (5,000 pounds) into a geo-
synchronous orbit. With a single shuttle flight and a three-stage IUS,
up to a 36-Gbps satellite (9,000 pounds) can be deployed.

(4) The above satellite weight and power estimates assume the following
advanced technology: a CMOS computer based on the present Fault-Tolerant
Computer, composite material for the antenna structure and support, high-
efficiency solar cells (20 Watts/pound), NiH_2 batteries, a star tracker
for guidance and control and 10 Watt/20-GHz TWTs. All these technologies
are presently in development and, it appears, will be available by the
late 1980's. All the other systems are assumed to use current technology.
Reduction of system weight below these estimates is feasible.

4.3 ANALYSIS

4.3.1 MAJOR BUS SYSTEMS

4.3.1.1 RCS (Reaction Control System)

The RCS includes the secondary propulsion engines, tankage, feed
system and electronics, but excludes the propellant. Appendix A4.6
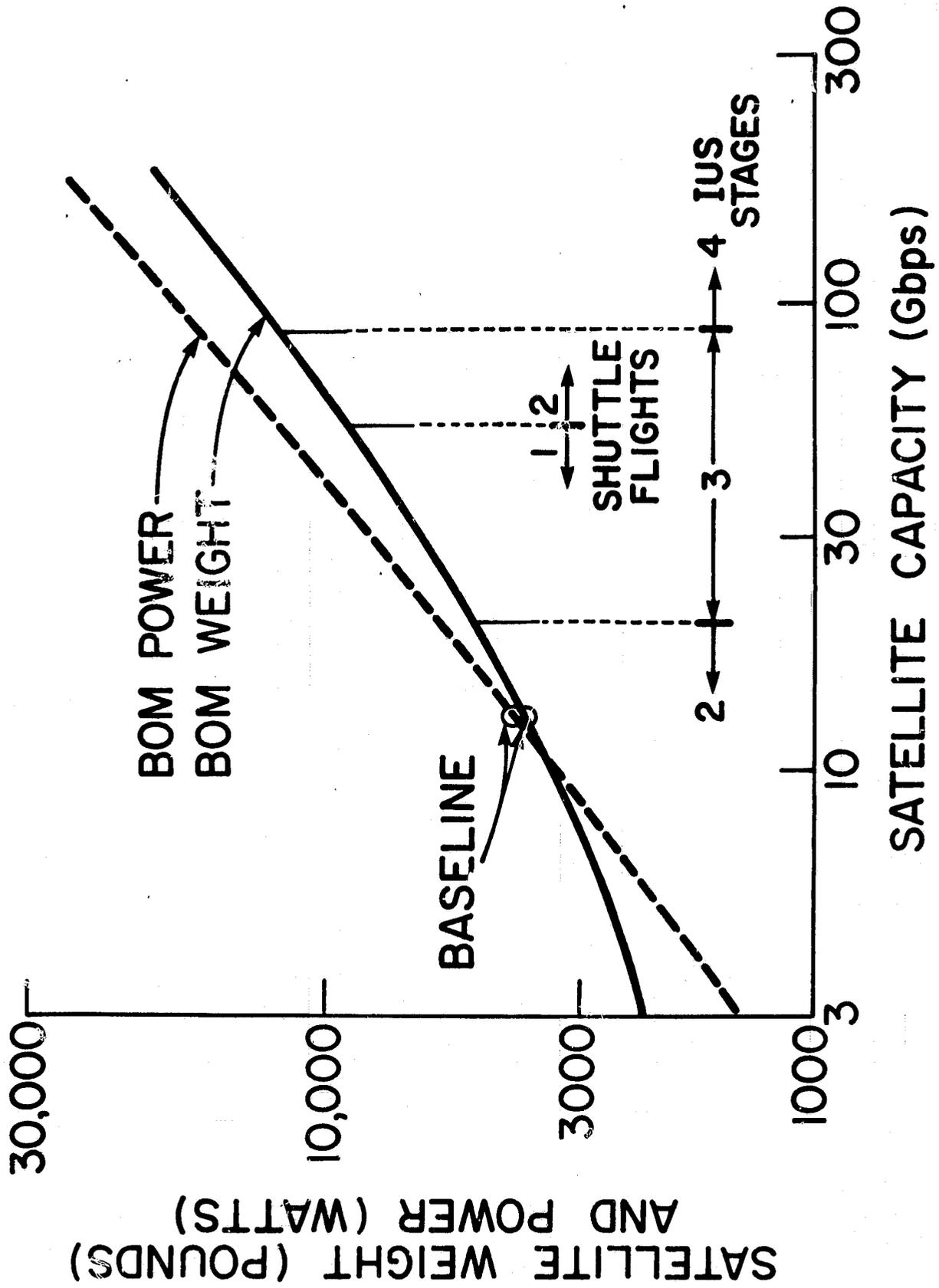
Figure 4-1. Estimated satellite weight and power at the beginning of mission.
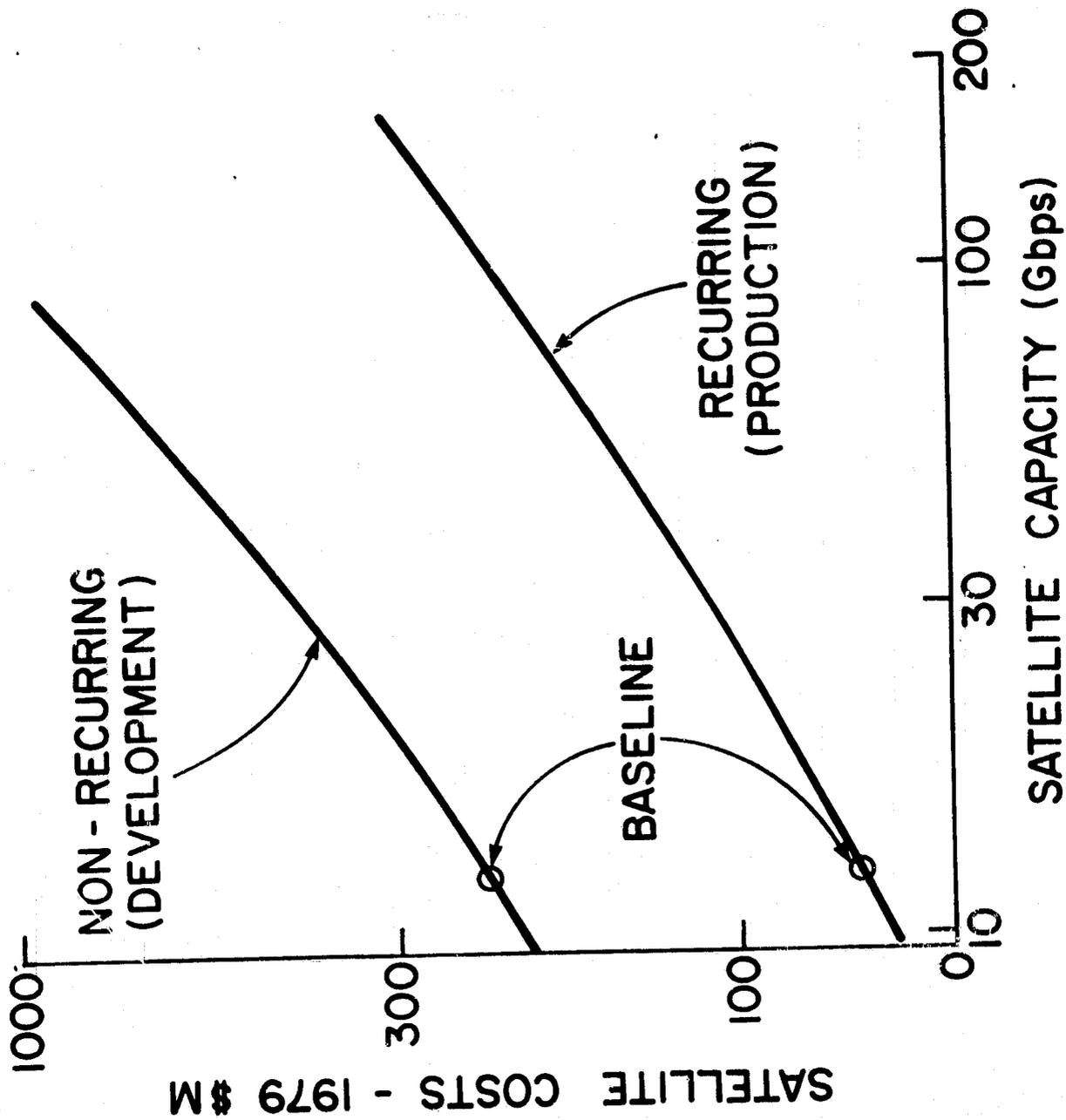
Figure 4-2. Estimated recurring and non-recurring costs for large switched communications satellites, as a function of capacity.

shows that the total propulsion requirement of the RCS is about 1310 ft/
sec for a 7-year mission with North/South and East/West station keeping
to less than 4.5 arc min.[*] This propulsion requirement is summarized in
Table 4.3-1. Assuming a pressurized monopropellant hydrazine system
$(I_{SP} = 220 \text{ lb}_f\text{sec/lb}_m)$, the wet-to-dry weight ratio of the satellite is
about 1.2. The tankage and feed system weight is estimated by a formula
based on flight hardware (Appendix A4.6). Since the amount of propellant
and tankage weight depends on the dry weight of the satellite, an iterative
procedure must be used for estimating the satellite BOM weight and power
(Section 4.3.2). Figure 4-3 shows the RCS weight over the range of
satellite BOM weights of interest.

Table 4.3-1. RCS Propulsion Requirements.

		ΔV
Station Keeping (7 years)	North/South	1170 ft/sec
	East/West	40 ft/sec
Orbit Trim		30 ft/sec
Momentum Dumping		70 ft/sec
		1310 ft/sec

4.3.1.2 ACS (Attitude Control System)

The ACS includes the sensors for determining position and pointing,
reaction wheels for rotating the satellite and microprocessor-based
control electronics. A zero momentum system is assumed to allow more
flexibility compared to a momentum bias system in accommodating large
asymmetric antennas with large solar pressure imbalance torques.

Appendix A4.2 shows the ACS weight and power of selected satellites
and components. Based on these designs, the assumed ACS for a WIDENET
satellite is shown in Table 4.3-2. Since a satellite may have a downlink

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[*]The uplink 1-dB beamwidth of a 2.4-meter antenna at 30 GHz is about
10 arc min.
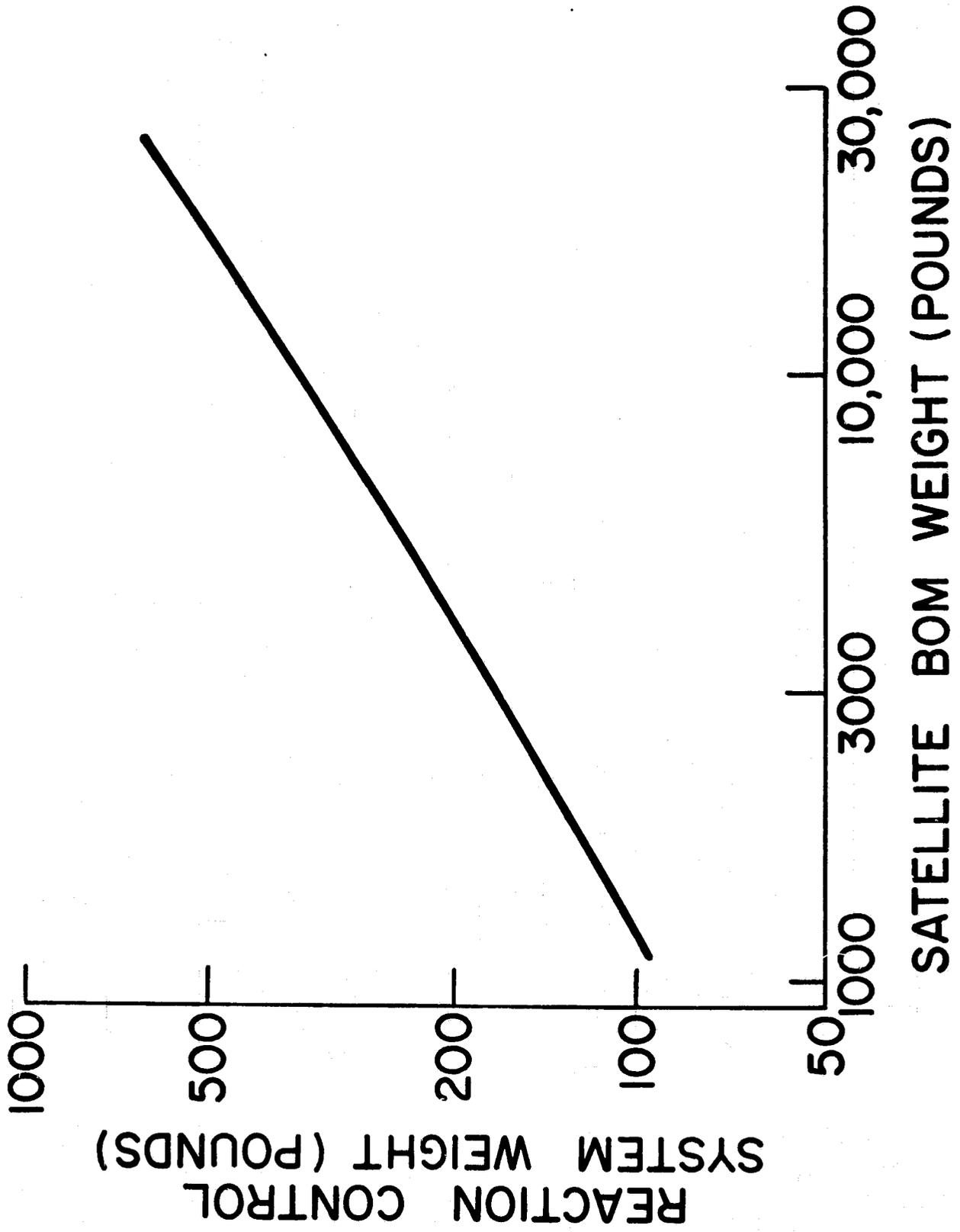
Figure 4-3. Estimated satellite reaction control system weight.

antenna pointing requirement of less than 1 arc min. a star tracker is included in the ACS to permit measurements to less than 1 arc sec.[*]

Table 4.3-2. Attitude Control System.

Component	Power	Bus Watts
Reaction Wheels (4)	68	50/wheel
Accelerometers (3)	3	–
Third Generation Gyros (6)	7	54 (3)
Star Tracker	43	45
Electronics	25	5
Processor/Computer	30	30
Contingency	4	6
Total:	180 lbs	140W + 50/Wheel

4.3.1.3 Control Processor

Considerations of subsystem integration and efficient on-orbit operation suggest that the on-board computing tasks be divided between two separate processors. The communication processor (Section 4.3.2.7) could be a special purpose computer with modular redundancy for efficient execution. A separation control processor consisting of a state-of-the-art general purpose computer or an FTC (fault tolerant computer), if available, could control the launch sequencing, supervise the communication processor, and provide autonomous in-orbit operation when the satellite was not in a ground-control mode. Distributing the on-board computing tasks between a communication processor and a control processor structures the system into functional parts with maximum independence, simple interfaces and a minimum of required interaction. The communication processor can then be primarily a hard-wired, efficient machine with fault tolerance provided by modular redundancy to be switched in by the on-board control processor or a ground-control terminal. Figure 4-4 schematically suggests

[*] The downlink 3-dB beamwidth at 30 GHz is about 7 arc min. Satellite antenna pointing could also be done via an uplink beacon, thereby simplifying the ACS. This tradeoff remains to be examined.
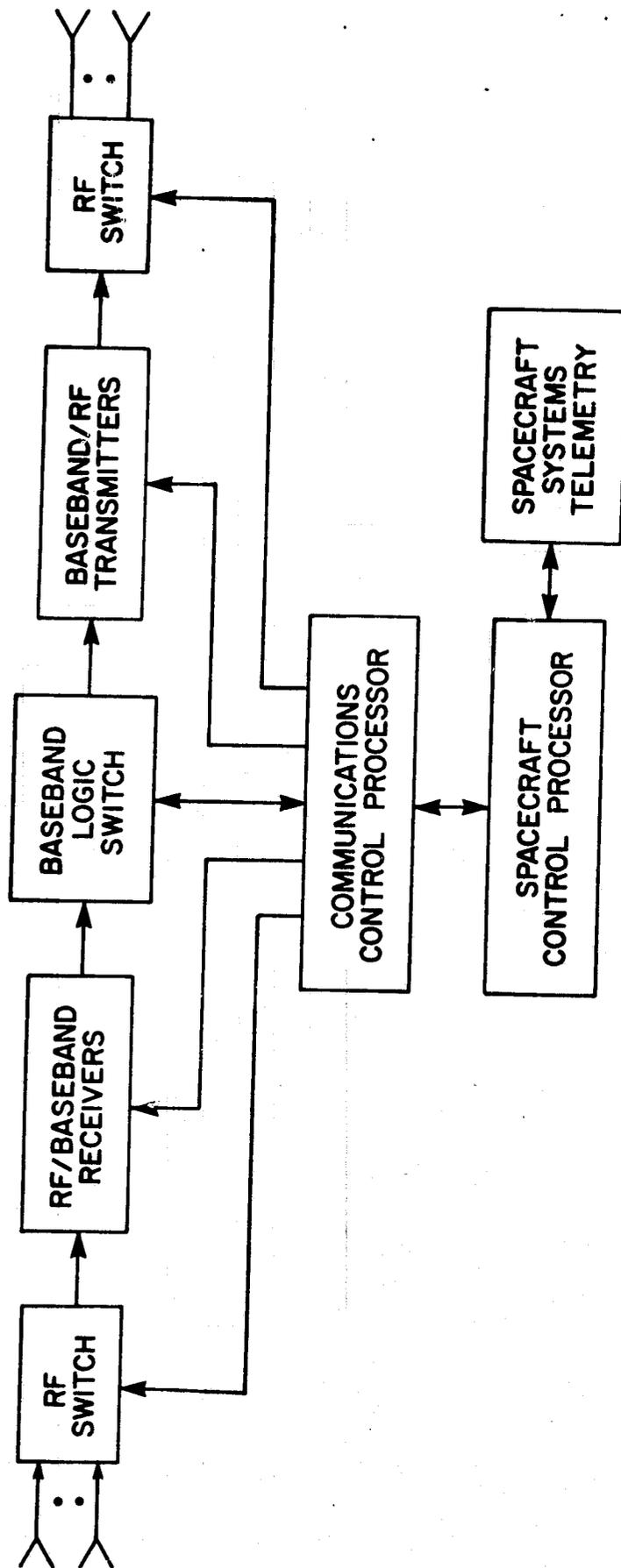
Figure 4-4. Satellite electronics configuration; role of the communications control processor.

how the computational tasks could be split between the two processors. This division may not be optimal, but it appears to be a feasible approach for simplifying the design and testing of a complete system to meet a late 1980's launch date.

An estimate of the control function computer requirements is based on other studies of large communication satellites. Table 4.3-3 summarizes the speed and memory requirements assuming that the communication channels are monitored once per second on a non-interference basis. Weight and power estimates are shown for both a state-of-the-art LS/TTL (low power Schottky/transistor-transistor logic) (Aukstikalnis, 1974). and a scaled-down TFC of the projected flight model (Burchby and Kern, 1976).[*] If the satellite is used primarily for voice traffic, then the computer memory would have to be considerably larger (say 20 Mb) to handle the switch commands. This would increase weight and power only moderately for 1985 technology.

Based on these estimates, 5 lbs and 5 (conditioned) Watts are assumed for the satellite control processor.

4.3.1.4 Power

Significant performance improvement in satellite solar array and battery systems in the 1983 to 1988 time frame appears likely. Tables 4.3-4 and 4.3-5 summarize the current and projected technology for solar arrays and batteries, respectively (Barthelemy, 1978).

Current flight-qualified oriented solar arrays have a generating capability of about 9 Watts/pound (Rauschenbach, 1976). The projected performance in the 1985 time frame varies from 25 Watts/pound, using the best production cells with 12 to 13% efficiency, to about 60 Watts/pound, assuming the potential 25 to 30% efficiency of multi-bandgap cells is realized. For preliminary design purposes, the conservative performance of 20 Watts/pound is assumed. This specific power corresponds to the long-lifetime, radiation-hardened, flexible rollup array, known as the Harden Array Power System, whose development was completed in 1978.

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[*] One nominal FTC flight configuration (50 lbs, 35 Watts, 250,000 ops/s) is considerably larger than is necessary for the control processing tasks.

Table 4.3-3.   Control Processing Requirements.

	Speed (ops/s)	Memory (8-bit Words)
Launch		
Launch Sequencing	200	2,500
Orbit Injection/Station Acq.		
Deployment/Separation		
On-Orbit		
Control		
Station Keeping	3,000	200
Attitude Control	750	500
D/L Pointing	500	250
D/L Search	200	500
TTC Buffering	N/A	1,600
Autonomous Control	100	200
Communications		
Channel Supervision	7,500	15,000
Total	12,250	20,750
	(Equivalent Adds)	
LS/TTL	1.3 lbs/3.0W	
FTC	1.7 lbs/2.0W	

Table 4.3-4. Solar Power Technology.

Type	Status	Watts/Pound (5-7 Year Geosync Mission)
Spinner	Flight	3
Oriented	Qualified	9
Hardened	Development Completed 1978	18
12% EFF SI 25 kW Array		25
15% EFF SI	Initial Development	30
20% EFF GAS		40
25-30% Multi-GAP		60
WIDENET Design Value		20

Table 4.3-5. Satellite Battery Technology.

Type	Status	W-HR/Pound
NiCd	Flight Qualified Projected (1985)	4.5 - 6.8 10
Ni-H$_2$	Two Successful Flight Tests in 1978	14 - 20 (1985)
WIDENET Design Value		16

Current flight-qualified NiCd (nickel-cadmium) batteries have an effective energy capacity of 4.5 to 6.8 Watt-hour/pound and a 1985 projected capability of 10 Watt-hour/pound. In 1978 NiH_2 (nickel-hydrogen) batteries completed a major development phase and two successful flight tests. The projected 1985 capacity is 14 to 20 Watt-hour/pound. For preliminary design purposes, the conservative capacity of 16 Watt-hour/pound is assumed.

Comparisons of solar battery and nuclear-electric power systems based on specific power show nearly equivalent performance in the 1985-1990 time frame for power levels above 50 kWatts (Barthelemy et al., 1979). Below 50 kWatts the solar/battery systems appear to maintain their present advantage. Current flight-qualified solar battery systems could be used in this application while accepting the associated weight penalties. The solar option with current technology is compared to the projected solar technology in Fig. 4-10. In contrast, current flight-qualified nuclear systems are too small for this application and projected technology programs must be assumed if a nuclear power system is selected.[*] For these reasons only solar battery systems are considered in this preliminary design. The choice between solar and nuclear must ultimately be made on the basis of life-cycle cost. This analysis is yet to be done for this application.

4.3.2 COMMUNICATION SYSTEMS

4.3.2.1 Receiver Channels

A block diagram of the complete satellite communication subsystem is shown in Fig. 3.3-2. Figure 4-5 shows a typical receiver channel and the assumed per-unit weight and (conditioned) power for each component. These unit weights and powers are based on current design practice for flight hardware. The TFM demodulator weight and power are based on Dekker (1979). The total number of units is a function of the number of

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[*] The largest flight-qualified nuclear power systems are the RTGs (radioisotope thermoelectric generator) on the LES-8/9 spacecraft. They produce ∿ 300 Watts, whereas the baseline satellites in this system require ∿ 4 kWatts.
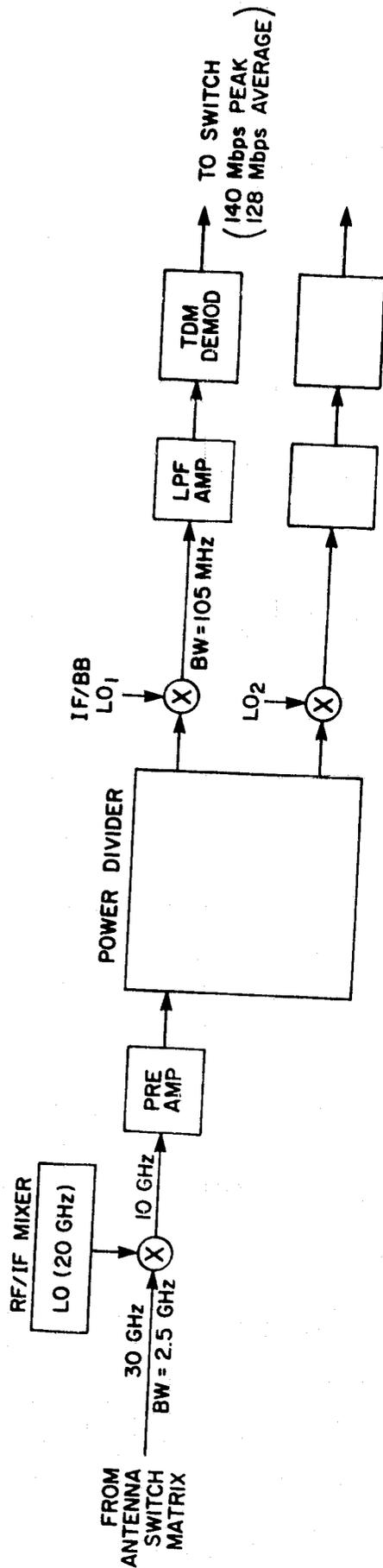
	UNIT WEIGHT (lb_m)	UNIT POWER W	UNITS* (400 Ch)	WEIGHT (lb_m)	CONDITIONED POWER (W)
RF/IF MIXER	0.4	—	50	20	—
IF AMP	1.0	0.5	50	50	25
INPUT MUX	0.2	—	50	10	—
IF/BB MIXER	0.2	—	100	20	—
LPF/AMP	0.2	0.5	100	20	50
DEMOD	1.0	1.0	100	100	100
				TOTAL 220 lb_m (100 kg)	175 w

*INCLUDES MAINTENANCE

Figure 4-5. Typical satellite receiver channel configuration and the assumed per-unit weight and power requirements for major components.

channels. Figure 4-5 shows the number of units of the 12.8 Gbps baseline system, taken from Table 3.3-2, and the resulting total receiver weight (220 pounds) and conditioned power (175 Watts).

4.3.2.2 Transmit Channels

Figure 4-6 shows a typical transmit channel based on Fig. 3.3-2 and the assumed per-unit weight and power for each component. Appendix A4.3 gives the present and projected (1983-1988) spaceborne, 20-GHz power generation capabilities together with other technical data. This information is based on the technical literature and contacts with several manufacturers. The data suggest that TWTs are likely to maintain a lead in power output and efficiency while having acceptable reliability and intermodulation products. For preliminary design purposes a 10-W (RF) TWT with 30% efficiency is assumed. These values are below the projected limits of 30 Watts and 33% efficiency. The number of units of the 12.8-Gbps baseline is shown in Fig. 4-6 and gives a total transmitter weight of 455 pounds, 150 Watts of conditioned power, and 1,750 Watts of bus power.

4.3.2.3 Local Oscillator Bus

Figure 4-7 shows a typical LO (local oscillator) bus for the transmit and receive channels. The assumed component per-unit weights and powers are indicated. There are separate LO busses for the receive RF-to-IF, receive IF-to-baseband, and transmit baseband-to-RF mixers. The number of mixers is a function of the satellite data rate and is 250 for the 12.8-Gbps system. The total LO bus subsystem weight and power for the 12.8-Gbps baseline is 55 pounds and 30 (conditioned) Watts. The unit in Fig. 4-7 can be reduced in weight and power by a factor of ~ 3 at the expense of not covering all 24 bands in a single satellite. A 12.8-Gbps system requires only 5-10 bands.

4.3.2.4 Switching Matrix

Appendix A4.4 shows that $\sim 12N \log_{10} N$ switches can connect N input lines to N output lines with small blocking probability. For the baseline TDM format, the guard time between message packets varies from about 50 μsec to 200 nsec, depending on the user-to-user rate. Hence, the

BB
FROM SW
LO₁ → RF TDM MOD → GAIN CONTROL → MUX → DRIVER → TWTA 10W RF → MUX → TO ANTENNA FEED

UP TO FOUR OUTPUT CHANNELS
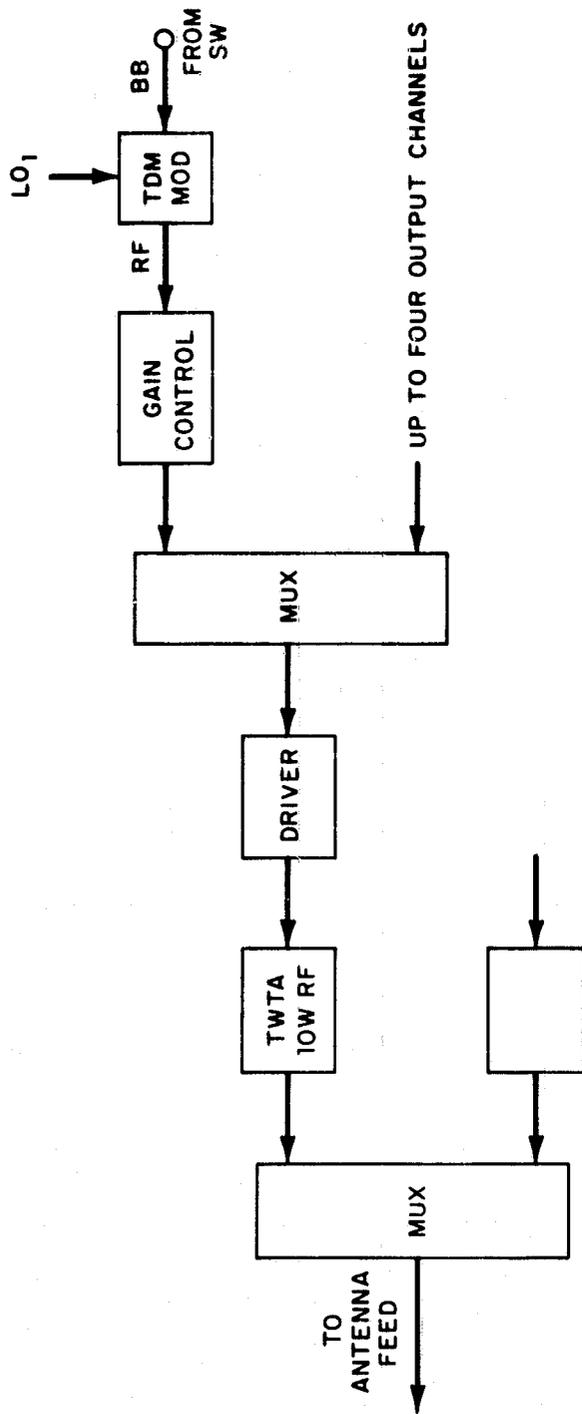
	UNIT WEIGHT (lb_m)	UNIT C.POWER (W)	UNIT P.POWER (W)	UNITS* (400 Ch)	WEIGHT	CONDITIONED POWER	P. POWER
TDM MOD	1.0	1.0	—	100	100	100	—
GAIN CONTROL	0.2	0.5	—	100	20	50	—
MUX	0.2	—	—	50	10	—	—
T_x/DRIVER	6.5	—	35	50	325	—	1,750
MUX	0.5	—	—	—	—	—	—
				TOTAL	455 lb_m (210 kg)	150 W	1,750 W

* INCLUDES MAINTENANCE

Figure 4-6. Typical satellite transmitter channel configuration and the assumed per-unit weight and power requirements for major components.
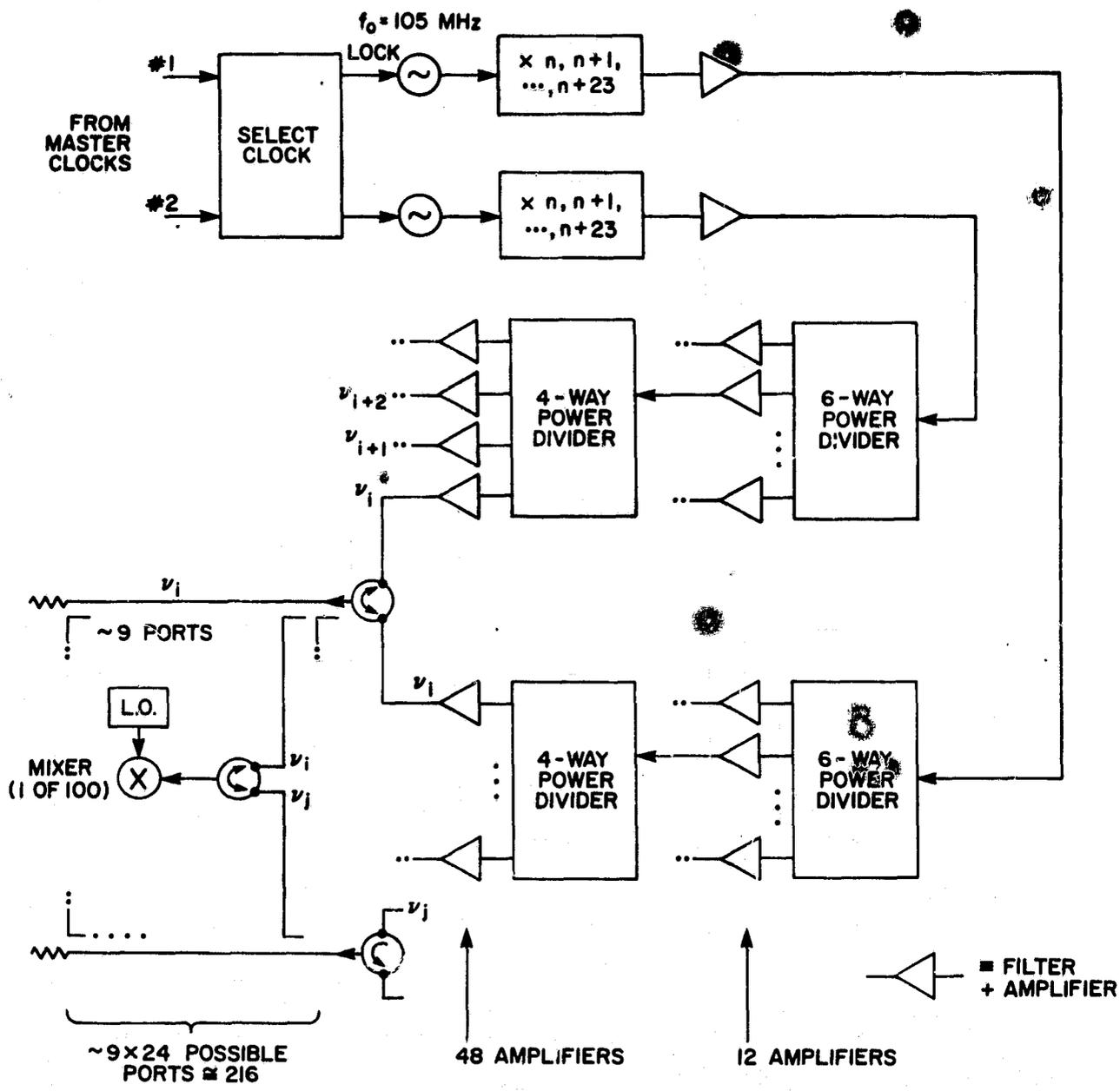
Figure 4-7. Possible local oscillator system for the satellite transmitters and receivers.

required switching speed varies from about 25 kHz to 5 MHz. A single
switch would generally be thrown no more often than $\sim$ 125 kHz, which
would correspond to 256-kbps packets arranged in the worst possible way.
Table 4.3-6 shows the estimated weight and power of a switch matrix
assuming, for preliminary design purposes only, low power Schottky tech-
nology. As shown, the 12.8 Gbps baseline switch would weigh 5 pounds and
require 5 (conditioned) Watts. The maximum number of switches that can
be integrated into one chip is limited by power dissipation. Typical LSI
chips today have a maximum dissipation of about 1 Watt (Waser, 1978).
Since the above switch power exceeds this present limit, a detail design
of the switch would need to address this cooling problem.

Table 4.3-6. Satellite Switch Matrix Summary.

Capacity Gbps	No. 32-Mbps Links	No. Input Lines	No. SPST SW	Cond Pwr	Design Value
12.8	390	98	2,342	2.3W	5W
25.6	770	202	5,588	5.6	10
42	1,290	356	10,900	10.9	15
74	2,270	618	20,698	20.7	25

Assumes:

1. LS/T^2L
2. 1 mW per switch
3. Interchannel guard times 48 μsec (21 kHz) to 200 nsec (5 MHz)
4. $N_{SW} = 12\ N\ \log_{10}N$, N_{sw} = No. of (SPST) switches, N = No. of lines

4.3.2.5 Communications Weight and Power, Summary

The preceding receive, transmit, LO and switching subsystems consti-
tute the portion of the satellite that is directly a function of the
satellite communications capacity. These subsystems are referred to as
COMM in the algorithm for computing the satellite weight and power
(Section 4.3.3). Table 4.3-7 summarizes the four systems of COMM for the
cases of 12.8, 25, 42, and 74 Gbps channels. Figure 4-8 shows the curves
of satellite capacity vs. COMM weight, conditioned and bus power.

Table 4.3-7. Communications System Weight and Power Requirements.

12.8 Gbps	Pounds	Cond. Watts	Bus Watts
Rx	220	175	-
Tx	455	150	1,750
LO Bus	55	30	-
SW	5	5	-
COMM Total	735	360	1,750
25.6 Gbps			
Rx	426	343	-
Tx	859	303	3,220
LO Bus	55	50	-
SW	5	10	-
COMM Total	1,345	706	3,220
42 Gbps			
Rx	668	553	-
Tx	1,332	534	4,725
LO Bus	55	82	-
SW	5	15	-
COMM Total	2,060	1,184	4,725
74 Gbps			
Rx	1,124	957	-
Tx	2,162	927	7,420
LO Bus	55	141	-
SW	5	25	-
COMM Total	3,346	2,050	7,420
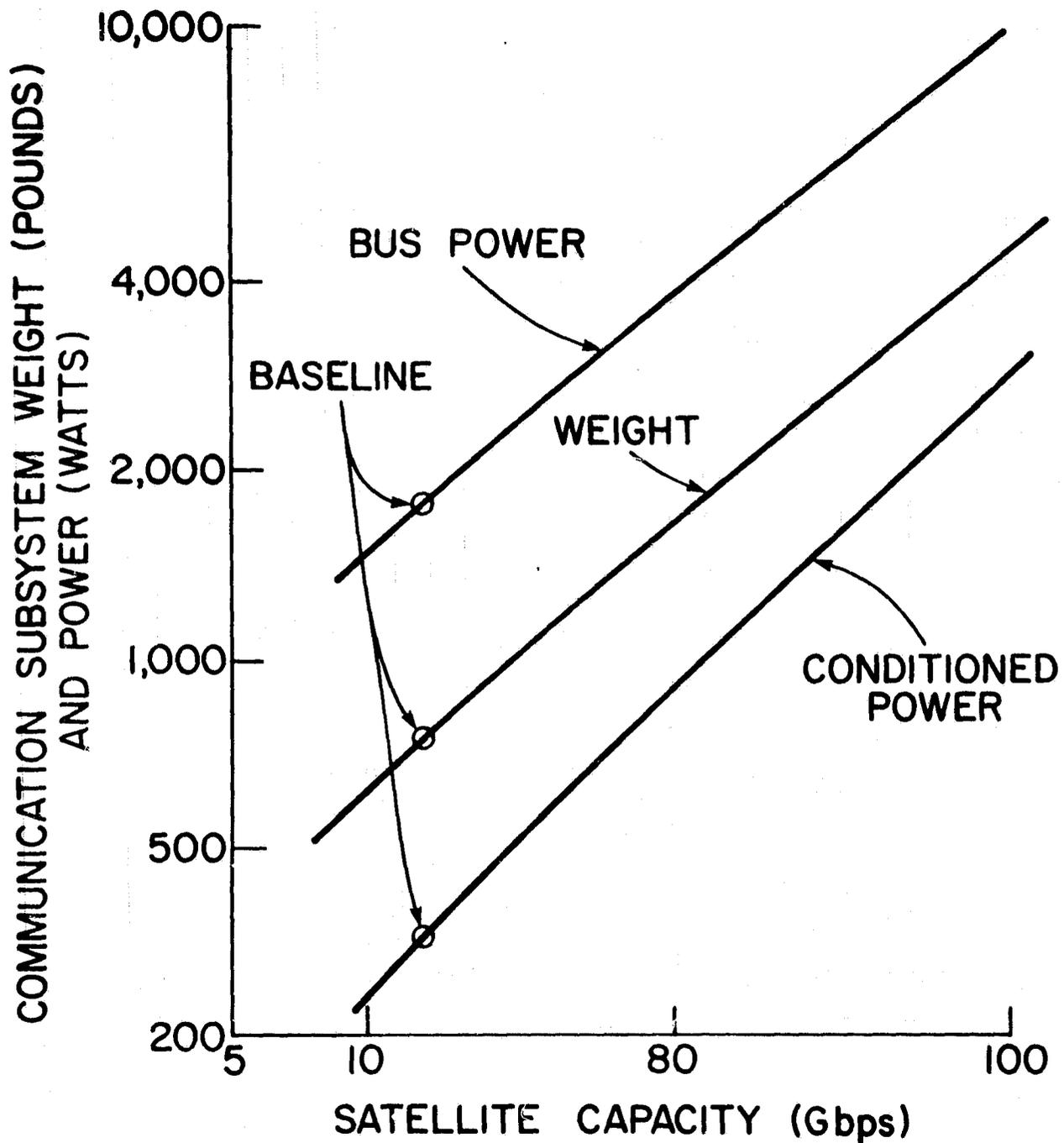
Figure 4-8. Satellite communications subsystem conditioned and bus power
and weight.

4.3.2.6 Antenna

The antenna assembly includes the reflector surfaces, structural supports, feed and diplexer assembly, and the ferrite switching matrix. The following paragraphs give the weight and power estimates for each of these systems.

Figure 3.3-11 gives a schematic of the antenna structure. For preliminary design purposes the reflector weights are based on the wrapped-rib construction technique since this is a method that gives accurate surface shapes. In practice another technique may be used, e.g., with composite materials; however, the wrapped-rib weight estimate should be an upper bound. For antennas in the 20-foot diameter class, the specific weight of wrapped-rib antennas based on projected area is about 0.4 pound/ft^2 (LMSC, 1970). The total area of the primary and secondary reflector surfaces is about 860 ft^2 giving a reflector weight of about 345 pounds.

It is assumed that a composite material is used for the structural supports. Powell and Browning (1978) show a typical beam assembly for space structures that weighs about 1.1 kg/meter. The material is a thermoplastic resin with glass and graphite fiber reinforcement. For a 4-meter equivalent length and a safety factor of 5, the antenna structure would weigh about 50 pounds.

The feed and diplexer assembly is an integrated structure. Assuming 1 cm^3 of copper per feed (including a diplexer), 400 feeds, and a factor of 3 for the supporting structure, the total weight of this assembly is about 25 pounds.

The weight of the ferrite switches for the receive and transmit channels is based on 91 gm and 0.1 Watts per switch (Electromagnetic Sciences, 1978).[*] The total weight for 1,000 switches is about 250 pounds, including 50 pounds of supporting structure; the weight of each switch might be reduced by appropriate engineering prior to 1985.

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[*]ESI-Model 408-6.

4.3.2.7 Communication Processor

A WIDENET system may be controlled by ground-based or spaceborne computers. To bound the maximum satellite weight and power, it is assumed that the network is controlled by a spaceborne computer. As will be seen below, there may be a technical risk with this approach due to radiation effects. The ground-controlled system may be preferable for this reason, in addition to economic and other issues.

For purposes of estimating the basic computer parameters, a baseline computer architecture, shown in Fig. 4-9, is assumed. Appendix 4.6 shows the model used to estimate the memory size and computational speed of this baseline architecture. The weight and power are estimated assuming CMOS/SOS implementation. For the 12.8-Gbps baseline, the communications computer would have a memory of 1.2 Mbits, a speed of 2.3 Mop/sec (equivalent adds), weigh 20 pounds and use 45 (conditioned) Watts. Table 4.3-8 summarizes the computer parameters for other channel capacities.

Table 4.3-9 shows the cumulative radiation hardness of current state-of-the-art CMOS devices (Borkan, 1977). Assuming a residual radiation exposure of about 70 krads (Si) per year (Reagan, 1977) for devices shielded by the equivalent of 0.1 inch of Al (plus 0.010 inch Ni covers), marginally acceptable devices for a 7-year mission must be hard to at least 0.5 Mrad (Si) total dose. Allowing for processing variation in hardened devices, a hardness level of at least 1 Mrad (Si) must be required or additional shielding must be used. The current state of the art of hardening technology yields CMOS devices which are marginally acceptable. Unhardened MOS is totally unacceptable. The availability of CMOS/SOS switches and useful devices in full sets (processors, memories, etc.), and the effect of CMOS LSI hardening processing technology and design variation of long-term reliability of parts, remains to be assessed.

Typical LS/TTL is hard to several Mrads (Si) and thus could easily meet the requirements of a 7-year mission with inherent spacecraft structural shielding at the 0.1 inch of Al equivalent level. Implementation by LS/TTL would increase the power required by about a factor of 4.
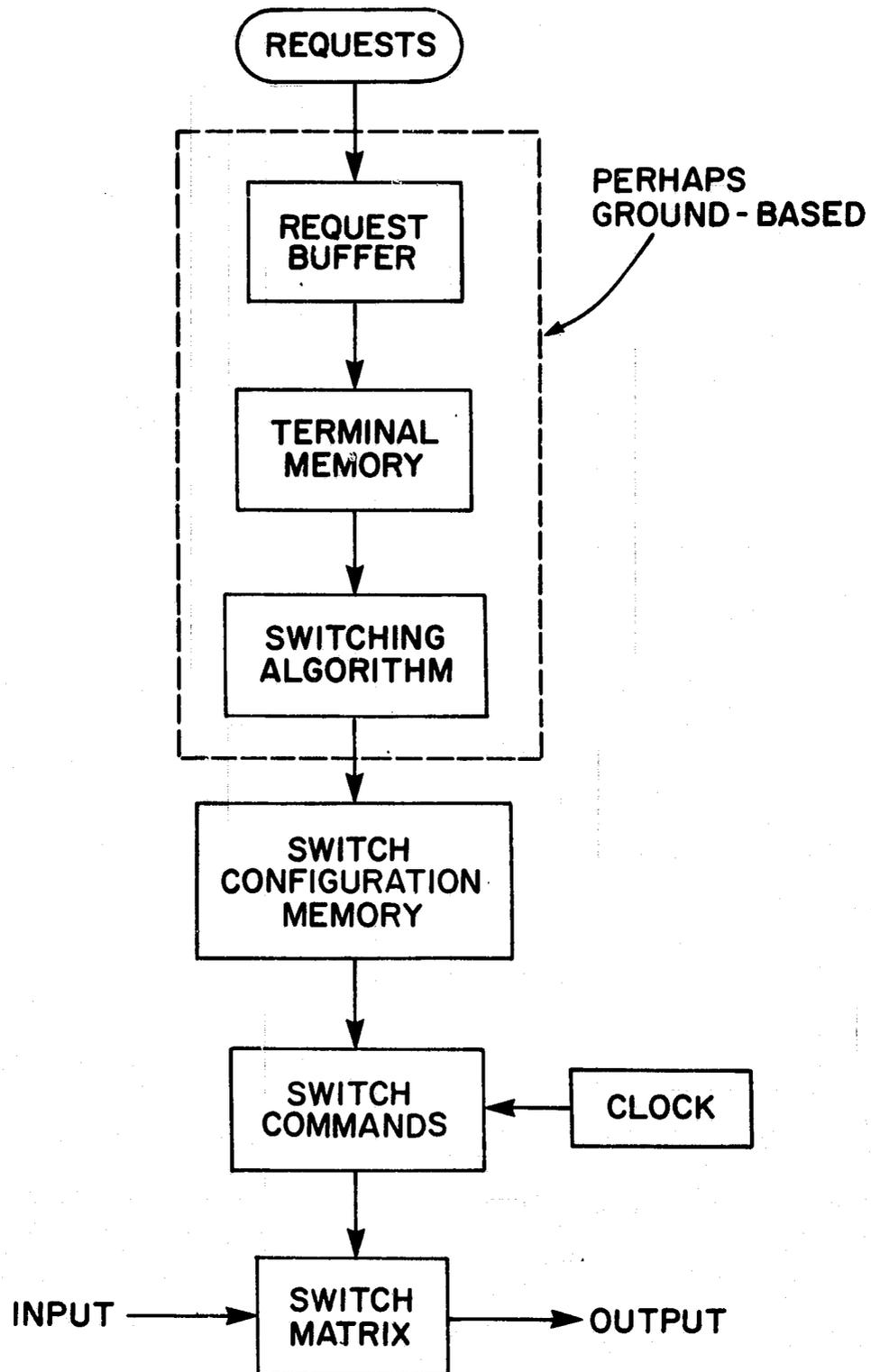
Figure 4-9. Baseline computer architecture.

Because of these considerations, a detailed design of a WIDENET system may indicate that a ground-controlled routing system is preferable.

Table 4.3-8. Satellite Communication Processor.

	12.8 Gbps	25 Gbps	42 Gbps	74 Gbps
Req. Buffer (kbits)	1	1	1	1
Terminal Memory (kb)	1,000	1,000	1,000	1,000
SW CUNF Memory (kb)	18.7	44.7	87.2	165.6
Contingency (kb)	180	154	112	33
Total Memory (kb)	1,200	1,200	1,200	1,200
No. of SW	2,342	5,588	10,900	20,698
Speed (Mops)	2.3	5.6	10.9	20.7
Weight (lb) } CMOS/SOS	19.1	46.7	90.8	172.5
PWR (W) }	41.4	100.8	196.2	375.6
Design Values				
Weight (lb)	20	50	50	175
(COND) Power (W)	45	100	200	375

Table 4.3-9. Cumulative Hardness of CMOS Technology.

Technology	Cumulative Hardness
AL-GATE/BULK SI	1 Mrad (Si) typical
	3 Mrad (Si) max achieved
AL-GATE/SOS	0.5 Mrad (Si) PROM
	3 Mrad (Si) Time-base generator
	10 Mrad (Si) MUX
SI-GATE/BULK SI	0.3-0.5 Mrad (Si)
SL-GATE/SOS	1 Mrad (Si) (low dose rate)

4.3.3 SATELLITE WEIGHT AND POWER ALGORITHM

The satellite weight and power are estimated by an algorithm gener-
ated for large communication satellites. Table 4.3-10 shows the
algorithm applied to the FLTSATCOM satellite. Using the assumptions and
models outlined previously for the various systems, the above algorithm
with minor changes was applied to the WIDENET satellites with different
channel capacities. Table 4.3-11 shows the resulting weight and power
breakdown for the 12.8 Gbps baseline. It is seen that the BOM weight
and power are 3,925 pounds and 4,917 Watts, respectively, for this case.
Table 4.3-11 shows that all items following Item 10 are computed. An
iteration is required since the RCS tankage depends on the propellant
weight and, hence, the BOM weight (Fig. 4-3). Repeated application of
this algorithm for different communication capacities was used to generate
Fig. 4-1.

The linear dimensions of the satellite body can be estimated from
the black-box densities of other satellites. For the 12.8-Gbps baseline
(Table 4.3-11), the satellite body weight is estimated to be 2,575 pounds,
i.e., 3,925 pounds BOM minus 1,350 pounds (654 pounds RCS propellant, 55
pounds RCS tankage, 246 pounds solar array, 395 pounds antenna reflector).
Assuming a density of 15 pounds/ft^3 (LES 8/9), the body volume is about
172 ft^3 and has a linear dimension for this case of about 5.6 feet
(1.7 meters).

Figure 4-10 shows the sensitivity of a typical large future 20/30 GHz
satellite BOM weight to assumptions about the power system technology.
The current (advanced) satellite power technology assumes 9 Watts/pound
(20 Watts/pound) for the solar array and 15 Watt-hour/pound (16 Watt-hour/
pound) for the batteries. The figure indicates a 25% to 30% reduction in
BOM weight with advanced power technology. As discussed in Section A4.1.4,
the WIDENET baseline design assumes advanced power technology. Nevertheless,
the above advanced technology is on the low end of the projected technology
range (Table 4.3-4) and an additional 25% weight reduction is possible if
the more speculative performances are realized.

It is clear that many similar tradeoffs can be done with the other
satellite systems. This task remains for a detail design exercise.

Table 4.3-10. Satellite Weight and Power Algorithm Example.
(This example uses FLTSAT communications
payload weight and power.)

Item	Description	Pounds	Watts	Remarks
1	Comm. Payload	490	881	Electronics, Antennas
2	Attitude Control	125	60	
3	TTC	60	40	
4	RCS (Less Tankage)	50	25	
5	Sub-Total	725	1006	
6	Thermal Control Power		20	2% of Item 5
7	Sub-Total		1026	
8	Power Contingency		100	$(.10) \times$ Item 7
9	Battery Charge Power		135	$(.12) \times$ (Items 7 + 8)
10	Array E.O.L. Power		1261	Items 7 + 8 + 9
11	Power System Weight	544		W = 40 lb. + 0.4 lb/Watt
12	Total Fixed Weight (WF)	1269		
13	Structure	325		.16 WD (Dry Weight)
14	Thermal Control Weight	81		.04 WD
15	Hardness	183		.09 WD
16	RCS Tankage	28		.014 WD
17	AKM Case	145		.072 WD
				.376 WD + WF = WD
18	Total Dry Weight (WD)	2031		WD = (1.60) WF
19	RCS Propellant	181		(.072) WD + 35 lb
20	Total Wet Weight (WW)	2212		
21	AKM Propellant	2041		(.923) WW
22	Total Launch Weight (WL)	4253		

Table 4.3-11. Satellite Weight and Power Estimates
(12.8-Gbps Baseline System).

Item	(Formula)	Pounds(A)	Cond Watts(B)	Bus Watts(C)
1	COMM	735	360	1750
2	ACS	180	–	190
3	RCS	75	–	25
4	Control Processor	5	5	–
5	Communication Processor	20	45	–
6	CMD/TLM (S-Band)	20	20	–
7	Ant Reflector and Structure	395	–	–
8	Ant Feed and Diplexer	25	–	–
9	Ferrite Switch Matrix	250	–	100
10	Sub-Total	1705	430	2065
11	Pwr Conditioning Loss (10% Item 10B)			43
12	Conditioned Power			430
13	Bus Pwr			2538
14	Thermal Control Pwr (2% Item 13)			51
15	Sub-Total			2589
16	Pwr Contingency (10% Item 15)			259
17	Sub-Total			2848
18	Pwr Dist/Cond (5% Item 19C + 10% Item 10B)	200	(10% Item 16)	285
19	Sub-Total	1905		3133
20	Harness (5% Item 19A)	95	(5% Item 19C)	156
21	Sub-Total	2000	Night Pwr =	3289
22	Batteries (7.5% Item 21C)	246	(15% Item 21C)	493
23	Sub-Total	2246	EOM Pwr =	3782
24	Solar Array (20 W/1b) (5% Item 32C)	246		
25	Sub-Total	2492		
26	Thermal Control (4% Item 28)	125		
27	Spacecraft Structure (16% Item 28)	498		
28	Sub-Total (125% Item 25)	3115		
29	Wgt Contingency (5% Item 28)	156		
30	EOM (Dry) Wgt	3271		
31	RCS Propellant	654		
32	BOM (Wet) Wgt (120% Item 30)	3925	(130% Item 23C) BOM Pwr	4917
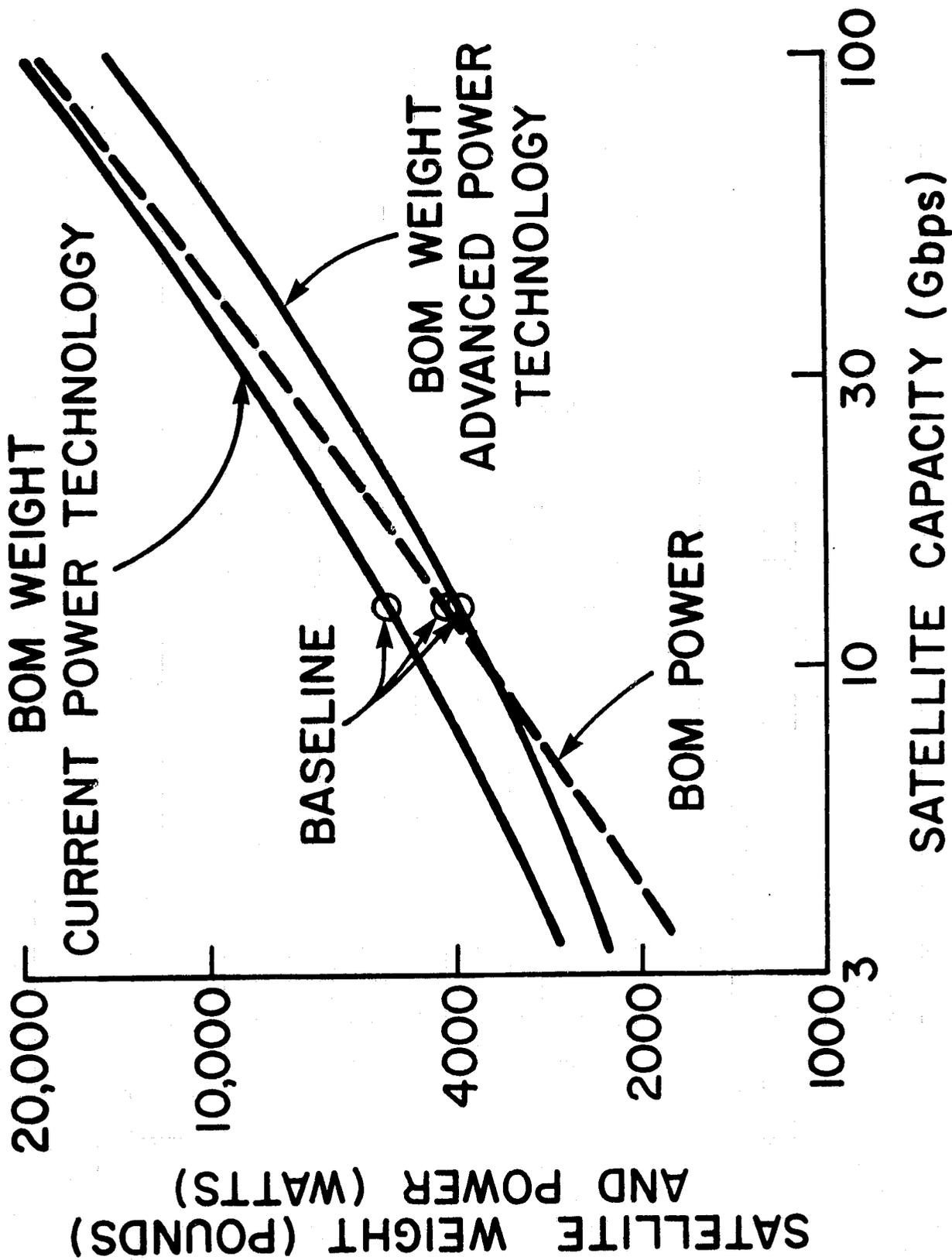
Figure 4-10. Satellite weight and power versus satellite capacity.

4.3.4 SATELLITE COST ALGORITHM

During the past few years cost-estimating models have been developed based on components and/or major subassemblies (Fong, 1977; Bekey, 1978). The advantages of such models are that they give a more accurate description of a given subsystem and that they can take into account the development status of particular components. The disadvantage of these models is that they cannot be applied to advanced concept satellites where there is insufficient information about the subsystems (assuming they agree on subsystem definitions).

Satellite development (nonrecurring) costs appear to be the most sensitive to program peculiarities while production (recurring) costs are less sensitive and are much better estimated by all the cost models. Recent studies (Dryden and Large, 1977) suggest that cost models should not be used mechanically. While the models themselves differ sharply and give different results, nevertheless all appear to agree that the most important variable is weight and that very few other variables are useful.

For purposes of a preliminary design, the cost estimates for the WIDENET satellites are based on an algorithm generated for communication satellites in a recent DCA study (DCA, 1976). This algorithm, based on satellite weight, grossly agrees with other models for communication satellites. Figure 4-11 shows the 1979 recurring and nonrecurring costs according to the DCA model, and Fig. 4-12 presents the estimated costs ($1975) for launch to synchronous orbit. Figure 5-3 shows the recent inflation rate for materials and labor. Based on this data, the WIDENET costs have been adjusted to 1979 assuming 8% inflation per year. Figure 4-2 shows the resulting 1979 costs per satellite as a function of communication capacity.

4.4 FINAL COMMENTS

This communication satellite is big and complex. Its design, construction and deployment would be a major undertaking. Nevertheless, based on the foregoing preliminary examination, the satellite appears to be technically feasible in the late 1980's, and the costs seem reasonable.
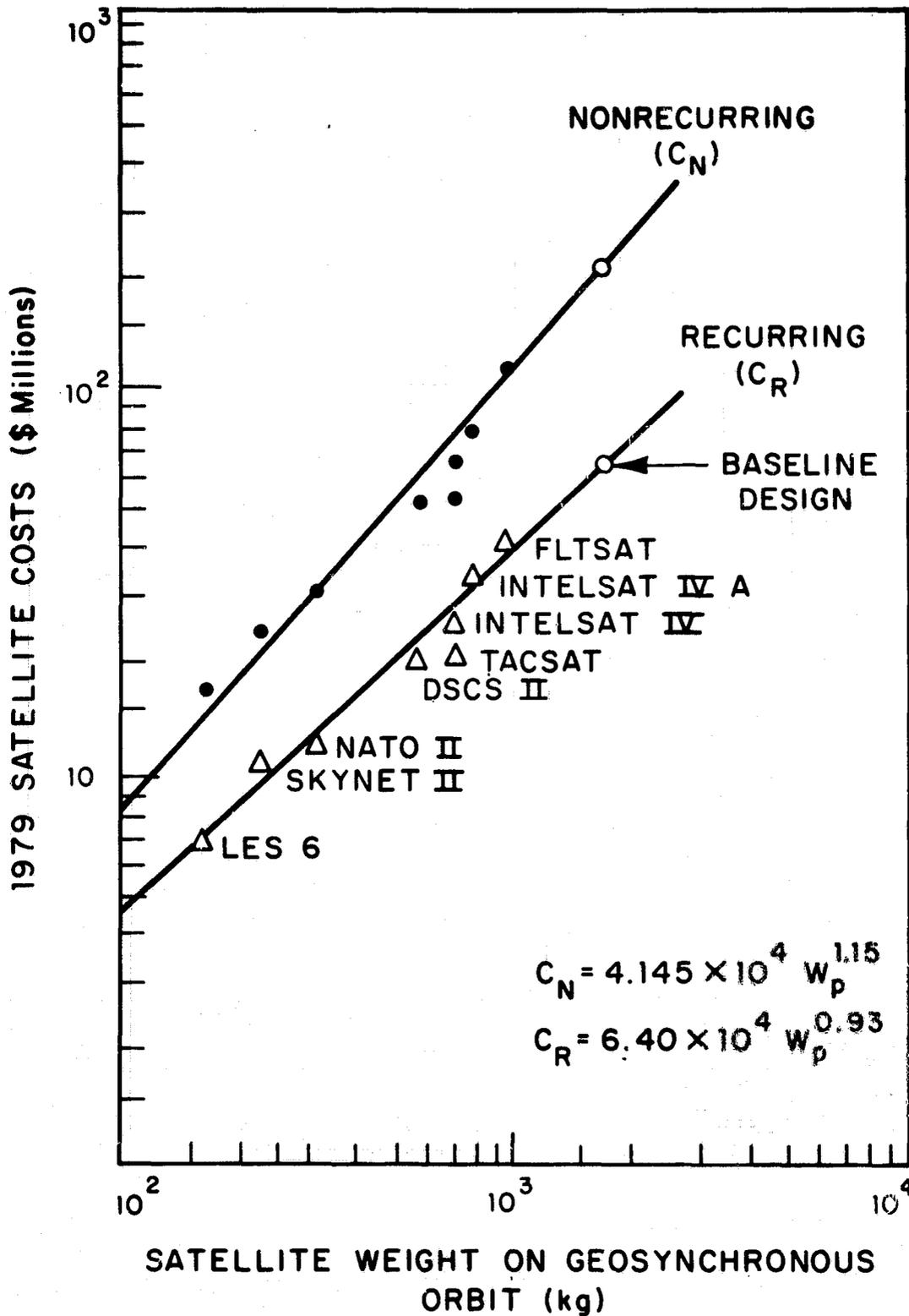
Figure 4-11. DCA model for recurring and nonrecurring spacecraft costs in 1979 dollars.
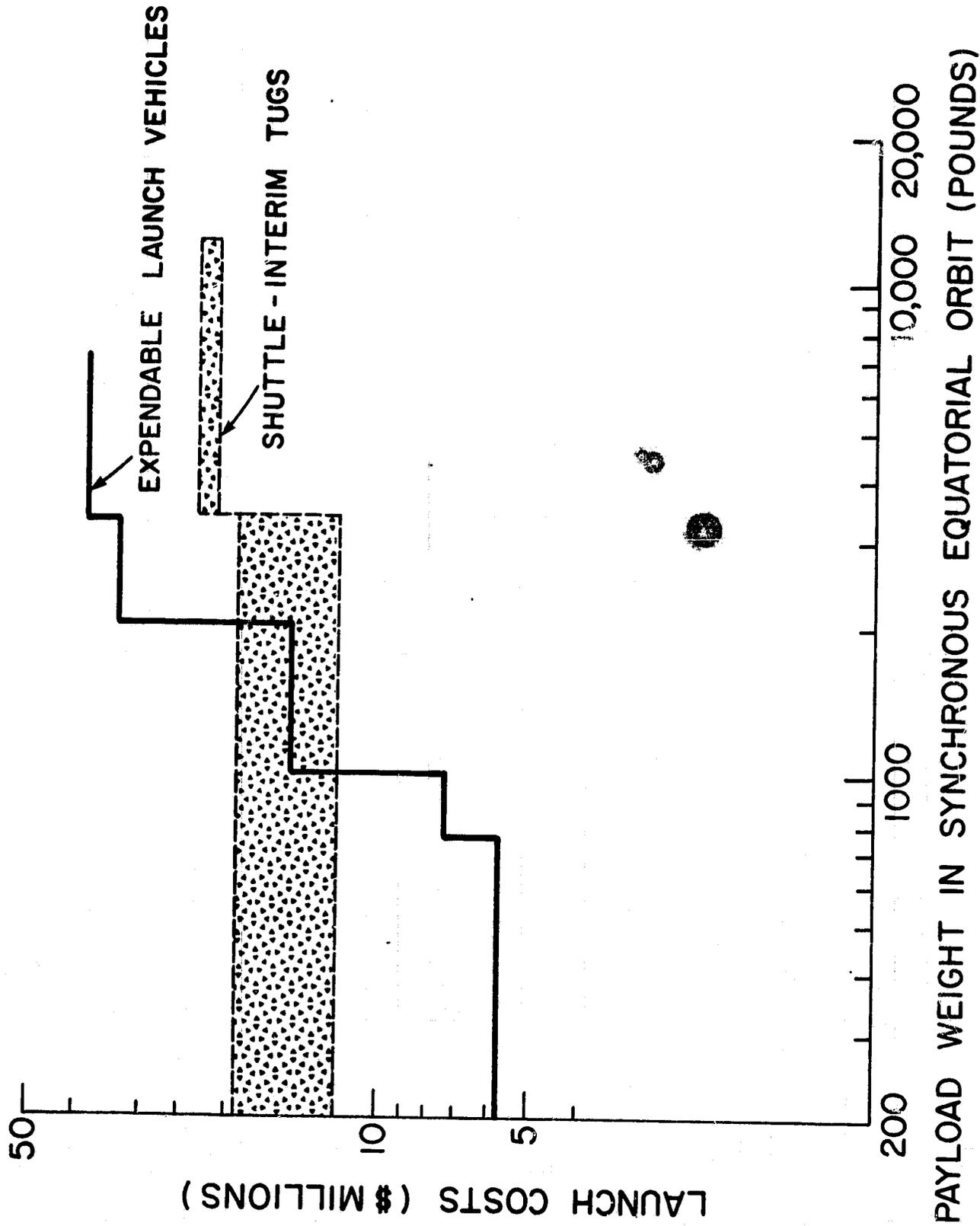
Figure 4-12. Launch costs versus payload weight and launch vehicle.

EXPENDABLE LAUNCH VEHICLES

SHUTTLE - INTERIM TUGS

LAUNCH COSTS ($ MILLIONS)

50

10

5

200

1000

10,000 20,000

PAYLOAD WEIGHT IN SYNCHRONOUS EQUATORIAL ORBIT (POUNDS)

ACKNOWLEDGMENTS

Chapter 4   References

1.   Aukstikalnis, A. J., "Spacecraft Computers," _Astronautics and Aeronautics_ (July/August 1974), pp. 33-40.

2.   Barthelemy, R., "Aerospace Power Systems," _Astronautics and Aeronautics_ (December 1978), pp. 26-27.

3.   Barthelemy, R., "Aerospace Power Systems -- A Building Surge," _Astronautics and Aeronautics_ (February 1979), pp. 64-71.

4.   Bekey, I., "Preliminary Definition and Evaluation of Advanced Space Concepts, Volume II: Analyses and Results," The Aerospace Corporation, ATR-78 (7674)-1, Vol. II, El Segundo, California, 30 June 1978.

5.   Borkan, H., "Radiation Hardening of CMOS Technologies: An Overview," _IEEE Transactions on Nuclear Science_, Vol. NS-24, No. 6 (December 1977).

6.   Burchby, D. and Kern, L., "Specification of the Fault-Tolerant Spaceborne Computer (FTSC)," _FTSC-6 Proceedings_ (June 1976).

7.   Davis, P., _et al._, "A Versatile New Reaction Wheel Used on FleetSat-Com and Canadian CTS," _EASCON '74 Proceedings_, pp. 159-165, Washington, D.C., June 1974.

8.   DCA, "MILSATCOM System Architecture," Annex G Cost Models, Military Satellite Communication Systems Office, Defense Communications Agency, Washington, D.C. (March 1976).

9.   Dekker, C. B., personal communication, January 3, 1979.

10. Dryden, J. A. and Large, J. P., "A Critique of Spacecraft Cost Models," The Rand Corporation, R-2196-1-AF, September 1977.

11. Fong, F. K. SAMSO unmanned spacecraft cost model – updated cost estimating relationships and normalization factors (An interim report), USAF Space and Missile Sys. Org., TR No. 77-247, March, 1971.

12. Frediani, D. J., "Technology Assessment for Future MILSATCOM Systems: The 30/20 GHz Band," Project Report DCA-4, Lincoln Laboratory, M.I.T. (24 August 1978).

13. Free, B. and Hudson, G., "Selected Comparison among Propulsion Systems for Communication Satellites," _AIAA Progress in Astronautics and Aeronautics: Communications Satellite Technology_, Vol. 33, edited by P. L. Bargellini, The M.I.T. Press, Camhridge, MA., 1974, pp. 165-190.

14. Isley, W. C. and Duck, K. I., "Propulsion Requirements for Communications Satellites," _AIAA Progress in Astronautics and Aeronautics: Communications Satellite Technology_, Vol. 33, edited by P. L. Bargellini, The M.I.T. Press, Cambridge, MA., 1974, pp.

15. LMSC/A969503, "The Wrap Rib Parabolic Reflector Antenna," Lockheed Missiles & Space Co., Inc., Sunnyvale, CA., April 10, 1970.

16. Marcus, M. J., "The Theory of Connecting Networks and their Complexity": a Review, Proc. IEEE, 65, 9, 1263-1271 (1977).

17. Pippenger, N., "Complexity Theory," Scientific American, Vol. 238, No. 6 (June 1978), pp. 114-124.

18. Rauschenbach, H. S., "Solar Cell Array Design Handbook, Vol. 1 and 2," California Institute of Technology, Jet Propulsion Laboratory, Pasadena, CA., JPL SP 43-38 (October 1976).

19. Reagan, J. B., et al., "The Effects of the Geosynchronous Energetic Particle Radiation Environment on Spacecraft Charging Phenomena," Proceedings of the Spacecraft Charging Conference, NASA TMX-73537 (February 24, 1977).

20. Rowher, C. J., et al., "Space and Missile Systems Organization Unmanned Spacecraft Cost Model," Third Edition, USAF Space and Missile Systems Organization, Cost Analysis Division, El Segundo, CA., August 1975.

21. Schindler, R. C. and Schoenman, L., "Development of a Five-Pound Thrust Bipropellant Engine," J. of Spacecraft and Rockets, Vol. 13, No. 7 (July 1976), pp. 436-442.

22. Staeker, P. W. and Peterson, P. F., "A Survey of Solid-State Microwave Power Devices," Technical Note 1977-14, Lincoln Laboratory, M.I.T. (April 1977).

CHAPTER 5

BASELINE GROUND STATION DESIGN

5.1 INTRODUCTION

Ground station costs are a critical factor in determining the feasibility of a WIDENET system. The total ground station cost consists of the component costs plus other costs such as operation and maintenance, design, assembly, etc. Preliminary estimates of both ground station and terminal costs are included here for completeness.

Section 5.2 gives the main conclusions including the summary table and figure. Section 5.3 gives the analysis consisting of the underlying assumptions (Section 5.3.1) and a system-by-system (recurring) cost estimate of the major ground station components (Section 5.3.2). Ground link costs are discussed in Section 5.3.3 and user facilities in Section 5.3.4. Final comments are given in Section 5.4.

5.2 CONCLUSIONS

The following is an estimate of the ground station component recurring costs for a 1985-1990 system employing 10-watt transmitters, 128-Mbps data, and 8-ft antennas. The cost estimates are summarized in Table 5.2-1 and Figure 5-1.

1) The total initial price ($79) per ground station is estimated to vary from ∿ $380K to $150K as the lot size varies from one to five-thousand. The estimating algorithm involved 1) determination or estimation of catalog prices for key components, 2) multiplication by the number of units per station, 3) incorporation of an esti-mated learning factor, 4) use of a price multiplier which includes allowances for cost markups, other components, packaging, etc., and 5) addition of contingency, consultant fees, etc.

2) Although baseband costs comprise roughly half the ground station costs (1985 technology) for small lot sizes, they drop to less than one-third for lot sizes of 5000. For such large lot sizes the RF and antenna system and the personal service charges become more important because of their assumed higher learning factors. Lot sizes of a couple of hundred units are consistent with the ground

Table 5.2-1. Ground Station Cost Summary ($K'79), as a Function of Lot Size.

ITEM	UNIT RECURRING COST (1 UNIT/$K'79)	UNITS	LEARNING FACTOR	TOTAL RECURRING COSTS ($K'79) 1	10	100	1000	5000	PRICE MULT.	TOTAL RECURRING PRICES ($K'79) 1	10	100	1000	5000
ANTENNA														
1. REFLECTOR (8')	8.41	1	0.93	8.41	6.61	5.19	4.08	3.45	1.5	12.61	9.92	7.79	6.12	5.18
2. MOUNT (8')	3.20	1	0.93	3.20	2.50	1.97	1.55	1.32	1.5	4.80	3.75	2.96	2.32	1.98
3. FEED	2.00	1	0.93	2.00	1.60	1.23	0.97	0.82	2	4.00	3.20	2.46	1.94	1.64
SUBTOTAL				13.61	10.71	8.39	6.60	5.59		21.41	16.87	13.21	10.38	8.80
RF														
4. TRANSMITTER/PS	14.9	2	0.95	29.8	25.2	21.2	17.94	15.9	1.5	44.70	37.8	31.80	26.91	23.85
5. RECEIVER/PS	12.84	1	0.94	12.84	10.45	8.51	6.93	6.0	2	25.68	20.9	17.20	13.86	12.00
6. LO	1.00	2	0.94	2.00	1.60	1.23	0.97	0.82	2	4.00	3.20	2.46	1.94	1.64
SUBTOTAL				44.64	37.25	30.94	25.84	22.72		74.38	61.90	51.46	42.71	37.49
BASEBAND														
7. MODEM	2.0	2	0.85	4.0	2.33	1.36	0.79	0.54	4	16.0	9.32	5.44	3.16	2.16
8. TDMA BUFFER	0.50	16	0.85	8.0	4.66	2.77	1.58	1.09	4	32.0	18.64	11.08	6.32	4.36
9. SWITCHING/MUX	0.40	4	0.85	1.60	0.9	0.5	0.3	0.2	4	6.4	3.6	2.0	1.2	0.8
10. CODEC	1.32	8	0.85	10.59	6.17	3.60	2.10	1.44	4	42.36	24.68	14.4	8.4	5.76
11. CYPHER/DECYP	0.50	8	1.0	4.00	4.00	4.00	4.00	4.00	4	16.00	16.00	16.00	16.00	16.00
12. BW COMP/DECOMP	1.00	8	0.85	8.00	4.66	2.77	1.58	1.09	4	32.00	18.64	11.08	6.32	4.36
13. A/D-D/A	1.51	8	0.85	12.08	7.04	4.11	2.39	1.64	4	48.32	28.16	16.44	9.56	6.56
SUBTOTAL				48.27	29.76	19.11	12.74	10.00		193.08	119.04	76.44	50.96	40.00
CONTROL/SUPPORT														
14. COMPUTER	4.0	2	0.85	8.0	6.7	5.7	4.8	4.3	2	16.0	13.4	11.4	9.6	8.6
15. MASTER CLOCK	2.0	2	0.95	2.0	1.7	1.4	1.2	1.1	2	4.0	3.4	2.8	2.4	2.2
16. POWER SUPPLY	1.0	2	0.95	1.0	0.8	0.7	0.6	0.5	2	2.0	1.6	1.4	1.2	1.0
SUBTOTAL				11.0	9.20	7.80	6.6	5.9		22.0	18.4	15.6	13.2	11.8
RECURRING HARDWARE COSTS				117.52	86.92	66.24	51.78	44.21		310.87	216.21	156.71	117.25	98.09
17. CONTINGENCY		1		2.0					2	31.09	21.62	15.67	11.73	9.81
18. PACKAGING	2.0	1		4.0					2					
19. ENCLOSURE	4.0	1		4.0					2					
20. INST/START-UP	4.0	1		4.0					2					
21. LICENSE	10.0	1		10.0					1					
22. CONSULTANT	10.0	1		10.0					1					
TOTAL				147.52										

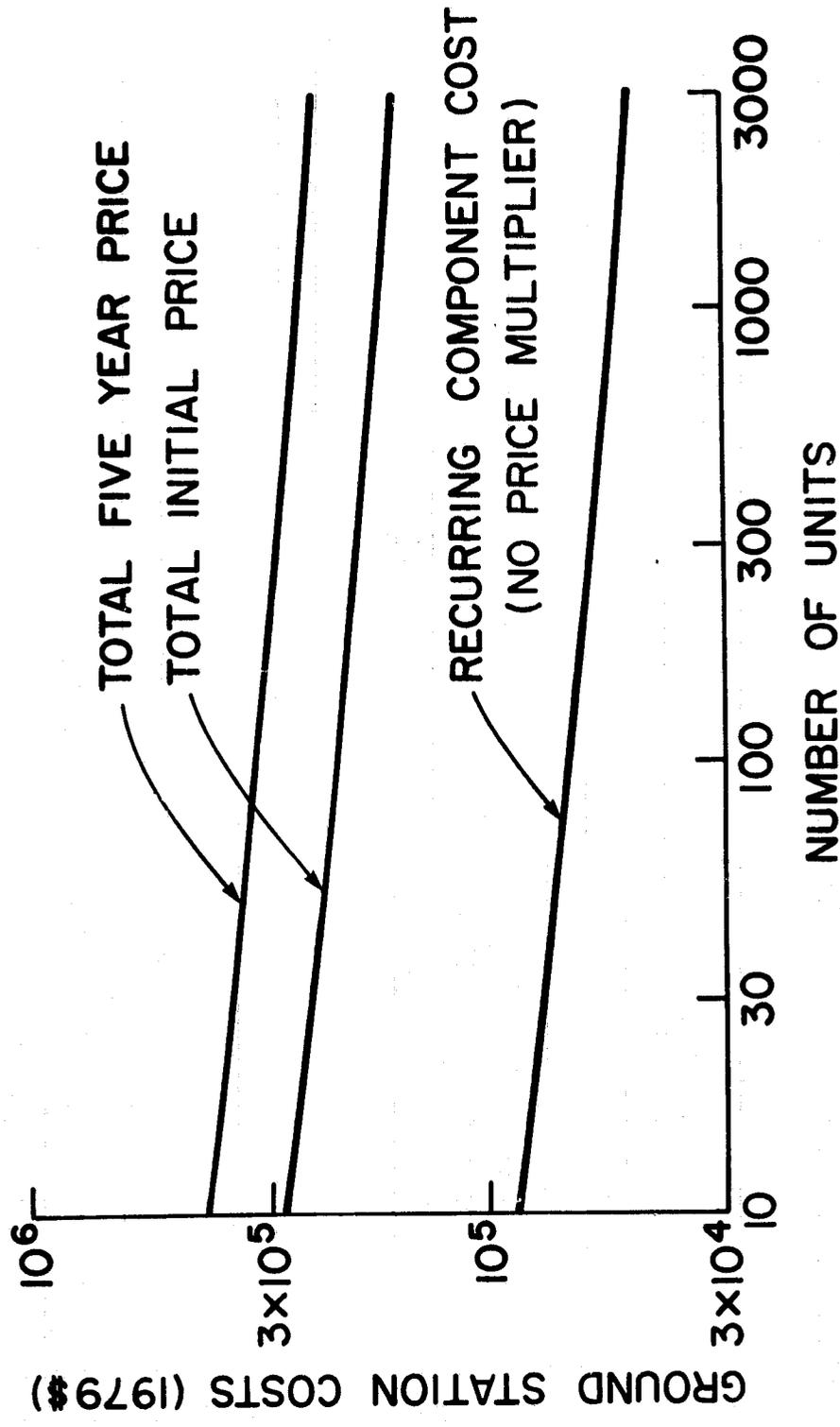| TOTAL INITIAL PRICE	381.96	277.83	212.38	168.98	147.90
5 YEAR O&M	190.98	138.92	106.19	84.49	73.95
5 YEAR TOTAL PRICE	572.94	416.75	318.57	253.47	221.85

Figure 5-1. Summary of ground station cost estimates versus number of units.

station costs incorporated in the total communications system cost analysis.

3) An operation and maintenance budget of 10 percent per annum is estimated. If half goes to site-visit labor, this labor involves ∿ 0.3-0.1 man-years per year for lot sizes of 1-5000, respectively.

5.3 ANALYSIS

5.3.1 ASSUMPTIONS

5.3.1.1 Baseline Block Diagram

Figure 5-2 shows a block diagram of a typical ground segment unit. The unit consists of a ground station, ground links to the terminals (optical links are shown in this example), and one or more terminals. The ground station contains the antenna system, RF and baseband systems, computer, interfaces with the ground link, and other peripheral systems. In Section 5.3.2 the major component costs of the ground station segment are estimated. The component costs of the ground links and terminals are estimated in Sections 5.3.3 and 5.3.4.

5.3.1.2 Inflation

Figure 5-3 shows the recent inflation rates for materials and labor (McGraw-Hill, 1979). Based on this data the component costs have been adjusted to 1979 dollars assuming 8% inflation per year.

5.3.1.3 Lot Size

In general large production lot sizes reduce the average per unit cost. The cost reduction factor, $Q(N)$, from one unit to N units is modeled by $Q(N) = L^{\log_2 N}$, where L is the learning factor. For mature technologies that are not labor intensive or complex, such as antenna systems, L is near unity and exhibits modest cost reduction. For example, a typical value for antenna systems is L = 0.93 (Kelley, 1977; Stanford, 1977) giving an average unit cost reduction of 0.79 for 10 units. For technologies that are rapidly changing, labor intensive or complex, L is smaller and significant average cost reductions can
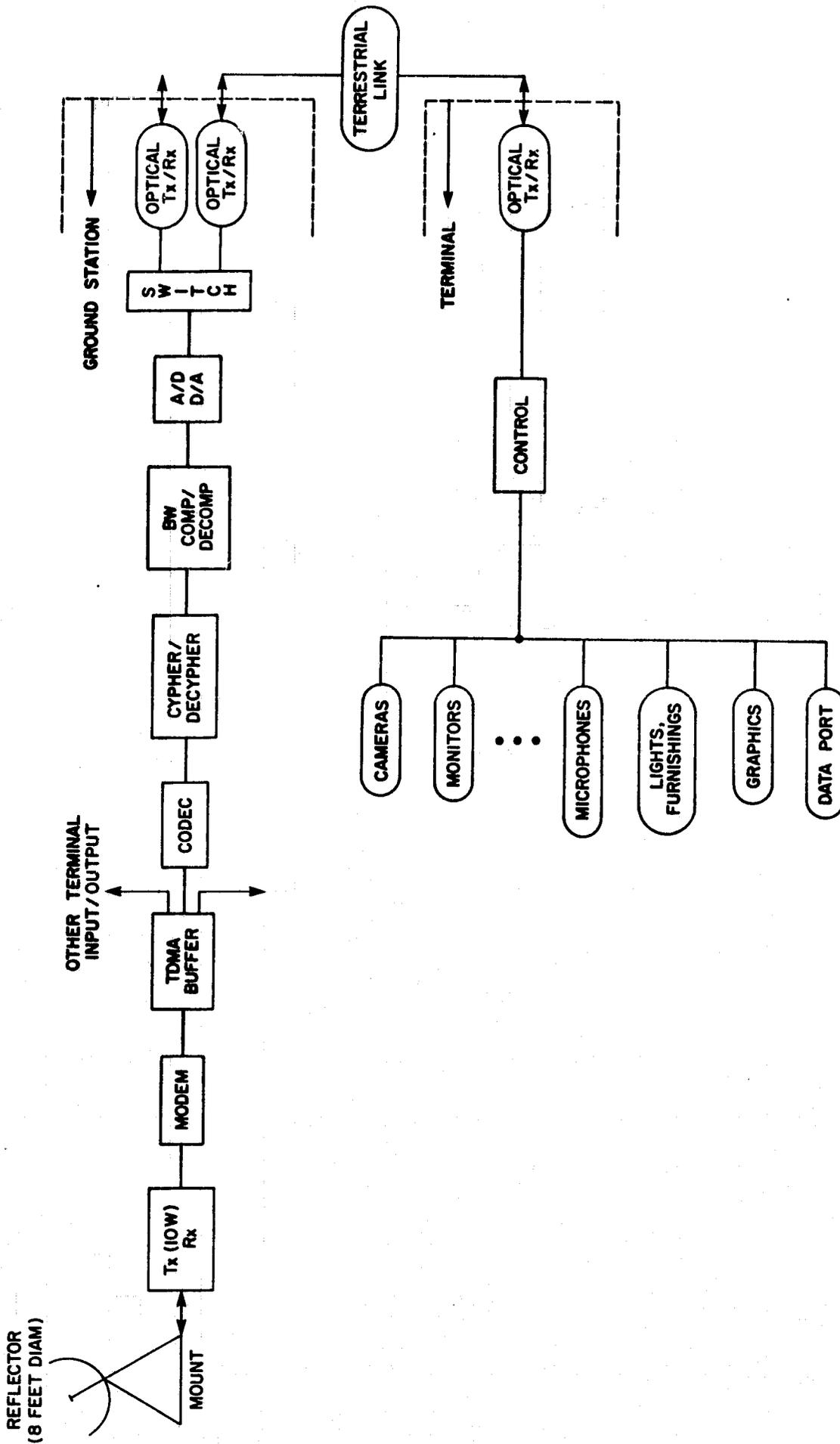
Figure 5-2. Configuration for a typical ground segment unit.
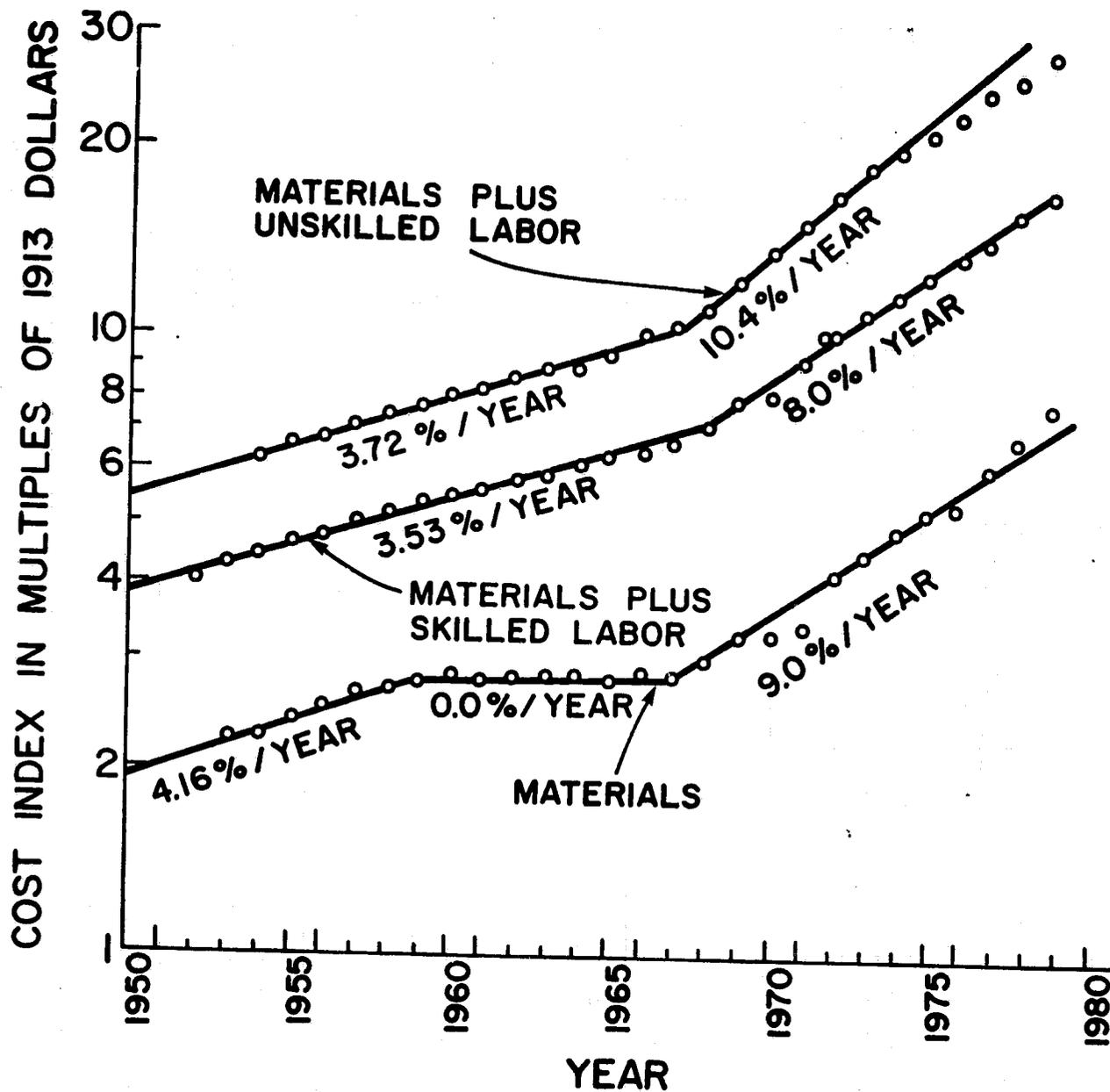
Figure 5-3. Recent inflation rates for labor and materials.

result for large lot sizes. For example, the assumed value for base-band systems is L = 0.85 giving a 10-unit cost reduction of 0.58. In general L ranges from 0.85 to 0.95. Table 5.3-1 shows the design values for the learning factors.*

In the following analysis only lot sizes up to 5,000 units are considered because, even if more units were produced, it is unlikely that one manufacturer would be the sole producer. Finally, while learning curves give an insight into how costs could decrease with increasing lot size, there is no substitute for quotations based on a vendor's actual cost calculations. Such an exercise remains for a point-design of the ground segment. It is interesting to note here that unpublished Stanford memoranda show that engineering decisions based on L = 0.95 for all technologies are generally not sensitive to the particular value of L (Russell, 1978).

5.3.1.4 Technology

The technological state of the art of several major ground station systems is rapidly improving in performance and/or decreasing in cost per function. This trend is particularly strong at this time in signal processing. Where noted, cost estimates are based on projected mid-1980's technology using published data.

5.3.2 MAJOR GROUND STATION SYSTEMS

5.3.2.1 Antenna Reflector and Mount

The Prodelin Company and others have developed a simple non-steerable space frame mount which is easy to transport and assemble in the field. Figure 5-4 shows the mount cost (no price multiplier) versus the reflector diameter based on the Prodelin Catalog (1976). Since the pointing accuracy of these mounts is limited to ±3 degrees elevation and ±6 degrees azimuth, an additional cost is added to bring the pointing accuracy to the ±0.1 degrees required for this application. This additional cost can be

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*The learning factor is also a function of the production rate, i.e., units per year. This effect is not explicitly modeled. The analysis assumes the total units are produced in less than five years.

Table 5.3-1. Design Learning Factors.

Item	Learning Factor	Reference
Antenna		
1. Reflector	0.93	(Stanford, 1975)
2. Mount	0.93	(Stanford, 1975)
3. Feed	0.93	(Stanford, 1975)
RF		
4. Transmitter	0.95	(Stanford, 1975)
5. Receiver	0.94	(Stanford, 1975)
6. LO	0.94	(Stanford, 1975)
Baseband		
7. Modem	0.85	(Assumed)
8. TDM buffer	0.85	(Assumed)
9. Switching	0.85	(Assumed)
Control-Support		
10. Computer	0.85	(Assumed)
11. Master Clock	0.95	(Assumed)
12. Power Supply	0.95	(Assumed)
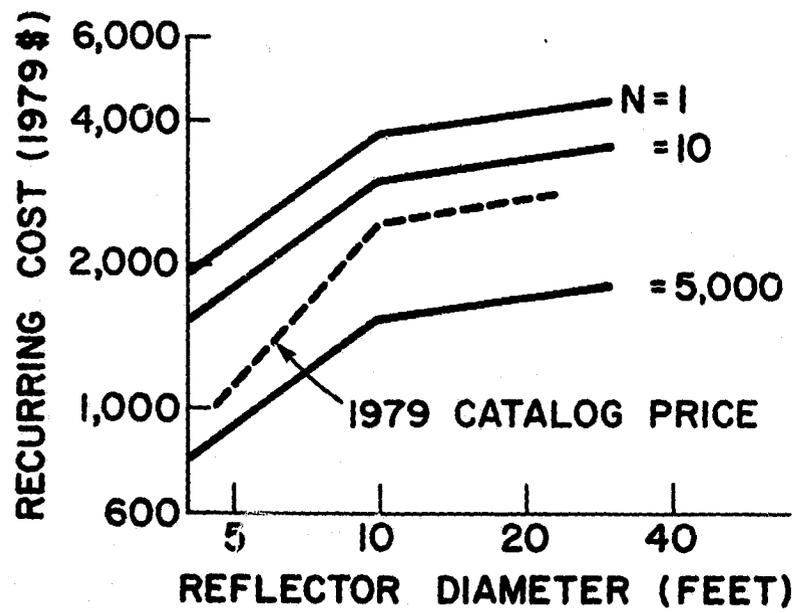
Figure 5-4. Antenna mount cost versus reflector diameter.

allocated to either augmenting the structure, adding an electronic steering capability, or some combination. The design curves for lot sizes of 1 to 5,000 units (L = 0.93) are shown. For example, for a lot size of 10 and a reflector size of 8 feet diameter, the cost of the mount alone would be about $2,520 prior to any cost multiplier.

Reflector costs are primarily functions of the diameter and surface accuracy. Variations in f/D ratio do affect the link margin slightly, but the change is small and 0.33 is a reasonable compromise between deep and shallow reflectors (Philco-Ford, 1974). Figure 5-5 shows the 1974 costs as a function of diameter and link loss at 30 GHz due to surface inaccuracies (Philco-Ford, 1974). Assuming a 1-dB maximum loss at 30 GHz for this application, Fig. 5-6 shows the reflector 1979 cost for lot sizes of 1 to 5,000 units (L = 0.93).[*] As shown, an 8-foot diameter reflector would cost $6,610 in lots of 10 units.

5.3.2.2 Transmitter

The transmitter cost (includes power supply, controls, etc.) is based on a survey of published data. Figure 5-7 shows the 1976 transmitter cost over the frequency range of 6 GHz to 25 GHz and saturated output powers of 5 Watt to 10 kWatt (Philco-Ford, 1974; NASA, 1976; Rafuse, 1976; Kelley et al., 1977). Also shown are the approximate 30 GHz technology breakpoints at this time for solid-state, TWT and klystron devices. The data suggests that output power is the dominant parameter over this frequency range. Based on this data, Fig. 5-8 shows the non-redundant transmitter design cost curves for lot sizes of 10 to 5,000 units (L = 0.95). As shown, the cost of a 10 Watt transmitter in lots of 10 would be about $12,600 (1979).

5.3.2.3 Receiver

The receiver cost is based on a survey of published data. Figure 5-9 shows the 1976 receiver cost versus frequency (Stanford, 1975; Kelley et

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[*]It is assumed the sidelobe levels satisfy the interference standards. This issue is site dependent and remains to be addressed.

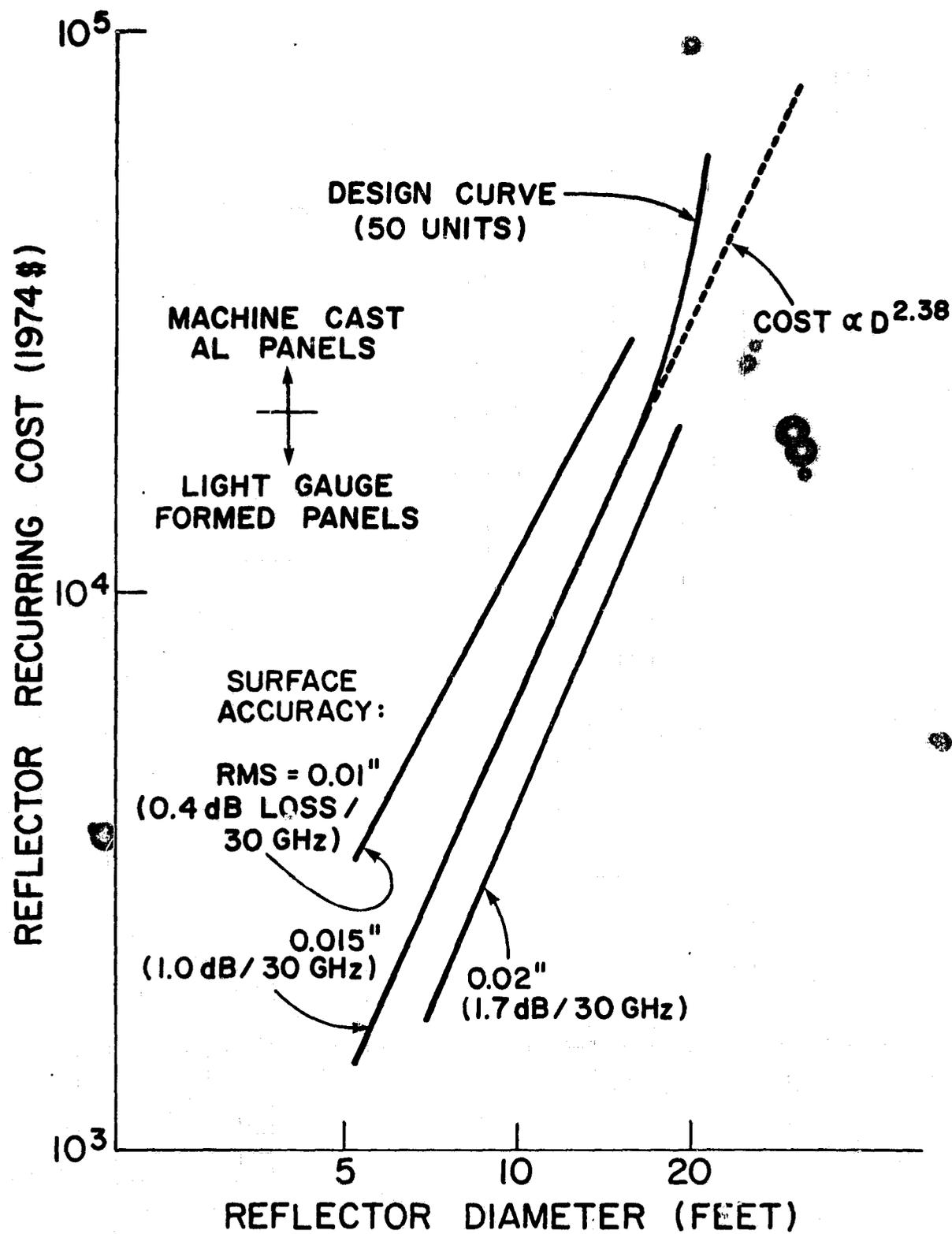Figure 5-5. Recurring antenna reflector costs versus diameter and surface tolerances.
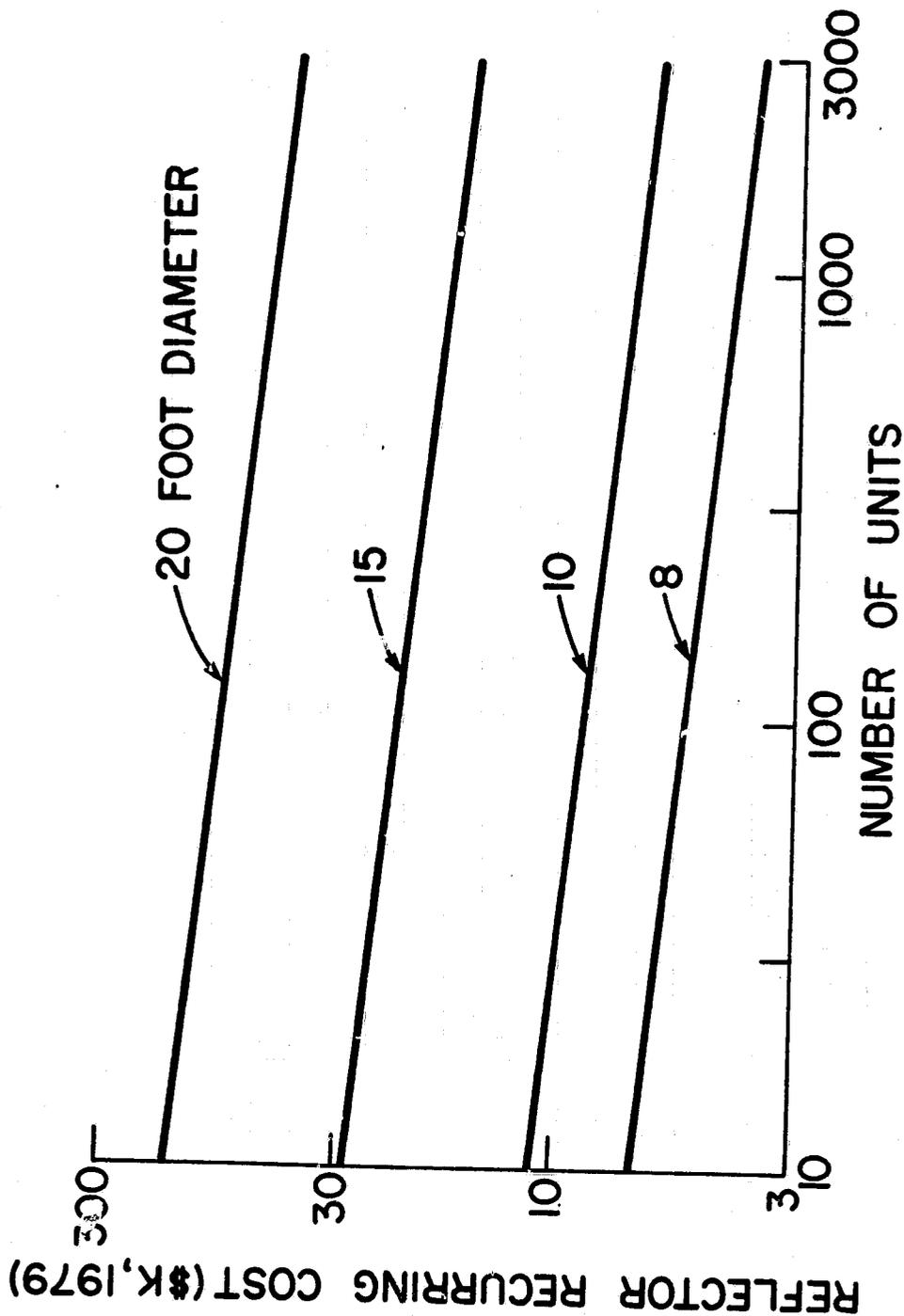
Figure 5-6. Antenna reflector costs versus lot size.
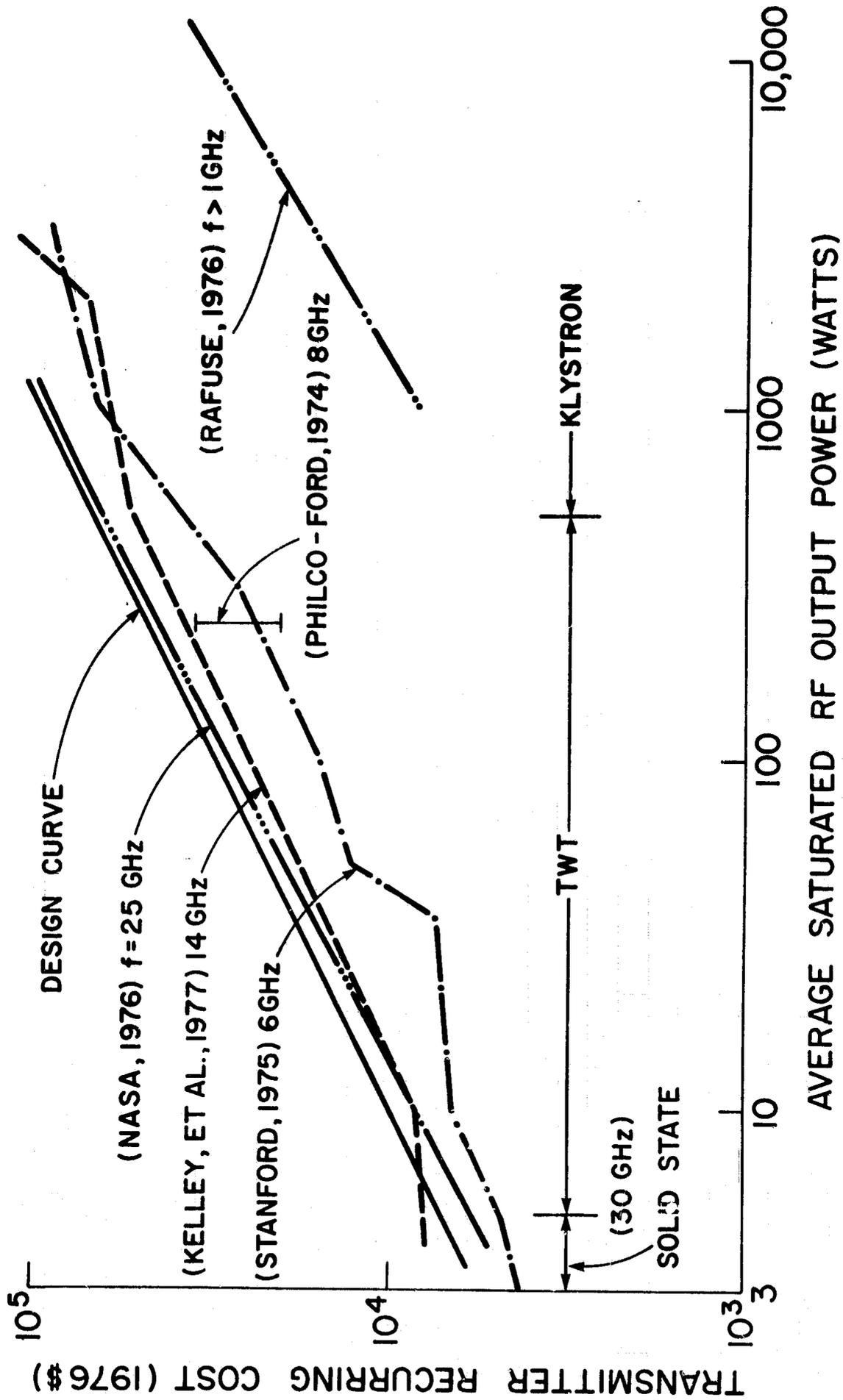
Figure 5-7. Transmitter costs versus frequency and r.f. power.
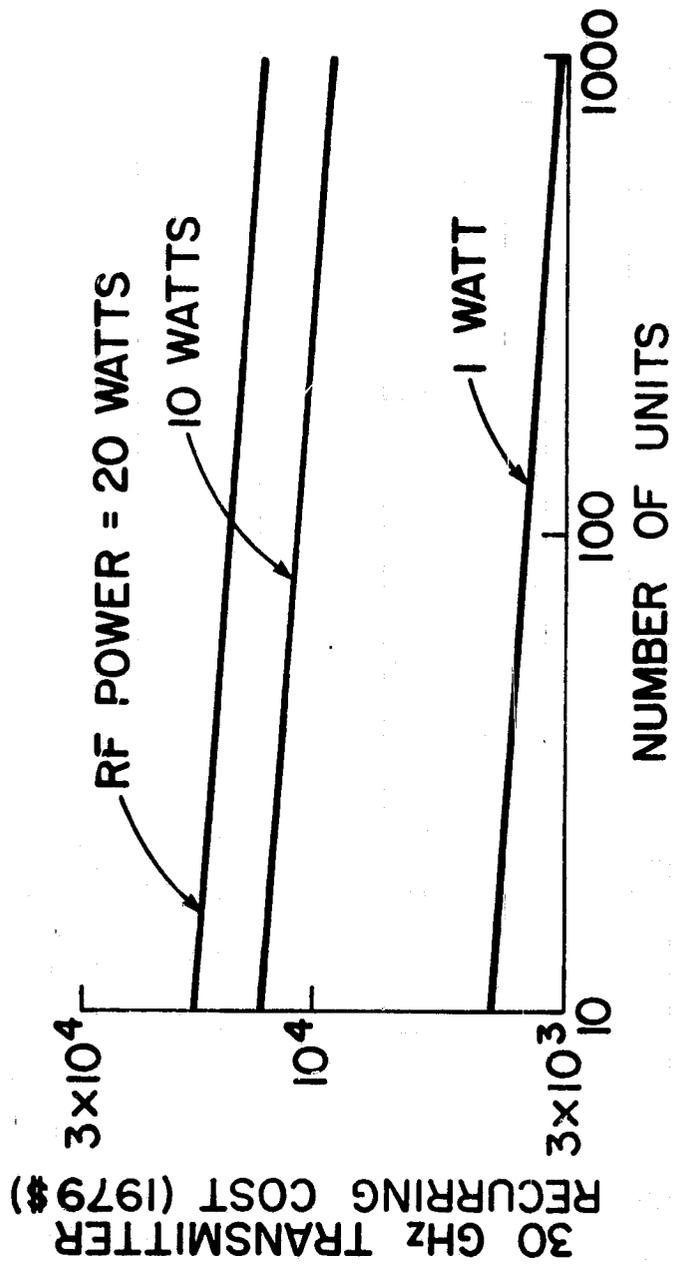
Figure 5-8. Estimated 30-GHz transmitter costs versus power and lot size.
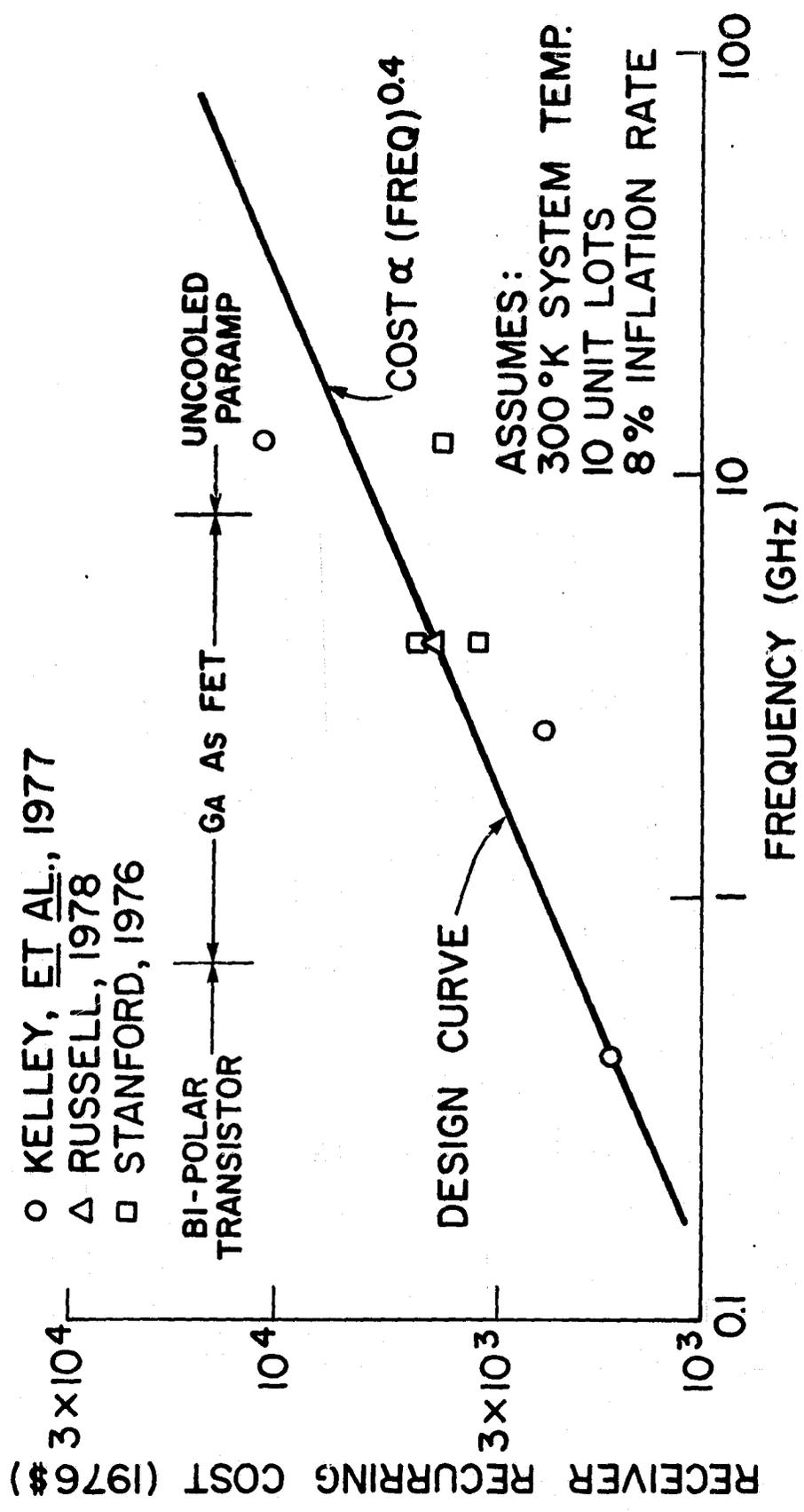
Figure 5-9. Estimated receiver costs versus frequency.

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al., 1978; Russell, 1977) for a 300°K system noise temperature.[*] Based on this data Fig. 5-10 shows the receiver design curves for lot sizes of 10 to 5,000 units (L = 0.94). The cost of a receiver in lots of 10 units would be about $10,500 (1979).

5.3.2.4 Baseband Systems

Modem: The baseline design for the modem uses TFM (tamed frequency modulation) because of its high power and spectral efficiencies (deJager and Dekker, 1978).[**] Based partly on Dekker (1979) and Russell (1978), a recurring 1979 cost of $4,000 is assumed per unit plus a 3-3.5 man-month nonrecurring cost.

Buffer: The baseline design uses a TDM (time division multiplex) system. Section A5.1 shows that the TDM buffer for multiplexing 8 duplex channels would cost, assuming mid-1980's signal processing technology and costs, about $600 (1979) per ground station if projected technology gains are realized. For design purposes a cost of $8K (1979) per ground station is assumed.

CODEC: The baseline design for the CODEC assumes convolutional encoding and Viterbi decoding on each channel. Appendix A5.2 shows the estimated memory size and computational speed for a rate 2/3 code. As expected, these parameters are dominated by the decoding function. Assuming 1979 technology and paralleling six state-of-the-art LSI's, the CODEC recurring cost for 100 unit lots is estimated to be about $450 per 35-Mbps channel or $3,600 for eight 35-Mbps channels.

Encryption/Decryption: Assuming a commercially available NSA approved DES (data encryption standard) system (IEEE, 1978), the estimated

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[*] An optimization study of the antenna size, transmitter power and receiver temperature shows that the combined cost is a strong function of the EIRP and a weak function of the system noise temperature (Kelley, 1977). Figure 5-9 costs include a redundant preamp, all components through the IF amplifier, and the power supply.

[**] TFM is a type of QPSK modulation. Compared to QPSK its power efficiency is about 1 dB less and its spectral efficiency is about 3 dB more (Section A3.1).
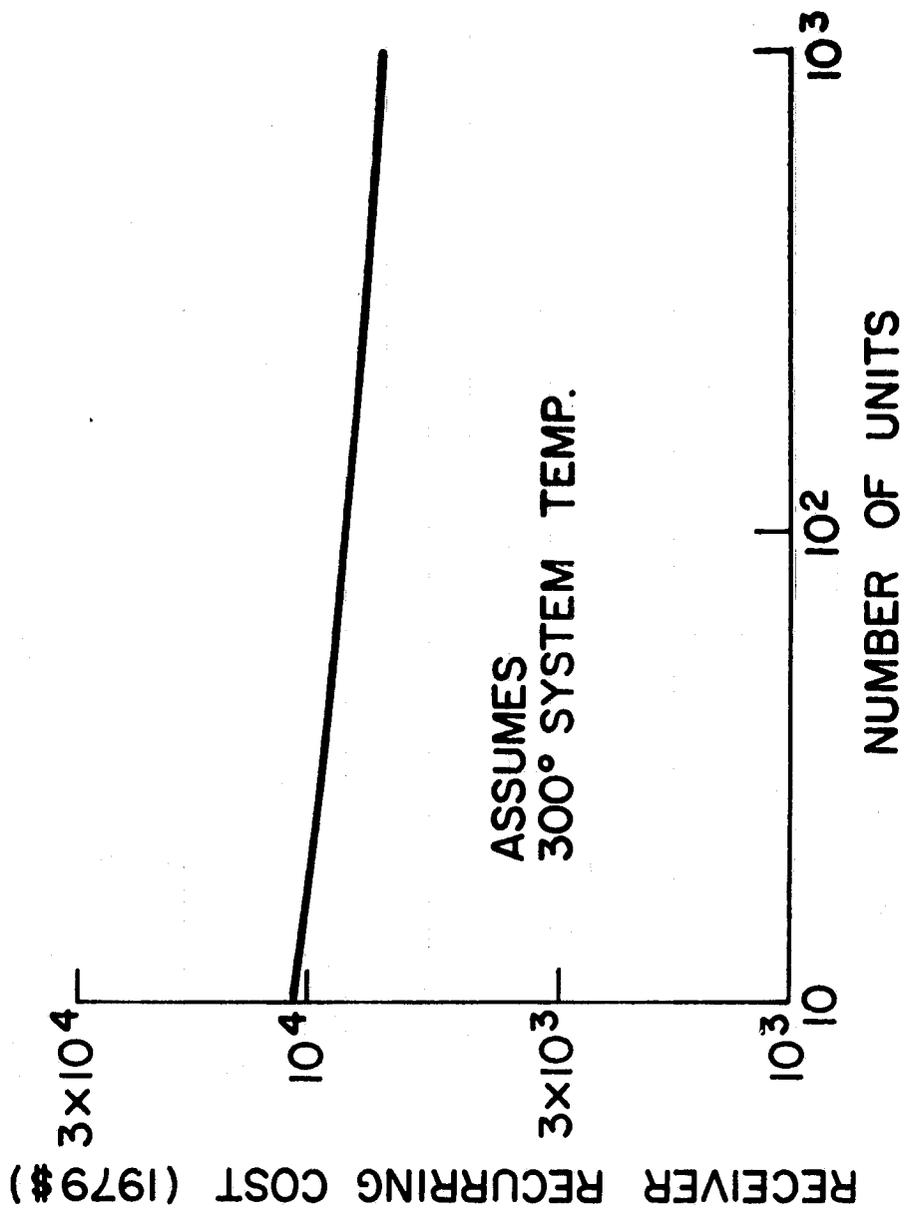
Figure 5-10. Estimated 20-GHz receiver costs versus lot size.

cost to encrypt and decrypt one channel is $100 (1979). In addition, assuming that each user would have an individual DES key to control the common ground station DES system increases the cost per terminal to $200. A design value of $500 per terminal is assumed for component costs. A public cypher system could distribute DES keys at a pace sufficient to ensure security. Integrated circuits of the same order of complexity as the DES chip can perform this function.

Bandwidth Compression: Recent unpublished work suggests that with interframe coding the data bit rate can be reduced to 3 Mbps for a real-time video channel. The required processing appears to involve a 3.5-Mbit memory with an access time of 30 msec. Projected 1980's memory cost at this access time is 0.5 millcents per bit (Feth, 1976). This projection gives a per-channel cost of $44 (1979). Since this is well below the estimate based on current technology, a design value of $1K per channel is assumed for component costs.

A/D and D/A Converters: Current catalog prices for DAC of video quality in 100 unit lots is $26 (1978). Current catalog prices for ADC of video signals in 100 unit lots is $485 (1979)(TRW TDC 10075). On a per-channel single lot basis, the A/D and D/A component costs are assumed to be $1.5K (1979).

5.4 FINAL COMMENTS

The ground station components appear to be technically feasible; cost is the critical parameter. One important technical task remaining at this time appears to be the design of the overall system control function. Details for implementing this function remain to be specified. Basic options need to be outlined regarding the location of the control hardware (ground or space), subsystem interfaces, channel protocols, control function evolution from the initial system, computer architecture, etc. This task is chiefly a design problem and it appears to have a low technical risk.

Useful follow-on work regarding the ground station centers in three areas. Given the ground segment parameters generated by this study, e.g., transmitter power, antenna size, data rate, etc., a point design would study, first, how to optimize the design for lowest cost; secondly, how

to implement the control function of the system; and thirdly, generate more accurate cost data based on quotations from component manufacturers. A second point design at lower data rates per band, say 12.8 Mbps, could be more relevant for ground stations serving sparsely populated areas; see the discussion in Chapter 7.

ACKNOWLEDGMENTS

Chapter 5   References

1. de Jager, F. and Dekker, C., "Tamed Frequency Modulation, A Novel Method to Achieve Spectrum Economy in Digital Transmission," IEEE Transactions on Communication, Vol. COM-26, No. 5, pp. 534-542 (May 1978).

2. Dekker, C., private communication, January 1979.

3. Feth, G. C., "Memories: Smaller, Faster, and Cheaper," IEEE Spectrum, June 1976.

4. Harloff, H. J., "Structure, Organization and Applications of CCD Memories," in Digital Memory and Storage, edited by W. E. Proebster (Vieweg, 1978).

5. IEEE Communications Society Magazine, Special Issue on Communications Privacy, Vol. 16, No. 6 (November, 1978).

6. Kelley, R. L., "Low Cost Ku-Band Earth Terminals for Voice/Data/ Facsimile," Exposition Proceedings, Vol. 1, International Telecommunications Exposition, October 9-15, 1977, pp. 283-289.

7. Kelley, R. L. et al., "Communications Systems Technology Assessment Study," Vols. 1 and 2, NASA CR 135224 (October 1977).

8. McGraw-Hill Engineering News Record, 20 March 1979.

9. NASA, "A Forecast of Space Technology 1980-2000, "NASA SP-387, January 1976.

10. Philco-Ford, "Tactical Multi-Use Terminal Design Concepts Study," Vol. 1, WDL-TR5387, February 12, 1974.

11. Rafuse, R. P., "Radar Search for High-Altitude Satellites -- An Economic Analysis," Project Report SC-25, Lincoln Laboratory, M.I.T. (9 January 1976).

12. Russell, S. P., "Techno-Economics of U.S. Domestic Satellite Orbit-Spectrum Utilization," Ph.D. Dissertation, Stanford University, December 1977, published by University Microfilms International, Ann Arbor, Michigan, 1978.

13. Stanford Communications Satellite Planning Center, "Communication Satellite and Earth Station Hardware Review," Vol. 2, Technical Report No. 2, Stanford Electronics Laboratory, Stanford University, August 1975.

CHAPTER 6

BASELINE SYSTEM: USER FACILITIES AND LOCAL LINKS

6.1 USER FACILITIES

6.1.1 INTRODUCTION

The purpose of this chapter is discussion of cost estimates for
user facilities and local links associated with the baseline 20/30 GHz
satellite communications system. The major necessary premise is that the
costs of interest are only those associated with incremental additions of
new equipment to existing plant which will utilize the increased capacity
made available by the satellites. Thus the links and user equipment of
interest will be oriented primarily toward video and facsimile equipment,
because these are the services which most uniquely require the expanded
bandwidths of the satellites and which have the most expensive terminals.
The links of interest are also broadband units capable of handling the
3-6 Mbps traffic appropriate for compressed video and very-high-speed
facsimile circuits.

6.1.2 VIDEO FACILITIES

There are two major classes of video facilities; those desktop units
serving one person as a videophone, and those which occupy a conference
room serving groups of people. The cost of a videophone terminal would
presumably be in the range one to ten thousand dollars, or a few times
greater than the cost of the video camera and monitor it contained. They
could be made more elaborate with mirrors for graphics communications and
switchable zoom lenses for conferences, for example, but then they start
to approach the costs of inexpensive video-conference rooms.

Video conference services can span a very wide range of quality and
cost. The basic specifications should be market-driven. As discussed in
Chapter 2, the primary incentive for video conferences would be informa-
tion sharing, problem solving, and discussion of ideas; often it would be
used in lieu of traveling or to involve people who otherwise could not
attend. It is a particularly useful tool for extending the presence of

top management and professional expertise over large geographic areas.

The principal means of non-verbal communications in conference include gestures, facial expressions, prepared and spontaneous graphics, documents, and models. Full motion video services are required to convey the gestures and facial expressions, and to maximize the sense of "presence"; such attributes would generally be preferred if the cost were modest. The cost of these user terminals will be approximately the same whether or not full video is employed; in fact, freeze-frame service may require extra equipment.

In order for a conference to be effective, it must not only convey the types of information noted above, but it must also be convenient and comfortable to initiate and conduct, with a minimum of delays and interruptions due to the need to make system adjustments. For this reason the baseline system assumes that such facilities are simple, standardized, and capable of operating largely untended under the control of standard automated decision algorithms.

A typical system would consist of a standard meeting table shaped in a vee so that up to six or seven people might simultaneously see each other as well as the video cameras and monitors positioned in front of the group. The table should make sense even if the video services are not employed. The table should have microphones which are permanently mounted and adjusted for each participant. They and the loudspeakers located well behind them should also be focused and shielded so as to minimize feedback and echos. To further minimize echos and extraneous noise, the baseline audio control system would also attenuate for the first half second or so any speakers who interrupt; microphones below a certain threshold for a period longer than a minute or so would be turned off until they are stimulated above some audibility threshold. Such algorithms for assigning microphone gain and priorities would be under the control of a small microprocessor located in the control console.

Similarly automatic assignment of video resources to speakers could be implemented. These resources might include a camera focused on the lecturer's position at the table, cameras focused on each side of the vee-shaped table, and cameras which view the entire group. The switching on and off of these cameras, or the equivalent adjustment of one of them, could be automatically controlled by the same signals and algorithms which control the microphones. In addition, the lecturer's position might also

have override controls to permit switches to be made between views of the speakers and views of the graphics, etc.

A control panel would be provided which has a very simple set of video and audio override options and network access controls. It would also contain a less accessible set of more detailed and flexible controls which could instantly be reset to the default option appropriate to less sophisticated users. These controls are assumed to employ digital algorithms and signals in order to take maximum advantage of cost reductions available with LSI circuits.

The most expensive items for a conference room would probably be the video cameras and monitors. One zoom camera might be located on the ceiling to view transparencies or other graphics placed in front of the speaker's position at the table. It might also have a mirror which could be flipped to permit the camera to view the front of the conference room, a model, a flip-chart, or a blackboard. Two other zoom cameras might be located in front of the table in the cluster of video monitors; they could interchangeably view the lecturer's position or any or all of the other participants, as governed by the allocation algorithms. A fourth camera might serve as a spare or some other purpose. One or two large-screen video monitors might present the received and transmitted video signals, or perhaps higher-resolution locally generated signals from transparencies or from a high-resolution graphics telecommunications terminal. Other small monitors would present other video signals. Such a system might provide either full-motion or freeze-frame video services, or both.

A good facsimile or graphics terminal would be an important adjunct to such a conference room. Often letters, contracts, tables of data, etc. are important in a conference and yet are beyond the resolution capabilities of conventional video equipment. Such a terminal might transmit rapidly high-resolution copies of short documents or transparencies which then could be viewed or projected locally. The cost of such a two-way terminal would be perhaps two or three times that of a copier machine capable of comparable image quality and printing capacity. Copier prices now range from $\sim$$1,000 for the simplest unit to several thousand dollars for moderate quality, and over ten thousand dollars for high volume units.

Transmitting copiers of good quality and reasonable cost are just now beginning to be marketed, and the range of performance and price should improve significantly over the coming years.

In order to control the costs of manufacture, installation, and maintenance, such equipment should be standardized and packaged in large modules which can be interconnected flexibly and easily. For example, the table module might be standardized with the microphones and loud- speakers premounted and adjusted, so that only one or two cables need to be plugged in. The table might also contain one or two mounting posi- tions for the control panel (one near the lecturer's seat) and built-in slots for transparency projection, etc. Each participant's position might also have a small set of lights to indicate the status of the microphone or the speaker's priority. Switches could also be provided at each posi- tion to gain microphone access or to communicate other information, if desired.

A second standardized module might contain all the video monitors and cameras with appropriate signal lights or other features. It would be important to provide a minimum of controls, and perhaps to control them exclusively through the control panel with its built-in automatic reset- to-default-option switches.

By standardizing all the modules it should be possible to install a conference room with a minimum of design and engineering. The baseline cost estimates assume that approximately 10 percent of the capital cost is allocated to design functions, and 10 percent to installation and start-up. The design function might be split, half being allocated to a consultant who would analyze an organization's communications needs, and half for the engineering of the installation itself.

These general assumptions about the character of a video-conference room, together with catalogue prices for presently available video and copier equipment, lead to the following estimates for the cost of such a facility. Three different estimates are presented in Table 6-1; they are for low-quality, medium-quality, and high-quality rooms. The "price multi- plier" is an estimate of the ratio of the catalogue price to the price that would be paid by the customer; it reflects handling, interface, integration, and other costs.

Table 6-1. Cost Estimates for Video-conference Rooms ($1979).

Item	Quantity and Costs ($K) per unit			Price Multi-plier	Total Costs ($K)		
	Low	Medium	High Quality		Low	Medium	High Quality
Video cameras, color	3@$1	4@$3	5@$25	1.5	4.5	18	187.5
Video monitors, color	3@ 1	4@ 2	5@ 3	1.5	4.5	12	22.5
Conference facsimile	3	6	9	1.5	4.5	9	13.5
Audio equipment	1	3	6	1.5	1.5	4.5	9
Lighting	1	2	4	1.5	1.5	3	6
Control console, interfaces	1	3	7	2	2	6	14
Wired conference table	2	4	6	1.5	3	6	9
Communications consultant	1	3	12	1	1	3	12
System engineering	1	3	12	1	1	3	12
Installation and start up	2	6	24	1	2	6	24
Totals					25	70	310

The costs for these three types of video-conference rooms are thus
$25K, $70K, and $310K for low, medium, and high quality facilities. The
range of possible costs for video services spans two orders of magnitude
as the system progresses from a simple $3K videophone to an elaborate
$300K conference room. Other variations are also possible, such as the
inclusion of video recorders, but the total cost range would not be signi-
ficantly impacted. For the baseline system we assume the full span of
facilities would be used, with the inexpensive systems being the most
common, and the moderate quality systems being closest to the average cost.

This average cost is assumed to be $60K in 1979 dollars, and the average life is assumed to be 5 years.

In order to estimate the fraction of the total system investment allocated to user facilities, it is necessary to estimate the number of such units installed. For a fully operational national video communications system sufficiently large that most major offices of most major organizations could communicate with each other, there might be one video terminal per 2000 employees or per ∿$50M gross national product; this corresponds to approximately 50,000 terminals in the United States. If each transmitted 3 Mbps for 8 hours per work week, the average total traffic would be 30 Gbps, comparable to the total capacity of the baseline system.

6.1.3 · OTHER SERVICES

The major communications service will continue to be voice for many years. The introduction of extensive satellite circuits will lower the costs of long-distance calls, but will probably increase the numbers of installed telephones only moderately. The baseline system is not applicable to proposals that extremely large satellites be used to connect wrist watch mobile radios worn by a significant fraction of the population, nor are there any other evident ways in which the numbers of user voice terminals could be significantly increased.

The services which will benefit most from reduced costs will be those requiring large bandwidths. Besides video, these include many types of facsimile and high-speed data transmission. Adaption of existing copier technology to electronic transmission is moderately straightforward, and such systems were included in the cost estimates for video services described in Section 6.1.2. Because many of these systems could employ existing voice circuits and are being introduced on that basis, they are not included here in the economic analysis of the baseline satellite network. If they were included, they would simply increase further that fraction of the total investment allocated to user terminals. A similar situation prevails for high-speed data transmission systems; high-speed computer-to-computer links could be very important, but their market penetration is difficult to estimate, as is the fraction of such growth that should be credited to satellites.

To first order, the cost of the user equipment associated with 30-Gbps traffic is the same for video or voice. The baseline 30 Gbps capacity could handle 10,000 3-Mbps video links, and a 20 percent duty cycle implies 50,000 terminals exist. If the average terminal each is $60K, the total investment would be $3B. The same 30-Gbps capacity might handle 10^6 voice links, corresponding to the equivalent of perhaps 10^7 additional phones. If these phones and associated hook-ups cost $300 each, then the total investment would again be $3B; this is obviously a very crude estimate, but it does suggest that user facilities are an important part of the total investment.

6.2 TERRESTRIAL LINKS

As in the case of the user terminals, the object is to estimate the costs associated with the increased capacity of the satellite system. For example, to the extent that the satellites motivate and handle video-conference traffic, and that increased local capacity is required to support that same traffic, then those local costs should be reckoned in the total satellite systems cost analysis.

To simplify this analysis for the baseline system, we assume that the new local links stimulated by the satellite handle commercial traffic of ∿30 Gbps in the aggregate. For convenience, the cost summary in Chapter 7 associates the total satellite capacity with 50,000 high-data-rate users. The costs would probably be higher if the same local capacity were spread more uniformly over the entire voice service population. This is so because the local costs are to a reasonable extent simply proportional to local circuit miles but are less dependent upon circuit bandwidth; therefore broadband services can be less expensive in the aggregate.

Cost estimates are often expressed as costs per circuit mile. In Figure 6-1 are presented comparisons of the costs for installed voice circuits for three types of terrestrial link. In the time period of interest here, the average investment costs are approximately $10 per mile for both microwave radio and fiberoptic cable. These estimates were prepared for NASA by Western Union (1979). If we assume that 400 such voice circuits are capable of handling a nominal 3-Mbps compressed full-video circuit, and that annualized costs are approximately 10 percent of the installed costs, then the annual cost per video circuit mile would be approximately $400, and the cost per voice circuit mile would be $1.00. These estimates

Figure 6-1. Estimated costs per circuit mile for three types of local terrestrial links.

are close to those prepared for NASA by the ITT U.S. Tel. & Tel. Corporation (ITT, 1979), which appear in Figs. 6-2 and 6-3.

These last two figures further separate the capital and operating costs. The average annualized cost per video-channel mile is perhaps most relevant to the baseline system estimates, because the satellite-induced additions to local plant would probably consist of one or two video-channels linked to each of perhaps 50,000 major user facilities, or the equivalent. The ten-year total cost for the ITT estimate would be approximately $5000 per video-circuit mile, and this is the estimate we use for the baseline system. However we assume 10-year straight-line depreciation and that the annual operations cost is only 10 percent of the purchase price of $2500 per mile. The ITT estimate allocated a larger fraction of the cost to operating expenses, 80 percent each year instead of 50 percent. The lower percentage used for the baseline estimate may be appropriate if the operating cost is more nearly proportional to the number of circuits than to the link bandwidth, and if low maintenance fiberoptic cables are a large part of the total plant. This assumption is reconsidered in Chapter 7.

To determine the link cost we must estimate their average length; this depends upon the separations between ground stations, and therefore upon their numbers. Equation 3.2-5 predicts this number in terms of the annualized basic ground station costs and the costs per circuit mile. If we use the ground station cost estimate of $212.38K (for lots of 100) less the baseband equipment cost of $76.4K, we obtain a basic ground station value of $140K (see Table 5-1). Five-year straight-line depreciation plus 10 percent operating costs total $42K per year. The annual cost per voice circuit is $\sim$$5 (Fig. 6-2) and therefore Table 3.2-2 suggests that case B is most appropriate for determining ground station separations.

In Section 3.2.3 it is argued that case B would probably correspond to 1800 ground stations across the United States if we assumed that 80 percent of the population were distributed uniformly over 5 percent of the land, and the other 20 percent uniformly occupied the rest; half the ground stations would be rural. The 900 urban ground stations distributed over 150,000 mi^2 would be spaced an average of 13 miles and the mean link length would be $\sim$4.3 miles. The 900 rural stations would be spaced 58 miles, and
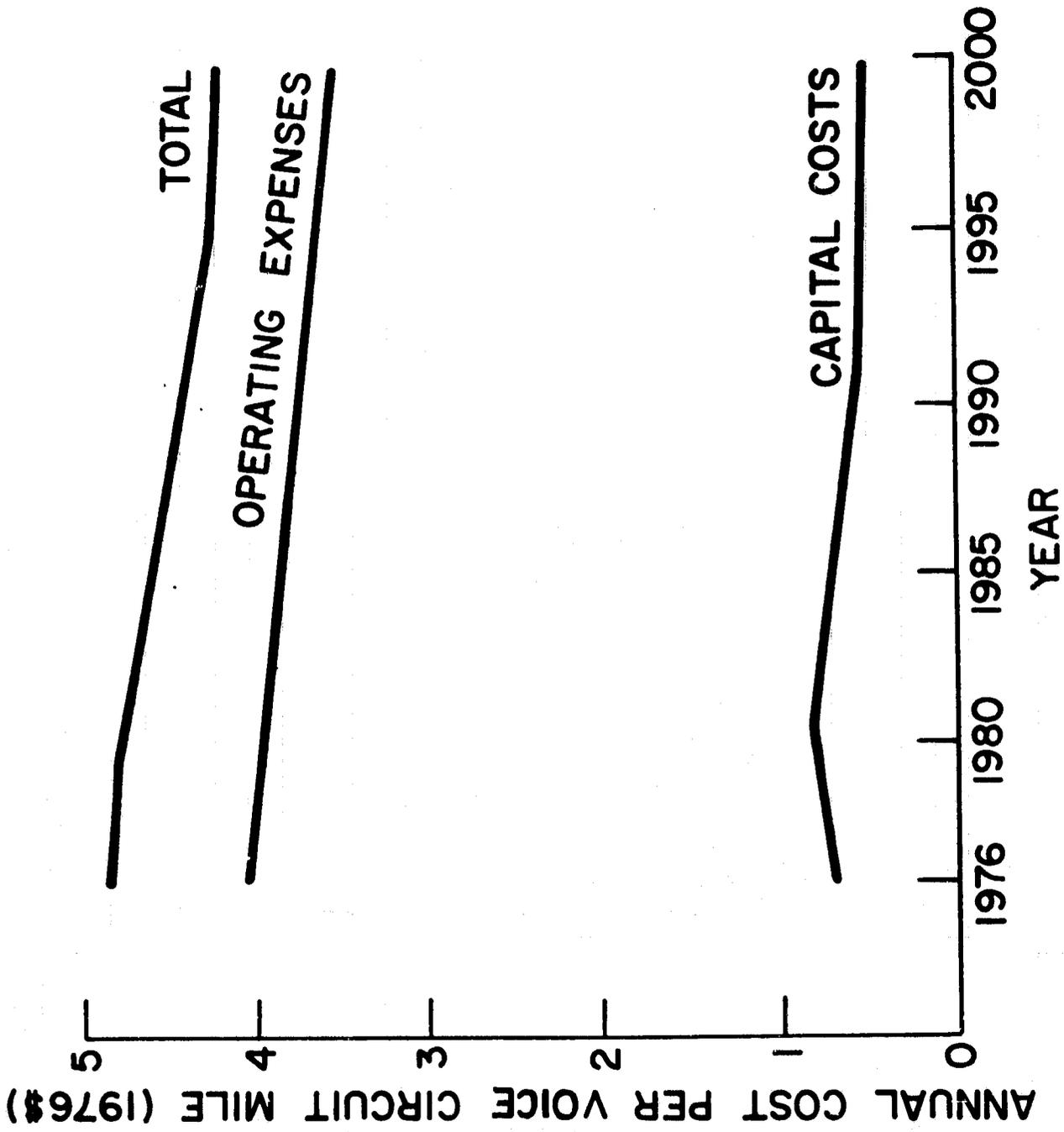
Figure 6-2. Estimated annual costs per terrestrial voice-circuit-mile.
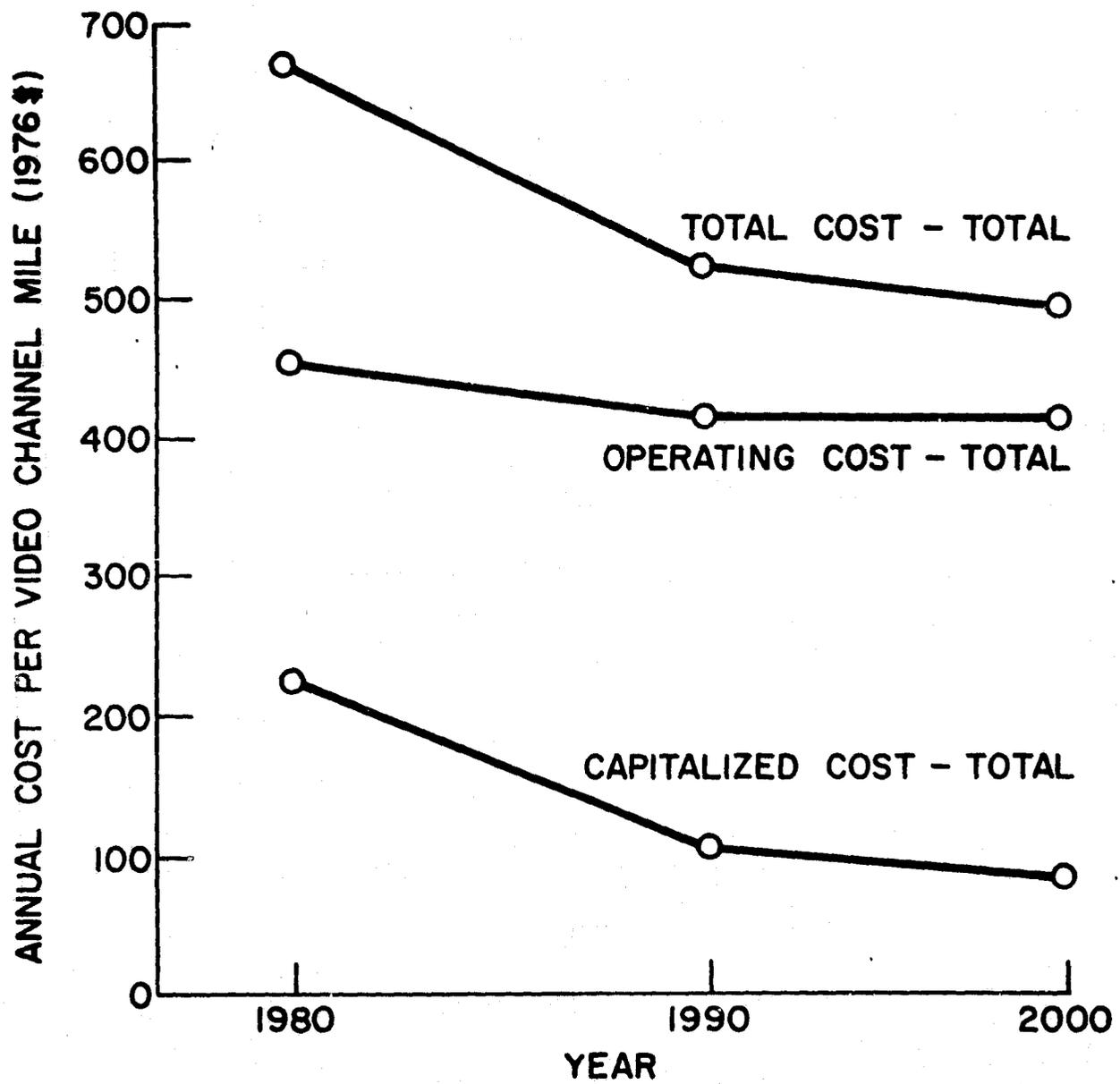
Figure 6-3. Estimated annual costs per terrestrial video-circuit mile.

the mean link length might be ~15 miles. If 80 percent of the links are 4.3 miles and the rest 15 miles, then the average length would be 6.4 miles and initially cost ~$16K at $2500 per mile; for an estimated 30-Gbps load, this implies a total investment in 50,000 links of $805M, and an annual cost of ~$160M.

It is easy to determine average data rates for these stations. If 900 handle 80 percent of 30 Gbps, the average rate is 27 Mbps, and that for rural stations is only 6.7 Mbps. There are about 10,000 local offices, 800 toll centers, 230 primary centers, 70 sectional centers, and 10 regional centers in the Bell system; thus all toll and higher centers might have ground stations, plus key rural local offices.

Xerox Corporation, in their 1978 petition for rule making to the Federal Communications Commission, proposed establishment of special-purpose microwave communication links designed to couple large bandwidth services (say 256 Kbps) to dedicated regional satellite ground stations. Each major client facility would have its own private microwave link of several miles length which would connect it to the nearest network node. These nodes would in turn be linked by microwaves to the appropriate ground station. This configuration is quite compatible with the cost estimates prepared for the baseline system. Even though the present market for such systems is very thin and technological improvements are needed, low-cost microwave links are already available. Typical of such new systems is the Model DM18 18-GHz digital microwave radio transceiver which can handle two Bell System digital line rates--DS-1 at 24 channels and 1.544 Mbps and DS-2 at 96 channels and 6.312 Mbps; the system is offered by Farinon Electric of San Carlos, California. The estimated price for one transceiver with a 2-ft antenna, enclosure, mounting structure, and a flexible waveguide for one T-1 line would be $9500. Although two such systems would be required to link a user to a local network, and therefore these present costs are ~20 percent above the baseline link cost estimate, future improvements in technology should reduce these prices over the next five to ten years; such private microwave links would be necessary for only a portion of the customer base, in any event.

Another option is to use existing wire pairs for data. For unloaded 22-gauge wire pairs Even et al. (1979) have suggested that 200 kbps could be sent 2-3 miles if the signals are properly conditioned to handle reflections and noise. Large numbers of T1 cables have been installed in recent years, and they can handle 1.5 Mbps if properly conditioned. Thus many customers could significantly expand their digital capacity without new cables simply by adding appropriate electronics to those lines already in place.

Chapter 6   References

1. ITT U.S. Telephone and Telegraph Corp., 30/20 GHz fixed communications systems service demand assessment, NASA Rept. No. NASA-CR159620, August 1979.

2. Western Union Telegraph Co., 18/30 GHz fixed communications systems service demand assessment, NASA Contractor Rept. No. NASA-CR159547, July 1979.

CHAPTER 7

SYSTEM ECONOMICS AND GENERAL CONCLUSIONS

7.1 INTRODUCTION

This chapter summarizes the analyses and estimates presented earlier
for large broadband switched satellite communications networks. The mar-
ket estimates in Chapter 2 led to the discussions in Chapter 3 of the
network architectural issues that arise for such large satellite systems.
The understanding developed in Chapter 3 then led to the definition of a
baseline system design and its cost estimates; Chapter 4 analyzed the
space segment, Chapter 5 treated the ground stations, and Chapter 6 dealt
with the terrestrial links and user facilities. Those economic estimates
in Chapters 4-6 are summarized and combined here in Section 7.2 to yield
a portrait of the economics anticipated for large satellite networks like
the baseline system, and to explore how those economics might vary with
total traffic and technology.

Because Chapters 3-6 provide cost estimates for each of the major
subsystems of the baseline system design, it is possible to examine the
economic effects of design changes. Such tradeoff analyses are presented
in Section 7.3 for the basic system engineering specifications. These
studies lead to a revised baseline design which is believed to be more
nearly optimum for communications systems of the size studied here. Future
point design studies might wish to begin using specifications such as
these. Section 7.4 then combines the baseline system economic analysis
(Section 7.2) with the traffic estimates of Chapter 2 to determine whether
or not smaller versions of these systems are economically competitive.

Section 7.5 draws upon all of the preceding discussion in order to
arrive at the final technical and economic conclusions derived from this
study effort. Conclusions relevant to issues of public policy and NASA's
program options are presented separately in the chapters devoted to those
topics, and all results are reviewed in the executive summary (Chapter 1).

7.2 ECONOMIC SUMMARY: BASELINE SYSTEM DESIGN

The baseline system includes a space segment, ground stations, local

loops, and user facilities. The primary purpose of the baseline system design was to enable the relative costs of these elements to be estimated and to enable their dependence upon total traffic and other assumptions to be better understood. The major architectural assumptions were that a 20/30 GHz satellite communications system was desired which could provide pervasive, fully switched digital communications to the entire United States at levels up to ~ 38 Gbps. Although it would presumably be thoroughly intertwined with the existing communications plant, the cost estimates were not significantly affected by this assumption because the baseline system was assumed to require new facilities.

The costs of the four basic elements are summarized in Table 7-1, together with estimated total investments, tariffs, and revenues. The space segment costs were estimated in Chapter 5 on the basis of estimated spacecraft weight and the DCA weight-based cost model. Although the accuracy of general cost models is always uncertain, this model performs acceptably well for most other communications satellites that have been launched. The formulas given in the table show how the estimated cost depends on the 3822-lb weight of each satellite (revised to 3925 lb in Table 4.3-11).

The baseline system is assumed to consist of three 12.8-Gbps satellites plus one spare (each satellite alone has a redundant architecture), which would cost an estimated total of $386M if space-shuttle launch costs were $30M per satellite. The nonrecurring costs are assumed to be recovered during the initial 5-year period, although conventional design practice should permit longer lifetimes. The total recurring and nonrecurring investment in the space segment is thus ~ $600M. The annual maintenance and operating costs for the satellites alone are assumed to be 5 percent of the recurring space segment costs, which should cover the costs of monitoring and controlling the system from the ground, and certain general and administrative costs. This estimate is doubled in the right-most column of the table to provide a more conservative accounting.

These costs can be allocated to the users as fixed monthly charges or as use charges per minute, as listed in the table. For example, the nonrecurring satellite costs could be recovered by spreading a monthly cost

Table 7-1. Summary of Estimated System Costs and Revenues ($FY79).

COST ELEMENT	UNIT COST ($K)	USER COST/MO ($K)	USER COST/ 3-MBPS MIN(¢)	EQUIVALENT COSTS(†4,5) N=28,L=50,000 $K/MO	¢/MIN	EQUIVALENT COSTS(†4,5,6) N=1, L=50,000 $K/MO	¢/MIN	TOTAL SYSTEM INVEST-MENT ($B)	REVENUE (†7) ($M/YR)	REVENUE (†9) (2×M&O)
SPACE SEGMENT COSTS	(†5)	(†5)	(†5)							
Non-recurring [$16K(3822 lb)$^{1.15}$]	210K	$3.5K/\bar{L}$	$$336/\bar{L}$	0.07	3.4√	0.07	3.4√	0.21	60	60
Recurring, per launch (†1)	(97K)	—	—					--	--	--
4-Satellite System (5-yr life)	386K	$6.4K/\bar{L}$	$$618/\bar{L}$	0.13	6.2√	0.13	6.2√	0.39	116	116
Maintenance and Operation (5%/yr)	--	$1.6K/\bar{L}$	$$155/\bar{L}$	0.032	1.6√	0.032	1.6√	0	29	58
GROUND STATION COSTS										
Facilities – Basic (5-yr life) (†2)	140	2.3N	$22/\bar{N}$	0.08√	3.9√	2.3√	111	0.25	76	76
Facilities – User-Specific (†3)	$15\bar{N}$	$0.25\,\bar{N}/N$	2.4	0.05	2.4√	0.25	2.4√	0.15	45	45
Maintenance and Operation (10%/yr)	--	$\dfrac{1.2}{N} + \dfrac{0.13\bar{N}}{N}$	$12/N + 1.2$	0.07	3.3√	1.3√	61	0	62	124
GROUND STATION LINK (10-yr; 10%/yr)	16	0.27	$2.7\,N/\bar{N}$	0.27√	14	0	0	0.8	240	360
USER FACILITIES COSTS	(†4,5)	(†4,5)	(†4,5)							
On-Site Facilities (5-yr life) (†8)	60	1	$10\,N/\bar{N}$	1√	50√	1√	50√	3	900	900
Maintenance and Operation (10%/yr)	--	0.5	$5\,N/\bar{N}$	0.5	25√	0.5	25√	0	450	900
TOTALS (†4) (for one 3-Mbps one-way circuit)				2.2 or 110		5.6 or 260		$4.8B	$2.0B	$2.6B
TOTAL PRICE = 1.5 × Cost (†4) (for one 3-Mbps one-way circuit)				3.3 or 165		8.4 or 391			--	--
TOTAL TARIFF (Elements marked √)(for one 3-Mbps one-way circuit)				2.0 and 63		7.4 and 54		--	$2.0B	$2.6B

(†1) [$31K(3822 lb)$^{0.93}$ + $30M launch].

(†2) Consultants, licenses, site, equipment, start-up; 8-ft fixed antenna; redundant electronics for 128 Mbps; no baseband; 1800 stations.

(†3) Baseband: bandwidth compression, cryptographic and error-correction circuits, TDMA buffers, etc.; 5-yr life; 1.5 × average use.

(†4) $K/mo and ¢/min represent the same costs.

(†5) N = possible users/ground station, $\bar{N} \triangleq$ average active ($\bar{N}/N \triangleq 0.2$); L = possible system users, $\bar{L} \triangleq$ average active ($\bar{L}/L \triangleq 0.2$); 5-yr life; 40-hr week implies 10,400 min/mo.

(†6) $N \triangleq 1$, ($\bar{L}/L \triangleq \bar{N}/N \triangleq 0.2$), $L \triangleq 50,000$.

(†7) Price $\triangleq 1.5 \times$ cost; N = 28, L = 50,000.

(†8) Consultants, equipment, start-up; 3 video cameras, 3 monitors, facsimile, data interface, control, lights, table, etc.

(†9) Maintenance and operations budgets are doubled.

of \$3.5M over L designated users or, equivalently, by spreading the
average nonrecurring system cost per 3-Mbps minute, \$336, over the
average number $\overline{L}$ of 3-Mbps system users during that minute. These costs
per minute assume there are 10,400 minutes per month, which corresponds
to 40-hr weeks. This arbitrary assumption is also equivalent to saying
the average system load is 24 percent of the peak load. The equivalent
costs listed in the table are representative numbers for the same 3-Mbps
example if there are 50,000 potential users, of which 10,000 are active
at once. Thus, according to the table, the nonrecurring space segment
costs could be recovered if each of the assumed 50,000 users paid \$70
per month or, equivalently, 3.4¢ per 3-Mbps minute of actual use, which
is assumed to average 8 hours per week per user.

The total-system numbers at the right end of the table present the
total investment, \$210M for the nonrecurring costs, and the associated
revenue per year (\$60M) if the costs were spread uniformly over 5 years
and then multiplied by 1.5. These two very simple approximations, i.e.
the factor of 1.5 and the 5-yr straight-line depreciation for facilities
which probably would last 7 years or more, are intended to reflect average
loading factors of perhaps 65 percent and the cost of capital. The same
approximations are applied to all capital cost items in the table.

The loading factor deserves special comment. Although linear traf-
fic growth reaching saturation at the end of a single satellite's life
might normally yield 50 percent loading, or 25 percent if there is an
idle spare, the four-satellite system proposed here would instead have
50 percent loading with an idle spare and properly timed launches, as
discussed in Section 3.2.5. Furthermore, one might choose to load the
satellite up to 100 percent by transferring terrestrial traffic. Although
this is extreme, it is important to note that the "mobility" of satellite
capacity enables it to augment any overloaded or failed terrestrial long-
lines circuit. Therefore terrestrial circuits can be operated with much
less excess capacity than otherwise due to the "overload insurance"
provided by the satellite back-up. Thus the capacity of a new satellite
could be committed immediately to this insurance function, permitting
postponement or omission of terrestrial improvements otherwise needed.
For example, it is not uncommon to find certain telephone routes over-
loaded at certain times of day; to install terrestrial plant adequate

to obtain 100 percent availability would be prohibitive. The capacity of a new switched satellite could immediately increase availability performance if 100 percent loaded. When availability degrades unacceptably, the next satellite could be launched.

Another way to state the same fact is to say that the value of a switched satellite circuit is greater than its terrestrial counterpart, even if the hardware costs are equal, because of its ability to substitute rapidly for any of a large number of potentially overloaded circuits, each of which might otherwise need greater capacity. Thus the effective loading factor for the satellites might well exceed 50 or 60 percent (multiplied by the 24 percent factor for load fluctuations) if the satellite capacity is not excessive in relation to statistically saturated terrestrial plant.

The ground station cost estimates tabulated in the figure were derived in Chapter 5. The basic facilities include everything but the user-specific baseband circuits which are proportional to the average traffic. Equivalent costs are tabulated for two sets of assumptions. In the first case 1800 ground stations were assumed (see Sections 3.2.3, 6.2) and 50,000 users, i.e. there is an average of 28 3-Mbps potential users per ground station. Under this assumption the average user's share of the basic and user-specific ground station costs would be $80 and $50 per month, respectively. This is equivalent to 3.9 and 2.4 cents per minute. For the case where a user must provide his own station (N = 1), the monthly costs would be $2300 and $250 for the basic and user-specific circuits.

The ground station links are assumed to have an average cost of $16K per 3-Mbps capacity (Section 6.2). Microwave links would typically be slightly more, and cables in old conduit or the use of data-above-voice could be significantly cheaper; the cost estimate is an average.

User facilities costs depend on the service; video is assumed here. As discussed in Chapter 6, assumption of voice services being dominant might lead either to the same or to significantly lower costs depending on whether the satellite traffic growth is associated with new phones or with the increased use of old phones. The reason the costs might be comparable is that those services with lower data rates must have a

comparably larger number of terminals, albeit less expensive, to utilize the assumed 30 Gbps system capacity. It is clear from the table that the user facilities costs are dominant for video services, followed by the local loop costs.

The total cost of communications can be estimated by summing the various components. For the assumptions noted above, the average total cost per month of a 3-Mbps one-way video link would be $2200 or, equivalently, $1.10 per minute; the corresponding prices might be $3300 per month or $1.65 per minute. It is more customary, however, to separate charges into two components, one more nearly related to fixed costs, and one proportional to variable costs. In the table each item is characterized as being more nearly fixed or variable, and is summed in the appropriate category to yield an estimated total tariff for the assumed video-conference services. These estimated tariffs are $2000 per month plus 63¢ per minute for 3-Mbps full-motion video teleconference services augmented by high-speed facsimile and high-speed data ports. If a user insists on his own private ground station, these could rise to $7400 per month plus 54¢ per minute.

The investments for the video option are approximately $600M, $400M, $800M, and $3000M for the space-segment, ground-station, ground-link, and user-facilities costs, respectively; these represent 12, 8, 17, and 63 percent of the total 4.8 billion dollar investment. The investment in new network plant alone is thus only $1.8B. The revenue streams associated with these elements are also listed in the table, and they total $2B per year. Since the revenues associated with maintenance and operations are approximately half those associated with 5-year depreciation, an alternative accounting appears in the right-most column of the table, where the maintenance and operations revenues are arbitrarily doubled to yield total annual revenues of $2.6B, a 30 percent increase.

The obvious conclusion is that the costs are dominated by the users' video-conference room equipment, and that the remaining 37 percent of the costs are divided approximately equally between the space, ground-station, and ground-link elements, with only 12 percent devoted to the satellites themselves. The second conclusion is that the estimated tariffs for video-conference services are quite low, perhaps sufficiently low to

stimulate substantial use of the service, even beyond the 30-Gbps assumption, as discussed in Chapter 2.

These estimates can be viewed in other ways, for other assumptions. For example, the tariffs per 3-Mbps one-way user-to-user link would average ∿ $525 per month plus 25¢ per minute for 20 percent utilization during the work week. A fully dedicated link would be $2625 per month plus 25¢ per minute. The corresponding voice tariffs for a dedicated link, neglecting multiplexing and user-equipment costs, could be as low as $50 per month plus 0.5¢ per minute; thus the multiplexing, signal conditioning, and other user-equipment costs could dominate. The annual tariff for a single dedicated 60-kbps user-to-user one-way circuit, neglecting multiplexing costs, could be $1080, and 20 percent utilization plus sharing could reduce the cost further.

All of these estimates are based upon the assumed 30-Gbps baseline system; it is interesting to explore how the costs might vary for systems of different capacities. If the 12.8-Gbps satellite were developed, the costs for traffic in the range from ∿ 10 to 60 Gbps would be approximately those quoted above because of the flexible multi-satellite architecture. Significant departures from this range would require re-examination of the assumptions developed in Chapters 3, 4, 5, and 6; a simple cost model for much smaller or larger systems is described below.

In Section 3.2.2 it was argued that the number of ground stations should be proportional to the two-thirds power of total satellite traffic, and Table 5-1 indicated a small learning-factor correction was appropriate for ground station unit costs. These two considerations result in the total ground station cost being approximately proportional to $T^{0.6}$, where T is the total traffic (Gbps). The cost of the satellite as a function of size was presented in Fig. 4-10; the cost is proportional to the 0.5 power of the capacity if all other specifications are fixed. For capacities below 12.8 Gbps, fewer than 400 beams would be more cost effective, thus increasing slightly the cost dependence upon capacity; a reasonable approximation would again be ∿ $T^{0.6}$. The cost of the local terrestrial links is proportional to the product of their average length, which varies as the distance between ground stations, and the total traffic T. The average length varies as the square root of the number of ground stations,

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and thus it is proportional to $T^{-0.33}$; the product is proportional to $T^{0.67}$. To assume that the total baseline system costs are approximately proportional to $T^{0.6}$ is probably quite reasonable. This relationship will be useful later in understanding the growth problems of such large networks.

7.3 TRADEOFF STUDIES: BASELINE DESIGN SPECIFICATIONS

One of the important benefits of a detailed baseline design study is that any of the assumptions can be altered to explore the relative merits of various design alternatives. Perhaps the most basic common denominator relating various design specifications for the space link is link margin. For each element contributing to link margin there is a cost per decibel for small departures from the baseline specifications; by identifying these various costs, a more nearly optimum solution can be determined. The cost per decibel will generally be equal for all variations only at the optimum design. Such an analysis appears below, and more nearly optimum design specifications are determined.

There are seven design variables which appear to be significant; these are listed in Table 7-2. For each cost element the present price is estimated, together with the prices expected if the link margin were to be improved or degraded 3 dB. These estimates generally follow from the discussion in the chapters on cost analysis. The rightmost columns present the increase and decrease in total system costs associated with each of these potential 3-dB design changes. The perturbations are with respect to the 1800-ground-station system described in Table 7-1; the system capacity remains constant.

Since all the increments in total system cost are not equal, design specifications can be altered to improve the system economics. It is clear that the least expensive way to improve link margin is to increase the size of the ground station antennas; a 3-dB improvement costs only $\sim$ \$20M. Improving all system noise temperatures would cost \$113M, increasing the number of beams to 800 would cost \$240M, and decreasing the data rate to 64 Mbps would cost \$337M. The cost estimates for receiver improvement and 800 beams are more uncertain because these technology options were not analyzed and could stretch the future state of the art. Conversely, the greatest cost savings are obtained by increasing the data rate, and by reducing the number of antenna beams and the transmitter powers.

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Table 7-2. Baseline System Costs: Sensitivity to Changes in Design and Link Margin.

Variable	Change	Unit Prices *,# ($K)			Total Baseline System Cost ($M)†	
		Present Price	Higher Price (+3 dB Margin)	Lower Price (−3 dB Margin)	Increase (+3 dB)	Decrease (−3 dB)
Ground station antenna diameter (8 to 11.3 or 5.7 ft)	reflector mount site costs	8 3 4	16 4 6	4 2 3	20	11
Space antenna, number of beams (400 to 800 or 200)	antenna, structural wt., ferrite switches, etc.	30%#	70%?	15%	240?	90
Data rate per band (128 to 64 or 256 Mbps)	ground receivers transmitters modems	17 32 5	34 64 11	9 16 3	 55	 26
	satellite costs (receivers, transmitters, modems, etc.)	47%	94%	24%	282 337	144 170
Satellite transmitter power (10 to 5 or 20 watts)	transmitter tube and driver; associated costs	32%	64%	16%	192	96
Ground transmitter power (10 to 5 or 20 watts)	transmitter tube and driver	32	45	23	24	16
Satellite system noise temperature (800 to 400 or 1600°K)	preamplifiers	3%	9%?	2%	36?	6
Ground system noise temperature (500 to 250 or 1000°K)	preamplifiers, antenna backlobes	17	60?	15	77?	4

*Per ground station; lot size is 100.
†1800 ground stations, 4 satellites.
#Percent of $600M space segment investment.
?Technology and costs uncertain.

The size of the ground station antenna appears to be the single most important parameter to consider. Since the cost of the antenna is approximately proportional to its area, its diameter might be increased from 8 to 16 ft to yield 6-dB improvement at a cost of $60M-$80M. One uncertainty is the site cost necessary for such large antennas because they no longer can freely be placed on secure rooftops, but must have special footings, enclosures, and utility services provided on the ground. If the increase in each site cost were $25K, then the incremental cost of 16-ft antennas could even be ∿ $105M.

This 6-dB improvement could then be exchanged for a 6-dB degradation in other specifications. Examination of the table suggests that a 3-dB loss due to an increase in data rate, plus 1.5-dB losses due to reductions in transmitter powers and the number of antenna beams, would yield a nearly optimum design. These changes in system specifications and their consequences are summarized below in Table 7-3.

Table 7-3. Improved Baseline Design; Changes in Specifications and Costs.

Specification	Change	Change in Margin	Change in System Cost
Ground station antenna diameter	8 ft to 16 ft	+6 dB	+$60-105M
Data rate per band, average	128 Mbps to 256 Mbps; halve number of transponders	-3 dB	-$170M
Transmitter power, space and ground	10 W to 7 W	-1.5 dB	-$ 65M
Satellite antenna, number of beams	400 to 285	-1.5 dB	-$ 52M
TOTAL		0 dB	-$200M

Another design change worthy of consideration is the substitution of solid state amplifiers for the assumed TWT's in the spacecraft. The link power budget summarized in Table A3.1-1 shows that if each amplifier handles one band, as it might during rain fading, then the margins are 15.4 dB for the downlink and 15.8 dB for the uplink at the peak of the

beam, and that in a null the downlink margin is greater than the uplink margin. Since the fading induced by rain is approximately twice as great for the uplink, greater symmetry in uplink and downlink margins could be achieved by reducing the downlink transmitter power from the 7 watts suggested in Table 7-3 to perhaps 4-5 watts, which appears to be achievable with lighter weight solid state units. Furthermore, it may become practical to replace each TWT with two such amplifiers, each handling one band instead of two. The efficiency of the transmitters could be improved if their linearity requirements could be reduced in this way.

The replacement of the baseline switched-feed antenna with a segmented phased-array system such as described by Acampora et al. (1979) would alter the optimum specifications only slightly. Because the downlink transmitter power can readily reach 10 watts, the other parameters might alternatively be relaxed an aggregate of $\sim$ 1 or 2 dB. If K_u band is used, the reduced link margin requirements might release another few dB, although the antenna diameters must then be scaled upward with the increase in wavelength.

In general, the optimum design specifications occupy a broad minimum in a multidimensional cost function, and changes by a factor of two in most parameters may be economically feasible provided the total performance is acceptable. For example, the design changes proposed in Table 7-3 reduced the total cost of the spacecraft by an estimated $250M (see also Table 7-2), or 42 percent. On the other hand, the ground station costs increased by $\sim$ $40M, or 10 percent. The total change in the satellite and ground station costs was an estimated $200M, or 20 percent.

7.4 SYSTEM GROWTH AND ECONOMIC VIABILITY

The very attractive costs discussed earlier in this chapter for the baseline system are based on traffic levels of 30 Gbps; it is important to understand whether or not they are still attractive for the smaller traffic levels anticipated during the growth years of such a system. Although complete analysis of this issue is well beyond the scope of this study, it is nevertheless still possible to model the economics with sufficient fidelity that the nature of the answer can be understood.

In Fig. 3.2-1 the basic traffic allocation diagram suggests that the fixed costs per circuit for satellites will lead to satellite supremacy for links longer than some breakpoint distance where terrestrial and space costs are equal. The figure also displays the nominal traffic distribution as a function of distance. This simple model combined with the baseline cost estimates make clear the strong economic incentives in favor of satellites, even for systems much smaller than the baseline design; the analysis is summarized in Table 7-4.

The second column of the table (derived from Fig. 3.2-1) lists the relative number of circuits of a given length, ± 1 mile, and the third column represents the product of the circuits per mileage band and the nominal width of the link-length interval of interest. That is, the first band (30 miles) extends approximately from 20 to 50 miles, and the product of this width (40 miles) and the 0.2 relative circuits yields the 8 relative circuits listed in column three. It is evident from column three that most circuits are a few hundred miles long, but that there is a significant fraction at still greater distances.

Because satellites are assumed to carry all traffic for links longer than the breakpoint distance, the fourth column sums all such circuits enumerated in column three. Thus the last entries in columns three and four are the same. Column five lists the equivalent number of 50-kbps circuits longer than the given mileage; it is arbitrarily normalized such that the total long-distance market is 30 Gbps or 6×10^5 50-kbps voice circuits. Column twelve is the same as five, but expressed as Gbps. The table suggests that, for these assumptions, a 30-Gbps system could handle all long-distance traffic, and a 10-Gbps system could handle all traffic over $\sim$ 1200 miles.

This relation between total satellite traffic and breakpoint mileage (columns one and twelve) can be used to relate the costs of satellite service to breakpoint mileage. Thus column six lists the baseline cost per circuit year deduced from the baseline cost estimates as a function of traffic T; the assumed relation is that total system cost is proportional to $T^{0.6}$, and that the cost per circuit is therefore proportional to $T^{-0.4}$ (see Section 7.1).

Table 7-4. Capacity Supply and Demand as a Function of Cost.

1	2	3	4	5	6	7	8	9	10	11	12
Mileage	Relative Circuits per Mileage Band	Relative Circuits	Relative Circuits Longer than Mileage	T, 50-kbps Circuits Longer than Mileage ($\times 10^5$)	Baseline Cost per 50-kbps Circuit Year ($)	Breakpoint Cost per Circuit Year ($)	Maximum Baseline Cost per Circuit Year ($)	10% Market Share Baseline Cost per Circuit Year ($)	50% Market Share Baseline Cost per Circuit Year ($)	Maximum Baseline Cost per Circuit Year ($)	Traffic (Gbps)
30	0.2	8	3,598	6	1,080	120	2,590	4,300	1,640	3,925	30
100	1.0	90	3,590	6	1,080	380	2,590	4,300	1,640	3,925	30
200	2.8	280	3,500	5.8	1,095	750	2,630	4,360	1,660	3,990	29
300	3.8	380	3,220	5.4	[1,126]	[1,200]*	2,700	4,480	1,710	4,090	27
400	4.0	400	2,840	4.7	1,190	1,550	2,860	4,740	1,800	4,335	24
500	3.3	495	2,440	4.1	1,258	[2,000]	3,020	5,010	[1,910]	4,580	20
700	1.6	400	1,945	3.2	1,388	2,800	3,330	5,525	2,100	5,050	16
1,000	0.8	320	1,545	2.6	1,509	[3,800]	[3,620]	6,010	2,290	5,490	13
1,500	0.7	350	1,225	2.0	1,676	6,000	4,020	6,670	2,540	6,090	10
2,000	0.6	300	875	1.5	1,880	[8,700]	4,510	[7,480]	2,850	[6,835]	7.5
2,500	0.6	300	575	1.0	2,210	10,000	5,300	8,800	3,350	8,035	5
3,000	0.5	275	275	0.5	2,918	12,000	7,000	11,620	4,420	10,610	2.5

*Circled costs are those which mark the breakpoint distance.

This cost per circuit (column six) can now be compared with the cost per terrestrial circuit at that breakpoint mileage. These terrestrial costs are assumed to be proportional to circuit miles; a value of $4 per circuit-mile-year is used here, and is intended to reflect approximately the marginal capital costs plus operating costs. The analysis can readily be repeated for other assumptions. The annual terrestrial circuit cost for the given mileage is listed in column seven; it extends from very low values of $120 at 30 miles to very high values of $12,000 at 3000 miles. Comparisons of columns six and seven produce the important result that satellites are cheaper for circuits longer than ∿ 300 miles, and that a 27-Gbps system could capture this market. These numbers are obviously sensitive to the many assumptions involved; for example, all traffic numbers are directly proportional to the assumed 30-Gbps size of the total long-distance communications market. Also the impacts of the "medium-haul" market and the "free-fiber limits," etc. (Fig. 3.2-2) have not been considered.

Less sensitive is the very important observation that smaller satellite systems are actually more competitive than large ones because they are restricted by their capacity limitations to the most profitable very long routes. For example, a 2.5 Gbps system would have annual circuit costs of $2918, which is much less than the breakpoint cost of $12,000 appropriate to that restricted 3000-mile market. This result stems from the fact that the per-circuit cost of satellites varies much more slowly with system size than do the terrestrial costs with respect to mileage and the corresponding traffic. It should be noted that this result follows in part from the assumed distribution of circuit lengths presented in column two of the table and discussed further in Section 3.2.1. An independent but similar tabulation of the same traffic distribution function appears in Tables 2-3 and 2-5, as presented by Western Union (1979) and ITT (1979).

To indicate the relative insensitivity of the general conclusions concerning the value of satellites we may alter the cost assumptions. Table 7-1 suggests that the annual revenues for the baseline system would equal approximately 40 percent of the initial investment cost, a ratio generally consistent with AT&T's present ratio of annual revenues to book

value. For many businesses this ratio is closer to unity. Therefore the satellite cost entries in column eight have arbitrarily been increased a factor of 2.4 to reflect a higher ratio of revenues to investment. Even with these inflated costs, the breakpoint distance is 1000 miles and the total satellite traffic is 13 Gbps. The satellite traffic would include, in addition to this, any load which is desirable to relieve momentarily oversubscribed terrestrial routes, even if less than 1000 miles long.

Although a single entity, such as AT&T or a group of carriers including AT&T, might reasonably plan on total system traffic of 30 Gbps or more, independent companies forced to provide their own separate net-works could face more difficult economic alternatives. If such a company obtained a 10 percent market share for those route distances where it was economically viable in competition with terrestrial circuits, then its higher costs per circuit would lengthen the breakpoint distance and reduce its traffic. The column in the table for 10-percent market share suggests that the baseline design scaled by $T^{0.6}$ would yield a breakpoint distance of 2000 miles and a load of 750 Mbps. A 50 percent share of the satellite market would decrease the breakpoint distances to 500 and 2000 miles for the baseline and maximum baseline cost estimates; the corresponding loads are 10 and 3.2 Gbps. The maximum baseline cost estimates would make a 10 percent share of the satellite market untenable at any distance for the present assumptions.

If subsystems of the various communications vendors are to some extent interconnected, then they may to that extent all take advantage of the scaling laws appropriate to the total joint system capacity. Market share remains an issue, however, if there is competition between satellite communications organizations of different sizes. At this point the technical, marketing, and policy issues become thoroughly intertwined, and their resolution becomes obscure. Some of the relevant issues are addressed in Chapter 8.

7.5 SUMMARY OF CONCLUSIONS: NETWORK ARCHITECTURE, ECONOMICS, AND MARKETS

7.5.1 NETWORK ARCHITECTURE

This study attempted to define the most cost-effective architecture for a large pervasive broadband fully switched satellite communications

network capable of providing 10-60 Gbps capacity for the United States in the late 1980's. Although this network would presumably be intertwined with the existing telecommunications plant, the architecture is not greatly sensitive to this assumption. The design was optimized by modifying slightly the parameters of a baseline design so as to minimize total system cost; the baseline design costs were estimated to the subsystem level on the basis of technology projections for the mid-1980's. Although changes of a factor of two in any parameter would generally alter system costs less than 20 percent, changes greater than this may well be economically inferior. The optimum design is summarized below in Table 7-5, and discussed in greater detail in Section 7.3.

Table 7-5. Summary Specifications for Optimum 20/30 GHz Switched Satellite Communications Network of 10-60 Gbps Capacity.

1. 3-6 similar satellites, each of 3-13 Gbps capacity, share one synchronous orbital slot; they provide fully switched long-haul capability.

2. Multiple FDMA TDMA bands, each at 256 Mbps, are synchronized and assigned so that memoryless digital switching occurs at the satellite complex without intersatellite traffic.

3. ∿ 1800 ground stations, typically at existing toll centers.

4. Terrestrial links between ground stations provide diversity protection; 99.99 percent reliability.

5. Satellite has 4-7 watt transmitters, uncooled super-heterodyne receivers, and a 285-beam antenna simultaneously activating independent switched beams that address limited but overlapping service areas.

6. Ground stations typically have 16-ft antennas, 7-watt transmitters, and dual-redundant 256-Mbps electronics.

In general ground stations would not be on customer premises because the cost of linking most customers to a local ground station would normally be significantly less than that of the station. The first ground station in a given locality could be on the premises of a major customer, however, but it then would be more economic to connect subsequent traffic to that same station. The total number of ground

stations should be approximately proportional to $T^{2/3}$, where T is the traffic in Gbps. For a 30-Gbps system the optimum number of ground stations would be very approximately 1800, of which about half might be rural and about half might be located near existing toll centers (Sections 3.2.3, 6.2).

The concern about propagation statistics at 20/30 GHz may be excessive. Since the communications capacity of a nominal ground station significantly exceeds its average load, and since the separations between ground stations would typically be only $\sim$ 13 miles in urban areas and $\sim$ 58 miles in rural areas, the cost of space diversity is only the cost of a short terrestrial link (Section 6.2). Furthermore, since most of the satellite traffic might originate from existing toll centers, and since these centers are already well inter-connected, the costs of space diversity could be quite modest, generally less than 10 percent of the costs of the satellite system (Section 3.2.4), and perhaps much less.

Significant improvements in system flexibility and loading efficiency can be achieved by the use of multiple cooperating switched satellites in the same orbital slot (the loading factor might be double); they would comprise a "pseudo-platform" with significant technical and economic advantages. They would have all the inter-connectivity and orbit-conservation advantages of platforms plus a significantly increased loading efficiency because capacity could be added incrementally as needed. The reliability advantage of having several simultaneously operating self-contained systems is obvious (Sections 3.2.5, 3.3.6).

One scenario for technical establishment of such a large switched satellite system is the following. An initial series of satellites of $\sim$ 3 Gbps each (comparable to the existing Japanese CS satellite, but fully switched) might be launched beginning in the late 1980's, and these might be followed by a second series in the 1990's with 12 Gbps per satellite. Ground stations would be established first at regional and sectional centers, and then at an increasing number of primary and toll centers as traffic grows and the costs decrease. Costs for smaller carriers will be minimized to the extent they can share in the economies of scale available to larger carriers. At one extreme, each

carrier could have an independent system; alternatively they could share one or all of the cooperating satellites, or even share the ground stations. The present requirements for AT&T to connect other carriers with the terrestrial long-lines network could be translated into a requirement that any large switch in space must provide direct access to adjacent switches in space and/or to all accepted ground stations.

Cost effectiveness is maximized if the rather long-lived ground-station antennas are built initially to the specifications anticipated to be optimum later, and if the same foresight is applied to as many of the other specifications as possible.

7.5.2 SYSTEM ECONOMICS

On the basis of the cost estimates developed for the baseline system, several conclusions can be drawn; these concern the total costs of large switched satellite communications systems, the associated tariffs, the dependence of the costs upon system size, and the competitiveness of such systems as a function of size.

The total costs in 1979 dollars of the three major elements of a 30-Gbps system are listed in Table 7-6 together with the costs estimated for video user facilities sufficient to utilize that capacity. The costs of user equipment for other services would vary. These estimates are based upon 1985 technology and therefore do not include the costs of intervening research and development efforts. The only nonrecurring costs included in the estimate are those for development of the satellites; nonrecurring costs for development of the ground station design, local links, etc. are not included. These should be a small part of the total. Also listed in the table are the investment costs estimated for the revised baseline design and the baseline system revenue estimates. The most important conclusions to be drawn from this table are that total costs for a large communications satellite system could be relatively modest, and that the value of the user facilities and local distribution systems clearly dominate the total.

The revenues estimated in Table 7-6 can be equated to estimated tariffs for dedicated switchable links. Such price estimates are presented in Table 7-7 for a variety of data rates, where the prices are

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Table 7-6. Summary of System Economics ($FY79).

System Element	Number of Units	Investment* ($M)		Baseline Revenues ($M/yr)
		Baseline System	Revised Baseline	
Satellites	4	600	350	205
Ground stations	1,800	400	450	185
Local terrestrial links (50,000 users)	-	800	800	240
User facilities (video assumed)	50,000	3,000	3,000	1,400
Total network (no user facilities)		1,800	1,600	630
Total (with user facilities)		4,800	4,600	2,030

*Omits all nonrecurring costs except those for satellite development.

simply proportional to the rate because multiplexing costs are not included; the basic data rate for the baseline system is 3 Mbps. The monthly price for a dedicated one-way 3-Mbps link is $3390 ($FY79), and this could be reduced to ∿ $1100 if the link is committed only 20 percent of the time (Table 7-1). These prices include everything but the equipment on the user's premises. Although these estimates may be no more accurate than a factor of two, increases of a factor of three or more would probably result only if policy issues were controlling.

Table 7-7. Summary of Tariff Estimates ($FY79).*

Service+ (one-way dedicated line, to wall sockets)	1990's		1978
	30 Gbps ($/mo.)	3 Gbps ($/mo.)	($/mo.)
10 kbps	12	56	-
60 kbps	68	315	10,000&
256 kbps	290	1,350	18,000&
3 Mbps	3,390	15,700	-
30 Mbps	33,90ſ	157,000	50,000#

*Based upon baseline cost estimates for 3 Mbps service.
+Omits multiplexer and user equipment costs for 100% line use.
&Approximately 85% is for dedicated earth terminals.
#For transmission of analog TV 8 hr/day and uplink costs only.

These tariffs are a function of system size and of time. For comparison, the table also presents the tariffs estimated for the same dedicated services with a 3-Gbps system capacity and with 1978 prices (also see Table 2-7).

The costs of any system depend on the size of that system. The arguments that the number of ground stations should be proportional to $T^{2/3}$ (where T is total system traffic, Gbps), and similar arguments concerning the satellite capacity and the costs of the local links, all suggest that the total system cost is approximately proportional to $T^{0.6}$ (Section 7.2). The plausibility of this rule and the estimated costs for a 30-Gbps system can be partially tested by combining them to estimate the 1979 costs of a nominal 1-Gbps system; the estimate is approximately 235 million dollars ($FY79). Although the cost advantages of 1985 technology are assumed for the baseline design, the switching power is then compensatingly greater.

The final conclusion is that if a particular system is cost competitive with terrestrial circuits, then it becomes more competitive for smaller versions of that same system. This assumes that the satellite system has the same market share of all traffic longer than the particular breakpoint distances appropriate to each case (Section 7.4). For example, if concept X can profitably capture 20 percent of all long-distance traffic longer than 1000 miles, then a smaller system with capacity adequate only to handle 20 percent of the traffic longer than 2000 miles would be more competitive economically. This result follows if the terrestrial costs are proportional to circuit miles (and vary a factor of 2 in this example), because the satellite costs are proportional only to the 0.6 power of traffic and therefore are more invariant, provided that the traffic distribution assumptions described in Section 7.4 are correct. Of course, smaller systems can be less profitable if their smaller versions capture a smaller market share at a given distance, in addition to losing the shorter routes. The converse is also true; if a small system with x percent of the traffic at some distance is enlarged, it will become less profitable per Gbps unless x is sufficiently increased.

7.5.3 MARKETS

One basic conclusion is that total domestic long-distance traffic will continue to grow strongly over the next 20 years, with voice growing approximately 9 percent per year, and the other services perhaps growing more. Voice is expected to remain the largest single service. The total traffic carried by domestic satellites is also expected to grow quite fast, with peak rates nearing $\sim$ 10-40 Gbps in 1990 and $\sim$ 30-100 Gbps in the year 2000. These projections assume the market share of domestic long-distance traffic allocated to satellites will become $\sim$ 10-30 percent by 2000 (Section 2.2).

The baseline cost analysis here suggests that satellites might even capture more than half the long-distance market, if other considerations don't intervene. The traffic routes allocated to satellites will probably include those which are sufficiently long that the traffic-dependent terrestrial costs exceed the costs per satellite circuit. A second potentially important market for satellites is that "medium-haul" set of routes for which the fixed costs of satellites are less than the fixed traffic-independent costs of the terrestrial route; this is most relevant to thin routes which otherwise are shorter than the nominal breakpoint distance (Section 3.2.2).

One of the most important conclusions is that the anticipated low costs for interframe-compressed full motion video could motivate significant use of full-motion video conferencing and desk-top type picturephone services; this possibility appears to be sufficiently realistic and profound that it deserves much more careful examination than was possible in this study. If we assume that it is reasonable for the user facility to cost approximately the same as the communications link, then a $60K user video facility might correspond to a 3-Mbps circuit and 63¢ per minute plus $2000 per month; a $10K desk-top picturephone might employ 512 Kbps and cost 15¢ per minute plus $500 per month. Approximately 75 percent of the monthly fee represents the lease cost for the user's terminal equipment. With marginal prices approaching those of audio services it is clear that there could be significant demand (Sections 2.3, 6.1.2, 7.2).

The same estimated costs also strongly suggest that compressed full
motion video should supersede freeze-frame video because the price of
the video equipment is approximately the same for either service, and
generally greater than the potentially low tariffs for 500-3000 kbps
video circuits. Thus for little extra cost the generally preferable
performance of full motion video could be obtained. Freeze-frame video
makes sense only if transmission costs are very high (as they are now)
or if data rates above 250 kbps are unavailable. Similar conclusions
apply to the eventual displacement of slow facsimile by high-resolution
fast facsimile employing data rates in the 50-500 kbps range, which
corresponds to facsimile terminal costs on the order of a few thousand
dollars.

7.5.4 CRITICAL ASSUMPTIONS AND SUGGESTIONS FOR FUTURE WORK

7.5.4.1 Assumption that Decisions are Based on Cost

The most important single assumption is probably that the satellite
capacity will indeed grow beyond several Gigabits per second and that the
anticipated economies of scale can be achieved. If the allocation of
traffic to satellites versus terrestrial circuits is made on the basis
of cost alone, then such growth in satellite traffic should certainly
occur. However, this assumption that cost considerations will dominate
may be invalid, as discussed further in Chapter 8. Even if domestic
satellite traffic is artificially curtailed, many of the basic architec-
tural arguments would still apply to the smaller systems, and it is
unlikely that the same constraints would similarly curtail the inter-
national market.

7.5.4.2 Availability of Critical Technology

A second important assumption is that certain critical technologies
will indeed be ready by the mid-1980's. The most important here include
1) switched multi-beam antennas with $\sim$ 100-400 potential beams and $\sim$ 5-50
transponders, 2) efficient broadband 20-GHz satellite transmitters with
$\sim$ 3-20 watts power, 3) compact pulsed modems, frequency translators,
oscillators, and related r.f. equipment, 4) space-qualified compact
logic switches for up to $\sim$ 100 × 100 connections which carry a few
hundred Megabits per second (e.g. 256 Mbps), 5) design and acceptance

of command, control, access, and communications protocols, including those for cryptography, error-correction coding, and bandwidth compression, and 6) low-cost LSI modules which implement the chosen protocols. With aggressive NASA support of these technologies, they should be sufficiently developed to validate this important assumption; significant progress is also being made in private development programs in several of these areas, including significant programs abroad.

7.5.4.3 Importance of a Flexible Inter-frame Video Compression Standard

Special importance should be attached to the design and acceptance of efficient high-performance inter-frame video bandwidth compression algorithms which can meet both immediate and future needs and opportunities. An ideal protocol would be a very general one which could be implemented by a rather simple receiver but which could permit almost arbitrarily great sophistication on the part of the transmitter; it could become increasingly efficient over the years and transmit at whatever rate was economically appropriate for the task at hand. The rate should be capable of varying semi-continuously from freeze-frame to broadcast quality. Thus no user's equipment would become obsolete or incompatible, it would simply not be as efficient as the latest models. A simple example of such a protocol would be one which involves the sending of variable-length packets with variable addresses which either replace or add to portions of the receiver's memory of the current image being displayed. The burden would then be upon the transmitter to make the most of the substantial opportunities for improvement such limited flexibility provides. The development of such a protocol could be one of the most important ingredients in the successful establishment of pervasive full-motion video services. It will be important not to sacrifice temporary expediency for long-term value, or vice-versa.

7.5.4.4 Minimum-Cost Ground Stations

The system architecture developed here envisions ground stations spaced many miles apart and serving entire towns. The system configurations suggested by the SBS and Xerox XTEN proposals are more individualized; their visions of the market would be enhanced by the development of much lower cost ground stations which could be placed much closer to individual clients.

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Ground station cost is related principally to size, if we assume that technology will rapidly drop the cost of the electronics. The best way to reduce the size of the ground station is to reduce its bandwidth, perhaps to data rates on the order of 0.25 - 12 Mbps. The resulting 10-26 dB improvement in link margin could reduce the size of the ground station antenna to $\sim$ 4 feet and the ground transmitter power to $\sim$ 0.1-4 watts, which could be implemented with solid-state devices. Such a development would require, however, an entirely different approach to the satellite because the dwell time of the beams must necessarily be much longer on each spot, and because each transponder must handle a much larger number of adjacent signals without excessive intermodulation. Whether or not the signals are demodulated, they must be separated and passed through a very much larger switch. The problems with this approach are formidable, but the rewards are sufficient to warrant further effort.

7.5.4.5 Choice of 12/14 versus 20/30 GHz

Another area worthy of attention is the question of frequency selection. The relative merits of the 12/14 GHz band versus 20/30 GHz are not clear. If the demand for switched satellite capacity of tens of GHz is realistic, then the 500-MHz bandwidth of the 12/14 GHz allocation forces a very high degree of frequency reuse, perhaps 40 times for a 30-Gbps system. The burden this places upon the satellite antenna could be intolerably expensive compared to the smaller cost of antennas at 20/30 GHz. Although the surface tolerances are relaxed slightly at 12/14 GHz, the areas of the ground station and space antennas must be approximately four times greater than those at 20/30 GHz to provide the same gain. When these factors are combined with the greater ease of finding sites for smaller antennas and other considerations, it is not obvious which band will be more cost effective in 1985. To incorporate both 12/14 and 20/30 GHz ground stations in one switched system would involve either multiple ground stations at each site or the use of significant inter-satellite communications links to couple the two systems. This issue of band selection thus requires further examination too.

7.5.4.6 User Acceptance of Services

Much of the projected traffic growth presumed that users would not mind significantly the delays and residual echoes present on satellite circuits. If the services are not well encrypted, there could be another market acceptance problem. The ease and reliability of access is also an important factor. The present cost estimates should be adequate to eliminate all these problems except for the delay, and we have assuemd that this delay would not be an important factor if only one satellite link were used. These assumptions are being tested now by various carriers.

Chapter 7 References

1. Acampora, A. S., C. Dragonne, and D. O. Reudink, A satellite system with limited-scan spot beams, IEEE Trans. Comm., COM-27, 10, pp. 1406-1415, 1979.

2. ITT U.S. Telephone and Telegraph Corp., 30/20 GHz fixed communications systems service demand assessment, NASA Rept. No. NASA-CR159620, August 1979.

3. Western Union Telegraph Co., 18/30 GHz fixed communications systems service demand assessment, NASA Contractor Rept. No. NASA-CR159547, July 1979.

CHAPTER 8

ECONOMIC AND REGULATORY ISSUES

8.1 INTRODUCTION

Discussion of future communications satellites might be confined to issues of technology, economics, and markets, but the degree to which these opportunities are eventually realized may well be determined as much by national policy as by technology. Because development of technology without reference to constraints posed by policy could be inefficient, the present chapter attempts to illuminate some of these relevant policy issues. Their full exploration would be far beyond the scope of this report. In this chapter economic issues and regulatory history are surveyed briefly in Section 8.2, the introduction of new technology is discussed in 8.3, various policy options are described in 8.4, possible satellite ownership and use patterns, including estimates of satellite size, are mentioned in 8.5, and all these issues are summarized in 8.6.

8.2 ECONOMIC ISSUES

The following discussion highlights a few of the economic considerations that enter in determining proper investment and prices for telecommunications. It is apparent that the subject is quite complex, and that this could itself be one of the central policy issues. In the face of this difficulty, there have evolved some general principles which guide policies, and some of these are also discussed below. A good survey of these issues is that of Yordon (1979), and much of the discussion here follows his presentation.

In an idealized economy it is well known that social benefit is maximized by setting prices equal to marginal costs. In this situation rational consumer decisions maximize productivity. For the ideal consumer, his marginal utility per dollar spent is the same for all commodities; utility signifies the value of a commodity to a consumer and marginal utility is the incremental change in that value for the last unit consumed.

One problem arises when an industry has costs which strongly increase or decrease with the scale of production. An example of an increasing-cost industry is oil. The cost of early barrels per year is low, it almost flows out of the ground by itself, but the last barrel may involve Arctic drilling and long-distance piping. If marginal pricing were used, the profits of the oil industry would now be very large because the marginal cost for the last barrel is much greater than the average cost.

Telecommunications is under many circumstances a decreasing-cost industry; the cost to provide the last increment of transmission in the existing size market may be less than to provide earlier increments.* For example, the fixed cost of installing long lines for thin routes is much greater than the bandwidth-dependent cost (Kahn, 1971), and the local access cost per subscriber might drop from $450 to $290 as the number of subscribers in a given area increases from 1000 to 100,000 (Mandanis et al., 1977). Marginal pricing would set the price per transmission to the very low cost associated with the last unit, and total revenues would then be below cost. Under these circumstances the largest vendor can charge less than smaller ones, thus driving them out and ultimately securing a monopoly position for itself, after which it could raise prices. Some typical major industries characterized by strongly decreasing costs include telephone utilities, the distribution of water, gas, and electricity, and the automotive and semiconductor electronics industries. These are all industries in which the trend toward monopoly is strong.

The belief that telephone service was an essential good and that the industry was characterized by declining costs has led to its regulation almost since its inception. Other issues have also been important. For example, Theodore Vail (President of AT&T, 1885-87 and 1907-19) argued successfully that it was appropriate for residential customers to be spared paying in proportion to their own marginal costs because of the value which each such subscriber confers on the total network; everyone benefits by being able to call a particular subscriber, not just the subscriber himself.

If the average price must be maintained above the marginal cost of telephone service, then the regulator must determine how to preserve economic efficiency at the same time as he pursues various other

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*See FCC Doc. 20,003. The FCC has questioned AT&T's "Economies of Scale" theory.

objectives. One concept that has achieved wide acceptance, especially abroad, is "value-of-service' pricing. Since different market sectors value a service differently, equity is said to be maximized for fixed total revenues if the sectors are charged differently. Although such value-of-service prices involve charging what the market will bear, or some price proportional to that, it also involves not charging what the market will not bear. Thus a businessman might be charged more than a homeowner because telephone service is of greater importance to a business, even if the marginal costs are greater for the homeowner.* Homeowners would still pay a price sufficient to cover their marginal costs.

Regulators may decide to permit the homeowner rates below any economic criterion as a matter of social policy. For example, the early view that telephone service is a luxury has increasingly been replaced by the view that it is a necessity, and that below-cost "lifeline" rates should be available to individuals.

In opposition to "value-of-service" pricing and to concessionary rates is the currently popular doctrine that dominant carriers should face competition to the maximum extent possible. Theoretically an unrestrained dominant carrier might establish low predatory rates where it faces competition and establish high prices elsewhere. Therefore this current American doctrine argues for "rate-of-return" pricing under which each service pays its own true costs; these are average, not marginal costs. Because various services generally share certain facilities, the allocations of "true costs" to various services can be controversial.

Much debate has centered on what constitutes marginal costs. To exaggerate one facet of the problem, the additional wear-and-tear on the network caused by a customer using idle capacity may be zero, but the customer whose blocked call stimulated plant expansion instigated a very high marginal cost. Different users have different probabilities of being among the high-cost blocked-call set, and thus their marginal costs would differ one from another and from time to time. Some feel that prices should reflect short-run marginal costs (e.g. lower rates at night or for use of under-utilized plant), and some feel that long-run incremental costs (e.g. charging for temporarily under-utilized plant)

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*Higher business rates are also justified by businesses' greater impact during "peak" hours.

should guide rate setting. Fully distributed costs (FDC) make cross-subsidization easier to audit. Perhaps for this reason AT&T was unsuccessful in its arguments before the FCC that long-range incremental cost accounting (LRIC) should be used for rate-setting in preference to FDC accounting.*

The foregoing discussion can be summarized simply. The declining-cost and essential-service character of the telephone industry has led to its regulation. A sophisticated form of marginal-cost pricing which considers long-range incremental costs and relative demands can result in economically and socially desirable results, even though the rates may appear to be discriminatory; what is socially desirable involves value judgments by the regulators.

However, because of the great complexity of the issues and the lack of well accepted cost and demand data:

> The rate structure for myriad telephone services is only haphazardly, if at all, related to the structure of costs. In telephone, as in transportation, the rate structure which has evolved is the product of vaguely conceived rate-making principles and historical happenstance. The present structure, contained in thousands of tariffs and exceptions, is based in part on cost considerations, in part on demand considerations, but for the most part is inexplicable (Office of Telecommunications Policy, 1976).

In the early days the natural monopoly characteristics of telephone service resulted in a large number of local monopolies which, by 1914, were largely (85%) under the umbrella of AT&T; long-lines services were then provided almost entirely by AT&T (Yordon, 1979).[†] Most customers paid flat rates, with businesses typically paying more, although some paid fees proportional to the number of calls or to other measures of use. Some competition existed in the private-line area, but economic and aesthetic considerations (unsightly poles) also favored monopolies; the Bell System, Western Union, and a few independents dominated this business, but it is now becoming increasingly competitive. Although terminal equipment is not characterized by strongly declining costs, it was effectively excluded from competition by the argument that such "foreign" attachments could jeopardize service quality. In 1968 the FCC Carterphone decision began to open this terminal market to competition

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*See FCC Doc. 18128. The FCC favored FDC methods for equity and fair competition reasons.

[†]Good access to long lines was one motivating factor for small firms to join AT&T.

too. Much recent history has been dominated by growing interest in competition and deregulation.

Telephone rate structure has traditionally recognized two broad classes of service, basic and non-basic. Basic refers only to local exchange services, and non-basic is everything else, including long-distance, private, data, and luxury user facilities. The philosophy has been to maximize contributions (revenues minus costs) from non-basic services so as to subsidize or "benefit" the high fixed costs of basic services. Basic service tariffs were then set to yield the necessary aggregate return on investment approved by the regulators. The actual degree of cross-subsidization or "benefitting" depends on controversial cost accounting methods. The FCC does not now favor this approach.

One key cost item is the local subscriber loop and the first switch. These are used for both local and long-distance calls; how should the costs be allocated between them? In theory one might wish to benefit the basic local exchange costs by drawing upon the non-basic long-distance users. Such a transfer of revenue occurs in fact in the form of separations payments from AT&T's Long Lines Department to all local telephone companies in proportion to a complex formula. In 1974 these payments were $3 billion; without them the rates for basic exchange service might have been ∿ 24% higher and the message-toll-service (MTS) and wide-area-telephone-service (WATS) might have been ∿ 29% lower (Yordon, 1979).

Regulator and phone company collaboration in distributing costs "equitably" has been disturbed in recent decades by a series of decisions which have introduced elements of competition into the equation. Two key areas of growing competition are private lines and user equipment. In 1950 the FCC licensed TV networks to establish microwave links to remote areas and subsequently granted similar permission to railroads, remote lumber camps, etc. In 1959 these temporary privileges were confirmed when the FCC decided to grant permission to most private groups if their private long lines were not shared; the local telephone companies prohibited connection of these lines to the local networks, however.

In 1966 the prohibitions against sharing were relaxed, and in 1969 the FCC approved Microwave Communications, Inc.'s (MCI's) request to

establish a shared (up to five corporate subscribers) long-lines service between Chicago, Saint Louis, and nine intermediate points. More importantly, the FCC also permitted MCI to connect these private lines with the local telephone networks, a decision upheld by the Supreme Court.* Although by 1975 such microwave lines had captured only ∿ 2% of the private line market, they impacted AT&T's long-lines revenues far more significantly because AT&T responded by lowering its rates for heavy users. Such rate-cutting appeared in the form of WATS and TELPAK in 1960. The latter service involved leases of 60 to 240 voice grade circuits at rates 51 to 85 percent below those existing at the time.

Protest by Motorola against the TELPAK rates resulted in a cost analysis of Bell's interstate services (The Seven-Way Cost Study). The FCC used FDC accounting methods to show that certain TELPAK rates were indeed discriminatory, although AT&T unsuccessfully argued that LRIC accounting was more appropriate and that the charge was false. AT&T charged in turn that the private carriers were "cream-skimming" by taking the profitable heavy routes and leaving the expensive routes to AT&T to service. In addition to the advantage of being able to skim the cream, the new competitors also have the advantage of employing the latest technology at low costs. These two advantages helped overcome disadvantages posed by AT&T's economies of scale.† The additional advantage of avoiding separations payments has since diminished as a result of a recent agreement that small private-line carriers will also participate in the separations process (Elec. News, April 16, 1979, p. 23).

The FCC has indicated that WATS and MTS should not be subject to competition, perhaps because of the implications to local exchanges of serious erosion of long-lines revenues. However, the Justice Department recently told the FCC that MTS and WATS should also lose their monopoly status and that protection of rural and residential customers was an inadequate motive (Elec. News, July 24, 1978, p. 61).# Thus the social benefits of competition, which stimulates innovation and efficiency, are balanced by reduced power to allocate costs in the previously perceived optimum fashion. Restricting the competition to the private-line market appears to be an attempt by the FCC to achieve both benefits.

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*See also the specialized common carrier decision (29 FCC 2nd 870) and Execunet.

†See FCC Doc. 20003; the economies are questioned.

#MCI, ITT, and SPC now offer limited MTS-like services.

The second area of competition opened with the court Hush-A-Phone decision in 1956 and the subsequent FCC Carterphone decision in 1968. These and subsequent rulings permit users to attach computers, facsimile machines, key telephone systems (KTS), private branch exchanges (PBX), etc. to the local network subject to FCC safety certification. Because the telephone monopoly had previously permitted charges for these non-basic services to contribute to basic exchange costs, competition in this "interconnect" market now places an additional burden on basic subscriber rates and the remaining non-basic charges. AT&T has claimed that if all services other than residential basic exchange were repriced to eliminate their contribution to access cost, the average residential exchange rate would have to be increased 79% -- this is apparently a worst-case situation. The FCC disagreed strongly with this assessment and suggested that local rates might even decline (FCC Docket 20003, Sept. 23, 1976, pp. 123-125).

Satellite technology alone has also been the focus of several specific rulings designed to control competition. In 1972 the FCC authorized U.S. common carriers to construct and operate domestic satellite telecommunications systems in the competitive free-enterprise mode; this "open-skies policy" has encouraged application of satellite technology to development of new private-line services. This opportunity excluded AT&T, which was at least temporarily prohibited from entering the private-line satellite market. AT&T subsequently leased space on Comsat's Comstar satellite and on other satellites, but intends to launch its own replacements to Comstar beginning in the early 1980's.

AT&T was similarly restricted under the terms of the 1956 consent decree from selling data processing services, a restriction that may be loosened under legislation or other means. One motive behind these restrictions of AT&T's entry into new technologies and markets has been the fear of AT&T's potential ability to cross-subsidize the new services and to extend its effective monopoly powers into new markets. Many of these issues are being more sharply focused in the current debates on the possible revision of the Communications Act of 1934. This somewhat obsolete legislation drafted in simpler days has guided in part the various rulings of the FCC and the courts, and its modernization could possibly clarify many of the present uncertainties besetting the industry.

The response of the Bell System to growing competition appears to be 1) restructuring of its internal organization into aggressively managed market divisions (business, residential, and long-lines) rather than remaining divided in terms of technical function, 2) seeking increased depreciation rates on certain equipment to reflect its technical obsolescence as well as its physical life, and 3) increased "unbundling" of rates and the growth of elaborate usage-sensitive pricing of all aspects of service. These steps, in combination with a variety of political, legal, and other means, are intended to preserve the basic financial and technical integrity of the system in the face of competitive threats encouraged in various court and FCC rulings and in the massive antitrust suits now underway.* It is also possible that one of the basic objectives of increased competition is being realized; there may be an increased sense of urgency to translate technical innovations into the marketplace for competitive purposes and for the benefit of the general public. Examples of such innovations include the Advanced Communications Service (ACS), proposed to provide data manipulation and communications services, the AT&T Dataspeed 40/4 terminal, capable of both communications and data processing, and the introduction of satellite technology.

8.3 INTRODUCTION OF NEW TECHNOLOGY

The opportunities and problems posed by new technology are perhaps best understood in terms of simple idealized situations. Assume there is some new technology that permits existing services to be provided more cheaply and that also offers new service opportunities for the same reason. A benign monopoly acting in the public interest would not retire any existing equipment prematurely unless it were cheaper to do so, all factors considered. Unless the new technology were so cost effective that it could win a marginal cost competition with the old technology, including premature retirement of old equipment, it would be introduced only in plant expansion, where it would presumably dominate until yet another economic technological improvement were made. The cost benefits of the improvement could be conferred upon existing users in the same proportions the previous benefits were distributed. The new users attracted to the new services would generally pay a tariff greater than the marginal costs of their utilization, but less than the maximum price

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*Over 40 separate suits.

they can afford. The particular price compromise would usually depend upon the perceived marginal utilities, costs, and social good associated with the expanded services.

The behavior of a regulated monopoly acting in its shareholders' interests is less clear. In theory regulation is intended to provide investors with a "fair" return on their investment, and therefore the investors should not be greatly impacted by managerial details; the behavior of a regulated monopoly should approximate that of a benign monopoly.

Some have claimed that management would seek to maximize the investment base, because profit formulas are often tied to total invest- ment. In this case a monopoly might choose to denigrate possible tech- nological improvements which could reduce plant investment; recognition of such new opportunities would imply that present plant may be over- valued and should be depreciated faster. A competitive environment can force earlier recognition of technological opportunities, and lead to an increased role for technological obsolescence in depreciation schedules.

Another school of thought is that the primary thing to avoid is a "service crisis" of the sort New York City experienced a few years ago. Additional plant was required at the very time deteriorating service quality angered customers who wanted punitively lower rates because they felt the telephone company had performed poorly. A good strategy for avoiding such crises is to steadily lower costs and rates while improving service, both by upgrading the quality of existing services and by intro- ducing new ones that fulfill needs and expand the revenue base sufficiently to compensate for contractions elsewhere. By thus introducing improvements a regulated monopoly can hope to stay ahead of uncertainty. It is debatable whether reliance upon "regulatory lag" is as effective an incentive for innovation as is competition. It may depend largely upon the degree to which the regulated monopoly is allowed to profit from its innovative activity. Innovation is a difficult activity for regulatory bodies to reward because of the complex technical issues involved, and the public character of regulatory decisions.

Competition increases the complexity of the problem. To the extent that telecommunications is a declining-cost industry, the dominant firms

can retain or even expand their dominance in a cost competition. The
complexity of cost accounting issues unfortunately makes prevention of
cross-subsidization very difficult, and simple steps, such as requiring
separate subsidiaries for separate operations, do not fully solve the
problem. At present the courts are the final arena in which the fair-
ness of competitive practices must be determined, but the legal process
can be very lengthy, expensive, and uncertain. One might hope that the
proposed revisions to the Communications Act of 1934 could clarify some
of these issues or could provide a speedier and more efficient process
for adjudication.

If one or more firms in a competitive market are partially or fully
regulated, then much depends on the regulators. If the regulators refuse
to recognize fully technological obsolescence in establishing depreciation
rules, or fail to define market sectors properly, then the competitive
marketplace will be distorted. For example, if a broad class of customers
is tariffed the same, but the costs of providing that service vary, then
there is a potential opportunity for "cream skimming" by a carrier which
serves only the high profit market sectors. By use of their market
entry, market exit, and tariff setting powers regulatory bodies can have
considerable control over the character of partially regulated competitive
markets; and independent judicial action can also have a significant
impact.

In such a partially regulated environment, what are the incentives
for introducing new technology? The incentive to the new competitors is
abundantly clear. They wish to drop prices sufficiently that their
market share is assured. If the dominant firm is not free to follow suit
due to regulation, and if the new firms' profits are unregulated, then
technological improvements directly improve their profit margins. If
their profits are also regulated, then their strategy with respect to new
technology should depend upon the particular tariff and accounting rules
imposed. The optimum technological strategy for a regulated dominant
firm competing against unregulated or partially regulated firms is
obscure because it is so sensitive to the present and anticipated rulings
of the regulators, the courts, and the Congress. In general, the dominant
firm would want to decrease "true" costs as rapidly as possible in the

competitive areas so as to contain market expansion by their competitors, and improved technology could be very helpful.

In summary, there are several regulatory climates which appear favorable to technological innovation. It is also interesting to identify factors which can inhibit innovation. One such factor can be non-recognition by regulatory bodies of the carriers' risks; they may not reward successful risk taking with higher allowed profits while they still may penalize unsuccessful ventures. Such a posture was taken when rates of return were negotiated with Comsat. The FCC claimed that satellites are no riskier than terrestrial phone service and that the same rates of return were equitable for both terrestrial and satellite services. If failures are punished but risks are not rewarded, then risks and any associated new technology tend to be inhibited.

Another inhibiting factor can arise if the market and/or regulatory climate are unsettled. For example, if AT&T were to be unfettered, competitors could be more reluctant to enter the affected markets. The net effect of all such regulatory, legislative, or judicial uncertainties is to increase the risks and to raise the effective discount rate used by companies to compute the present worth of anticipated future cash flows resulting from any proposed investment. Thus uncertainty depresses sound long-term investments by focusing attention on short-term gains.

Another powerful depressant to risk-taking and innovation can be bureaucratic decision making -- a situation where the personal careers of the decision makers are motivators, and where again the penalties for failure can significantly exceed the rewards for success. Heavily regulated environments are often suspected of this lethargic form of behavior, and the present trend toward deregulation is driven in part in response to such perceptions.

Innovation can be encouraged by lowering its costs or by increasing its rewards. The costs and risks can be lowered, for example, by government pursuit of relevant technological developments. The development of packet communications by the Department of Defense and NASA's satellite communications program are examples of such assistance. The proposed revisions to the Communications Act of 1934 also offer the opportunity to reduce the uncertainties in the marketplace by resolving

some of the uncertainties as to what is acceptable behavior and/or by
providing improved mechanisms for doing so in the future; for example,
the FCC could be given an enlarged role in regulating competitive be-
havior in preference to the courts, which have introduced delays and
uncertainties in adjudicating certain antitrust and other cases.

In addition to risk reduction there are opportunities to increase
rewards by deregulating certain market sectors. This is perhaps one of
the most uncertain areas of current regulatory interest, for it is pos-
sible that some forms of deregulation could have undesirable results.
For example, an abused public could react with unpredictable effects if
service were degraded or if some prices became unreasonable. Certain
innovations could also be inhibited if they require a long-range mono-
lithic approach to development. The Bell System has been the principal
architect of our national telephone plant, and long-range planning has
been an important factor in its success. In a competitive environment
the role of architect may become somewhat fractured with unknown effects.
For example, establishment of an efficient integrated satellite communica-
tions system could become more elusive unless means can be found to
combine deregulation with effective joint planning of such large
national facilities.

8.4 POLICY OPTIONS; STIMULATION OF SATELLITE TECHNOLOGY

Four major markets are impacted by the satellites of interest here:
dedicated long-lines, long-lines network switching, broadband local
exchange services, and the broadband interconnect market. With the use
of local multiplexing, the local narrowband data and voice markets could
also be impacted for large users if they piggy-back on low broadband
tariffs made possible in part by satellites. The incentives for the
industry to develop and use advanced satellite technology for these
markets will depend to a great extent upon the regulatory and competitive
environment, as discussed in the previous section. Here we have attempted
to identify some of the major policy options and to estimate crudely
their possible impact on the marketplace and on incentives for develop-
ment. The discussion is intended to be suggestive more than definitive.

We may characterize the range of policy options in terms of the degree of competition permitted and the degree of government control imposed. Neglecting for the moment competition in the interconnect market, we may divide network competition into four broad categories of possibilities: 1) no competition, 2) competition in private-line networks decoupled from the public long-distance network, 3) the same, but fully coupled with the public network, and 4) full competition, including MTS and WATS available to the general public. Four degrees of government control include: 1) prohibition of undesired linkages, 2) government taxation of undesired linkages, 3) carrier tariffs which inhibit undesired linkages, and 4) no restrictions. The resulting 16 policy options and some representative possible outcomes are summarized in Table 8-1.

In the first case, where there is no significant competition, the non-basic services benefitted the basic services via differential tariffs, separations payments, and other intra- and inter-corporate transfers of funds. Although the government could have used taxation and subsidies to accomplish the same thing, it elected to use its regulatory powers to stop competition instead.

In the case of private line competition without restrictions on the non-dominant carriers, the loss of potential benefits to basic services is relatively small because the maximum market without network connection privileges is small, and because without economies of scale the small carrier cannot realize the full potential of cream skimming. In the case of MCI it initially received permission only for very specific routes, and thus market share could be controlled by that mechanism. Imposing requirements on MCI for separations payments and permitting AT&T to reduce tariffs to some lower threshold could enable further control of MCI's market share.

By broadening the scope of competition to include private lines with arbitrary local connections via the public network (the current situation), the potential impact on long-lines benefits increases to moderate levels, but extension of the separations concept to all long-haul carriers minimizes this effect, albeit with a competition-reduced revenue base (presumably). Additional benefits can be extracted via special access charges for network interconnections, and by government intervention.

Table 8-1. Illustrative Policy Options for Preserving Basic Service Subsidies for Voice.

CONTROL OF NON-DOMINANT CARRIERS \ COMPETITION	None	Private Lines	Private Lines; Guaranteed Local Network Access	All Long Lines; Guaranteed Network Access
None	X	Some reduction in benefits to basic services.	Significant reduction in benefits to basic services.	Loss of benefits. Possible financial loss to AT&T, etc. depending on regulation of AT&T. Significant unpredictable government presence.
Financial (tariffs, private transfers)	Long-lines separations payments benefit local exchanges (pre-MCI situation).	Dominant company market share partially controllable by tariff policy. Separations reduced; can include all long-lines carriers (early post-MCI situation).	Separation payments, network access charges. Market shares are controllable. Moderate reduction in benefits (present MCI, SPC situation).	Separations payments. Back-up fees? Difficult to allow multiplexing and also obtain low broadband tariffs. Significant government presence.
Financial (government taxes)	Local exchanges, etc. benefitted by subsidies. Selective taxes; may fund subsidies. Benefits are controllable.	same as: ⟵	same as: ⟵	same as: ⟵ Multiplexing and back-up taxes. Possible subsidy of long lines, local exchanges, etc. Significant government presence.
Government prohibitions, entry controls	X	Market shares controlled by route allocations, other entry controls.	same as: ⟵	same as: ⟵ Significant government presence.

At this level of competition there is some small incentive for competitors to develop novel services and protocols, which may introduce some compatibility problems.

The final competitive alternative has not yet been tested, and it is the most combative of all for it directly affects all of long-lines services. In this case small carriers would be permitted to establish long lines, and provide local access to the general public at either end using either lines they provide or the local network, as they choose. Thus the Bell System WATS and MTS services would face direct competition. As noted earlier, it is unlikely an unfettered AT&T could not dominate such a market, but there is little public sentiment evident to the effect that it should be unfettered, and the courts must rule on the antitrust implications of such a situation.

Several serious issues must be addressed in this situation, including 1) how to preserve economic efficiency despite the great legal and political uncertainties wide-open competition would introduce into such a large vital newly deregulated industry, 2) allocation of financial losses arising from accelerated depreciation of competitively displaced plant; should cross-subsidies be used or should the stockholders pay? (unfortunately much telephone plant has historically been depreciated at rates appropriate to physical rather than technological life), 3) who becomes the system architect? AT&T has designed a system with full interconnectivity and compatibility between equipment and services introduced over a wide span of years; in a fully competitive environment the role of the FCC in protocol definition, ensuring efficient interconnectivity, and providing for efficient reliable evolution, could become vastly important -- are they or any government organization equipped to handle the difficult tasks in a timely and correct manner? and 4) to what extent can and should basic services continue to be benefitted?

The first issue listed above concerns distortions in decision making which increase when the regulatory, legislative, and judicial environment becomes more unpredictable. In particular, investment incentives can be reduced because uncertainty causes the future to be discounted more, thus reducing the present value of expected future cash flows and the estimated return on investment for proposed capital improvements. Short-range

programs are then preferred over superior long-range developments. The powerful economic incentives afforded by switched satellites would probably survive such hurdles, but the pressures for inferior short-range approaches could be significant.

The second issue may diminish if revised depreciation policies can correct some present errors before competition makes further corrections painful. Consider the extreme case where satellites can economically replace enough terrestrial plant that, on certain routes, it becomes inadequate to serve the nation in time of war if all satellites were destroyed. To insure against this possibility some form of tax on satellites might preserve the terrestrial option, or, more efficiently, DoD might purchase terrestrial long-lines back-up capacity adequate to maintain essential but uneconomic routes until needed in wartime. Fortunately the number of such routes that are both essential and economically vulnerable may be very limited or even non-existent due to the network economic issues discussed here in Section 3.2.2. The same sort of subsidy for uncompetitive lines might be obtained by charging successful competitors "back-up" fees. The concept arises from the notion that a large customer dependent upon a single small-carrier microwave link or other interruptible element might transfer all of its traffic to the terrestrial network if that element failed, thus degrading everyone's service unless spare plant were already available; back-up fees could help support such emergency capacity.

The present concern about the interconnectivity of private lines with the public network would persist in this case where a portion of the switching function is performed competitively in space. Suppose Company X purchases SBS's service and installs a wide range of broadband terminals for intra-corporate communications. It would obviously be in the public interest for those terminals to be able to communicate effectively with those of Company Y even if Y were a customer of Xten, AT&T, etc. The link might be made via several alternative routes such as: 1) SBS to satellite to Xten, 2) SBS to SBS-satellite to Xten-satellite to Xten, 3) SBS to SBS-satellite to SBS-ground to AT&T Long Lines to Xten-ground to Xten-satellite to Xten, etc. In terms of cost and performance, the first or second options are preferable, but they would require compatibility between the systems.

Obviously such interconnectivity must be planned before satellite designs are frozen, and the penalty for omitting interconnectivity would be higher costs and/or reduced performance. Although interconnectivity was not a design consideration in the early unswitched satellites, it should be a major concern in the next generation if the full service-promotion benefits of competition are to be achieved; without it competition could be counter-productive.

Broadband switched satellites do introduce one additional complication that is less important in the present narrowband long-lines competition, and this is the low cost of very broadband channels. If video conferencing and very high-speed facsimile are to be widely accepted, then the costs for channels of 1.5-6 Mbps must be made quite low; presumably less than $\sim$ $1 per minute. But a 3-Mbps channel could be multiplexed to carry 100 30-kbps voice streams, and with 1985 electronics such multiplexing could be very inexpensive. This should have little impact if competition is restricted to private lines, because even total loss of basic-service benefits from that service would not be much different from present circumstances. In the case of open competition for WATS and MTS, however, small carriers might multiplex local long-distance voice traffic and send it cheaply on AT&T's or someone else's long lines. In terms of satellite economics this is quite acceptable, but in terms of network economics it poses a problem beause this traffic would otherwise flow at higher tariffs that would cover depreciation charges for the present network.

The estimates in this report suggest that costs per minute for a 3-Mbps link could indeed be below $1.00 (see Table 7-1), and that the problem is real. Industry behavior could take many forms. For example, AT&T could 1) depreciate their long-lines plant as rapidly as possible, 2) invest in large broadband satellites to carry voice and a growing list of broadband services, including video, and 3) compensate for reduced investment in terrestrial long-lines by increased investment and earnings from local distribution and other services. By aggressively capturing the low-cost market, competition could be foreclosed; even though AT&T's revenues might shrink, this scenario is favorable to broadband services. Alternatively, AT&T could seek to 1) block deregulation of MTS and WATS,

2) oppose and/or underprice large satellite ventures of its competitors,
3) generally seek to raise the risks and uncertainties faced by the
competitors so that they are pressured into smaller, less-efficient
short-term investment options, and 4) generally not seek to provide
low-cost broadband links in the absence of protection against rate-
breaking multiplexing by competitors. In this scenario the prospects
for video services are bleak. At present AT&T appears to be pursuing
some combination of these strategies. AT&T's competitors could also
pursue a variety of strategies. For example, they might 1) seek
deregulation of WATS, MTS, etc. and expansion of their network access
privileges so as to expand their opportunities for multiplexing, cream
skimming, and sales of new services, and 2) seek to establish the
largest satellites and other systems possible consistent with the risks
involved.

Because of these possible developments, the prognosis for broadband
services is uncertain. However, almost regardless of the competitive
situation, it is still possible for regulators or Congress to endorse
different tariffs (per Hz) for broadband and narrowband services and
thus encourage video and other broadband offerings. A similar problem
exists today with telegraph circuits which carry perhaps 300 bps, whereas
a multiplexed voice-grade circuit could carry 30 such lines. Despite
this possibility, the tariffs are now approximately the same per minute
for both services. By extension, a video circuit might have a comparable
tariff per minute, so that tariffs might best be characterized as cost-
per-circuit-minute, nearly independent of bandwidth. Such a result can
be obtained only by regulation, as has been the case for telegraph.

Because telegraph is a small specialized service, there are no great
enforcement problems in prohibiting the public from such multiplexing.
An example is the controversy surrounding Consortium Communications
International's (CCI's) multiplexing of its Telex and TWX traffic on
AT&T's broadband circuits. CCI provides up to 60 percent savings for
their customers. If telegraph were as widespread and popular as voice,
the enforcement problem could be more severe. However, since the private
line market is characterized by large firms who would not wish to
jeopardize their communications privileges, and the same is true of
non-dominant carriers, the enforcement problem should be quite tractable.

Thus, although the initial introduction of competition into the regulated marketplace may enable a certain degree of government withdrawal, should that deregulation eventually include all long-distance services, the resulting controversies concerning system architecture and performance, the financial health of AT&T, antitrust issues, protection of broadband and other classes of service, etc. could all produce the contrary and counterintuitive result that an increase in effective government presence might be required to ensure stability and service improvement.

8.5 OWNERSHIP AND USE OF SATELLITES

The ownership and use of satellites for general telecommunications will follow directly from decisions concerning deregulation and the introduction of competition into the industry. In the event that only private lines are competitive, then the market might be divided as follows. ITT (1979) and Western Union (1979) projected that private-line services might comprise $\sim$ 20 and $\sim$ 38 percent of total voice, respectively, in the 1990-2000 time period. If 30 percent of all satellite traffic were private line, and if total satellite traffic were $\sim$ 10-100 Gbps, as projected in Section 7.5.3, then domestic private-line satellite traffic would be $\sim$ 3-30 Gbps, of which perhaps 1-10 Gbps would be non-AT&T. AT&T would handle perhaps 2-20 Gbps of private-line traffic plus 7-70 Gbps in other categories, or a total of 9-90 Gbps (author's guess).

The satellites serving this market could be organized as one jointly owned system, two systems, or a multiplicity of systems, one per competitor.* A single system might comprise 4-8 satellites in orbit, each of $\sim$ 3-12 Gbps capacity; a second satellite system which amalgamated AT&T's small competitors might comprise $\sim$ 3-5 spacecraft of $\sim$ 0.4-3 Gbps capacity each; and each small competitor acting alone might alternatively have a system of $\sim$ 2-4 spacecraft of $\sim$ 0.15-1 Gbps capacity each, if there were three small firms dividing the nominal 1-10 Gbps non-AT&T private-line satellite market. If all long-distance services were competitive, then non-AT&T firms might capture as much as 30 percent of the total 10-100 Gbps satellite market, or 3-30 Gbps. A non-AT&T system might comprise 3-6 satellites of $\sim$ 0.5-6 Gbps each, and three equal competitors might alternatively each own $\sim$ 3-5 spacecraft of $\sim$ 0.3-3 Gbps capacity.

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*This discussion is restricted to large switched satellites for general telecommunications, not for services like direct broadcasting, etc. Consideration should also be given to resale and shared use options (FCC Doc. 20097).

These system sizes can then be evaluated in terms of an analysis such as that in Table 7-4, where for certain assumptions it was argued that a satellite system with only 10 percent of the market at any break-point distance would carry perhaps 7.5 Gbps profitably, and by extension a system with 3.3 percent of the market could be uneconomic compared to land lines. In the presence of such economics and in the absence of additional subsidies, it appears that there would be strong economic incentive for the small competitors to amalgamate their satellite systems so that the competition with AT&T would have some semblance of viability. Alternatively, the small firms might employ only land lines, but then the opportunities for such competition to enhance service development would be greatly restricted. Service development would probably be easiest in the intra-corporate broadband private-line market made practical only by satellites.

The ownership of a group of satellites by the small competitors could be by means of a consortium such as Intelsat, with ownership in proportion to use, or perhaps by means of a single protocol-establishing body plus inter-connectable satellites each launched and owned by the separate carriers, similar to the multi-satellite architecture of the baseline system. Similar options of ownership and control could be employed if AT&T and the small carriers shared the same set of satellites and confined their competition to the ground stations, local interconnections, and user services.

In the event that AT&T's competitors do sponsor a single system, or if all carriers cooperate together, including AT&T, it would be necessary for those firms to conduct protracted negotiations and obtain government approval. Because of the continual antitrust litigation in the industry, such negotiations concerning collaboration involve legal risks; even technical discussions involving details like protocols must be conducted cautiously. Fortunately there is a rather well established legal doctrine which may protect such discussions; this is the "Noerr-Pennington" defense to the Sherman Act.

In Eastern Railroad President's Conference v. Noerr Motor Fright, Inc (365 U.S. 127, 5 L. Ed. 2d 464 (1961)) a group of trucking companies sued under §4 of the Clayton Act alleging that a group of railroads

conspired to monopolize long-distance freight in violation of §§1 and 2
of the Sherman Act; the railroads had cooperated in a publicity campaign,
detrimental to the plaintiffs, which was intended to promote passage of
legislation favorable to the railroads. The Supreme Court held that the
railroads were protected under the First Amendment, even though their
purpose was to eliminate competition by the plaintiffs and even though
the plaintiffs were injured by the adverse publicity used in the campaign:

"[T]he Sherman Act does not prohibit two or more persons from
associating together in an attempt to persuade the legislature or the
executive to take particular action with respect to a law that would
produce a restraint or monopoly." (81 S.Ct. at 529).

Two exceptions to the Noerr-Pennington defense are of note. In
Cantor v. Detroit Edison Co., 96 S.Ct. 3110 (1976), it was alleged that
Edison injured a drugstore owner by distributing free light bulbs
pursuant to a tariff filed with the state regulatory authority. It was
held that Edison could not rely on Noerr because Noerr did not involve
any question of liability or exemption for private action taken in
compliance with state law (96 S.Ct. 3122). In California Motor Transport
Co. v. Trucking Unlimited, 404 U.S. 508, 3 L. Ed. 2d 642, 92 S.Ct. 609
(1972), it was held that the Noerr principle did not protect a "sham" use
of the First Amendment to harass and deter individuals from their free
access to agencies and courts. A number of similar cases have defined
further the "sham" use of the First Amendment to bring forward improper
(false) or frivolous information or suits so as to harass or injure
competitors.

The error of Edison was similar to the error involved in the forma-
tion of SBS; judicial review of FCC's approvals prompted re-examination
by the FCC of some of the antitrust issues. This risk could be reduced
if a group using the Noerr-Pennington defense successfully petitioned
Congress for approval of their plans instead.

Thus there appears to be at least one legal approach to corporate
cooperation in defining and seeking government authorization for jointly
managed or owned facilities, even if those facilities would constitute a
monopoly.

8.6 SUMMARY AND CONCLUSIONS

The future development of large switched communications satellite systems will depend on legal and regulatory issues as much as upon technical and economic considerations. This is the result of the present monopolistic character of much of the industry, a situation which arose from the need to obtain rights-of-way, the declining-cost character of certain business elements, and other reasons. The resulting collaboration between telephone companies and regulatory agencies has produced an effective integrated national system with tariffs that have tended to cross-subsidize local exchange costs at the expense of long-distance and other services.

This moderately comfortable relationship is now becoming more volatile with the development of new low-cost technologies such as satellites and integrated circuits, and with the growing introduction of competition, initially in the interconnect and private-line markets. The prospective modernization of the Communications Act of 1934 and the current major antitrust cases involving AT&T are also sources of uncertainty and potential change.

In this newly competitive world the pressures for aggressive adoption of new technologies are as great as ever; the principal negative factor is that the current uncertainties encourage firms to discount the future more and to prefer smaller, more short-term investments instead of pursuing more cost-effective and better performing options which require more long-range planning and delayed returns on investment. Governmental reduction of some of these uncertainties could be to everyone's benefit. Satellites are now being aggressively developed, but the schedule for introduction of more effective switched satellites is presently uncertain.

Some of the critical policy issues which will impact establishment of large switched broadband satellite networks include 1) what will be the scope of competition -- for example, will it extend to all long-distance services and mandate full network interconnection privileges, or will it be constrained to private-line or other services? 2) to what extent will government policies reduce the level of uncertainty so as to encourage desirable long-range planning and investment? 3) what

institutional mechanism will replace AT&T as system architect -- and what are the risks? and 4) what mechanisms (if any) will establish tariffs in the public interest such as appropriately low tariffs for broadband services?

The ownership and use of large switched satellites will probably be dominated by AT&T and a few competititors such as SBS, Xerox, RCA, etc. The market projections in Chapter 2 plus reasonable estimates of market shares suggest that if all carriers collaborate, they might employ a satellite capacity of $\sim$ 10-100 Gbps divided among $\sim$ 4-8 cooperating satellites $\sim$ 2-12 Gbps capacity each. AT&T alone might employ a comparable system. If the smaller firms claim $\sim$ 30 percent of the total market, and share a single satellite cluster, it might comprise $\sim$ 3-6 satellites of $\sim$ 0.5-6 Gbps capacity each. If competition were restricted to private-line services, then perhaps $\sim$ 3-5 spacecraft of $\sim$ 0.4-3 Gbps could serve such a consortium. If three small firms divided the non-AT&T private-line market, each might own $\sim$ 2-4 satellites of $\sim$ 0.15-1 Gbps capacity each. Thus the total range of possibilities is spanned by satellite capacities of 0.15-12 Gbps each.

The principal incentive for AT&T's competitors to form a consortium is the resultant economies of scale and improved planning, and the incentive for all firms to join a single consortium is the improved interconnectivity and systems planning which could result; this need not be at the expense of service diversity because various subgroups of satellites could focus on particular objectives and yet provide full and efficient interconnections. The joint corporate proposal of such systems for government approval appears to be protected from antitrust action by virtue of the First Amendment, as articulated in the "Noerr-Pennington" doctrine.

The shape of the satellite communications industry will become increasingly well defined and firm over the next decade, and the quality and economy of the resulting system will very much depend upon the government policies being formulated now.

Chapter 8 References

1. ITT U.S. Telephone and Telegraph Corp., 30/20 GHz fixed communications systems service demand assessment, NASA Rept. No. NASA-CR159620, August 1979.

2. Kahn, A. E., The Economics of Regulation, Vol. 1, John Wiley and Sons, Inc., New York, 1971.

3. Mandanis, G. P. et al., Domestic communications and public policy (Systems Applications Inc., 1973) as reported in J. H. Alleman, The pricing of local telephone service, p. 114, U.S. Dept. of Commerce, Office of Telecommunications, Wash., D.C., April 1977.

4. Office of Telecommunications Policy, Executive Office of the President, Competition in Telecommunications - The Telephone Industry Bill, Wash., D.C., June 1976, p. 17.

5. Western Union Telegraph Co., 18/30 GHz fixed communications systems service demand assessment, NASA Contractor Rept. No. NASA-CR159547, July 1979.

6. Yordon, W. J., Telephone rate structure: theory and issues, in Telecommunications: An Interdisciplinary Survey, L. Lewin, Ed., Artech House, Inc., 1979 [Library of Congress 78-26665].

CHAPTER 9

TECHNOLOGY DEVELOPMENT: NASA PROGRAM OPTIONS

9.1 NASA PROGRAM OBJECTIVES

The NASA satellite communications program, begun in 1959, contributed a number of historically important technical developments and, more recently, has also demonstrated the usefulness of a variety of direct-to-user services, particularly in the public service area. The central thrust of the program has always been toward increasingly efficient and effective use of the radio spectrum.

The early enthusiasm for this program diminished in 1972 when budgetary pressures were combined with the perception that the private sector would support satellite technology development at levels appropriate to the promise of the technology. In subsequent years this perception has been questioned; evidently high-risk long-term technology development has not been vigorously pursued, perhaps because such risks were believed to be too great in view of market uncertainties and the volatile regulatory environment. Recent studies by the National Research Council, the IEEE, the AIAA, the Electronic Industries Association, and others have all urged revitalization of this NASA program, and such action has now been approved. The U.S. Civil Space Policy has now specifically asserted that the role of the Federal Government in satellite communications shall be carried out by NASA "toward the efficient and effective use of the spectrum and orbit". An overview of the NASA program has been presented by Dement (1979).

The National Research Council Committee, chaired by Wilbur B. Davenport (1977) specifically recommended that NASA implement an experimental satellite communications technology flight program subject to certain safeguards. They emphasized that it should be characterized by comprehensiveness, orderliness, accountability, and continuity, and that a wide range of private and governmental organizations, including users, be involved in the various phases of the program, including conceptualization. One initial formal mechanism for such interaction is the NASA Advisory Council serving communications, which has five carrier representatives and five technology managers.

At present the NASA program most relevant to wideband communications is the 20/30 GHz satellite communications technology program, for which this report was prepared. Although any satellite experiment will most likely employ the 20/30 GHz allocations, the program is conceived as also being relevant to bands at lower frequencies. It is the belief of these writers that first priority of such an effort should be technology development and demonstration, and that this view is widely shared. A lower priority should be attached to user familiarization experiments and similar activities which can be performed by the private sector with lower risks and better continuity with subsequent operational phases.

9.2 CRITICAL TECHNOLOGIES

The present study, by exploring further the architectural tradeoff issues in large switched communications satellites, permits refinement of previously prepared lists of research priorities. One such priority list has been presented by Durham and Stankiewicz (1979) based upon extensive interviews with government and industry people in the satellite communications field; it is repeated below:

1. System analysis and synthesis
2. Multibeam antennas
3. Communications processors
4. Low cost user terminals
5. Component technology
6. Propagation.

The present study, itself a priority-1 activity, supports this rank ordering, but permits elaboration.

The study suggests that one important class of system is a large multi-satellite fully-switched system operating as a coordinated entity in a single orbital slot and having a total capacity of ~10-60 Gbps carried by satellites of the ~1-12 Gbps class. Nominal system characteristics for the 1995 period might be:

1. Multiple FDMA TDMA bands, each at 256 Mbps; space-qualified burst modems are a critical element;
2. 285-beam antenna employing switched feeds or segmented electrically scanned arrays;

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3. 20-GHz satellite transmitters of ∿4-7 watts; solid-state and/or TWT (or ∿0.5 watt units plus phase-shifters for scanned arrays);

4. 30-GHz ground-station transmitters of ∿7 watts; great linearity may not be required.

5. Ground-station antennas of ∿16-ft diameter.

6. Fast 256-Mbps 8x8 to ∿128x128 digital switches for space.

7. Diversity protection to 99.99% reliability by means of terrestrial links ∿10-60 miles long between the ∿1800 ground stations typically located near toll centers or other local nodes.

If some carriers wish to maintain their own separate systems, despite the economic penalties of such a configuration, then such separate systems might be characterized by small clusters of satellites of ∿0.15-1 Gbps capacity. Althouth this option was not specifically analyzed, it would appear that 1) transmitter and ground antenna specifications might remain comparable, 2) the data rates might drop to ∿32-128 Mbps, and 3) the number of antenna beams might be ∿100; thus the number of transponders per satellite would remain a reasonable ∿6-8, and link margins would be preserved.

The range of desirable technical specifications appears to be sufficiently narrow that developing and proof-testing the elements of such a system would be useful to most switched satellite networks. One nominal 20/30 GHz NASA experimental payload (Wright, 1979) envisions testing a system with two transponders plus a spare, an 8x8 baseband switch, and a portion of a large multi-beam antenna. Such an experiment should be adequate to demonstrate most of the critical new technologies, and such a candidate experiment is defined and costed in the next section.

Communications processors, item 3 on the priority list, deserve further comment. The present study makes clear that the cost of bandwidth is relatively small by today's standards until it exceeds a few megabits per second, at which point total system costs become more nearly proportional to data rate. The analysis suggests that inter-frame video bandwidth compression to ∿1-6 Mbps will therefore be an important part of any large video network, and that the selection of a standard compression protocol could have significant consequences. Unfortunately, however, protocols with commercial significance are not always freely placed in the public domain; the algorithm employed in the commercially available NEC video inter-frame compression device is an example of this. If high-performance protocols are to be

developed and achieve easy acceptance as standards in a timely manner, then such technology should be an important part of the total program. For example, NASA might focus on the technology of algorithm compatibility-- compatibility between various present algorithms and between present and potential future improvements. Similar importance can be attached to broad-band error-correction circuits, cryptographic systems, TDMA buffering and packet technology; the fact that very broadband signals are involved here partially distinguishes these technical problems from those now being addressed at much more modest data rates.

9.3 CANDIDATE 20/30 GHz SATELLITE EXPERIMENTS

One possible benchmark experiment which would exercise most of the relevant technology is the following (Table 9-1); it is generally consistent with the nominal configuration described by Wright (1979). The purpose of the benchmark experiment definition is to provide a baseline cost estimate for a program which explores most relevant technologies for commercially relevant parameters; the detailed cost estimates permit the budgetary impact of reducing the number of feeds, limiting the number of ground stations, or other simple modifications to be assessed.

Table 9-1. Benchmark 20/30 GHz Communications Flight Experiment.

1. **Space Segment:**
    1 flight and 1 back-up satellite.
    1 20/30 GHz antenna reflector 3.4x6.7 meters, consistent with
      285 beams over the United States.
    80 switchable feeds, 70 on one polarization and 10 on the other,
      in a configuration resembling the baseline design, but par-
      tially filled; no more than one feed cluster would be complete.
    2 transponders at 256 Mbps and 2 at 12.8 Mbps, interchangeable.
      4-watt solid-state transmitters and 7-watt TWT's. TFM modulation.
    8x8 switch for 256-Mbps baseband logic signals.
    superheterodyne receivers, broadband.

2. **Ground Segment:**
    10 256+12.8 Mbps ground stations (5 mobile); 16-ft antennas,
      7W transmitters yield ∿13 dB up and 11 dB downlink rain margins
      (26, 24 dB at 12.8 Mbps).
    10 12.8 Mbps ground stations (5 mobile); 5-ft antennas, 4W
      transmitters yield ∿14 and 17 dB margins.
     5 diversity links 10-30 km long.
    10 local data links ≲ 4 km long.
    20 full-service experimental user facilities at NASA centers
      (video, facs, data), 2 per fixed station; facilities also
      use commercial circuits.

Using procedures similar to those described in Chapters 4 and 5 the weight and power requirements for the experimental satellite communications payload are estimated in Table 9-2, the spacecraft weight and power are estimated in Table 9-3, and the total program costs are estimated in Table 9-4. Since most of the program costs are technology development oriented, modest changes to the benchmark experiment specifications would have a relatively small impact on the budget.

Table 9-2. Benchmark Communications Experiment
Payload Weight and Power Estimate.

	Units	Unit Weight (lb)	Unit Power (W)	Total Weight (lb)	Total Power (W)
Receiver					
RF mixer	4	0.5	0	2	0
IF amplifier	4	1	0.5	4	2
IF mixer	4	0.2	0	1	0
LPF/amplifier	4	0.2	0.5	1	2
Demodulator	4	1	1	4	4
Total				12	8
Transmitter					
Modem	4	1	1	4	4
Driver	4	2	2	8	8
Final amplifier	4	2	20	8	80
Total				20	92
Local oscillators, clocks					
RF multiplier chain	2	6	1	12	2
IF multiplier chain	2	3	1	6	2
Total				18	4
Other					
Switch (8x8)	2	1	2	2	4
Miscellaneous, contingency				30	50
Total				32	54
TOTAL EXPERIMENT PAYLOAD				80 lb	160 Watts

Table 9-3. Benchmark Experimental Communications Satellite
Weight and Power Estimates.

SUBSYSTEM	Pounds	Cond. Watts	Buss Watts	Subtotals Pounds	Watts
Communications Electronics	80	160			
Attitude Control System	100		100		
Reaction Control System	100				
Spacecraft Computer	5	5			
Communications Computer	20	40			
Command, Telemetry	20	20			
Antenna Reflector (3.4x6.7m) and Structure	150				
Antenna Feeds, Diplexers (80)	10				
Ferrite Switch Matrix (100)	50		20	535	120
Conditioned Power			250		370
Thermal Control	30		8		378
Power Contingency			40		418
Power Distribution & Conditioning	25		42	590	460
Harness	30		23	620	483
Night Power			(400)		
Batteries	20		60	640	543
Beginning of Satellite Life					556
Solar Array, 20 lb/watt	30			670	
Spacecraft Body Structure	107			777	
Weight Contingency	78			855	
Attitude Control Propellant	136			991	556
TOTALS	991 lbs		556 Watts		

The total estimated budget is $275M in 1979 dollars, which is comparable to other NASA space flight programs and consistent with the budget levels discussed by the Davenport Committee in the 1977 National Research Council report (Davenport, 1977). Some of the largest items are the non-recurring costs associated with the satellites ($65M), and the ground stations and associated technology ($70M).

The experiment concept described by Wright (1979) involved testing both feed arrays and scanned beams. For smaller systems the segmented phased array concept developed by Bell Telephone Laboratories (Acampora et al., 1979) appears quite promising, but needs further development in order to be fully competitive with the switched feed configuration at 20/30 GHz. The difficulty involves fast broadband very low loss phase shifters; without them the number of active systems must apparently approximate the number of potential antenna beams, which becomes expensive for large systems. Addition of

Table 9.4. Budget Estimate: Benchmark
NASA Communications Satellite
Experiment.

Item	Number of Units	Unit Cost ($M'79)	Cost ($M'79)	Cost Sub-totals ($M'79)
1. Space Segment				
Recurring costs				
$\sim 2[\$31K(991\ 1b)^{0.93}] + \$30M$ launch	1	70	70	
Non-recurring costs*				
$\sim \$16K(991\ 1b)^{1.15} \times 1.5$(technology factor)	1	65	65	135
2. Ground Facilities				
256/12.8 Mbps ground stations	10	1	10	
12.8 Mbps ground stations	10	0.5	5	
Non-recurring costs, estimated	1	20	20	
Diversity broadband links 10-30 km	5	0.2	1	
Broadband user facilities (video, facsimile, data)	20	0.2	4	40
3. Other Program Costs				
Other ground station technology	1	30	30	
Other protocol technology	1	20	20	
Operations	3(yr)	10	30	
Supporting science, analyses (1981-1991)	10(yr)	2(avg)	20	100
TOTAL 10-YR PROGRAM COSTS			275	

*Assumes 1982 technology, $\sim$1986 launch

such a phased array experiment might add approximately 200 pounds to the communications payload, and perhaps 400 pounds to the spacecraft weight. This might add $14M to recurring costs and $34M to non-recurring costs, in terms of the DCA communications satellite cost algorithm.

Another potential subsystem to add to the experiment would be one designed to accept very large numbers of relatively narrowband signals which are nearly continuous, in time, and then to switch them among a large number of possible antenna beams. The difficulty with this otherwise attractive approach to reducing ground station costs is that there is no immediately evident way to continuously receive a large number of narrowband signals, separate them so they can be switched, and then reassemble them in different down-link beams, all with competitive economics. One critical technical problem is design of low-loss high-order frequency multiplexers which can buffer many beams simultaneously to one transponder. If such narrow signals are also demodulated and remodulated in the spacecraft, then the problem is compounded. If these problems could be solved in a practical way, then such a subsystem experiment could be an important addition.

To summarize, there are several varieties of large switched satellite experiments which are practical and could make very significant contributions to the understanding of these technologies, and to the more rapid and efficient introduction of them into the communications marketplace.

Chapter 9   References

1. Acampora, A. S., C. Dragonne, and D. O. Reudink, A satellite system
    with limited-scan spot beams, IEEE Trans. Comm., COM-27, 10,
    pp. 1406-1415, 1979.

2. Davenport, W., Federal research and development for satellite
    communications, Committee on Satellite Communications of the
    Space Applications Board, National Research Council. National
    Academy of Sciences, Washington, D.C., 1977.

3. Dement, D. K., An overview of the NASA satellite communications
    program, ICC'79 Conf. Rec., 1, June 1979 (79CH1435-7CSCB),
    p. 15.1.1.

4. Durham, A. F. and N. Stankiewicz, NASA communications technology
    research and development, ICC'79 Conf. Rec., 1, June 1979
    (79CH1435-7CSCB), p. 15.6.1.

5. Wright, D. L., 30/20 GHz wideband technology verification program,
    ICC'79 Conf. Rec., 1, June 1979 (79CH1435-7CSCB), pp. 15.3.1-
    15.3.2.

APPENDICES*

APPENDIX A3.1

SIGNAL CHARACTERISTICS

A3.1.1 INTRODUCTION

The selection of a modulation technique for a WIDENET system requires consideration of the bandwidth occupied by the signals, transmitter power of the terminal and spacecraft, end-to-end error rate, modulation waveform, interference between channels in the frequency, spatial, and polarization domains, and hardware implementation. All these factors place constraints on the system design and are discussed below.

High spectral and power efficiencies are desirable for a WIDENET system because of the limited spectrum available, the large data rate (up to $\sim$ 50 Gbps), and the transmitter power/antenna size constraints. Several techniques are available for close frequency packing of signals. The desired characteristics are constant envelope signals for convenient signal generation and amplification, close frequency packing with low crosstalk between users in adjacent channels, high modulation efficiency in the sense that the required energy-per-bit-to-noise-density ratio is low and, finally, relatively easy implementation of the transmitters and receivers. In general, these are conflicting characteristics and trade-offs must be made.

Section A3.1.2 gives the conclusions of this analysis. In Section A3.1.3.1 an estimate is made of the baseband E_b/N_0 (bit-energy-to-noise density ratio) and BER (bit error rate) required for a broadcast-quality color-video channel. The basic uplink and downlink parameters are shown. Section A3.1.3.2 summarizes the relationship between BER, E_b/N_0, and W/R (noise-bandwidth-to-bit-rate ratio). Section A3.1.3.3 briefly reviews current work in modulation waveforms that minimize the frequency spacing of adjacent channels. An estimate is given for the frequency spacing of two or more coherent, interfering signals as a function of modulation waveform. Section A3.1.3.4 gives an estimate of the interference between coherent signals in the same frequency band. These signals may be spatially separated on the ground by the satellite multi-beam antenna or

separated by the sense of polarization. A.3.1.3.5 considers the hardware implementation of a particular modulation waveform. A3.1.4 gives the mathematical details of the interference estimates and their relation with on-going waveform design work. Section A3.1.5 estimates the number of equal-power coherent channels that can be accommodated in an allocated band.

A3.1.2 CONCLUSIONS

(1) A DPCM bandwidth-compression coding system has been developed and experimentally verified for transmitting a 4 MHz NTSC color video signal with broadcast quality at a data rate of 32.064 Mb/s and a maximum BER of 10^{-7}. Interframe compression should permit acceptable reduction to a few megabits per second; the NEC unit presently being manufactured can probably be improved so that 30 GHz might accommodate up to $\sim$ 10,000 one-way video circuits.

(2) Use of a coherent QPSK (quadrature phase shift keying)-type modulation waveform appears to be a reasonable choice because of the high spectral efficiency compared to BPSK (binary phase shift keying) waveforms,and high power efficiency compared to higher-level MPSK (M-ary phase shift keying)-type waveforms. Use of coherent demodulation rather than differential demodulation appears to be possible because the ground terminals and satellite are stationary with respect to one another and interference reduction techniques such as precise frequency hopping are not required.

(3) A TFM (tamed frequency modulation) waveform (a type of QPSK) appears to give high spectral efficiency with about 1-dB penalty in E_b/N_0 relative to QPSK for a given BER. With DPCM signal encoding, 10% bit-rate overhead, and two polarizations, about 2.4 Gbps/GHz frequency allocation with less than 1-dB signal loss due to crosstalk interference from equal power users appears to be possible. In comparison, QPSK would allow about 1.2 Gbps/GHz with 1-dB crosstalk signal reduction.

(4) A TFM transmitter and receiver have been demonstrated. In view of the available block diagrams and the existence of breadboards for the transmitter and receiver, both TFM transmitters and receivers appear feasible for a WIDENET in the 1990 time frame.

(5) Antenna sidelobes of 30 dB are sufficient to limit the signal loss to 1 dB or less from co-channel crosstalk in adjacent beams.

(6) Polarization isolation of 20 dB is sufficient to limit the signal loss to 1 dB or less from polarization crosstalk.

A3.1.3 ANALYSIS

A3.1.3.1 CHANNEL LINK PARAMETERS

In recent years many redundancy reduction techniques have been investigated for video signals. Recently (Sawada and Kotera, 1978) an encoding system has been designed and built that encodes a luminance component and two chrominance components of a composite color video signal separately by DPCM. This system has been shown to give high quality and high coding efficiency compared to other redundancy reduction coding techniques. Experimental results suggest that this system is applicable for broadcast-quality color-video digital transmission at a 32.064 Mbps rate with a BER of 10^{-7} or lower. A field trial over a communication satellite link is planned.

If a 32.064 Mbps data rate per channel were required for a WIDENET video link, the required E_b/N_0 for a TFM waveform (see Section A3.1.3.3) and a BER of 10^{-7} is about 12.5 dB.[*] Therefore, the required P_R/N_0 per channel in a link calculation is about 87.6 dB Hz. Table A3.1-1 shows the downlink and uplink parameters for a 140 Mbps TDMA band. It is seen that the nominal downlink and uplink margins are 15.4 dB and 15.8 dB, respectively.

A3.1.3.2 BIT ERROR RATE, POWER EFFICIENCY AND BANDWIDTH EXPANSION

Figure A3.1-1 shows a schematic block diagram of a single 32-Mbps video channel. The channel encoder takes a baseband 32-Mbps bit stream (data symbol) and encodes the bits to select a channel waveform (channel

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[*] E_b/N_0 is related to the link signal-to-noise ratio (S/N) by $S/N = (E_b/N_0)(R/W)$; R is bits per sec (bps) and W is bandwidth (Hz). Coding would reduce the required E_b/N_0 while increasing the signal bandwidth, but this option appears counterproductive for TFM because of the great sensitivity of TFM BER to SNR.

Table A3.1-1. Space Link Performance.

LINK PARAMETERS	DOWNLINK (20 GHz)	UPLINK (30 GHz)
AVAILABLE SNR		
P_T (dBW)	10.0	10.0
G_T (dB; 2.4 m or 4×8) ($\eta_A = 60\%$, 65%)	59.3	55.7
EIRP (dBW)	69.3	65.7
L (dB)(synch orbit)	−211.0	−214.5
LINE LOSSES (dB)	−3.0	−3.0
NULL (dB)	(−3.0)	(−5.0)
G_R (dB; 2.4 m or 4×8) ($\eta_A = 65\%$, 50%)	52.2	62.0
N_o (dBW/Hz) ($T_s = 500°$, 800°K)	−201.6	−199.6
P_R/N_o (dB Hz)	109.4	109.8
AT NULL:	106.4	104.8
REQUIREMENTS		
R (dB Hz, 140 Mbps)	81.5	81.5
E_B/N_o (BER $= 10^{-7}$, TFM)	12.5	12.5
P_R/N_o (dB Hz)	94.0	94.0
MARGINS (dB Hz) − 1 BAND/AMP		
8-FT ANTENNA PEAK	15.4	15.8
NULL	12.4	10.8
12-FT ANTENNA PEAK	18.9	19.3
NULL	15.9	14.3
16-FT ANTENNA PEAK	21.4	21.8
NULL	18.4	16.8
MARGINS (dB Hz) − 2 BANDS/AMP		
8-FT ANTENNA PEAK	3.4	6.8
NULL	0.4	1.8
12-FT ANTENNA PEAK	6.9	10.3
NULL	3.9	5.3
16-FT ANTENNA PEAK	9.4	12.8
NULL	6.4	7.8
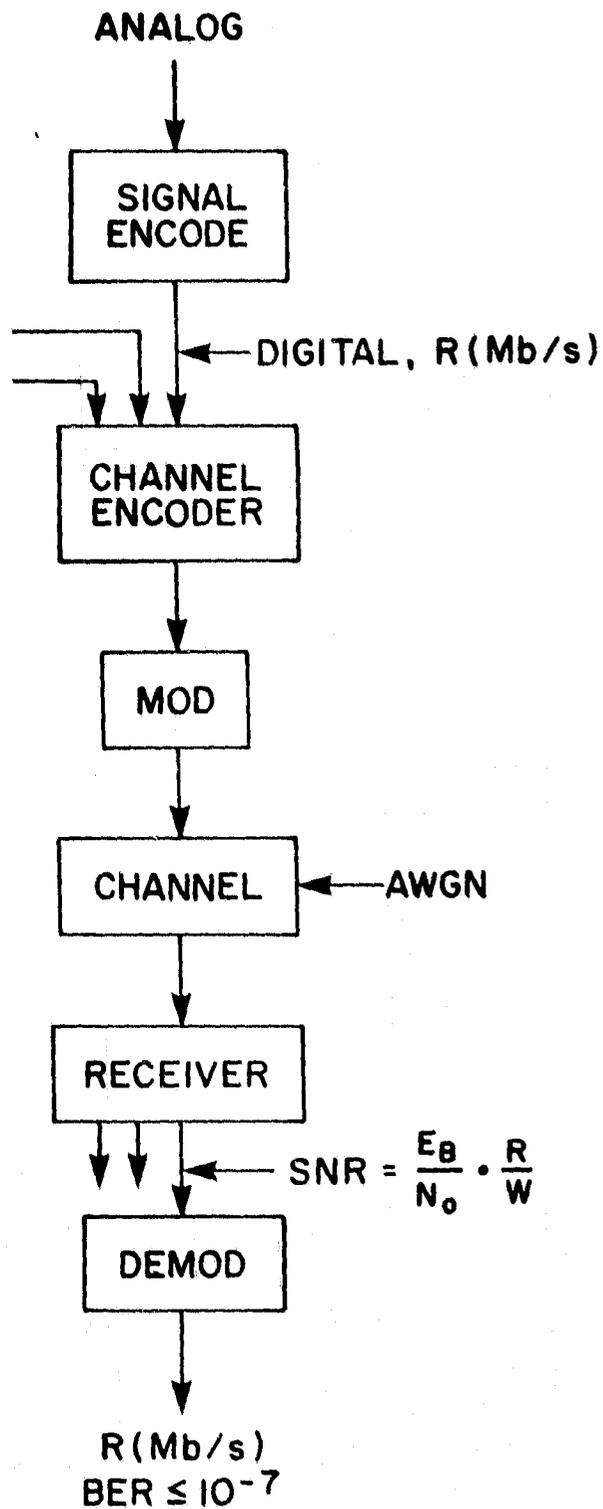
Figure A3.1-1.   Schematic block diagram for a single broadband digital channel, user-to-user.

symbol).[*] The channel symbols then modulate the carrier. Figures
A3.1-2 and A3.1-3 show the well-known relationships, referenced to the
data symbols, between the bit error rate BER, power efficiency E_b/N_0,
and bandwidth expansion ratio W/R.[**] In these figures M denotes the
level of modulation, e.g., M = 2 is BPSK, M = 4 is QPSK, etc. M'
denotes differential (encoded and decoded) PSK levels, e.g., M' = 2 is
DBPSK, etc. The noise bandwidth, W, corresponds roughly to the half-
power signal bandwidth.

Several observations can be made. Figure A3.1-2 shows that QPSK
modulation waveforms have a power efficiency comparable to BPSK (within
1 dB). MFSK with M > 4 suffers significant power penalties ($\sim$ 4 dB).
Figure A3.1-3 shows that QPSK waveforms have bandwidths $\sim$ 1/2 that of
BPSK. While higher level PSK waveforms have smaller bandwidths, the
bandwidth reduction over QPSK is decreasing slowly while the power
penalty grows rapidly. It should be noted that these results do not
permit estimating the interference between users in adjacent frequency
channels (crosstalk). The actual interference to an adjacent user is a
function of the receiver implementation, channel symbol synchronization
between the two bit streams and power ratios (see Section A3.1.3.3)..

It is concluded from these figures that for this application a
QPSK modulation waveform represents a reasonable choice for a power-
efficient and bandwidth-efficient modulation waveform. Section A3.1.3.3
discusses types of QPSK waveform. In addition, use of coherent modulation/
demodulation appears to be possible because the ground terminals and
satellite are stationary with respect to one another and interference
reductions techniques such as rapid frequency hopping are not required.

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[*]The nomenclature follows Lindsey and Simon (1973).

[**]The common practice is to give the error rate of the channel
symbols $P_E(E)$ versue E_b/N_0. It is believed that the bit-error proba-
bility $P_B(E)$ is more meaningful in this application. The two error rates
are related by $P_B(E)/P_E(E) = \frac{1}{2} M/(M - 1)$ for orthogonal block encoding
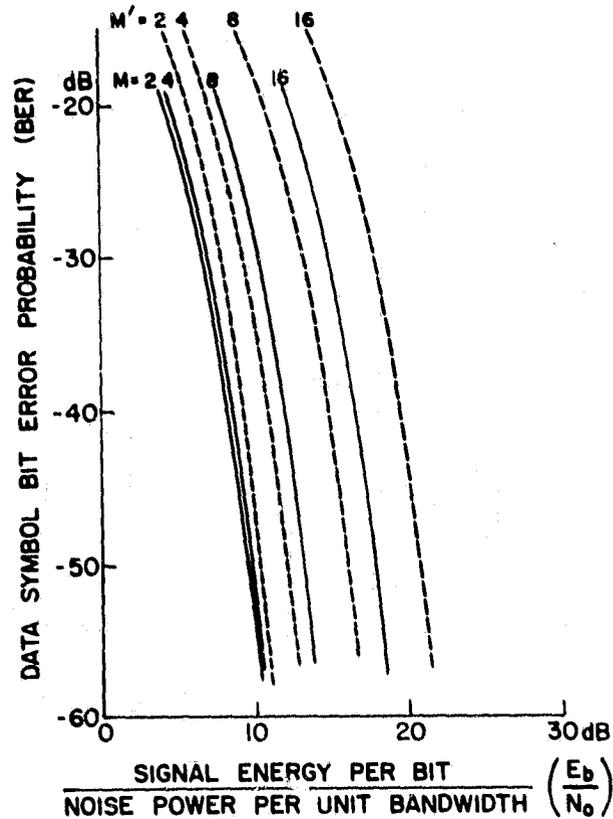and M-ary waveforms.

Figure A3.1-2. Bit-error rate as a function of signal-to-noise ratio for absolute M and differential M' phase encoding.
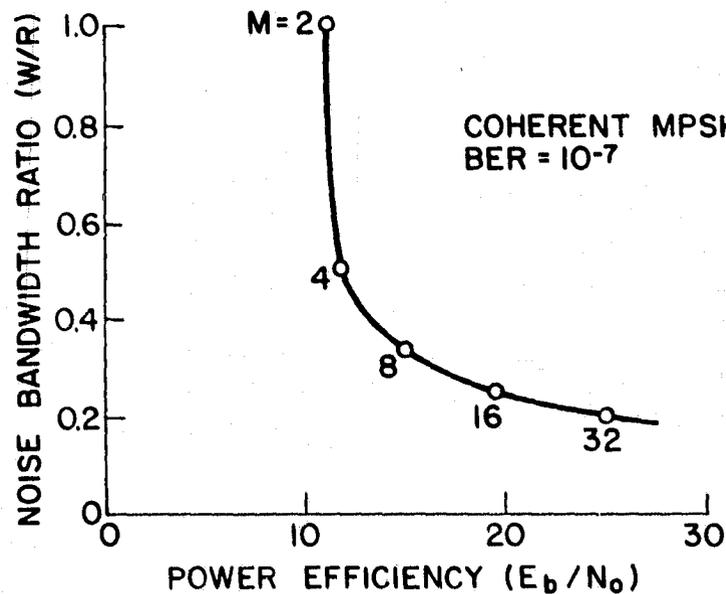

Figure A3.1-3. Equivalent noise-bandwidth ratio and power efficiency E_b/N_o as a function of M for coherent MPSK and a bit-error rate of 10^{-7}.

A3.1.3.3 ADJACENT CHANNEL INTERFERENCE, MODULATION WAVEFORM AND BAND-WIDTH EFFICIENCY

Modulation waveform design with high bandwidth and power efficiency is a presently active research area (Kalet and Weiner, 1977; Kalet, 1977; deJager and Dekker, 1978; Seay, 1978). Much of the work has focused on QPSK modulation for the reasons given previously. This section applies recent results to a WIDENET system.

Figure A3.1-4 (Kalet and Weiner, 1978) shows the predicted BER of a single channel due to the mean square crosstalk from an adjacent channel at the output of the integrators for a SFSK (sinusoidal frequency shift keying) modulation waveform (a QPSK waveform). The 0-dB curve indicates equal power channels, the 10-dB curve indicates the interfering channel signal is 10 dB larger, etc. These results were generated by a white noise analytic model (Appendix A3.1.4) that has been verified by computer simulation using differential demodulation. Recent hardware measurements have also confirmed this model. Figure A3.1-4 shows that there is a sharp threshold to the frequency spacing of two users. Below the threshold ($\Delta f/R \sim 0.9$ for equal power channels) the BER increases rapidly. This sharp threshold behavior suggests that estimates of the BER versus $\Delta f/R$ may give approximately the same threshold as computer or laboratory hardware simulations because of low sensitivity to modeling errors.

Two estimates of the signal degradation due to crosstalk at the output of a coherent demodulation receiver are derived in Appendix A3.1.4. Figure A3.1-5 shows the signal degradation due to equal power interfering users (assuming the interfering user signals are tone-like) versus the bandwidth spacing of one or more interfering channels as a function of several QPSK modulation waveforms. Comparison with Fig. A3.1-4 indicates that this estimate gives about the same threshold for SFSK. Figure A3.1-5 also shows that simple QPSK channels cannot be spaced closer than $\Delta f/R \stackrel{\sim}{=} 1.5$ without significant signal degradation loss (> 3 dB). Figure A3.1-6 shows the BER versus $\Delta f/R$ for the D/L and U/L channels of Table A3.1-1 with TFM using the white noise model. Both Figs. A3.1-5 and A3.1-6 show that if TFM waveforms are used, then the spacing can be reduced to $\Delta f/R$ of 0.65-0.75 with many adjacent channels.
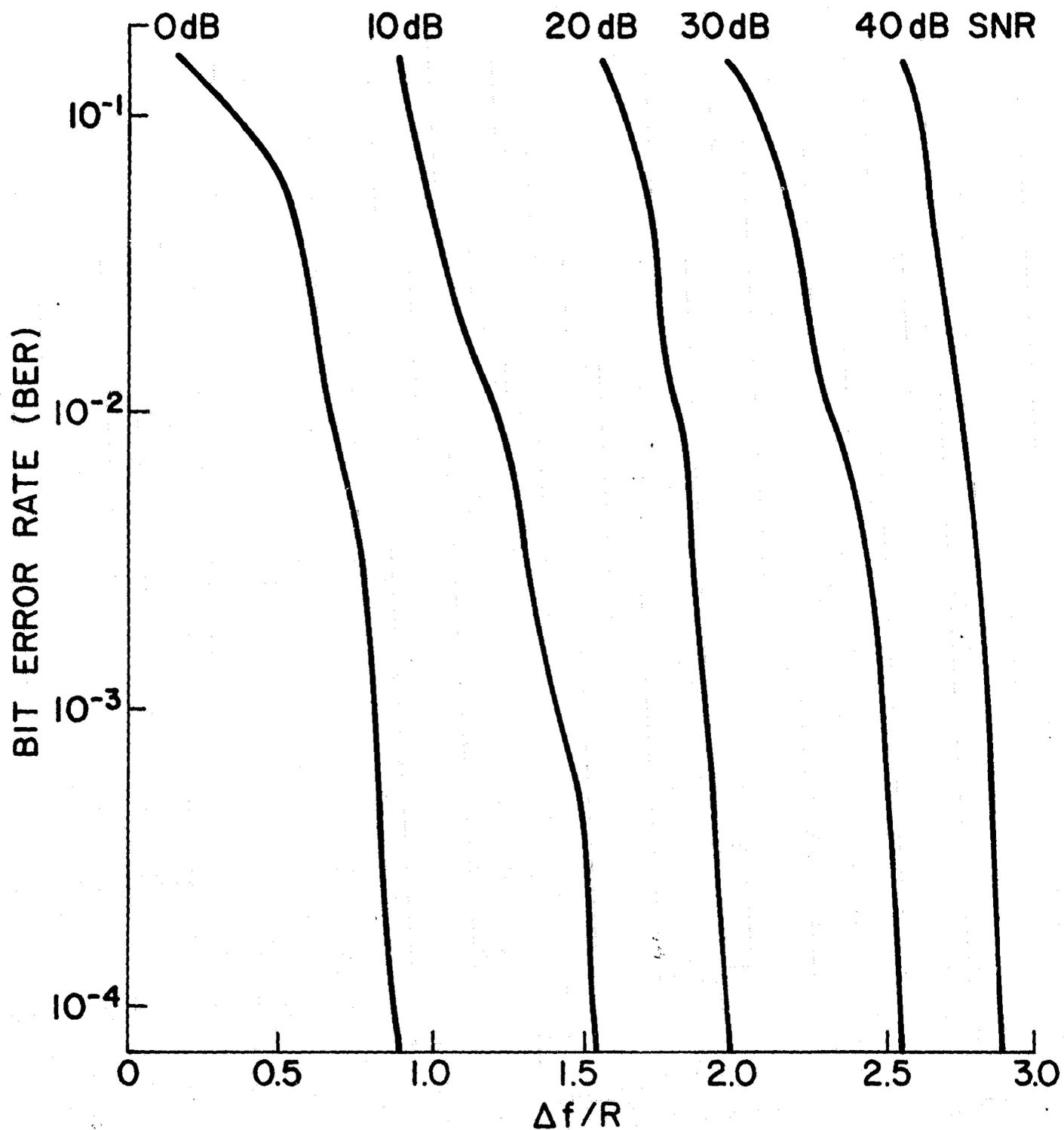
Figure A3.1-4. Bit-error rate as degraded by crosstalk from an adjacent-channel 0-40 dB more intense than the primary channel.
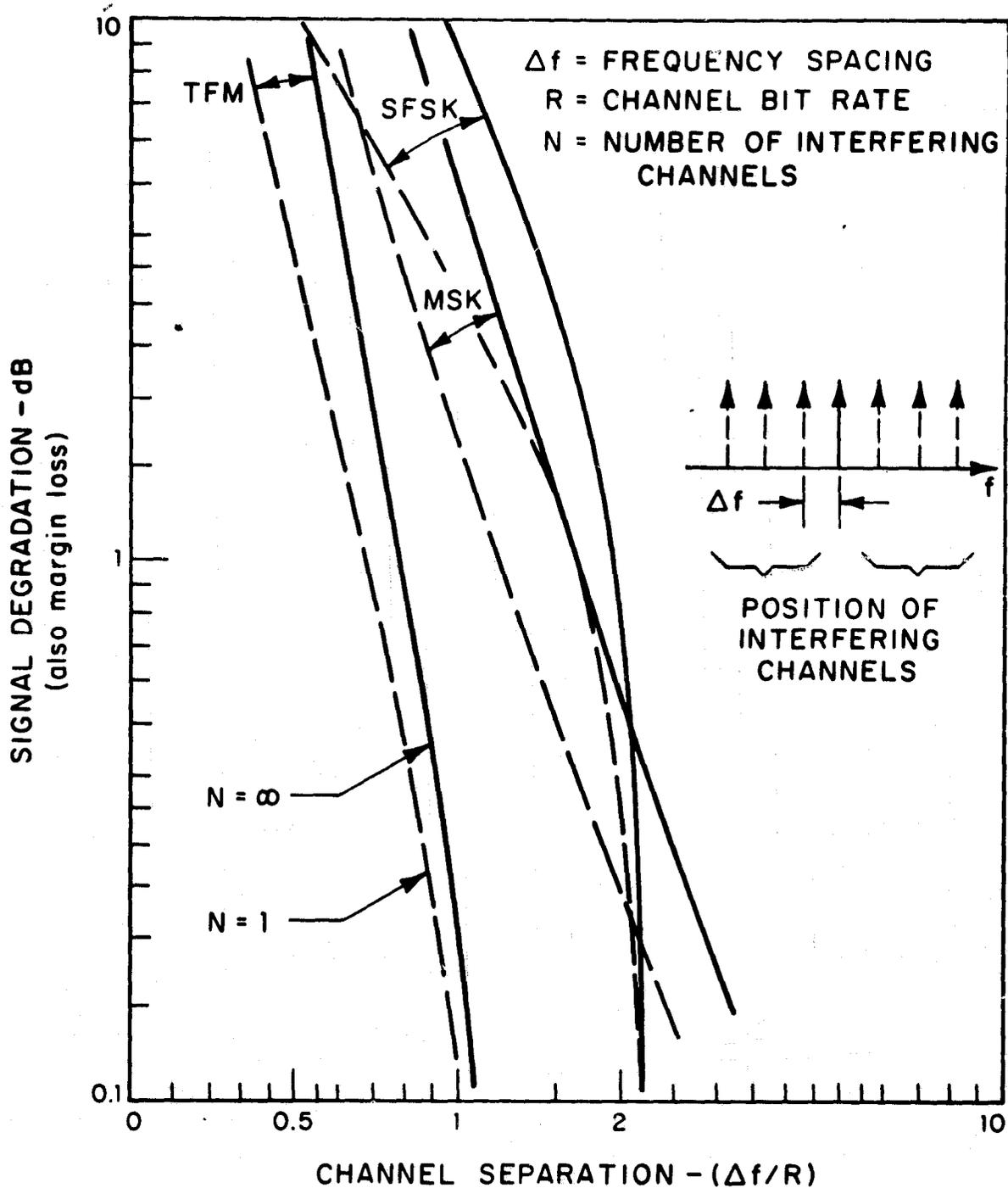
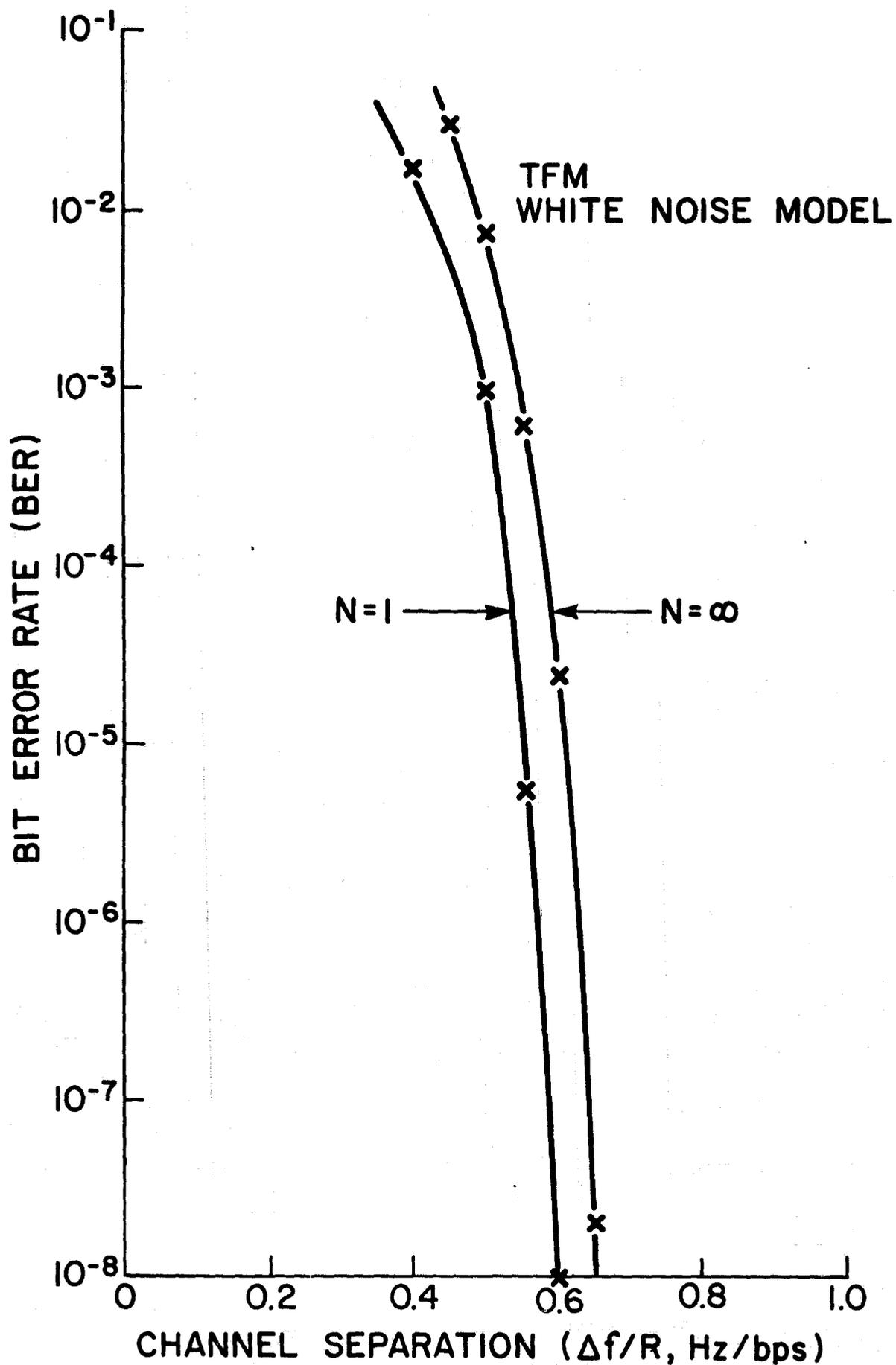Figure A3.1-5. Signal degradation due to N multiple interfering channels of equal strength.

Figure A3.1-6. Bit-error rate as a function of channel separation $\Delta f/R$ for $N = 1$ and $N = \infty$ interfering signals of equal amplitude.

Figure A3.1-7 shows the BER versus E_b/N_0 for TFM and other coherent MPSK waveforms. It is seen that TFM has about 1 dB loss in power efficiency compared to QPSK. All these results can be interpreted with reference to the auto-correlation functions and power density spectra of the various waveforms. Such a discussion is beyond the scope of this appendix and is discussed in the current literature. Suffice it to say that TFM has a broader, smoother correlation function and narrower spectrum than the other QPSK waveforms.

Section A3.1.5 shows that using TFM waveforms allows a spectral channel density of about 75 32-Mbps channels/GHz frequency allocation ($\Delta f/R = 0.75$) compared to 37 channels/GHz with simple QPSK.

It is concluded that since a WIDENET system will require high spectral and power efficiencies, TFM appears to be a reasonable initial choice. The increased hardware complexity compared to other QPSK waveforms is addressed in Section A3.1.3.5.

A3.1.3.4 CO-CHANNEL INTERFERENCE

In this section the tone interference model for the channel degradation developed in Appendix A3.1.4 is applied to estimate the interference effects on signals spatially separated on the ground by the satellite multi-beam antenna or separated by a polarization mismatch.

Equations (A3.1-15) and (A3.1-16) give the interference-to-signal power ratio for zero frequency offset and a power reduction due to either the polarization mismatch or antenna sidelobes, respectively. Figure A3.1-8 shows the resulting channel degradation from a single interfering channel with polarization mismatch L (N = 1). Also shown is the worst-case degradation due to six (N = 6) interfering channels (the maximum number of adjacent beams about a center beam) each with an antenna sidelobe level L.

It is seen that to limit the signal loss to 1 dB, a polarization isolation of 20 dB and an antenna sidelobe level of 30 to 40 dB are sufficient.

A3.1.3.5 TFM IMPLEMENTATION

In the TFM reference (deJager and Dekker, 1978), two different implementations are shown for the transmitter. In addition, breadboard
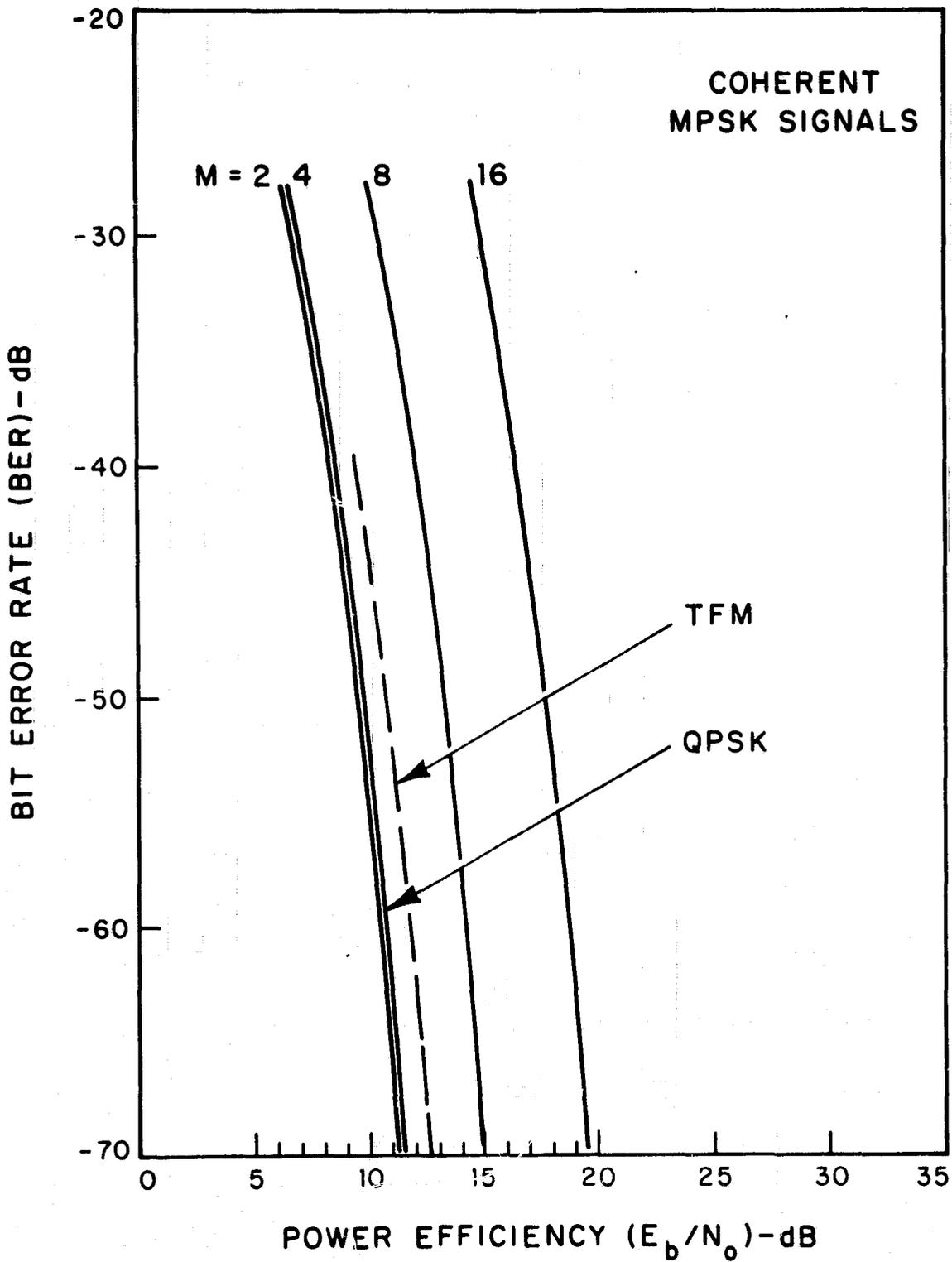
Figure A3.1-7. Bit-error rate as a function of power efficiency $E_b N_o$ for TFM and normal QPSK modulation.
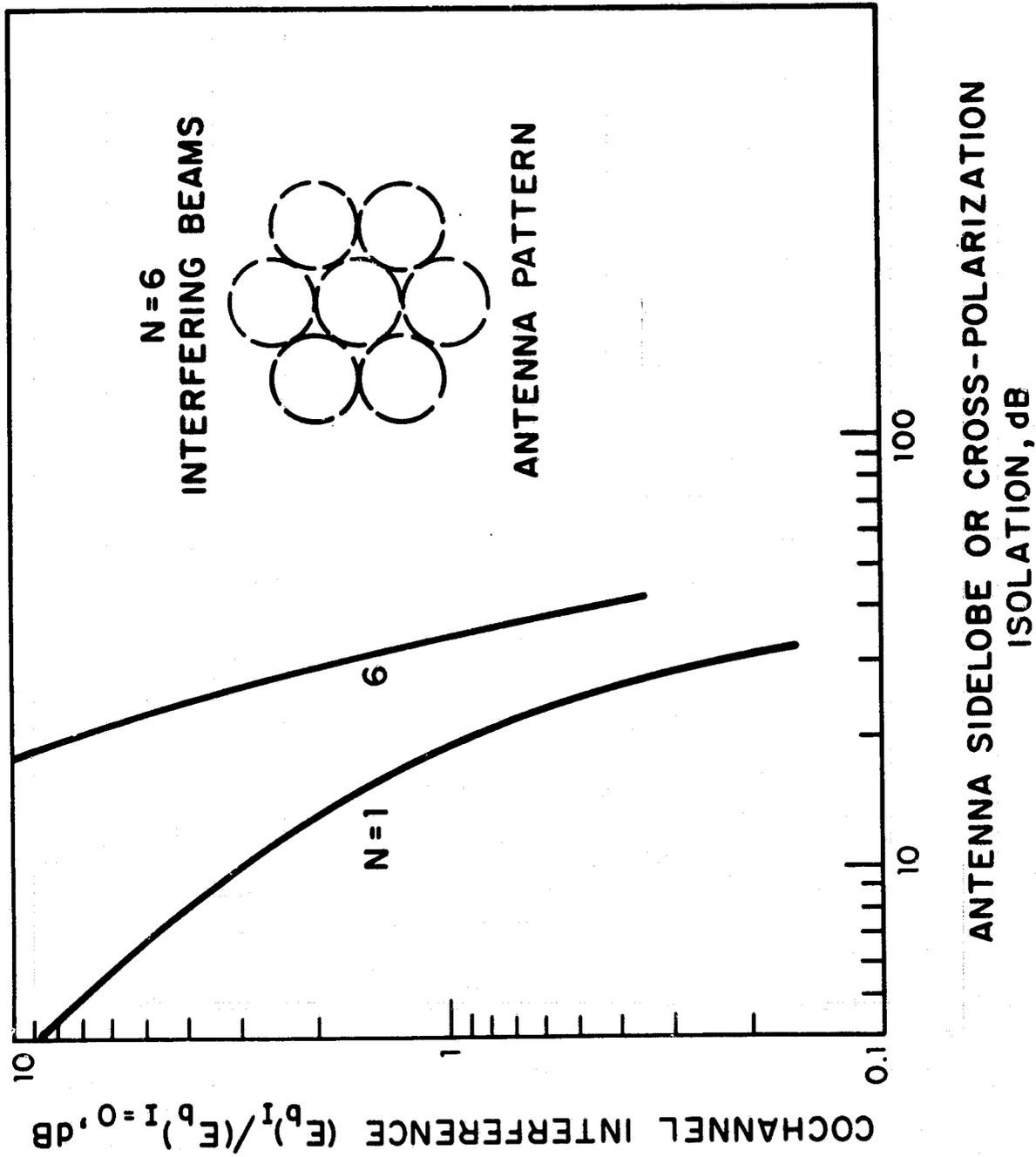
Figure A3.1-8. Loss of signal margin due to one and to six (worst-case) interfering signals.

prototypes are shown for both systems. Only a block diagram is shown for the receiver with the statement that its implementation is relatively simple. Recent correspondence (Dekker, 1978) has confirmed the implementation of the receiver; a TFM transmitter and receiver have been demonstrated in Europe. The measured error performance fits closely the calculated performance.

A3.1.4 AN ESTIMATE OF THE CO-CHANNEL AND ADJACENT CHANNEL INTERFERENCE FOR COHERENT DETECTION

In this section two models are derived that estimate the interference degradation of a coherent channel. Both models give about the same threshold for the adjacent channel frequency spacing that results in large BER. In addition, these models agree with the available computer simulation results for SFSK modulation waveforms.

The first model assumes that the interference is equivalent to white noise. The noise density in the presence of interference, $(N_0)_I$, is modeled by

$$(N_0)_I = N_0 + P_I/W, \qquad (A3.1\text{-}1)$$

where

N_0 = AGWN density,

W = noise bandwidth,

P_I = total interference power from the adjacent channels passing through the matched filter.

Or,

$$\frac{(N_0)_I}{N_0} = 1 + \frac{P_I}{N_0 W} . \qquad (A3.1\text{-}2)$$

The resulting channel degradation can be written as

$$\frac{(E_b N_0)_I}{(E_b/N_0)_{I=0}} = \frac{1}{1 + \left[\dfrac{E_b}{N_0}\right]_{I=0} \left(\dfrac{R}{W}\right) \left[\dfrac{P_I}{P_s}\right]} , \qquad (A3.1\text{-}3)$$

where

$P_S = E_B R =$ signal power from the matched filter,

$E_B =$ energy per data bit,

$R =$ data rate.

In the limit of $(E_b/N_0)_{I=0}(R/W)(P_I/P_S) \gg 1$, Eq. (A3.1-3) becomes

$$\left(\frac{E_b}{N_0}\right)_I = \frac{W}{R}\left(\frac{P_I}{P_S}\right)^{-1}. \qquad \text{(A3.1-4)}$$

This result is equivalent to the model used by Kalet and Weiner (1978) and it applies when the interference noise dominates the thermal noise.

In general, P_I is given by

$$P_I = \int_{-\infty}^{\infty}|H(f)|^2 \, G_I(f) \, df . \qquad \text{(A3.1-5)}$$

For a matched filter $|H(f)|^2$ is proportional to the signal power density spectrum

$$|H(f)|^2 \sim G_s(f).$$

Assume the interfering channels have the same shape power density spectra but different average powers and frequency offsets. For N interfering channels, with power ratios L_i, and frequency offsets Δf_i, $i = 1, \ldots, N$, with respect to the signal channel, P_I can be written as

$$P_I = \sum_{i=1}^{N} L_i \, (P_I)_i,$$

where

$$(P_I)_i \sim \int_{-\infty}^{\infty} G(f) \, G(f - \Delta f_i) \, df .$$

Similarly P_S is

$$P_S \sim \int_{-\infty}^{\infty} G^2(f) \, df .$$

Hence,

$$\frac{(P_I)_i}{P_S} = \frac{\int_{-\infty}^{\infty} G(f) \, G(f - \Delta f_i) \, df}{\int_{-\infty}^{\infty} G^2(f) \, df} \, . \qquad (A3.1-6)$$

$(P_I)_i/P_S$ can also be written in terms of the signal auto-correlation function, $R_S(\tau)$, and the mean crosstalk, $E[c^2(f)]$ (two functions frequently discussed in the literature)

$$\frac{(P_I)_i}{P_S} = \frac{F[R_S^2(\Delta f_i)]}{F[R_S^2(0)]} \qquad (A3.1-7)$$

and

$$\frac{(P_I)_i}{P_S} = \frac{E[c^2(\Delta f_i)]}{E[c^2(0)]} \, , \qquad (A3.1-8)$$

where $F[\ ]$ is the Fourier transform and $E[\ ]$ is the expectation operator.

Using published spectra, auto-correlation, or crosstalk calculations, $(P_I)_i/P_S$ can be computed from either Eqs. (A3.1-6), (A3.1-7), or (A3.1-8) and used to estimate the channel degradation by Eq. (A3.1-3).

The second model[*] is a lower bound on the interference effects. The amplitude of the signal is $\sim \sqrt{P_S}$. Likewise, the amplitude of the inter-ference is $\sim \sqrt{P_I}$. For coherent channels the worst case interference causes destructive interference during the entire matched-filter integra-tion time.[**] With N interfering channels, the amplitude at the detection output is

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[*]This approach was originally suggested by Louis S. Metzger.

[**]While it is impossible for two signals offset in frequency to have continuously destructive interference over a time interval of many carrier cycles, such an assumption is clearly a worst case for tone interference. Also, it can be shown that destructive interference leads to the maximum increase in BER even for QPSK where the decision boundaries in signal space are 45° to the quadrature signals.

$$\sim \sqrt{P_S} - \sum_{i=1}^{N} \sqrt{L_i (P_I)_i}$$

or

$$\sim \sqrt{P_S} \left[1 - \sum_{i=1}^{N} \sqrt{L_i \frac{(P_I)_i}{P_S}} \right].$$

Hence, the channel degradation is bounded by

$$\frac{(E_b/N_0)_I}{(E_b/N_0)_{I=0}} > \left[1 - \sum_{i=1}^{N} \sqrt{L_i \frac{(P_I)_i}{P_S}} \right]^2. \qquad \text{(A3.1-9)}$$

In general, the spectra of P_S and P_I will contain a continuous and a discrete component. The discrete portion of the power spectral density is caused by the nonzero average $E[\sin\theta(t)]$, where $\theta(t)$ is the phase modulation function (Spilker, 1977, p. 299).[*] $(P_I)_i$ can be written as

$$(P_I)_i = (P_{I_c})_i + (P_{I_d})_i$$

where

$$P_{I_c} = \text{continuous (mean) spectrum,}$$

$$P_{I_d} = \text{discrete (random) spectrum.}$$

Equation (A3.1-9) can then be written as

$$\frac{(E_b/N_0)_I}{(E_b/N_0)_{I=0}} = \left\{ 1 - \sum_{i=1}^{N} \sqrt{L_i \frac{(P_{I_c})_i}{P_S} \left[1 + \left(\frac{P_{I_d}}{P_{I_c}} \right)_i \right]} \right\}^2. \qquad \text{(A3.1-10)}$$

The power spectral density for a Markov source is (Lindsey and Simon, 1973, p. 17)

$$G(f) = \frac{1}{T^2} \sum_{n=-\infty}^{\infty} \left| \sum_{i=1}^{N} P_i S_i\left(\frac{n}{T}\right) \right|^2 \delta\left(f - \frac{n}{T}\right) + \frac{1}{T} \sum_{i=1}^{N} P_i |S_i(f)|^2$$

$$+ \frac{2}{T} \text{Re} \left| \sum_{i=1}^{N} \sum_{k=1}^{N} P_i S_i^*(f) S_k(f) P_{ik} (e^{-j\omega t}) \right|, \qquad \text{(A3.1-11)}$$

---

[*]The discrete spectrum occurs when $\theta(t)$ deviates from a rectangular shape.

where the symbols are defined in the above reference. The point being made is that

$$\frac{P_{I_d}}{P_{I_c}} = \frac{\frac{1}{T} \sum_{n=-\infty}^{\infty} G(\frac{n}{T}) \; G(\Delta f + \frac{n}{T})}{\int_{-\infty}^{\infty} G(f) \; G(f - \Delta f) \, df} < 1. \tag{A3.1-12}$$

Hence, Eq. (A3.1-10) can be written as

$$\frac{(E_b/N_0)_I}{(E_b/N_0)_{I=0}} > \left[1 - \sum_{i=1}^{N} \sqrt{2L_i \frac{(P_I)_i}{P_S}} \right]^2 \tag{A3.1-13}$$

where P_I is the continuous (mean) interference power as before and P_I/P_S is given by Eq. (A3.1-6), A3.1-7), or (A3.1-8).[*] This bound on the channel degradation was used to plot the channel degradation versus frequency spacing for two or more users and for different modulation waveforms.

The above model can also be applied to bound the antenna sidelobe isolation and polarization isolation by setting $\Delta f = 0$. For the case of co-channel interference, Eq. (A3.1-13) simplifies since $(P_I)_i = P_S$.

$$\frac{(E_b/N_0)_I}{(E_b/N_0)_{I=0}} > (1 - \sum_{i=1}^{N} \sqrt{2L_i})^2. \tag{A3.1-14}$$

For the case of interference between two channels with polarization isolation, L_p, Eq. (A3.1-14) becomes:

$$\frac{(E_b/N_0)_I}{(E_n/N_0)_{I=0}} > (1 - N\sqrt{2L_a})^2. \tag{A3.1-15}$$

For the case of N interfering channels spatially separated with an antenna sidelobe level of L_a, Eq. (A3.1-14) becomes:

$$\frac{(E_b/N_0)_I}{(E_b/N_0)_{I=0}} > (1 - N\sqrt{2L_a})^2. \tag{A3.1-16}$$

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[*]The identical lower bound for the effects of tone interference can be shown using the formulation in Spilker, 1977, pp. 326-331. For QPSK, BER $< 4/3 \; Q[\sqrt{2(E_b/N_0)}_{I=0} \; (1 - \sqrt{2P_I/P_S})]$.

A3.1.5 ADJACENT CHANNEL-SPACING DENSITY

The total bandwidth, W_T, occupied by N adjacent channels can be written as

$$W_T = R(1 + \eta)(N/2)(\Delta f/R), \qquad (A3.1-17)$$

where

R = data bit rate,

η = overhead factor and guardbands,

N = number of adjacent channels (two polarizations),

$\Delta f/R$ = frequency spacing ratio.

Assume

R = 32.064 Mbps,

η = 10%,

$\Delta f/R$ = 0.75 (TFM).

Then from Eq. (A3.1-17)

N(1 GHz) = 75.6 channels/GHz (192 MHz/16 channels).

For QPSK, $\Delta f/R \approx 1.5$, giving

N(1 GHz) = 37.8 channels/GHz.

Appendix A3.1   References

1. de Jager, F. and Dekker, C., "Tamed Frequency Modulation, A Novel Method to Achieve Spectrum Economy in Digital Transmission," IEEE Transactions on Communications, Vol. COM-26, No. 5, pp. 534-542 (May 1978).

2. Dekker, C., private communication with I. Kalet (10 October 1978).

3. Kalet, I., "A Look at Crosstalk in Quadrature-Carrier Modulation Systems," IEEE Transactions on Communications, Vol. COM-25, No. 9, pp. 884-892 (September 1977).

4. Kalet, I. and Weiner, L. N., "Close Packing of PCSFSK Signals—Model and Simulation Results," ICC Conference, Toronto, Canada (June 1978).

5. Lindsey, W. and Simon, M., Telecommunication Systems Engineering, (Prentice-Hall, 1973).

6. Sawada, K. and Kotera, H., "A 32 Mbit/s Component Separation DPCM Coding System for NTSC Color TV," IEEE Transactions on Communications, Vol. COM-26, No. 4, pp. 458-464 (April 1978).

7. Seay, T., "Bandwidth Efficient Modulation Techniques," International URSI Meeting, August 1978, Helsinki, Finland.

8. Spilker, J., Jr., Digital Communications by Satellite (Prentice-Hall, 1977).

APPENDIX A4.1

SATELLITE DEPLOYMENT

A4.1.1 INTRODUCTION

The STS (Space Transportation System) is being developed by NASA to meet the national space needs for the next two decades. Cargo weights up to 65,000 pounds will be placed in low earth parking orbits of 100 to 250 nmi altitude by the reuseable EOS (earth-to-orbit shuttle or Orbiter). Payloads to be deployed in higher orbits will be transferred from the parking orbit by an upper stage. Initially, the upper stage will be the SSUS (spinning solid upper stage). Later, the IUS (interim upper stage) will be available. Still later, the OOS (orbit-to-orbit shuttle or Space Tug) should be available (Davis, 1978).

In this section the upper stage propulsion requirements for deploying a WIDENET satellite are discussed. Also, the lifting capabilities of an IUS and a Centaur-based OOS (a current candidate for the reuseable OOS) are estimated.

Section A4.1.2 presents the conclusions of this analysis. In Section A4.1.3.1 the propulsion requirements for a parking-to-geosync (geosynchronous) transfer are summarized. Section A4.1.3.2 describes the Boeing IUS, and Section A4.1.3.3 describes a candidate Centaur-based OOS. Section A4.1.3.4 shows the satellite BOM (beginning of mission) weight versus shuttle cargo weight for an IUS and a Centaur-based OOS. Options and constraints for one and two EOS flights are outlined. Finally, Section A4.1.4 outlines the orbit transfer calculations.

A4.1.2 CONCLUSIONS CONCERNING PROPULSION SYSTEMS

(1) With a single Orbiter flight, a WIDENET satellite of up to 9,100 pounds can be deployed using a three-stage IUS, and up to 5000 pounds with a two-stage IUS. This IUS is based on the current Boeing IUS program and differs chiefly from the planetary three-stage IUS by the off-loading of propellant to give the proper perigee and apogee speed changes.

(2) With a single Orbiter flight, up to 17,000 pounds can be deployed

with a Centaur-based OOS used in an expendable mode. In a reuseable
mode, the Centaur-based OOS would have, roughly, the same lifting
capability as the IUS.

(3) With two Orbiter flights, up to 12,260 pounds could be deployed
with a three-stage IUS. Satellite weights above 12,260 pounds would
require a four (or more) stage IUS. With an expendable Centaur-OOS, up
to 34,000 pounds could be deployed with two Orbiter flights.

(4) The Boeing three-stage IUS would require few modifications for a
WIDENET mission and should be available in the mid-1980's. A Centaur-
based OOS also would require few modifications of the present Centaur
upper stage subsystems. The Centaur modifications mainly would be to
satisfy the safety requirements of the STS. (The Centaur vehicle has
to date flown 37 missions and currently there are missions planned into
1982.) However, at this time the Centaur-OOS is a long range NASA
project and may not be available for the initial WIDENET flights.

A4.1.3 ANALYSIS

A4.1.3.1 OOS STAGING REQUIREMENTS

STS operational flights will be launched from the NASA KSC (John F.
Kennedy Space Center) beginning in 1980. Payloads orbited by the EOS
can be placed into low earth parking orbits up to 250 nmi altitude for
orbit inclinations of 28.5° and delivery-only missions. For two or more
EOS flights requiring delivery and rendezvous missions, parking orbits
up to 190 nmi altitudes can be used. Figure A4-1 shows the maximum cargo
weight for delivery and rendezvous flights to circular parking orbits
(NASA, 1977). For this analysis it is assumed that each EOS flight
delivers 65,000 pounds to a 190 nmi altitude circular orbit with 28.5°
inclination. This is a near-optimum parking orbit for the WIDENET
mission.

Section A4.1.4 shows the equations for computing a parking-to-
geosync transfer. A Hohmann trajectory is assumed with zero plane change
at burn 1 (transfer orbit insertion) and 28.5° plane change at burn 2
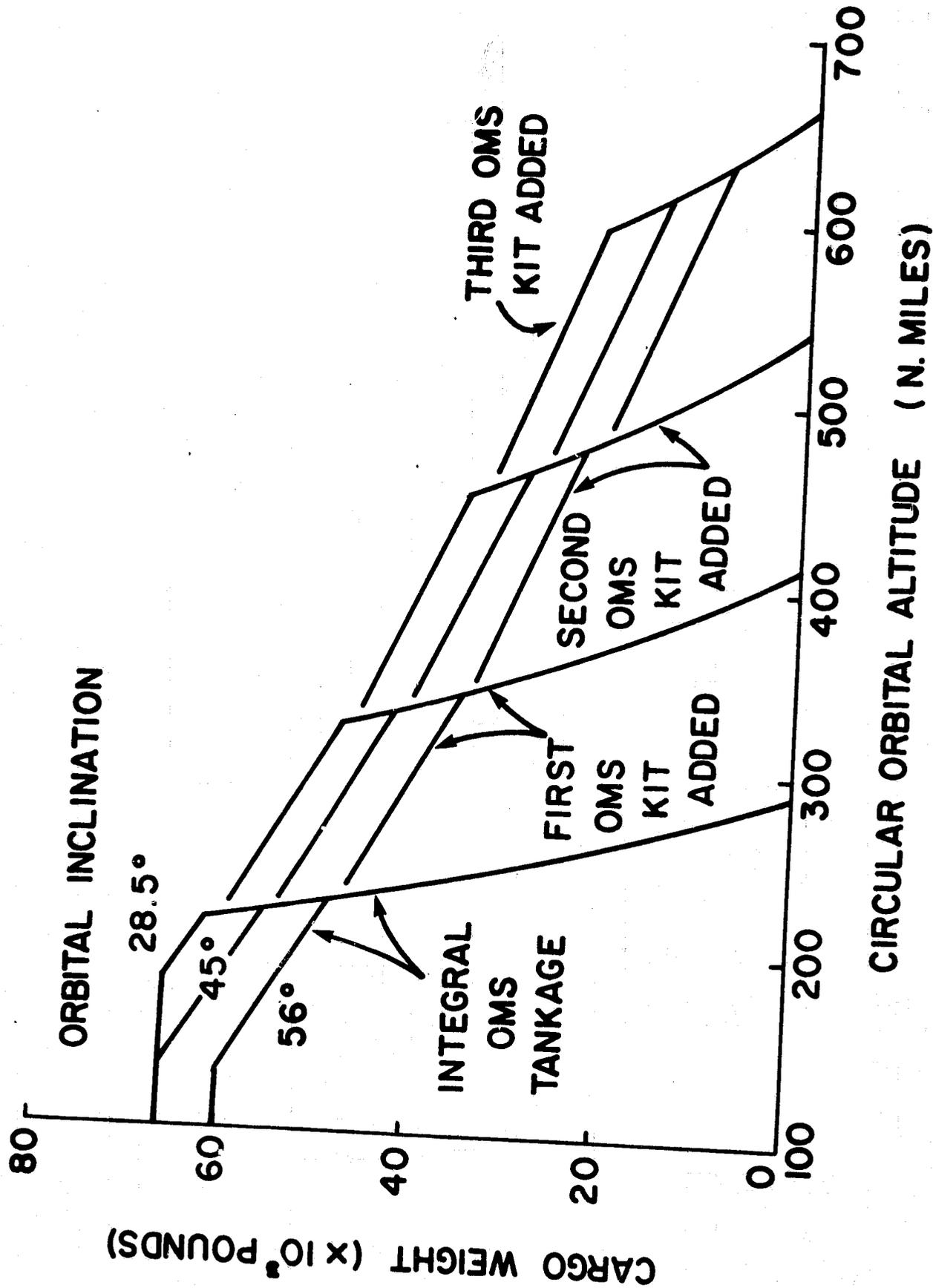
Figure A4-1. Maximum cargo weight for delivery and rendezvous flights to circular parking orbits.

(circularization at 1X sync).[*]   Table A4.1-1 shows the staging require-
ments for an upper stage operated in an expendable mode. For comparison
the corresponding requirements of the 100 nmi and 250 nmi parking orbits
are also shown. It is seen that the upper stage requirements are rela-
tively insensitive to the parking orbit altitude (within ±190 ft/sec)
and that about 13,915 ft/sec total ΔV is required of the upper stage
propulsion system for the baseline mission.[**]

Table A4.1-1. Staging Requirements for an Upper Stage.[***]

Burn	100 nmi (185 km)	190 nmi (350 km)	250 nmi (460 km)
Perigee	8,072 ft/sec	7,917	7,812
Apogee (28.5° plane change)	6,033 ft/sec	5,998	5,973
OOS Total ΔV	14,105 ft/sec	13,915	13,785

A4.1.3.2   IUS DESCRIPTION

The STS consists of the Shuttle plus upper stages. The Shuttle is
a manned, recoverable system that delivers payloads to low earth orbit.
The upper stages are required to deliver payloads into mission orbits that
are beyond the orbit capability of the Shuttle. A reuseable, upper stage
(Space Tug) is in the long range plan of the STS. However, in order to
cover the interim between the availability of the Shuttle and the
availability of the Space Tug, an IUS (interim upper stage) is necessary
and has been agreed to by DoD and NASA.

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[*]This is a near optimum strategy. Many "fine" adjustments are pos-
sible here and later in the analysis, e.g., trading cargo weight for a
higher parking orbit. The above preliminary results, neglecting these
refinements, are accurate to a few percent in the final satellite weights.

[**]For comparison, the optimum transfer would have a 2.21° plane change
at perigee and a 26.29° plane change at apogee and require a total ΔV of
13,823 ft/sec.

[***]A reuseable OOS would require the same speed increment to return
to the original parking orbit.

After two proposal competitions, the Boeing solid stage IUS has been selected for validation studies. The material presented here is for the Boeing IUS system under development by DoD; it is current with the beginning of the validation phase (Boeing, 1976).

Figure A4-2 shows the IUS family consisting of a basic two-stage vehicle with three- and four-stage configurations for the high-energy missions. The three-stage vehicle is formed by adding another existing large motor as a lower stage to the two-stage vehicle. The four-stage vehicle is formed by adding an existing motor to the three-stage vehicle. The three- and four-stage vehicles are required for the Earth escape missions.

The IUS has a three-axis stabilized propulsive and avionics system for trajectory and stability control. The possible RCS (reaction control systems) are common in design and differ only in the number (two, three or four) of propellant tanks required. The RCS is a hydrazine, mono-propellant, blow-down-pressured system with twelve thrusters, eight facing aft for pitch, yaw and velocity controls and four for roll control.

The IUS has simple interfaces with the spacecraft, Shuttle, supporting facilities, and ground equipment for a wide range of missions. Spacecraft are cantilevered from the interface adapter and all services to and from the spacecraft are through the IUS. Deployment in the parking orbit is by means of the remote manipulator system.

Application of the IUS to a WIDENET system is considered in Section A4.1.3.4.

A4.1.3.3 CENTAUR-BASED OOS DESCRIPTION

The Centaur D-IT is a key element in NASA's future space program with a backlog including Viking, Helios and Marine-Jupiter-Saturn missions.[*] The D-IT reconfigured for STS use is the basis for the OOS

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[*] The D-IT is an improved Centaur vehicle and it is currently used as the high-energy (LO_2/LH_2) upper stage on the Titan ("T" for Titan). The D-IT incorporates a space radiation shield insulation system and subsystem modifications to make it comparable with the Titan TIIIE. The TC-2 flight in December 1974 demonstrated the D-IT capability to OOS missions, including long coast and four starts (Jones and Heald, 1975).
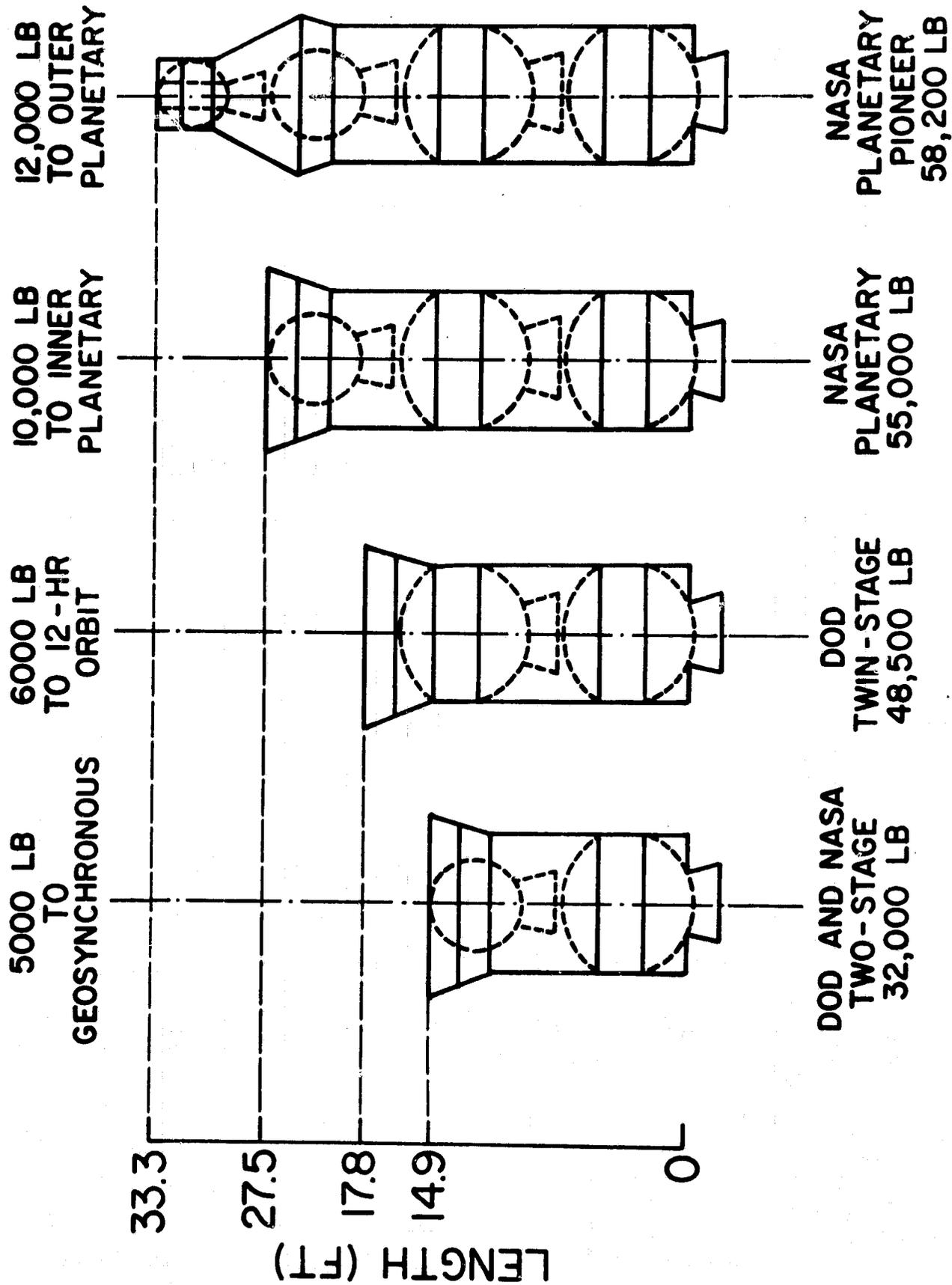
Figure A4-2. Interim-upper-stage (IUS) launch vehicle options, for use with the NASA space shuttle.

in the following analysis because it is being considered for the plane-
tary and stage reuse missions by NASA and because it represents a logical
choice for a high performance upper stage vehicle.

Figure A4-3 schematically shows an OOS candidate design configura-
tion based on the D-IT (Hazard, 1974). The OOS can be operated as an
expendable stage similar to current upper-stage operation or it can be
operated in a reuseable mode in which case the OOS will deliver a pay-
load and subsequently return to a parking orbit where it can be serviced,
refueled and maintained by an EOS. For more extensive repair the OOS
would return to earth by an EOS.

Major subsystems require few modifications to mount the Centaur
vehicle in the EOS and to meet the man-rated safety requirements (Jones
and Heald, 1975). Structural changes are the enlarged propellant tanks,
new equipment module and a new aft skirt for support loads. Main engine
and attitude control systems are unchanged. The fluid lines are modified
to match EOS interfaces including in-flight dump lines. The avionics
system is essentially unchanged, except for a new communications system.
The propellant tank redesign represents a new development task, but not
a high risk because design and fabrication techniques are state of the
art. A truss pallet forms the structural interfaces between OOS and EOS.

An overriding design and operating requirement is safety. During
EOS ascent any leak that might develop in a main propellant tank will
immediately gasify. Since the EOS payload bay is filled with nitrogen,
the leak will be into an inert atmosphere. Leaking propellant will con-
sequently be safely swept from the payload bay along with the venting
nitrogen. Once the EOS has attained an altitude greater than 110,000
feet, the atmospheric pressure is below the 0.1 psia required for
ignition of any mixture ratio of the propellants. During an EOS abort,
helium is used to purge the hydrogen tank before the EOS has descended
to 170,000 feet altitude.

Application of this OOS to a WIDENET system is considered in
Section A4.1.3.4.

A4.1.3.4 IUS AND OOS CAPABILITIES AND OPTIONS

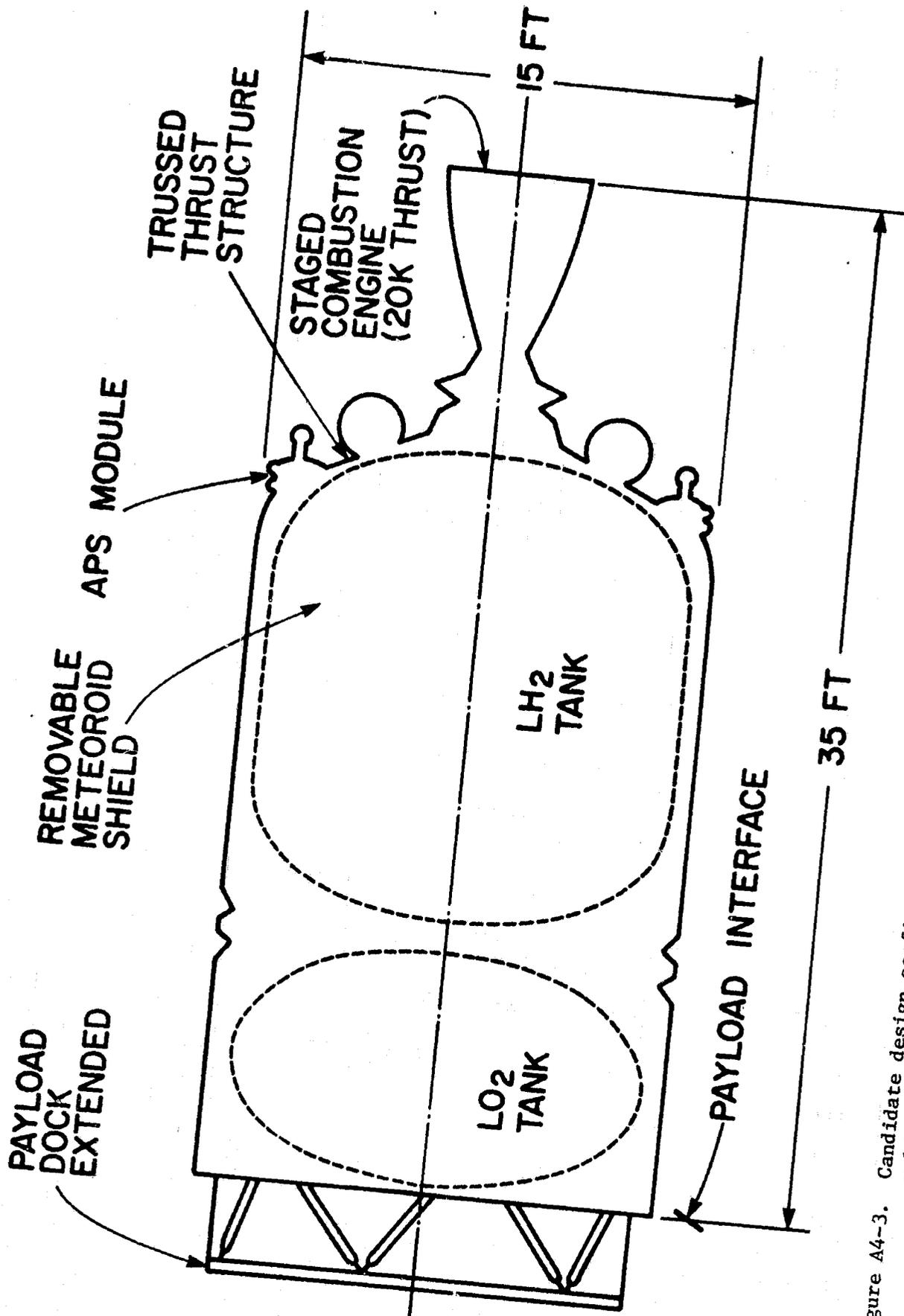In Section A4.1.3.3 the total propulsion requirement of an

Figure A4-3. Candidate design configuration for an OOS launch vehicle compatible with an improved Centaur vehicle.

expendable upper stage is shown to be about 13,915 ft/sec. The lifting
capability of an upper stage is given by the satellite weight inserted
into a geosync orbit versus the Shuttle cargo weight. A basic assump-
tion of the following staging calculations is that the Shuttle cargos
are weight but not volume constrained. This assumption should be checked
after an estimate of the satellite stowage envelope is made. For a
single Shuttle flight with a cargo weight of 65,000 pounds, the available
satellite stowage envelope is about 15 feet in diameter by 30 feet long
for an IUS upper stage and 15 feet in diameter by 38 feet long for a
Centaur OOS. Additional considerations of center of gravity, interface
design, etc. are tasks for an iterated design.

Table A4.1-2 gives an example sequential mass property summary for
a three-stage IUS and a 65,000 pound Shuttle cargo weight. These mass
data are not parametric values, but are the result of several Boeing
design iterations. Nearly 90% of the dry weight is based on either
existing hardware or detailed analysis of new hardware. A weight growth
allowance of 10% is included in the dry weights.

For the IUS some form of energy management is required to match the
speed increments obtained with each solid motor stage to the speed
increments required for a particular trajectory. In general, four methods
of energy management are available: trajectory design, ballasting,
attitude modulation and propellant off-loading. An optimum mix is a
future task. Propellant off-loading is an effective method of energy
management and it is the only one considered in this preliminary analysis.

Table A4.1-3 gives an example launch summary of a Centaur OOS and a
65,000 pound Shuttle cargo weight. These mass data are from representative
weights for the engines, guidance and control system, and other subsystems
based on Hazard (1974) and Jones and Heald (1975). The OOS weights are
based on a formula shown in Table A4.1-3, i.e., the residual propellant
weight is 1% of the total propellant weight and the dry weight is 13%
of the wet weight.

Table A4.1-2.   IUS Launch Summary.

Shuttle cargo weight	65,000 lbs
Adapter	3,500
EOS separation	61,500
RCS prop	20
Preburn 1	61,480
Prop	21,400
Inerts/RCS prop	170
$\Delta V = 4,031$ ft/sec	
$I_{SP} = 2.92.6$ lb$_f$ sec/lb$_m$	
Postburn 1	39,910
Staged/RCS prop	2,460
Preburn 2	37,450
Prop	12,876
Inerts/RCS prop	170
$\Delta V = 3,969$	
$I_{SP} = 292.6$	
Postburn 2	24,405
Staged/RCS prop	2,460
Preburn 3	21,945
Prop	10,219
Inerts/RCS prop	170
$\Delta V = 6,000$	
$I_{SP} = 292.6$	
Postburn 3	11,556
Staged/RCS prop	2,460
Payload	9,096 lbs

Table A4.1-3.   Centaur-based OOS Launch Summary.

Shuttle cargo weight		65,000 lbs
Adapter		<u>3,700</u>
EOS separation/Preburn 1		61,300
Prop		38,089
RCS prop		100
ΔV = 13,915 ft/sec		
I_{SP} = 445 lb_f sec/lb_m		<u> </u>
Postburn 2		23,111
Engine section	1,450	
Structure/tankage	3,464	
ACS	<u>850</u>	
OOS dry weight (13% wet)[*]	5,764	
Residual prop (1% total prop)	<u>385</u>	
Staged		6,149
Payload		16,962 lbs

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[*] OOS wet weight = EOS sep − payload = 44,338.

Figure A4-4 shows the launch options for both the IUS and OOS.[*]
These curves were generated by varying the weights in Tables A4.1-2
and -3.[**] It is seen that for a single Shuttle flight, the three-
stage IUS could deploy a 9,100 pound satellite and an expendable OOS
could deploy a 17,000 pound satellite.[***] Two Shuttle flights could
deploy a maximum satellite weight of 21,200 pounds with a four-stage
IUS or 34,000 pounds with an expendable OOS. For the Centaur OOS, if
the satellite weighs 23,500 pounds or less, then the satellite can be
first lifted to the parking orbit for assembly and checkout separately
from the Shuttle flight carrying the OOS. Above 23,500 pounds the
satellite Shuttle flight must carry some OOS propellant. This require-
ment may impact the allowable time between Shuttle flights because of
the cryogenic propellant boiloff.

Use of the Centaur OOS in an expendable mode gives the maximum
satellite weight. Preliminary estimates of the lifting capability
using a reuseable mode also have been made. The resulting satellite
weights are more sensitive to the assumptions about the vehicle charac-
teristics. However, a reuseable Centaur OOS would have, roughly, the
same lifting capability as the IUS.

Finally, higher satellite weights can be deployed only by using
more Shuttle flights and/or the development of a higher-performance OOS,
e.g., one with a nuclear propulsion system. Both these options appear
to decrease the feasibility of a WIDENET system compared to the above
cases.

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[*] For comparison, the SSUS is designed to carry two primary classes
of spacecraft. The Delta class (SSUS-D), which requires up to 2,400
pounds to be put into a geosync transfer orbit, and the Atlas-Centaur
class (SSUS-A), which requires up to 4,000 pounds to be put into a
geosync transfer orbit. It is expected that four Delta class or two
Atlas-Centaur class spacecraft can be carried on a single Shuttle flight.

[**] The slopes of the IUS and OOS curves differ slightly because the
OOS curve is based on the formula given in Table A4.1-3.

[***] For the IUS in this case, the thrust of the solid rocket motors is
60,280 pounds and produces a 5.2 g acceleration at the end of the third-
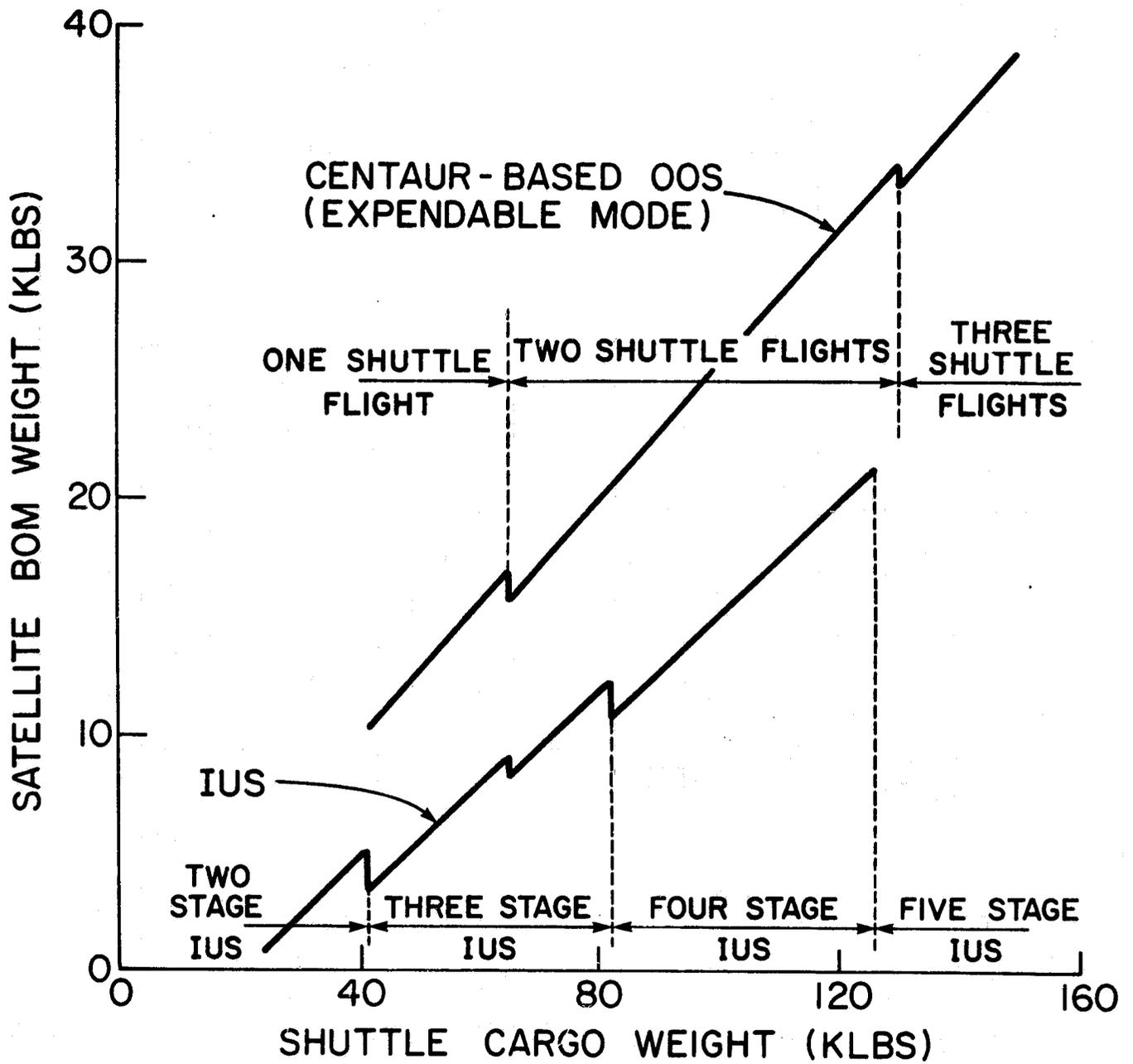stage burnout. This load may impact the satellite design.

Figure A4-4. Nominal launch options for the IUS and OOS.

A4.1.4 PROPULSION CALCULATIONS

The propulsion requirements shown in Section A4.1.3.1 for an upper stage are based on a Hohmann transfer from a low-altitude circular parking orbit to a geosynchronous orbit.[*] The first burn, ΔV_1, at the parking orbit is computed from Escobal (1968),

$$\frac{\Delta V_1}{V_I} = \left[\frac{2R}{1 + R}\right]^{\frac{1}{2}} - 1, \qquad (A4.1-1)$$

where

$$V_I^2 = \mu/r_I = \text{orbit speed of the parking orbit,}[**]$$
$$R = r_F/r_I = \text{final-to-initial orbit radii ratio,}$$
$$r_I, \ r_F = \text{initial and final orbit radii,}$$
$$\mu = 3.986 \times 10^5 \ \text{km}^3/\text{sec}^2.$$

The second burn, ΔV_2, at the final orbit is computed from

$$\frac{\Delta V_2}{V_I} = \left[\left(\frac{1}{R}\right)^{\frac{1}{2}} - \left|\frac{2}{R(1+R)}\right|^{\frac{1}{2}}\right]^2 + 2 \left|\frac{2}{R(1+R)}\right|^{\frac{1}{2}} \left(\frac{1}{R}\right)^{\frac{1}{2}} (1 - \cos\theta)$$

$$(A4.1-2)$$

where

$$\theta = \text{magnitude of the plane change at burn 2.}$$

Using Eqs. (A4.1-1) and (A4.1-2), ΔV_1 and ΔV_2 were computed for parking orbit altitudes of 100 nmi, 190 nmi and 250 nmi and are shown in Table A4.1-1.

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[*]A Hohmann transfer has an elliptic trajectory between the two (initial and final) burns with no plane changes. The above Table A4.1-1 calculations assume a 0° plane change at the first burn and a 28.5° plane change at the second burn.

[**]For a 190 nmi altitude parking orbit, $V_I = 25,253$ ft/sec and $R = 6.278$.

Appendix A4.1   References

1. The Boeing Company, "Interim Upper Stage (IUS) Performance Analysis," Document No. D290-10049-1 (October 1976).

2. Davis, R. C., et al., "Future Trends in Communications Satellite Systems," Acta Astronautica, Vol. 5, pp. 275-298 (1978).

3. Escobal, P. R., "Methods of Astrodynamics," (John Wiley and Sons, Inc.), 1968.

4. Hazard, H., "U.S. Space Launch Systems," Navy Space Systems Activity, Report No. NSSA-R-20-72-2 (April 1974).

5. Jones, D. J. and Heald, D. A., "Centaur as an Initial Stage for the Space Shuttle," American Astronautical Society, Twenty First Annual Meeting, Paper No. AAS 75-172 (August 1975).

6. NASA, "Space Transportation System User Handbook," NASA Space Transportation Systems Operations Office (June 1977).

APPENDIX A4.2

ATTITUDE CONTROL SYSTEMS

The ACS (attitude control system) orients and stabilizes the satellite in three axes after separation from the launch vehicle. For comparison Table A4.2-1 shows the ACS weight and power of several recent satellites.

Because the satellite antenna pointing requirement may be less than 1 arc min, a star tracker has been included in the baseline WIDENET ACS shown in Table 4.3-2. The ACS would provide coarse pointing of the entire satellite to about 0.1 degrees. Fine pointing of the antenna would be done by tilting the secondary reflector via an uplink beacon signal and/or the star tracker.

Reaction wheels can be categorized by their momentum range (Davis et al., 1974). Small wheels are from 0.1 to 7 ft-lb$_f$-sec and are used on the ERTS and VELA satellites, medium wheels are from 5 to 50 ft-lb$_f$-sec and are used on FLTSATCOM and CTS satellites, and large wheels are from 200 to 2000 ft-lb$_f$-sec and are used on Skylab and military spacecraft. For preliminary design purposes a 5 to 50 ft-lb$_f$-sec wheel size appears sufficient for WIDENET.

Table A4.2-1. Attitude Control Systems.

Satellite	Pounds	Bus Watts	Type
LES-9	105	25	bias
ATS-6	217	60	zero
FLTSATCOM (less array drive)	100	35	bias
DSCS-II	17	35	bias
DSCS-III	79	49	zero

See references at the end of Chapter 4.

APPENDIX A4.3

SPACEBORNE 20-GHZ TRANSMITTER TECHNOLOGY

Few 20-GHz power amplifiers are presently available because of previous lack of interest in this frequency band. An exception is the amplifiers for the JCS (Japanese Communications Satellite) program (TWT/4 Watts RF). The following paragraphs outline the current and projected (1983 to 1988) spaceborne 20-GHz power generation capabilities.

The devices considered are TWTs (traveling-wave tubes), IMPATT diodes, and FETs (field-effect transistors) because these appear to be the leading candidates for 20-GHz applications (Staecher and Peterson, 1977). Amplifiers have been developed at slightly lower (12-18 GHz) and slightly higher (35-40 GHz) frequencies. While high power/high frequency amplifiers are not simply scaled, nevertheless the technology necessary for a 20 GHz amplifier development is currently available.

Table A4.3-1 shows the 20-GHz output and DC to RF efficiencies with current technology. The TWTs give the highest power. These JCS tubes have not been space qualified to military specifications, but they could be so qualified in the 1980 time frame. Comparison between the solid-state devices indicates that IMPATTs offer twice the power and a more mature technology; whereas, FETs offer twice the efficiency, linearity, and less weight and combiner complexity. The difference in power between TWTs and the solid-state devices may be somewhat reduced by the introduction of other communication parameters such as IMP (intermodulation product) that could reduce TWT performance more than the solid-state device performance. Data to make such comparisons at 20 GHz are unavailable.

Tables A4.3-2 and A4.3-3 show the 1983 to 1988 projections at 20 GHz. The TWT data are for helix tubes. While a coupled-cavity tube offers higher output power, it is heavier, larger and more costly than its helix counterpart. In addition more than 95% of all spaceborne TWT experience is with helix tubes; consequently, the coupled-cavity tube would require substantially more development and demonstration of tube reliability.

Table A4.3-1. Current 20-GHz Spaceborne Transmitter Technology.

Diode	Performance	Source	Description/Comment
IMPATT Diode	P_{RF} = 0.7-1W η = 10-11%	Lincoln Laboratory Development Program	GaAs, modified profile subharmonic termination, package
FET	P_{RF} = 0.5-1W η = 10-15%	MSC, "End of '78 projection" based on Ku-band development work in progress	GaAs, unpackaged
TWTA	P_{RF} = 4W η = 17.5%	Hughes	Model 129411 (JCS program)

Table A4.3-2. 1983-1988 Projected 20-GHz Spaceborne Transmitter Technology.

Device	Performance	Source	Description/Comment
IMPATT	$P_{RF} \approx$ 2-4W $\eta \approx$ 20-25%	Raytheon	GaAs, double drift (no development work in F-band at present)
FET	$P_{RF} \approx$ 2-3W $\eta \approx$ 20T	MSC	GaAs, internal - matching as for packaged device
TWTA	2-4W/33% to 30W/33%	Hughes	250 H; development work for Bell Labs

Table A4.3-3. 1983-1988 Projected Transmitter Configuration.

Device	Power Out	Approximate DC Power	Approximate Size (cm)	Approximate Weight (Kg)	Description/Comment
IMPATT	2W	10W	25 × 8 × 2	.8	Series chain, 5-6 stages includes current regulation (90% eff.), circulator and interstage isolator loss. Microstrip environment.
	4W	20W	25 × 8 × 2		
FET	2W	10W	20 × 5 × 2	.3	Series chain, 6-8 stages. Microstrip environment.
	4W	20W	26 × 5 × 2	.4	Power combining at output likely for 4W.
TWTA	2W	6W	34 × 11 × 9	2.2	Similar to 250H.
	4W	12W	34 × 11 × 9	2.2	Size and weight from MOD 1294H.

From a survey of available tubes at other frequencies, 40 Watts appears to be the limit for a helix tube operating at 20 GHz (Frediani, 1978). Examples of current high power/high frequency helix-type TWTs are a 100-to-150 Watt tube (Thomson-CSF) operating from 10 to 16 GHz and a 200-Watt tube (AEG-Telefunken) operating at 12 GHz. A 10-Watt tube (Watkins-Johnson Type 3638) operating from 26 to 40 GHz (3 GHz bandwidth) is under development.

TWT intermodulation data extrapolated from lower frequencies suggests that for two equal amplitude signals, a 3-dB to 10-dB power backoff would be required for a 10-dB IMP reduction. Redesign of the TWT to optimize efficiency for operation in a backoff mode may be feasible. TWT lifetime is limited by cathode wearout and is a function of time and cathode loading. There is insufficient history at 20 GHz to determine a MTTF (mean time to failure). However, a design life of 7 to 10 years (6×10^4 to 9×10^4 hours) appears to be achievable. The effect of transient operation is unknown.

The above data suggest that TWTs are likely to maintain their lead in power output and efficiency while having acceptable reliability and IMP. For these reasons a 10 W (RF) TWT, 30% efficiency, 3 GHz bandwidth, and continuous operation are assumed for preliminary design purposes.

See references at the end of Chapter 4.

APPENDIX A4.4

SWITCHING MATRIX

In this appendix a model is given for estimating the number of SPST (single pole, single throw) switches necessary to interconnect N input lines to N output lines.

Following Shannon, consider a sequence in which the input line 1 is connected to one of N output lines, followed by input line 2 being connected to one of the N-1 remaining output lines, etc. The number of different sequences is n!. Each particular sequence corresponds to a particular state of the SPST switches. For S binary switches there are 2^S possible states. Hence, to have no blockage

$$2^S > N!$$

Or,

$$S > N \log_2 N$$

Using a sparse crossbar to interconnect, Bassalygo and Pensher (Pippenger, 1978) proved the existence of a switch matrix such that

$$S = cN \log_2 N$$

where c is a constant. We have examined a realization of a switch matrix based on a two-dimensional array of 4 × 4 switches. For N = 350 the number of switches was $S \overset{\sim}{=} 10,440$ for modest blocking probability. Clos networks are a more general class of multistage switching network. Marcus (1977) has reviewed their characteristics; his Figure 6 shows that rearrangeable Clos networks require only $\sim 12N \log_{10} N$ switches. Hence, as a design equation we used:

$$S = 12N \log_{10} N$$

for arbitrary N.

See references at the end of Chapter 4.

APPENDIX A4.5

COMMUNICATIONS PROCESSOR

The communications computer controls the switching matrix on board the satellite. Figure 4-9 shows the architecture assumed for estimation purposes. The following paragraphs give the model used to estimate the basic computer parameters of memory size, speed, weight and power.

The dominant function of the computer is the switch-command task, and the associated memory and command circuits dominate computer size and weight. We assume that the command algorithms reside largely on the ground and that the switch command sequence is communicated via a standard 20/30 GHz channel. The baseline digital switch has $\sim$ 2400 switches which could be thrown many times within each TDM cycle of $\sim$ 4 msec. If the smallest packet corresponds to a 256-kbps link, then $\sim 400 \times 2400 \stackrel{\sim}{=} 10^6$ bits specify an entire TDMA cycle, and can be repetitively executed; there are $\sim$ 400 256-kb packets per cycle. Such a bit stream must be generated by the computer once per TDMA cycle, or 250 times per second. If these are output in 250-bit words, then $\sim$ 1 Mops suffices.

The weight and power requirements for this computer are estimated by scaling a point design of a CMOS/SOS computer of 12.5 lbs/27 (conditioned) Watts for 500 kbit memory, 1.5 Mop/sec. Assuming a linear scaling according to speed, the 12.8 Gbps baseline computer is about 20 lbs/45 Watts as shown in Table 4-8.

APPENDIX A4.6

RCS PROPULSION REQUIREMENTS AND SYSTEM MODEL

The RCS propulsion requirements involve station keeping the satellite in a geosynchronous orbit after deployment, momentum dumping of the reaction wheels, and orbit trim to correct for launch vehicle tipoff. The following paragraphs estimate each of these factors.

Since the total WIDENET system cost is expected to be dominated by the ground segment, N/S (North/South) station keeping is done by the satellite to mitigate antenna tracking by the ground stations. The rate of long-term inclination buildup (about an 18-year period) varies uniformly from about 0.95 deg/yr in 1988 to 0.79 deg/yr in 1997 (Isley and Duck, 1974). Roughly, 75% of this buildup is due to lunar effects and 25% is due to solar effects. A maximum of about 167 ft/sec/yr is required to prevent long-term inclination buildup. The short-term latitude excursions (about a 14-day period) will be less than 1 arc min and, hence, are unnecessary for this application to correct. Thus, for a 7-year mission the N/S station keeping requirement is about 1170 ft/sec.

The E/W (East-West) drift is due to the asphericity of the earth's (J_{22} harmonic) gravitational field. Depending on the longitude, the CONUS E/W requirement can vary from 0 ft/sec/yr at a stable point (107°W) to almost 6 ft/sec/yr (60°W) for station keeping to within 4.5 arc min.[*] Assuming the maximum 6 ft/sec/yr, the E/W requirement for 7 years is about 40 ft/sec.

Orbit trim and momentum dumping are estimated to be 30 ft/sec and 70 ft/sec, respectively, based on the LES 8/9 and other satellites. A summary of the RCS propulsion requirements is shown in Table 4.3-1.

Tankage, feed system and thruster weights are estimated from flight-designed hardware. For a pressurized monopropellant hydrazine system (Free and Hudson, 1974).

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[*]CONUS is located roughly between 60°W (East Coast) and 125°W (West Coast).

$$W_{tank} = 7\left(\frac{W_p}{30}\right)^{2/3} , \qquad\qquad (A4.6\text{-}1)$$

where

W_{tank} = tankage and feed weight (lb_m),

W_p = propellant weight (lb_m).

Assuming 24 1-lb_f thrusters each weighing 0.8 lb_m, the design equation for the RCS weight, W_{RCS}, is

$$W_{RCS} = 20 + 7\left(\frac{W_p}{30}\right)^{2/3} . \qquad\qquad (A4.6\text{-}2)$$

The above system has a I_{SP} = 220 lb_f sec/lb_m.[*]

The RCS bus power is estimated to be 25 Watts based on current designs.[**]

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[*]By 1990 a bipropellant system may be available with a I_{SP} = 300 lb_f sec/lb_m (Schindler and Schoenman, 1976); hence, the above model may over-bound the RCS weight.

[**]DSCS-III (19 W), FLTSAT (18 W), ATS-6 (24 W).

See references at the end of Chapter 4.

APPENDIX A5.1

TDMA BUFFER

In this appendix the TDMA format of the baseline system is used to estimate the TDMA buffer parameters including cost.

Figure A5.1-1 shows a schematic of a TDMA system in which n input bit streams are multiplexed into a single output bit stream. One TDMA frame time (t_F sec.) corresponds to transmitting n packets (t_G sec) each with ℓ_M bits, separated by n gaps t_G. Thus $t_F = n(t_p + t_G)$. From these figures the following relationships can be written:

$$\ell_M = R_I t_F = R_0 t_P , \qquad (A5.1-1)$$

$$R_0 = \ell_M/t_P = n(R_I + R_{OH}) , \qquad (A5.1-2)$$

$$t_F = n(t_p + t_G) , \qquad (A5.1-3)$$

$$t_P = \frac{R_I}{R_0} t_F , \qquad (A5.1-4)$$

where

R_I, R_0, R_{OH} = input, output, overhead bit rates (bits/sec),

t_p, t_G, t_F = packet, guard, frame times (sec),

ℓ_M = buffer memory per channel (bits),

n = number of multiplexed channels.

The frame time, t_F, is related to the video frame time by:

$$t_F = \frac{t_{VF}}{n_F} , \qquad (A5.1-5)$$

where

t_{VF} = video frame time (two scans)(sec),

n = number of packets required to send one video frame (two scans).
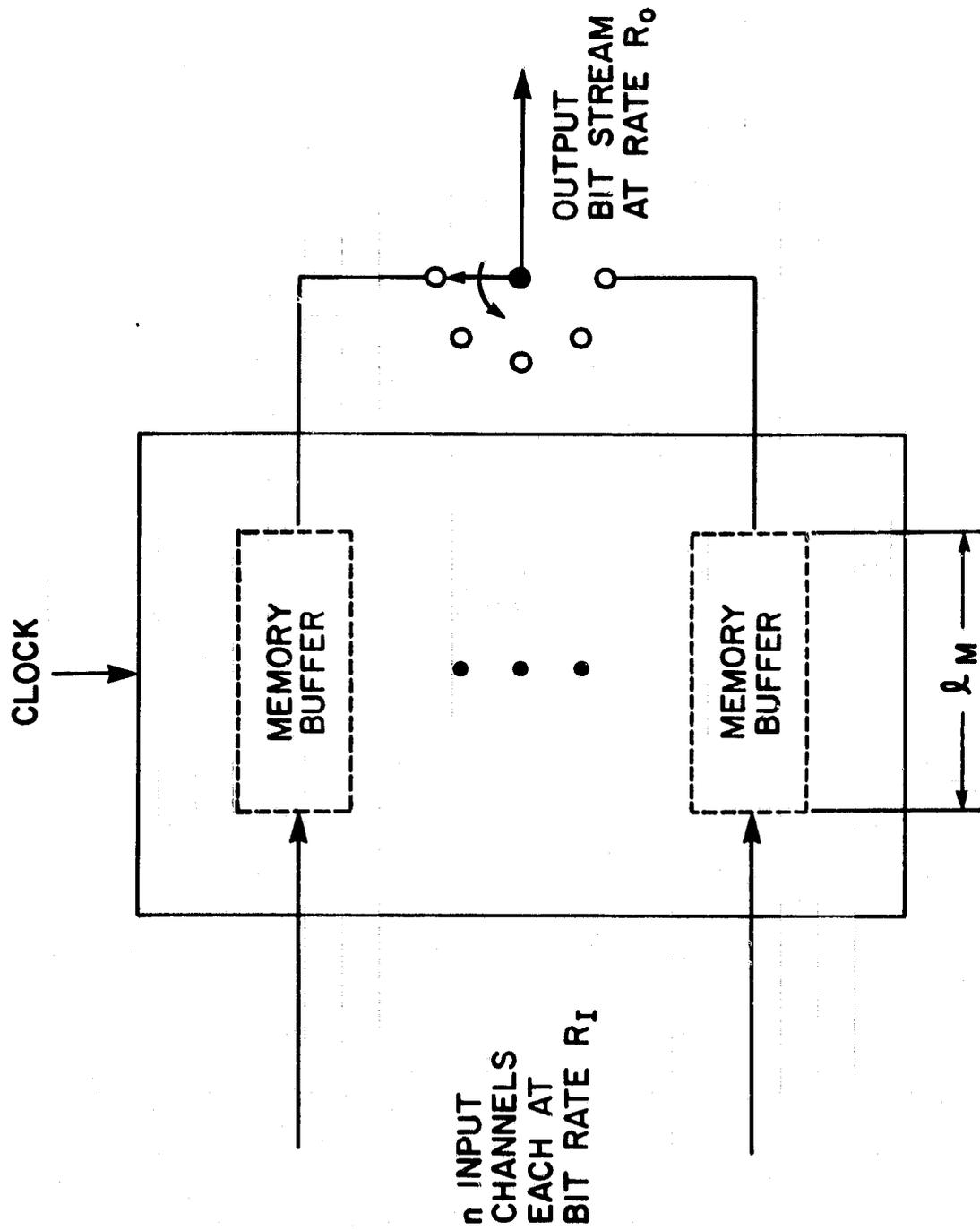
For the baseline system,

Figure A5.1-1. Possible configuration for a TDMA buffer.

$$n_F = 8 \text{ packets/frame,}$$
$$n = 4,$$
$$R_I = 32 \text{ Mbps,}$$
$$R_{OH} = 3 \text{ Mbps,}$$
$$t_{VF} = 33.3 \text{ msec (30 Hz video frame rate).}$$

Then, Eqs. (A5.1-1) to (A5.1-5) give:

$$t_F = 4.167 \text{ msec,}$$
$$t_P = 954.2 \text{ }\mu\text{sec,}$$
$$t_G = 87.5 \text{ }\mu\text{sec,}$$
$$R_0 = 140 \text{ Mbps,}$$
$$\ell_M = 133.3 \text{ kbits.}$$

Assume a CCD implementation using a LARAM (line addressable random access memory) system organization for short access time and high data rate (Harloff, 1978). For 133.3-kbit memory buffers on a single chip with a 10-MHz shift rate and a 1,000-bit length for each register, the average access time is 50 μsec. Taking data from 50 registers in parallel, one chip allows a 133.3 kbit block to be transmitted in less then 300 μsec resulting in a 0.3-msec block acquisition time. For 16 channels (8 transmit, 8 receive) per ground station, the module memory capacity is about 2 Mbits. Organization for smaller acquisition times would be straightforward and quite plausible by shortening the registers, using more chips in parallel or increasing the shift rate. The dominant cost item is memory, so a buffer for more channels at lower data rates could be nearly identical.

Projections for the early 1980's show a CCD cost of about 20 to 50 millcents per bit at these access times, including controls and buffering (Feth, 1976). For a 2-Mbit system (memory for 16 simultaneous links), the resulting cost per ground station is about $600 (1979). On a per link basis the cost is about $40 (1979). Since this cost is low by 1979 standards and the projected technology gains may not be realized, the per link cost is increased to $500 (1979) or $8K per ground station.

See references at the end of Chapter 5.

APPENDIX A5.2

CODEC

In this appendix the characteristics of a convolutional encoder/Viterbi decoder are used to estimate the cost of the CODEC.

Consider a convolutional encoder with a K-stage shift register. Assume k data bits are shifted each cycle through the shift register and n parity sums are formed to give a k/n encoding rate.

One decode cycle gives k decoder output bits. Assuming a Viterbi decoder, there are 2^K lookup, add and compares per decode cycle at data rate R or $\frac{R}{k} 2^K$ lookup, add and compares per second. There are 2^{K-k} old paths to consider each about 4K bits long, or $4K2^{K-k}$ path-bits to be stored. There are also 2^{K-k} path metrics. Each metric has $(\log_2 \frac{Kn}{k} + n_{MF})$ bits, where n_{MF} is the bits for matched-filter quantization, or a total $(\log_2 \frac{Kn}{k} + n_{MF})2^{K-k}$ metric-bits to be stored. Hence, the total decoder memory per channel is about $(4K + \log_2 \frac{Kn}{k} + n_{MF})2^{K-k}$ bits.

Assuming rate 2/3 encoding with K = 4, k = 2, n = 3, and n_{MF} = 8, the memory required is about 45 bits per channel. The speed is 8R for each lookup, add and compare. Assuming each lookup and compare is equivalent to an add, for R = 35 Mbps the speed is about 840 Mops/sec/channel. These numbers show that the speed to implement the Viterbi decoder is the dominant cost driver.

At present a chip can perform an 8-bit multiply in 70 nsec and costs $70 (1979) in lots of 100 units (TRW/TDC-1008J). Assuming this chip is equivalent to a 7-nsec add or 140 Mops/sec, paralleling six chips to allow for overhead gives a recurring cost of $450 (1979) per channel in lots of 100 units.