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30/20 GHz COMMUNICATIONS SATELLITE TRUNKING NETWORK STUDY

October 1981

Prepared for
NASA LEWIS RESEARCH CENTER
21000 BROOKPARD ROAD
CLEVELAND, OHIO 44135
under Contract NAS3-22496

ARINC RESEARCH CORPORATION

30/20 GHz COMMUNICATIONS SATELLITE TRUNKING NETWORK STUDY

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NASA Lewis Research Center
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EXECUTIVE SUMMARY

It is projected that the domestic satellite communications network will become saturated between the years 1990 and 2000 unless alternatives are found to alleviate the burden that growing demand places on the network. Advanced satellite technology being developed by NASA offers an attractive solution to this problem.

This report describes a study conducted by ARINC Research Corporation for NASA Lewis Research Center under Contract NAS3-22496. The study examined a number of alternative transmission systems so that it may be determined where advanced satellite systems can economically compete with trunking systems that use other technologies. The study considered domestic intercity voice, data, and video traffic projections for the period 1990 through 2000. Three scenarios were developed, representing three possible levels of implementation -- a 10-city network, a 20-city network, and a 40-city network. The cities in each case were selected from the top 275 major metropolitan areas.

The alternative technologies considered for each network included microwave radio, coaxial cable, fiber-optic cable, combined C- and Ku-band satellites, and 30/20 GHz satellites. The lowest-cost systems were mixtures of fiber-optic cable and satellite technology. Table S-1 shows the mix of these technologies found to be best for each network. On the basis of cost per video channel mile, a 20-city network was determined to be optimal in 1990. The 20-city network was particularly well matched to the 1990 design assumptions for 30/20 GHz satellites. The 40-city network, however, exhibited lower cost per mile using C- and Ku-band satellites. The 20-city network can also be expanded in the year 2000 to at least 40 cities, using 30/20 GHz technology, with no increase in the average cost per channel mile.

The study considered all intercity traffic carried more than 40 miles. In general, traffic less than 500 miles away was found to be better served by fiber-optic cable in 1990. By the year 2000, the crossover point would be down to 200 miles. All traffic beyond 500 miles is more economically served by satellite. Figure S-1 compares the most economical fiber-optic routes in 1990 with those in 2000. The competitive pressure of 30/20 GHz satellites over this 10-year period would essentially eliminate fiber-optic cables from consideration in the 10-city network. This emphasizes the need for long-term facility planning by communications carriers.

Table S-1. COSTS OF COMBINED FIBER-OPTIC CABLE AND SATELLITE NETWORKS

Number of Cities	Year	Crossover Point (Miles)	Type of Satellite	Average Cost per Video Channel Mile	Total System Cost (Millions of Dollars)
10	1990	500	30/20 GHz	273	102.2
10	2000	200	30/20 GHz	128	172.5
20	1990	500	30/20 GHz	243	157.1
20	2000	200	30/20 GHz	112	262.7
40	1990	800	C/Ku Band	344	402.2
40	2000	200	30/20 GHz	108	456.7

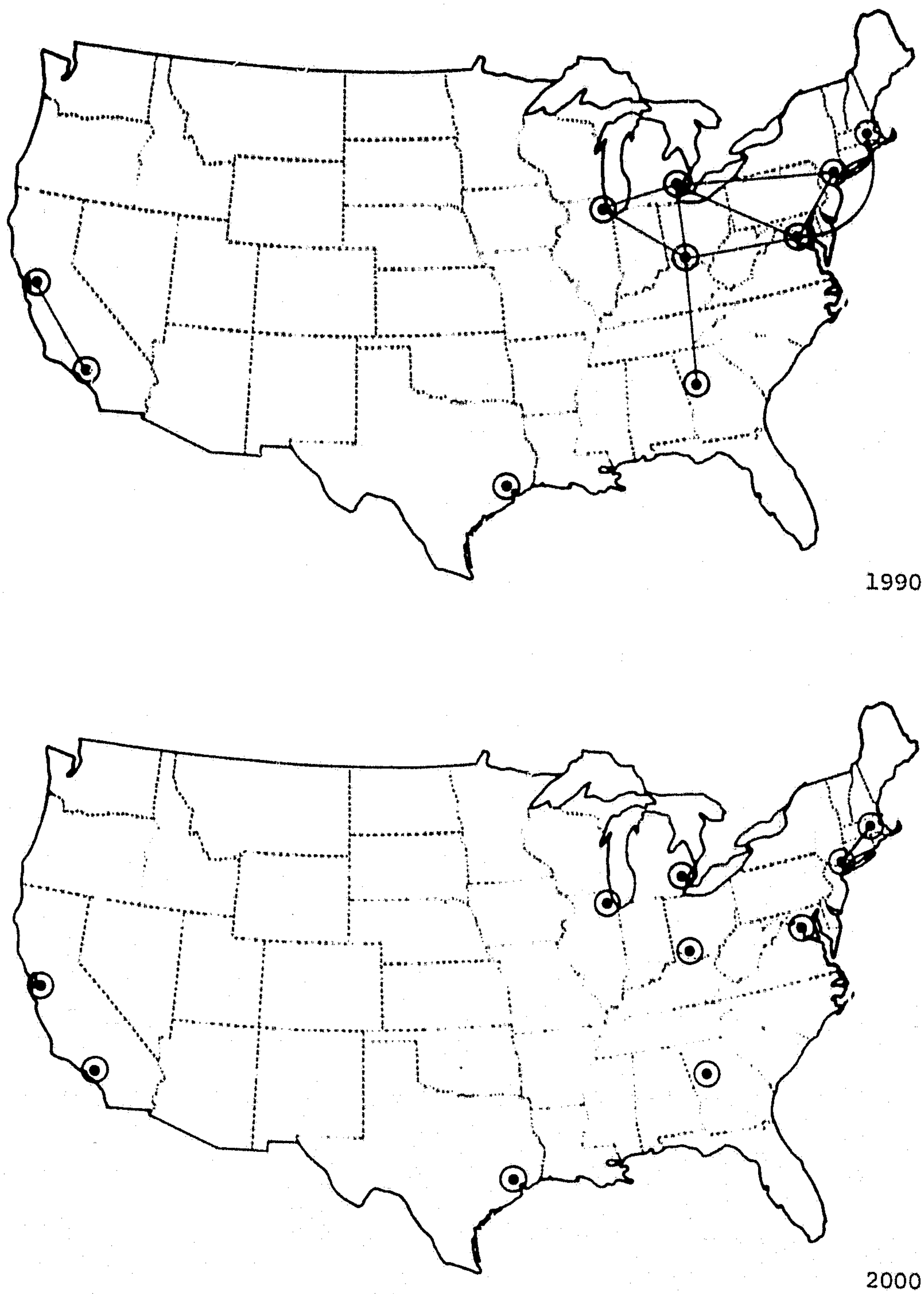

Figure S-1. COMPARISON OF FIBER-OPTIC CABLE ROUTES IN 1990 AND 2000 FOR A 10-CITY NETWORK

CHAPTER ONE

30/20 GHZ COMMUNICATIONS SATELLITE TRUNKING NETWORK STUDY

1.1 INTRODUCTION

The ability of the U.S. communications industry to continue to provide domestic services depends on its ability to meet a rapidly expanding demand for voice, data, and video services. Current trends indicate that major new systems must be installed during the next two decades to keep pace with demand. One promising solution to accommodate this unprecedented growth is the development of 30/20 GHz satellite communications technology.

This report describes a study conducted by ARINC Research to determine the most logical role for 30/20 GHz technology within the U.S. domestic marketplace. The study addressed the following major questions:

- What is the projected annual cost* of a 30/20 GHz communications satellite trunking system in 1990 and 2000?
- In view of competing technologies such as microwave radio, coaxial cable, fiber-optic cable, and C/Ku-band satellites, where are 30/20 GHz satellites likely to be used?
- On the basis of cost, what is the optimum configuration for a 30/20 GHz satellite trunking system?

1.2 SCOPE

The study focused on the growth in telecommunications services between the years 1980 and 2000 and the alternative technologies to be used to meet the projected increase in demand. Traffic demand satisfied by existing 1980 systems was not included, and only that portion of the future demand which represents a suitable target for satellite transmission was considered. For the purpose of this study, estimates of voice, data, and video demands for the busy hour were aggregated and treated as wideband traffic. The analysis was limited to three network scenarios -- configurations comprising 10, 20, and 40 cities. In each instance, these cities were selected from the top U.S. metropolitan areas on the basis of volume of communications traffic.

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*As used throughout this report, the term "cost" is the actual cost of providing a service without profit; "price" is the cost to the user.

Cost projections for satellite and terrestrial networks were based on advancing technology and quantity buying. The costs of local distribution tail circuits and central-office switching were not included, because these costs would be essentially the same regardless of the long-haul transmission media employed. The study only addressed system costs and did not attempt to project cost to the user, which may vary substantially depending on the carrier. All costs shown in this report are in 1980 dollars.

1.3 APPROACH

Several NASA studies have investigated communications media cost trends and traffic forecasts for the next two decades. These studies formed the basis of this analysis; they are referenced wherever they are used. A number of terrestrial-transmission alternatives described in these studies were compared, and the most cost-effective of these was chosen as the principal alternative to a satellite system. In this manner, the design of networks combining both terrestrial and satellite technologies was simplified.

Estimates of traffic for the years 1990 and 2000 were used to develop various network configurations so that network costs could be determined. On the basis of annualized capital and recurring costs, an optimal mix of terrestrial and satellite technologies was found.

Figure 1-1 illustrates the general procedure used in conducting the analysis. The process was repeated for 10-, 20-, and 40-city systems for the years 1990 and 2000. The results were used to determine the most cost-effective configuration for a 30/20 GHz satellite system.

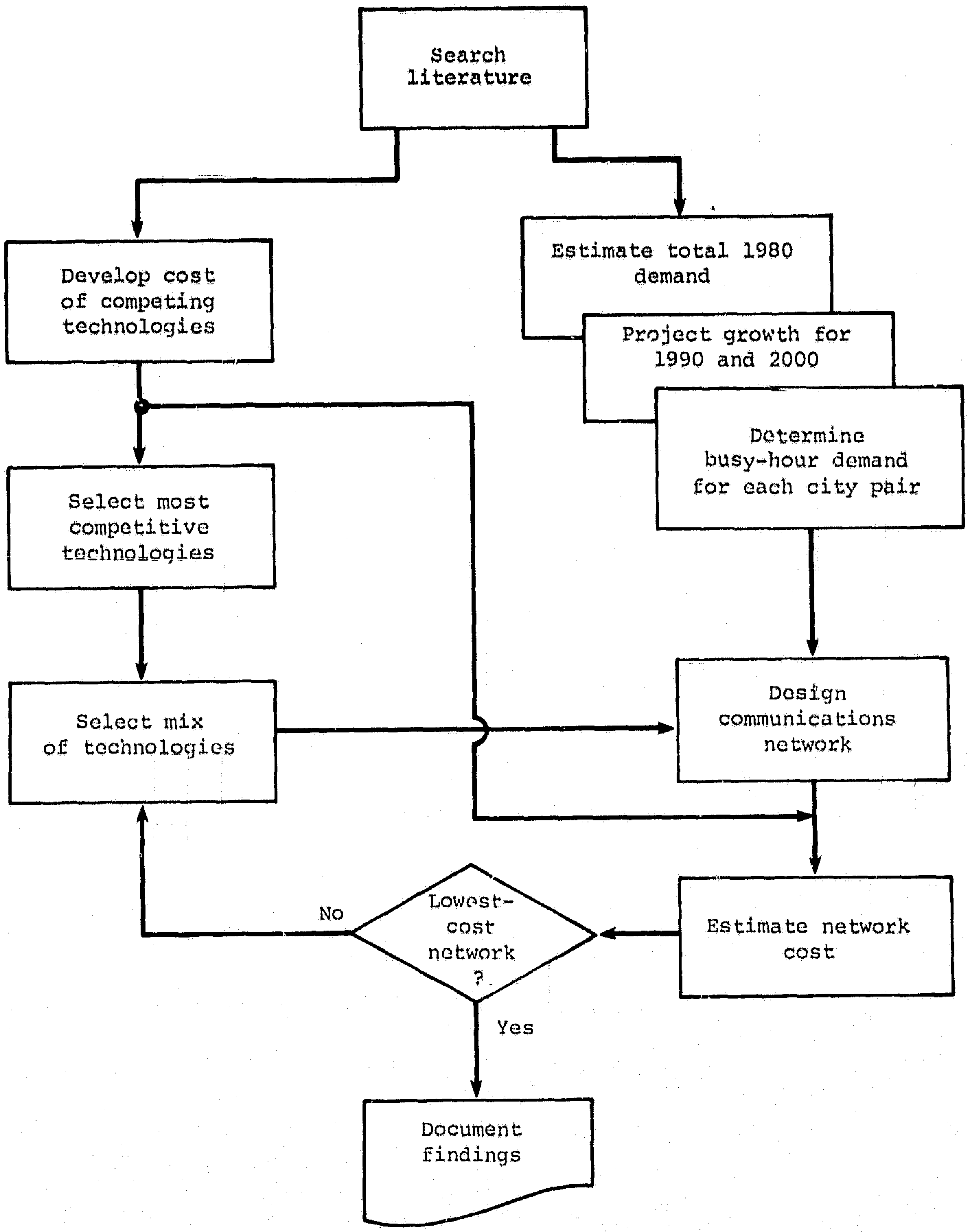

Figure 1-1. GENERAL APPROACH OF THE ANALYSIS

CHAPTER TWO

TRAFFIC PROJECTIONS

To design a communications network, traffic flow and volume must be specified so that the appropriate number of channels and the size of transmission facilities needed may be determined. The following sections document the development of traffic estimates for this purpose.

2.1 CURRENT NETWORK DEMAND

NASA provided three traffic matrices corresponding to 1980 demand between all pairs of cities in the current network (see Appendix A). The three matrices, representing 10-, 20-, and 40-city networks, were generated by the Western Union (WU) Market Distribution Model. Table 2-1 presents some statistics related to these networks. The demand between each city pair is expressed as a percentage of the total demand among the top 275 U.S. cities. Although more cities could have been included, the top 275 account for almost 85 percent of all intercity traffic.* The remaining intercity traffic, intracity traffic, and traffic carried less than 40 miles were excluded from the study as being inappropriate for satellite transmission.

2.2 FUTURE GROWTH

According to the WU report, approximately 88 percent of the 1980 demand is dedicated to voice services, about 11 percent is used for video services, and the remaining 1 percent is for data.** The report projected that voice traffic will increase 9.9 percent annually, video traffic 4.9 percent annually, and data traffic 17.6 percent annually.† Similar projections by

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*Western Union Telegraph Company, *18/30 GHz Fixed Communications System Service Demand Assessment*, Volume II, July 1979, p. 29. This study is referred to hereafter in this report as WU.

***Ibid.*, p. 79.

†*Ibid.*, p. 75. Average annual growth rates from 1980 to 1990.

Table 2-1. CHARACTERISTICS OF 1980 TRAFFIC			
Parameters	10-City Network	20-City Network	40-City Network
Percent of Total Intercity Demand Represented*	12.4	24.2	43.0
Percent of Demand Carried up to 500 Miles	24.9	33.7	32.4
Percent of Demand Carried up to 1,000 Miles	58.1	60.3	57.1
Average Distance Carried (Miles)	1,036	1,021	1,154
*Demand among the top 275 cities equals 100 percent.			

International Telephone and Telegraph (ITT) are in general agreement, but are lower because of somewhat different assumptions such as exclusion of all traffic carried less than 200 miles. The higher projections by WU were used throughout this study to estimate worst-case network costs. Table 2-2 shows the busy-hour traffic projected by WU and ITT for the years 1980, 1990, and 2000. (For this study, all traffic is expressed in digital equivalents.*)

Future communications systems need not be designed to carry the entire domestic-traffic demand, because existing systems already serve a significant portion of the total traffic. The traffic demand assumed in this study is therefore the difference between current and future traffic estimates. When these differences are combined with percentages from the traffic matrices, the projected demand between any city pair may be determined. Table 2-3 shows the derivation of estimated traffic volume for each network under consideration. The demand thus calculated was used for costing purposes in the design of each network.

*A full-duplex voice channel is assumed to equal 64 kbps; a typical video channel is assumed to equal 42 Mbps.

Table 2-2. BUSY-HOUR TRAFFIC PROJECTIONS

Year	Voice	Data	Video	Total
Western Union Estimates (Gbps)*				
1980	67.2	0.6	8.3	76.2
1990	170.1**	3.7	12.6	186.5
2000	440.7	16.0	17.9	474.5
ITT Estimates (Gbps)†				
1980	44.0	20.6	2.9	67.5
1990	107.9	51.1	13.2	172.2
2000	205.1	78.8	37.9	321.8

*WU, p. 79.

**Corrected data.

†U.S. Telephone and Telegraph Corporation, *30/20 GHz Fixed Communications Systems Service Demand Assessment*, Volume II, August 1979, p. 276. This study is referred to hereafter in this report as ITT.

Table 2-3. ESTIMATED TRAFFIC VOLUME FOR EACH NETWORK

Year	Total Traffic (Gbps)*	Percent of Total Demand	Estimated Network Traffic (Gbps)
10-City Network			
1990	110.3	12.4	13.7
2000	398.3	12.4	49.4
20-City Network			
1990	110.3	24.2	26.7
2000	398.3	24.2	96.4
40-City Network			
1990	110.3	43.0	47.4
2000	398.3	43.0	171.3

*Increase over 1980 net long-haul traffic totals. WU, p. 79.

CHAPTER THREE

NETWORK DESIGN

3.1 INTRODUCTION

Traffic estimates developed in Chapter Two were used to determine the number of channels required between each city pair. This in turn dictated the size of each transmission facility and the amount of equipment necessary. This chapter describes the methods used to design each network and the results of the design effort.

All terrestrial trunking systems were laid out on a fully interconnected airline-mile basis (see Figure 3-1). In practice, however, terrestrial systems usually consist of a backbone network with spurs connecting cities not directly on the backbone, as in Figure 3-2. This is a practical and economical limitation of conventional point-to-point transmission systems. Mileage penalties in a backbone network can amount to 20 percent or more as a result of indirect routes connecting cities. Furthermore, it is accepted practice to overdesign such networks by as much as 50 to 100 percent so that peak periods and future traffic growth may be accommodated. The result of these design considerations can be a system with many more miles and channels than at first appears necessary. For comparative purposes, however, excess capacity and mileage penalties were excluded from all terrestrial and satellite network designs. The costs of these systems as they would actually be implemented are therefore understated.

To estimate the cost of a fully interconnected terrestrial network, two factors are needed -- the distance between each city pair and the traffic between them. The American Telephone and Telegraph (AT&T) V&H coordinate system was used to obtain the mileage between each pair of cities, and busy-hour traffic was estimated for each scenario from the totals in Table 2-3 and the percentages in the traffic matrices. Table 3-1 shows the breakdown of traffic demand by distance and the percentage of total traffic carried by each network studied. A computer program was employed to simultaneously calculate channel capacity, length, and cost. The results are presented in Chapter Four.

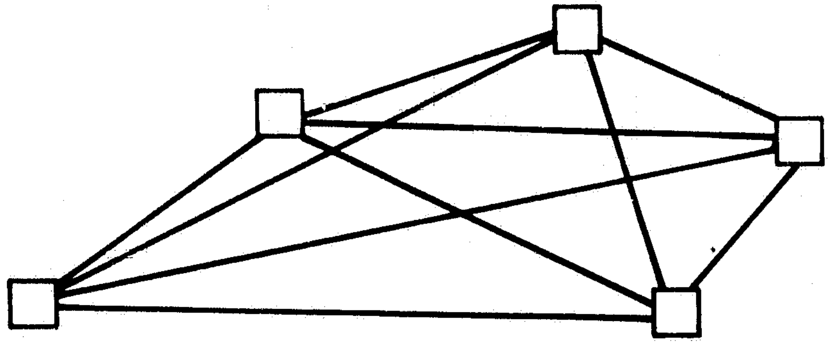


Figure 3-1. FULLY INTERCONNECTED TERRESTRIAL NETWORK

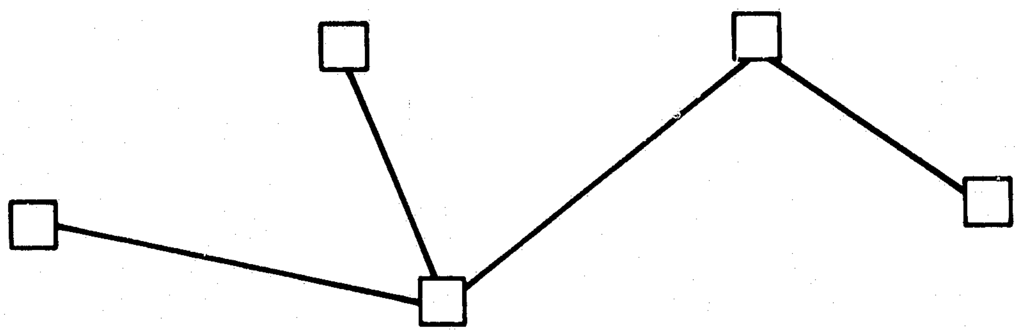


Figure 3-2. BACKBONE TERRESTRIAL NETWORK

Table 3-1. BREAKDOWN OF TRAFFIC DEMAND BY DISTANCE

Distance (Miles)	10-City Network		20-City Network		40-City Network	
	Demand (Percent)*	Cumulative Demand (Percent)	Demand (Percent)*	Cumulative Demand (Percent)	Demand (Percent)*	Cumulative Demand (Percent)
50 - 100	0.000	0.000	1.765	1.765	3.725	3.725
101 - 200	0.481	0.481	1.349	3.114	2.143	5.868
201 - 300	1.187	1.668	1.464	4.578	2.511	8.379
301 - 400	0.810	2.478	2.043	6.621	2.914	11.293
401 - 500	0.692	3.080	1.531	8.152	2.624	13.917
501 - 600	1.329	4.409	1.614	9.766	1.976	15.893
601 - 700	0.131	4.540	0.839	10.605	1.970	17.863
701 - 800	2.131	6.671	2.193	12.798	2.874	20.737
801 - 900	0.233	6.904	0.941	13.739	1.709	22.446
901 - 1,000	0.272	7.176	0.821	14.560	2.136	24.582
1,001 - 1,500	0.810	7.986	2.972	17.532	6.507	31.089
1,501 - 2,000	2.038	10.024	2.592	20.124	5.195	36.284
2,001 - 2,500	1.619	11.643	2.921	23.045	5.215	41.499
2,501 - 3,000	0.709	12.352	1.111	24.156	1.515	43.014

*Among the top 275 metropolitan areas.

3.2 SATELLITE NETWORK DESIGN

The total number of earth stations and satellites in any network design is highly dependent on the design assumptions. Reasonable capacity for operational 30/20 GHz trunking systems for the years 1990 and 2000 was estimated on the basis of data from several prospective suppliers. The parameters assumed are believed to be conservative. Design assumptions for combined C- and Ku-band satellites were based on technology spin-offs from the 30/20 GHz program that would permit frequency reuse in these bands. These assumptions may also prove to be somewhat conservative for 1990 and 2000.

Table 3-2 outlines critical design parameters for the 30/20 GHz satellite. The satellite is presumed to contain spot beams, each of which illuminates a single city. The half-duplex capacity of a spot beam was limited to 500 megabits per second (Mbps) in 1990, increasing to 1 gigabit per second (Gbps) by 2000. These values represent a design compromise between a few very-high-volume cities and many low-volume cities. Transmission rates of up to 2.5 Gbps, however, are theoretically achievable, based on available bandwidth. An on-board satellite switch capable of dynamically switching traffic between spot beams was presumed to have an effective throughput (input plus output) of 12 Gbps in 1990 and 20 Gbps in 2000. The number of spot beams was fixed at 12 in 1990 and 20 in 2000.

Table 3-2. 30/20 GHZ SATELLITE DESIGN ASSUMPTIONS

Feature	1990	2000
Number of Spot Beams	12	20
Capacity of Each Spot Beam	0.5 Gbps	1.0 Gbps
Satellite Throughput	12.0 Gbps	20.0 Gbps

In this study, combined C- and Ku-band satellites were assumed to obtain the maximum possible throughput for a satellite. C/Ku-band satellites were presumed to have two area beams capable of geographically dividing the United States so that the same frequency could be reused. Highly directional earth-station antennas using cross-polarization would reduce interference with other satellites using the same frequencies. An on-board switch capable of dynamic switching between beams would also be required. No significant improvements in C- and Ku-band satellite capacity between 1990 and 2000 was projected because of the limited bandwidth available. Table 3-3 lists the characteristics assumed for C/Ku-band satellites; the half-duplex capacity of each C- and Ku-band area beam was limited to 1 Gbps, based on bandwidth limitations.

Table 3-3. C- AND KU-BAND SATELLITE DESIGN ASSUMPTIONS	
Feature	1990 and 2000
Transponders (42 Mbps each)	48
Area Beams	2
Beam Capacity	1 Gbps
Satellite Throughput	4 Gbps

A computer model was employed to determine how many satellites and earth stations would be required for each network. The model assigned cities to a given satellite until the switch capacity was exceeded. No more than one beam per satellite was permitted to cover a given city to eliminate interference, and beam capacities were not allowed to exceed the limits shown in Tables 3-2 and 3-3. For the beam assignments, it was assumed that half the traffic between each city pair originated in one city and half originated in the other. The model was exercised in such a way as to derive a near-optimal assignment of cities to satellites. In most cases it tended to minimize the number of satellites and earth stations required. A more detailed discussion of the computer model is contained in Appendix B, and Appendix C is a FORTRAN listing of the model.

Table 3-4 illustrates how typical assignments were made for both C/Ku-band and 30/20 GHz satellites. Table 3-5 shows the number of satellites and earth stations required for each network. With one exception, the number of satellites and earth stations is less when 30/20 GHz technology is used. The difference is most pronounced in the year 2000, when projected traffic volume is highest. Earth stations were classified according to capacity, with the smallest station given an arbitrary transmission rate of 125 Mbps.

ITT estimated the maximum number of C- and Ku-band satellites to be 32, on the basis of three-degree spacing to limit interference and the necessity for sharing the orbital arc with other western hemisphere nations.* Under these assumptions, it would appear that C/Ku-band systems alone will be inadequate for the 20- and 40-city networks in the year 2000. The increased capacity of 30/20 GHz satellites will therefore be extremely important as the spectrum becomes more crowded.

3.3 HYBRID NETWORKS

In general, terrestrial networks are more cost-effective at shorter distances than are satellites, which are insensitive to distance. A certain combination of terrestrial and satellite technologies can thus lead to lower

*ITT, p. 247.

Table 3-4. SATELLITE ASSIGNMENTS FOR 10 CITIES IN 1990

C and Ku Band (Two Beams)			30/20 GHz (Ten Beams)		
Satellite Number	Cities Served	Satellite Utilization	Satellite Number	Cities Served	Satellite Utilization
1	New York, Los Angeles, Chicago	1.00	1	New York, Los Angeles, Chicago, Detroit, Washington, San Francisco, Boston, Cincinnati, Atlanta, Houston	0.87
2	New York, Chicago, Detroit, Washington, San Francisco, Boston	1.00	2	New York, Los Angeles, Chicago, Detroit, Washington, San Francisco, Cincinnati, Atlanta, Houston	0.46
3	New York, Los Angeles, Chicago Boston, Cincinnati, Atlanta, Houston	1.00	3	New York, Los Angeles, Chicago, Detroit, Washington, San Francisco, Boston	0.45
4	Los Angeles, Detroit, Washington, San Francisco, Chicago, Boston, Cincinnati	1.00	4	New York, Los Angeles, Chicago, Washington, San Francisco, Boston, Cincinnati, Atlanta, Houston	0.58
5	Los Angeles, Chicago, Detroit, Washington, San Francisco, Boston, Cincinnati, Atlanta, Houston	1.00	5	New York, Los Angeles, Boston, Cincinnati, Atlanta, Houston	0.24
6	Chicago, Detroit, Washington, San Francisco, Boston, Cincinnati, Atlanta, Houston	1.00	6	New York, Atlanta, Houston	0.13
7	San Francisco, Boston, Cincinnati, Atlanta, Houston, Washington	0.81			

Table 3-5. SATELLITE AND EARTH-STATION REQUIREMENTS

Number of Cities	Year	Number of Satellites	Number of Earth Stations				Total Number of Earth Stations
			125 Mbps	250 Mbps	500 Mbps	1,000 Mbps	
C and Ku Band							
10	1990	7	6	23	11	6	46
10	2000	25	4	19	30	41	94
20	1990	14	87	34	13	12	146
20	2000	49	84	65	61	66	276
40	1990	24	407	28	18	21	474
40	2000	86	532	113	79	106	830
30/20 GHz							
10	1990	6	8	8	27	N/A	43
10	2000	11	5	9	10	17	41
20	1990	9	23	30	48	N/A	101
20	2000	16	18	21	53	33	125
40	1990	33	260	67	59	N/A	386
40	2000	21	54	87	94	56	291

overall system costs than either technology alone. To derive the optimal hybrid network consisting of both technologies, several computer runs for each network were made, excluding various city pairs closer together than a given mileage. Separate satellite networks were designed for various distances. These configurations are shown in Table 3-6. Traffic that was not included within a given mileage area is carried by a terrestrial system.

Table 3-6. 30/20 GHZ SATELLITE NETWORK CONFIGURATIONS

Number of Cities	Year	Number of Satellites	Number of Earth Stations				Total Number of Earth Stations	Percent of Total Demand Carried
			125 Mbps	250 Mbps	500 Mbps	1,000 Mbps		
0 to 3,000 Miles								
10	1990	6	8	8	27	N/A	43	100.0
10	2000	11	5	9	10	17	41	100.0
20	1990	9	23	30	48	N/A	101	100.0
20	2000	16	18	21	53	33	125	100.0
40	1990	33	260	67	59	N/A	386	100.0
40	2000	21	54	87	94	56	291	100.0
200 to 3,000 Miles								
10	1990	6	8	7	25	N/A	40	96.1
10	2000	10	6	8	8	15	37	96.1
20	1990	8	20	31	38	N/A	89	87.1
20	2000	12	17	14	49	29	109	87.1
40	1990	28	227	54	53	N/A	334	86.4
40	2000	18	62	101	63	43	269	86.4
500 to 3,000 Miles								
10	1990	5	9	5	20	N/A	34	75.1
10	2000	8	4	3	10	12	29	75.1
20	1990	6	23	21	26	N/A	72	66.3
20	2000	10	9	14	34	24	81	66.3
40	1990	25	212	41	37	N/A	290	67.6
40	2000	14	63	53	63	35	214	67.6
800 to 3,000 Miles								
10	1990	4	5	10	10	N/A	25	46.0
10	2000	7	3	5	9	10	27	46.0
20	1990	6	26	17	18	N/A	61	47.0
20	2000	10	14	19	25	16	74	47.0
40	1990	20	179	36	24	N/A	239	51.8
40	2000	13	36	47	68	26	177	51.8

CHAPTER FOUR

SYSTEM COST ANALYSIS

4.1 INTRODUCTION

This section describes how costs were developed for various competing terrestrial and satellite communications technologies. The most economical terrestrial technology was combined with a satellite system to determine the least-expensive combination. Throughout, satellite earth stations were assumed to be collocated with major telephone company switching centers. Neither the wideband channel equipment required to connect with the terrestrial switched network nor the terrestrial tail circuits were included in any of the cost comparisons. These costs would be essentially the same regardless of the long-haul transmission media used.

4.2 TERRESTRIAL SYSTEMS

Primary candidates for wideband terrestrial channels of the future include microwave radio, coaxial cables, and fiber-optic cables. An in-depth analysis of the costs associated with each of these is presented in the ITT report and summarized in Table 4-1. The costs shown for each transmission medium include installation, depreciation, maintenance, real estate, and administration. The ITT analysis is based on the probable mix of analog and digital technology over the next two decades for both long-haul and short-haul channels using 90 Mbps facilities. These projections provide a reasonable base for the current study and are consistent with our expectations.

The least expensive wideband transmission medium in 1980 is microwave radio. By the end of the decade, however, it is projected that fiber-optic cable costs will fall below both radio and coaxial cable and will remain there. Fiber-optic systems were therefore selected as the most cost-effective terrestrial technology to be combined with a satellite system. No further consideration was given to the use of radio or coaxial cable in the current study, since both result in greater terrestrial network costs than does fiber-optic cable.

Fiber-optic cost can be estimated on the basis of video channel mile from data in the ITT study. Table 4-2 shows the variation in cost. For mileages not contained in the table, the following relationship was devised:

$$\text{Annual cost per mile in 1976} = 7{,}250\ m^{-0.3} \qquad (1)$$

Table 4-1. ANNUAL RECURRING COSTS PER TERRESTRIAL VIDEO CHANNEL MILE (DOLLARS)		
Facility	50-Mile Circuit*	500-Mile Circuit**
1980		
Microwave Radio	1,392	704
Coaxial Cable	1,495	1,034
Fiber-Optic Cable	1,960	993
1990		
Microwave Radio	1,214	615
Coaxial Cable	1,413	954
Fiber-Optic Cable	1,140	552
2000		
Microwave Radio	1,203	612
Coaxial Cable	1,376	888
Fiber-Optic Cable	1,128	541

*ITT, p. 241.
**ITT, p. 230. (A conversion factor of 1.346 was applied to ITT total weighted costs to obtain 1980 dollars.)

where

m = miles

This formula, which was obtained using standard curve-fitting techniques, is especially suitable for distances greater than 40 miles. The cost per mile is expected to decline significantly for longer circuits as costs of system engineering, maintenance, and fiber production are distributed over more miles.

The ITT study also shows how fiber-optics are expected to decline in cost as the technology matures. Table 4-3 illustrates the leveling-off expected by 1990 and the almost constant cost thereafter. If the annual

Table 4-2. FIBER-OPTIC COSTS PER VIDEO CHANNEL MILE IN 1976*	
Distance (Miles)	Annual Cost per Video Channel Mile (Dollars)
1	7,100
10	3,646
20	3,206
30	2,863
50	2,256
500**	1,124

*ITT, p. 239.
**ITT, p. 227. (Converted to 1980 dollars.)

Table 4-3. DECLINE IN FIBER-OPTIC COSTS WITH TIME	
Year	Cost per Video Channel Mile (Dollars)*
1976	2,256**
1980	1,960†
1990	1,140†
2000	1,128†

*Based on a 50-mile circuit.
**ITT, p. 239.
†ITT, p. 241. (Converted to 1980 dollars.)

cost is assumed to be constant after 1990, the cost per video channel mile from 1990 to 2000 can be estimated from formula 1, as follows:

Annual cost of a fiber-optic circuit after 1990 = (dollars per mile in 1976)(number of miles)(ratio of average cost after 1990 to cost in 1976)

$$= \left(7{,}250\ m^{-0.3}\right)(m)\left(\frac{1134}{2256}\right) \qquad (2)$$

$$= 4{,}195\ m^{0.7}$$

This relationship is based on a 90-Mbps full-duplex system and was used to estimate all terrestrial network costs in this study. The cost computed from formula 2 was linearly scaled for both higher- and lower-capacity fiber-optic channels.

Although fiber-optic costs were used as the basis for comparison with satellites, the difference between fiber-optic and microwave radio costs was not great. As shown in Table 4-4, the results of this study apply almost equally well if terrestial radio systems are substituted for fiber-optics.

Table 4-4. COMPARISON OF FIBER-OPTIC AND MICROWAVE RADIO COSTS (COST PER VIDEO CHANNEL MILE)

Length of Circuit (Miles)	1990 Fiber-Optic Costs	1990 Microwave Radio Costs
50	$1,140	$1,214
500	$ 552	$ 615

4.3 C- AND KU-BAND SATELLITE COSTS

Combined C- and Ku-band satellites being developed will have twice the capacity of an existing C-band satellite. Technology spin-offs from the 30/20 GHz program will further increase the capacity of C/Ku-band satellites. Thus a future C/Ku-band satellite using cross-polarized dual beams and an on-board switch could have a throughput capacity approaching 4 Gbps. Dual beams would be used to cover nonoverlapping geographical areas, permitting the reuse of frequencies; cross-polarization would minimize interference between beams. It is probable that by 1990 many transponder bandwidths and satellite capacities will exist. To simplify the current study, however, it was assumed that transponders with a usable bandwidth of about 42 Mbps would be common. Each satellite would carry 48 such transponders. Tracking, telemetry, and control facilities were assumed to be collocated with an earth station. On the basis of current industry experience with the INTELSAT series, it is estimated that a combined C- and Ku-band satellite would cost approximately $50 million. Table 4-5 shows the development of total on-orbit costs. No significant change in cost was projected between 1990 and 2000.

Earth-station costs would depend to some extent on capacity. Four stations of different sizes were therefore assumed -- a 125-Mbps station (with a 3-transponder capability), a 250-Mbps station (6 transponders), a 500-Mbps station (12 transponders), and a 1,000-Mbps station (24 transponders). Figure 4-1 shows a typical C/Ku-band earth-station configuration. Earth-station costs were based on probable decreases in cost resulting from

Table 4-5. COMBINED C- AND KU-BAND SATELLITE COSTS	
Cost Element	1990 Cost (Millions of Dollars)
Satellite (48 transponders)	50
Performance Fee	10
Shuttle Launch	30
Upper Stage	20
Insurance	12
Total	122
Annual Cost (10-year life)	12.2
Tracking, Telemetry, and Control	0.5
Total Annual Cost	12.7

advancing technology and quantity manufacturing. Earth-station specifications were based on current practices of communications carriers in the C-band. Table 4-6 shows how the cost estimates for C/Ku-band earth stations were developed.

Building and shelter costs increase somewhat faster than inflation. This has historically been the case when buildings and shelters are located within a major metropolitan area. High-power amplifiers (HPAs) were assumed to be the largest available. For Time Division Multiple Access (TDMA) operation, the trade-off between signal-to-noise and power would not substantially affect the cost.

One of the most expensive earth-station components is the TDMA burst modem. The current cost is about $35 thousand for a burst rate of 70 Mbps. By 1990, technology and volume are expected to reduce the price to about $25 thousand. One burst modem is required for each transponder with which the earth station must communicate. Channel units and port cards to interface baseband signals with these modems were not included in the cost estimate. Although their costs are fairly significant, they would be approximately the same for terrestrial and satellite systems alike. Other hardware costs were determined on the basis of current prices and our expectation of future reductions as a result of quantity buying and advancing technology. Operations and maintenance costs were based on coverage of 24 hours per day, with an average of two people per shift in three shifts. An average annual salary of $35 thousand was assumed, with 40 percent added for leave, holidays, and fringe benefits. Spares and inventory were 10 percent of annual capital costs. A general and administrative expense equal to 20 percent of the annual operating costs was included to cover management, engineering, services, accounting, and billing.

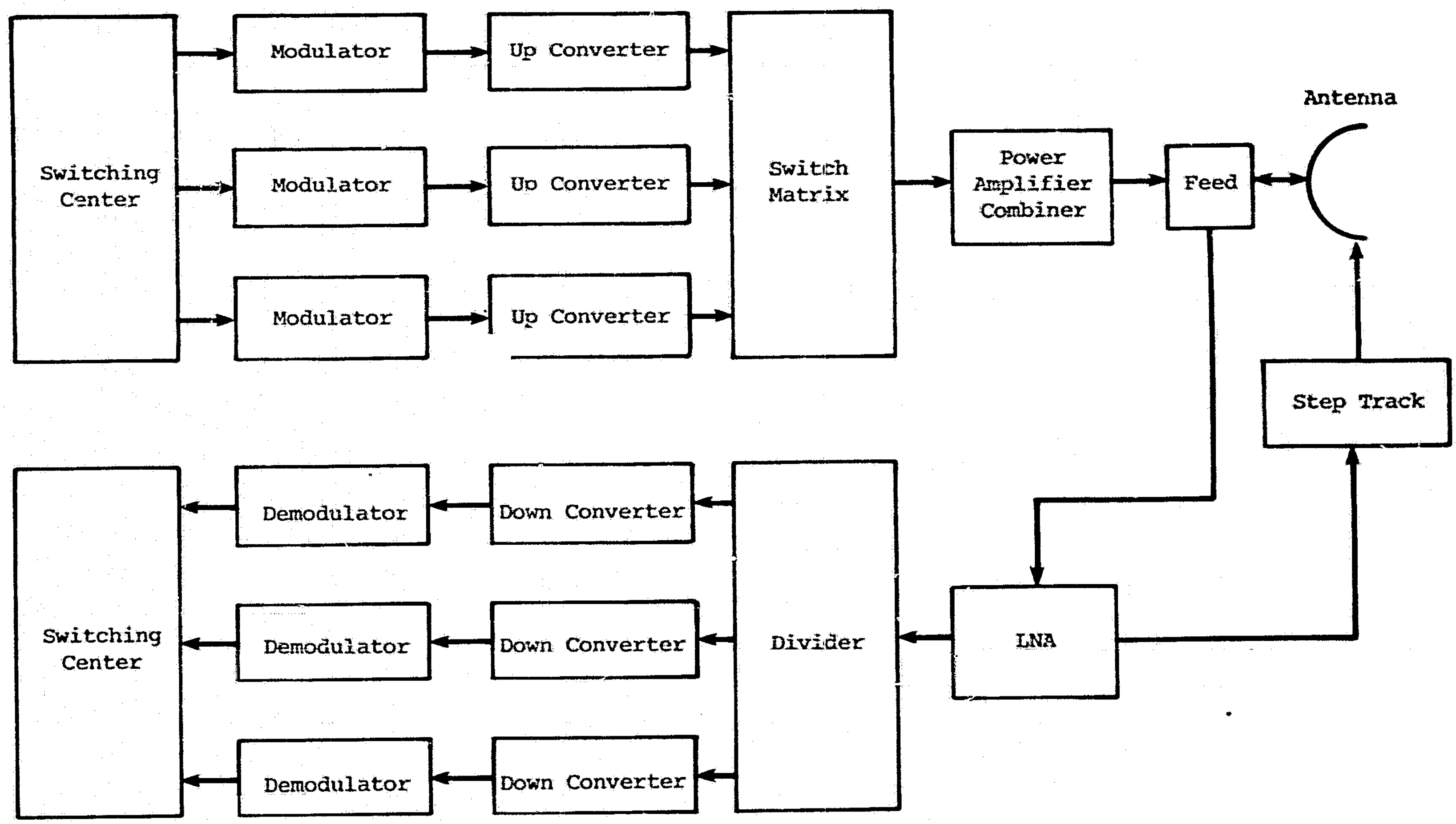


Figure 4-1. C/KU-BAND TERMINAL CONFIGURATION

Table 4-6. C- AND KU-BAND EARTH-STATION COSTS (THOUSANDS OF DOLLARS)

Cost Element	Single Station Purchase - 1980	Quantity Purchase - 1990				Quantity Purchase - 2000			
	125 Mbps*	125 Mbps	250 Mbps	500 Mbps	1,000 Mbps	125 Mbps	250 Mbps	500 Mbps	1,000 Mbps
13-Meter Antenna	180	90	90	90	90	80	80	80	80
LNA 35°K (Plus spare)	160	100	100	100	100	80	80	80	80
HPA 3 kW (Plus spare)	230	200	200	200	200	150	150	150	150
TDMA Burst Modems (One per transponder plus spares)	140	100	175	325	625	80	140	260	500
Up Converter (One per transponder)	30	30	60	120	240	10	10	10	10
Down Converter (One per transponder)	30	30	60	120	240	10	10	10	10
Step-Track System	10	10	10	10	10	10	10	10	10
Command and Control	20	20	20	20	20	15	15	15	15
Building and Shelter	65	80	80	80	80	100	100	100	100
Program Management and Installation	450	300	300	300	300	300	300	300	300
Total	1,315	960	1,095	1,365	1,905	835	895	1,015	1,255
Annual Cost (15-year life)	88	64	73	91	127	56	60	68	84
Operations and Maintenance	294	294	294	294	294	294	294	294	294
Spares and Inventory	9	6	7	9	13	6	6	7	8
General and Administrative	78	73	75	79	87	71	72	74	77
Total Annual Cost	469	437	449	473	521	427	432	443	463

*Station Size	Transponder Capability	Modems
125 Mbps	3	4
250 Mbps	6	7
500 Mbps	12	13
1,000 Mbps	24	25

4.4 30/20 GHZ SATELLITE COSTS

By the end of the decade, 30/20 GHz communications technology probably will have advanced to the point that an operational trunking system will be practical. The large uncertainty in 30/20 GHz satellite and earth-station cost estimates 10 years hence must be recognized. In most cases, conservative figures have been used so that costs would not be underestimated.

A 12-beam TDMA satellite configuration with on-board switching was assumed to be feasible in 1990. An input/output switching rate of 6 Gbps was presumed, for a total satellite throughput of 12 Gbps. To simplify the analysis, it was assumed that each spot beam on the satellite would illuminate a single city and have a usable bandwidth of 500 Mbps. By the year 2000, technology will have advanced enough to support 20-beam satellites with a switch throughput of 20 Gbps. Each spot beam in this scenario would have a usable bandwidth of 1,000 Mbps. (Rates of up to 2,500 Mbps are theoretically achievable, based on the bandwidth allocated to these frequencies.) Tracking, telemetry, and control facilities were assumed to be collocated with an earth station. Table 4-7 shows the development of 30/20 GHz satellite costs. Advancing technology is expected to produce satellites with a useful life of 10 years.

Table 4-7. 30/20 GHZ SATELLITE COSTS

Characteristics and Cost Elements	1990	2000
Characteristic		
Number of Spot Beams	12	20
Beam Capacity	500 Mbps	1,000 Mbps
Switch Throughput	12 Gbps	20 Gbps
Cost Element (Millions of Dollars)		
Satellite	53	63
Performance Fee	10	12
Shuttle Launch	30	30
Upper Stage	20	20
Insurance	12	12
Total	125	137
Annual Cost (10-year life)	12.5	13.7
Tracking, Telemetry, and Control	0.8	0.8
Total Annual Cost	13.3	14.5

30/20 GHz TDMA trunking earth stations (such as that shown in Figure 4-2) require terminal diversity. Use of TDMA offers greater savings in a large trunking system when compared with Frequency Division Multiple Access (FDMA). Each earth station would be backed up by a remotely operated diversity terminal to overcome path fade caused by heavy rain. An interconnecting microwave (or fiber-optic) link with relay and control equipment would be used to connect the main station with its diversity site. The cost of this equipment was derived on the basis of data obtained from a Ford Aerospace study.* At the frequencies used in this system, adequate gain can be achieved with smaller antennas. An eight-meter parabolic dish would provide sufficient gain for most earth stations; this was assumed for costing purposes.

It was assumed that each earth station would access a single wideband transponder on the satellite. Therefore, a single, high-burst-rate modem was sufficient for each earth station. Computations for operations and maintenance costs were based on coverage of 24 hours a day, with an average of two people per shift in three shifts. An average salary of $35 thousand was assumed, with 40 percent added for leave, holidays, and fringe benefits. Maintenance costs were 10 percent of annual capital costs, and general and administrative costs of 20 percent were included to cover management, engineering, services, accounting, and billing.

Table 4-8 shows the development of costs for 30/20 GHz earth stations for the years 1990 and 2000; price breaks for quantity and advancing technology are assumed.

4.5 NETWORK COST

The quantities in Table 3-5 may be used to estimate total costs in comparing satellite systems. Table 4-9 compares 30/20 GHz and combined C/Ku-band satellite networks. Both the 10- and 20-city networks were less costly with a 30/20 GHz system in 1990. The 40-city system could not be satisfactorily served with 30/20 GHz satellites because of the large demand carried and the limited capacity assumed in 1990. The situation in 2000, however, is completely different because of greater traffic volume and improvements in 30/20 GHz technology; here it is possible to cut annual costs by 49 to 68 percent in all cases.

A common-carrier system in 1990 or 2000 is likely to be a combination of terrestrial and satellite technologies. To determine the best mix of technologies from an economic point of view, various combinations of terrestrial and satellite technologies were considered. The terrestrial technology used in each case was fiber-optic cable.

Table 4-10 shows the annual cost when various portions of a given network are served by fiber-optic cable. These costs are based on the number of video channel miles required and the cost-estimating relationship

*Ford Aerospace and Communications Corporation, *Concepts for 18/30 GHz Satellite Communication System Study*, Volume 1, November 1979, p. 3.4-5.

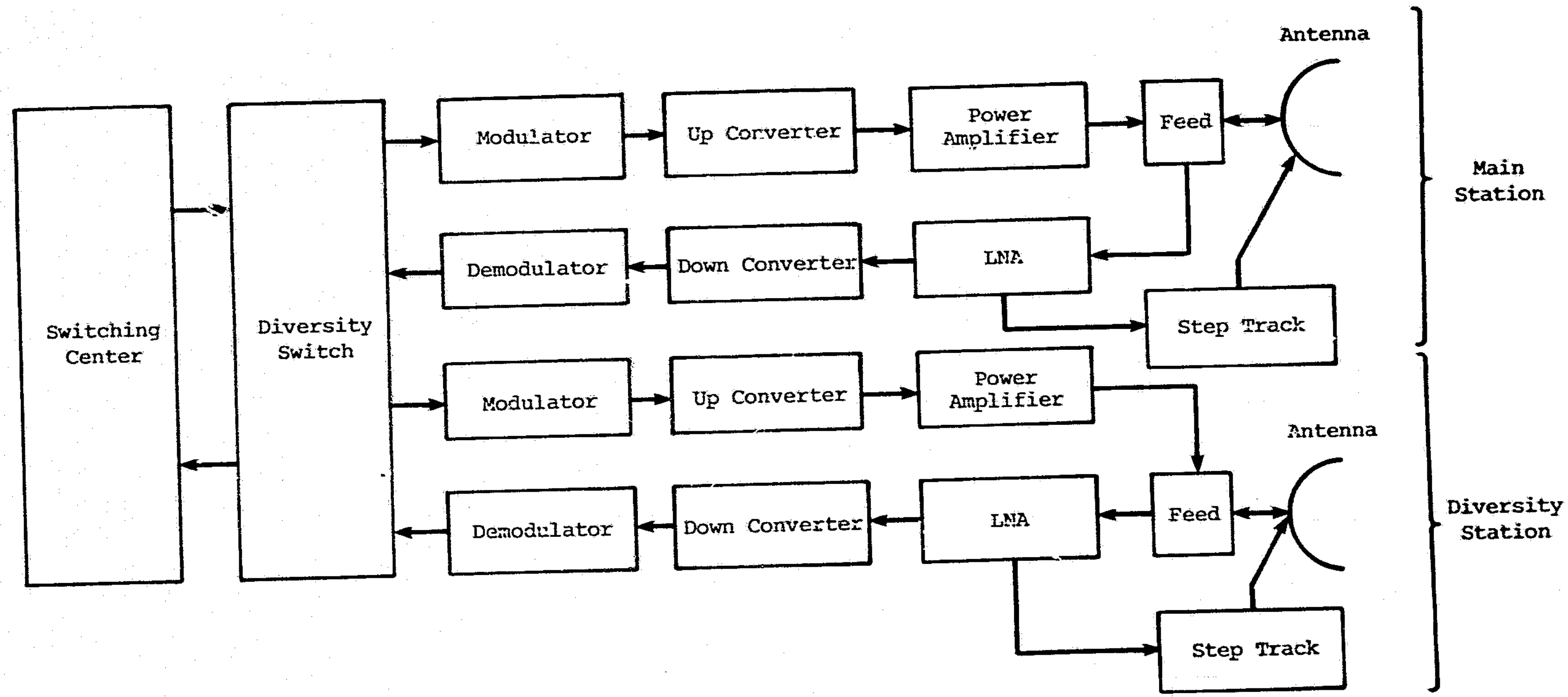


Figure 4-2. 30/20 GHZ TERMINAL CONFIGURATION

Table 4-8. 30/20 GHZ EARTH-STATION COSTS FOR 1990 AND 2000 (THOUSANDS OF DOLLARS)

Cost Element	1990 (Quantity Purchase)			2000 (Quantity Purchase)			
	125 Mbps	250 Mbps	500 Mbps	125 Mbps	250 Mbps	500 Mbps	1,000 Mbps
8-Meter Antenna	50	50	50	50	50	50	50
LNA 35°K (Plus spare)	100	100	100	80	80	80	80
HPA 3 kW (Plus spare)	200	200	200	150	150	150	150
TDMA Burst Modem (Plus spare)	50	70	90	50	70	90	120
Up Converter	10	10	10	10	10	10	10
Down Converter	10	10	10	10	10	10	10
Step-Track System	10	10	10	10	10	10	10
Command and Control	15	15	15	15	15	15	15
Diversity Interconnect	300	400	500	200	300	400	500
Building and Shelter	80	80	80	100	100	100	100
Program Management and Installation	300	300	300	300	300	300	300
Total	1,125	1,245	1,365	975	1,175	1,215	1,345
Annual Cost (15-year life)	75	83	91	65	78	81	90
Diversity Site	75	83	91	65	78	81	90
Operations and Maintenance	294	294	294	294	294	294	294
Spares and Inventory	15	17	18	13	16	16	18
General and Administrative	92	95	99	87	93	94	98
Total Annual Cost	551	572	593	524	559	566	590

Table 4-9. COMPARISON OF 30/20 GHZ AND C/KU-BAND SATELLITE NETWORKS (MILLIONS OF DOLLARS)				
Number of Cities	1990 Annual Cost		2000 Annual Cost	
	30/20 GHz	C/Ku Band	30/20 GHz	C/Ku Band
10	104.8	110.2	182.8	359.7
20	178.0	243.5	302.6	743.8
40	655.5	514.7	467.7	1,452.3

developed in Section 4.2. The remainder of each network is served using the least-expensive satellite technology. Satellite subsystem costs were computed from the quantities in Table 3-6 and the unit costs in Tables 4-7 and 4-8. The total system cost for each configuration was estimated by adding the cost of the fiber-optic subsystem to the cost of the satellite subsystem. These totals are shown in Table 4-11. A close look at the table reveals that there is an optimum combination of fiber-optic cable and satellite that results in minimum system cost. The crossover point in miles between fiber-optic cable and satellite that minimizes cost is highlighted in Table 4-11 for each scenario.

In general, 1990 traffic would be best served if all channels up to 500 miles in length were placed on fiber-optic cable. Because of the assumed limited capacity of satellites in 1990, the one exception would be the 40-city network, which would be more economically served if satellite channels less than 800 miles in length were omitted. In the year 2000, all channels less than 200 miles long should be placed in fiber-optic cable. The decline in economical fiber-optic routes due to competing satellite technology is illustrated in Figure 4-3. Channels installed in 1990 would not be economically competitive by 2000. *This presents a dilemma if fiber-optic cables have already been drawn 500 miles to meet 1990 demand. Obviously, long-range planning is required for any large-scale trunking system using advanced technology.*

4.6 OPTIMUM 30/20 GHZ CONFIGURATION

To obtain a comparison of the 10-, 20-, and 40-city networks shown in Table 4-11, the average cost per channel mile was computed. Table 4-12 compares these networks on the basis of video channel mile.

When costs of hybrid systems are compared with costs of terrestrial systems per video channel mile as in Table 4-1, it is apparent that satellites are capable of reducing overall network costs. Extensive use of satellite trunking systems in 1990, for example, could cut the average cost

Table 4-10. COMBINED FIBER-OPTIC AND SATELLITE NETWORK COSTS

Number of Cities	Year	Fiber-Optic Cable		Satellite Network			Total Annual Cost (Millions of Dollars)
		Crossover Points (Miles)	Annual Cost (Millions of Dollars)	Crossover Points (Miles)	Type of System	Annual Cost (Millions of Dollars)	
10	1990	0	–	0 – 3,000	30/20	104.8	104.8
10	2000	0	–	0 – 3,000	30/20	182.8	182.8
20	1990	0	–	0 – 3,000	30/20	178.0	178.0
20	2000	0	–	0 – 3,000	30/20	302.6	302.6
40	1990	0	–	0 – 3,000	C/Ku	514.7	514.7
40	2000	0	–	0 – 3,000	30/20	467.7	467.7
10	1990	0 – 200	1.8	200 – 3,000	30/20	103.0	104.8
10	2000	0 – 200	6.5	200 – 3,000	30/20	166.0	172.5
20	1990	0 – 200	7.5	200 – 3,000	30/20	157.7	165.2
20	2000	0 – 200	27.1	200 – 3,000	30/20	235.6	262.7
40	1990	0 – 200	12.6	200 – 3,000	C/Ku	456.6	469.2
40	2000	0 – 200	45.7	200 – 3,000	30/20	411.0	456.7
10	1990	0 – 500	16.0	500 – 3,000	30/20	86.2	102.2
10	2000	0 – 500	57.6	500 – 3,000	30/20	132.5	190.1
20	1990	0 – 500	36.0	500 – 3,000	30/20	121.1	157.1
20	2000	0 – 500	130.1	500 – 3,000	30/20	190.9	321.0
40	1990	0 – 500	58.8	500 – 3,000	C/Ku	364.6	423.4
40	2000	0 – 500	212.4	500 – 3,000	30/20	321.9	534.3
10	1990	0 – 800	48.6	800 – 3,000	30/20	67.6	116.2
10	2000	0 – 800	175.6	800 – 3,000	30/20	116.9	292.5
20	1990	0 – 800	77.8	800 – 3,000	30/20	114.5	192.3
20	2000	0 – 800	281.1	800 – 3,000	30/20	186.5	467.6
40	1990	0 – 800	120.7	800 – 3,000	C/Ku	281.5	402.2
40	2000	0 – 800	435.9	800 – 3,000	30/20	287.5	723.4
10	1990	0 – 3,000	155.7	0	N/A	–	155.7
10	2000	0 – 3,000	562.4	0	N/A	–	562.4
20	1990	0 – 3,000	275.2	0	N/A	–	275.2
20	2000	0 – 3,000	993.9	0	N/A	–	993.9
40	1990	0 – 3,000	496.3	0	N/A	–	496.3
40	2000	0 – 3,000	1,792.3	0	N/A	–	1,792.3

Table 4-11. OPTIMAL MIX OF FIBER-OPTIC AND SATELLITE TECHNOLOGY						
Number of Cities	Year	Total Annual System Cost (Millions of Dollars)				
		0*	0 to 200*	0 to 500*	0 to 800*	0 to 3,000*
10	1990	104.8	104.8	$\boxed{102.2}$	116.2	155.7
10	2000	182.8	$\boxed{172.5}$	190.1	292.5	562.4
20	1990	178.0	165.2	$\boxed{157.1}$	192.3	275.2
20	2000	302.6	$\boxed{262.7}$	321.0	467.6	993.9
40	1990	514.7	469.2	423.4	$\boxed{402.2}$	496.3
40	2000	467.7	$\boxed{456.7}$	534.3	723.4	1,792.3

*Number of miles in fiber-optic cable.

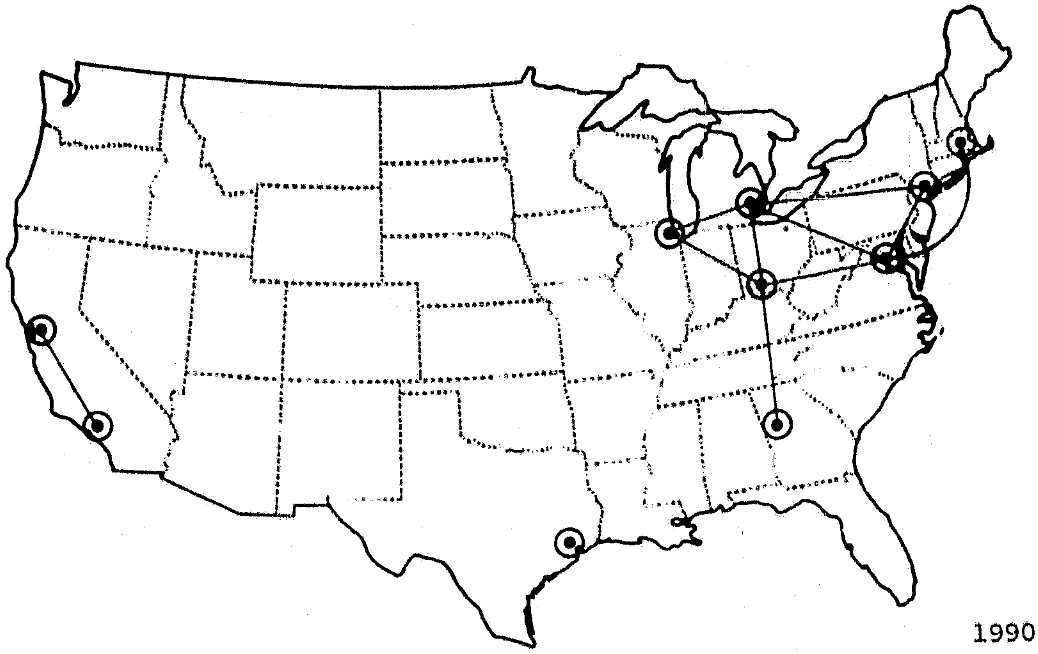
Note: Numbers in boxes represent the lowest cost for a given network.

of a video channel in half. By the year 2000, the average cost of a satellite video channel would be about one-fifth that of the best terrestrial transmission system.

In 1990, the lowest cost per mile would be achieved by a 20-city network using 30/20 GHz satellites and fiber-optics. The cost per video channel mile would be significantly greater for the 10- and 40-city networks, where C/Ku-band satellites were preferred. The best possible network might comprise more or less than 20 cities. The exact number could not be easily determined from the available traffic matrices, however.

By the year 2000, the average cost per video channel mile in Table 4-12 would be less than half the 1990 cost. As more cities were added to the network, the cost per mile would decline. Going from a 10-city to a 20-city configuration would produce a decrease of 11 percent in the cost per mile; going from 20 to 40 cities would result in a further decrease of only 3.6 percent. Although there is a downward trend, there appears to be a diminishing return on investment if network size is increased much beyond 20 cities. Nevertheless, at least 20 new cities could be added without increasing the average cost per mile. An even wider implementation would be possible if the estimates for 30/20 GHz facilities used in this study proved to be high.

The best implementation strategy would be to design a 20-city network in 1990 using 30/20 GHz satellites. Fiber-optic cables should be limited to 200 miles, with existing C/Ku-band technology picking up the difference. As C/Ku-band satellites reach the end of their service life, they could be replaced by 30/20 GHz satellites to increase spectrum utilization. Additional cities could be added if actual 30/20 GHz costs proved to be more



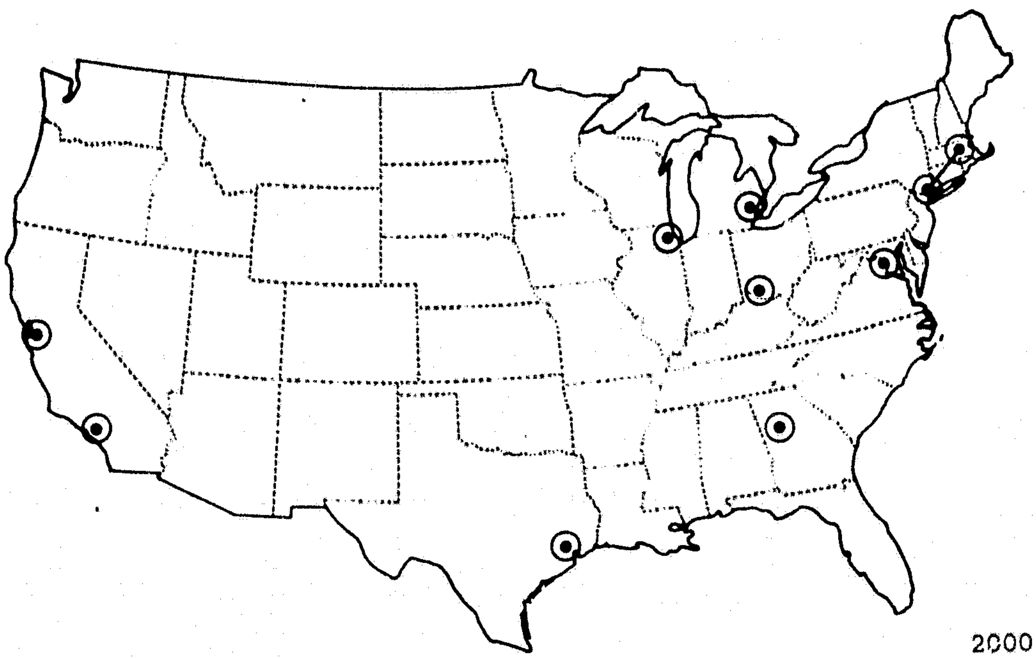


Figure 4-3. COMPARISON OF FIBER-OPTIC CABLE ROUTES IN 1990 AND 2000 FOR A 10-CITY NETWORK

Table 4-12. COST PER VIDEO CHANNEL MILE IN COMBINED SATELLITE AND FIBER-OPTIC NETWORKS

Number of Cities	Year	Type of System	Satellite Portion of Network				Total Network	
			Cost	Video Channel Miles Carried	Cost per Video Channel Mile (Dollars)	Total System Cost	Total Video Channel Miles Carried	Average System Cost per Video Channel Mile (Dollars)
10	1990	30/20	86.2 M	350,000	246	108.9 M	374,300	273
10	2000	30/20	166.0 M	1,345,000	123	172.5 M	1,352,000	128
20	1990	30/20	121.1 M	592,300	204	157.1 M	647,500	243
20	2000	30/20	235.6 M	2,307,000	102	252.7 M	2,338,000	112
40	1990	C/Ku	281.5 M	962,000	293	402.2 M	1,170,000	344
40	2000	30/20	411.0 M	4,170,000	99	456.7 M	4,226,000	108

favorable than the estimates. In the final analysis, however, the actual market will be the prime determinant of how much and in what cities 30/20 GHz communications systems are implemented.

CHAPTER FIVE

CONCLUSIONS

5.1 GENERAL FINDINGS

Long-haul communications traffic can be expected to increase five- or six-fold over the next two decades. This demand must be met without requiring capital expenditures five to six times greater than the costs of existing plants and facilities. Advanced fiber-optic and satellite systems are key candidates for these future networks.

On the basis of estimated costs, advanced satellites offer the most cost-effective means of providing communication for distances greater than 200 to 500 miles. The lowest-cost network in all cases studied was a mixture of fiber-optic and satellite technologies. Distances of a few hundred miles were shown to be more economically served by fiber-optics, while greater distances were better served by satellite. Costs of terrestrial microwave radio and fiber-optics were not found to be significantly different. Thus, if microwave radio were substituted for fiber-optics, the cost advantage of satellites would be about the same. In two of the 1990 scenarios, 30/20 GHz satellites were superior to C/Ku-band systems. 30/20 GHz satellites also were decidedly better for the 10- and 20-city networks in 1990 and for all networks in 2000.

The average cost per video channel mile was used to rate each network. The lowest projected cost per mile in 1990 was achieved with 30/20 GHz satellites in a 20-city configuration. In the year 2000, the projected cost per video channel mile decreased as more cities were added to the network. The greatest reduction in cost per mile occurred between 10 cities and 20 cities; a much smaller reduction resulted when the network was increased from 20 cities to 40 cities. On the basis of cost per mile, the optimal 30/20 GHz satellite system would be a 20-city network in 1990. As traffic demand increases, additional cities should be added in the year 2000 to further reduce costs.

If satellite system costs prove to be lower than the values estimated, greater network savings could be achieved, and the crossover mileage between fiber-optics and satellites would decrease. Some improvement in the costs of satellite systems can also be obtained by employing the optimal assignment of cities to each satellite. Test runs have shown that optimizing should reduce the number of satellites and earth stations about 10 percent by utilizing these facilities as efficiently as possible. Substantial savings may also be possible by collocating earth stations in each city. A substantial part of the recurring earth-station cost is personnel required to operate and maintain the earth station (see Tables 4-6 and 4-8). The greatest benefit of consolidating earth stations would be a reduction in total personnel required. A disadvantage of collocation is that the satellite antennas would probably have to be remote from the central office.

5.2 IMPLEMENTATION

The study emphasizes the need for long-range network planning. In 1990, fiber-optics would be desirable for channels up to 500 miles in length. In 2000, however, fiber-optics would be economical only up to about 200 miles. If fiber-optic cables with an estimated life of 33 years were installed in 1990 to minimize network costs, the introduction of less expensive technology during the following decade would be slowed down.

The 30/20 GHz network implementation suggested for 1990 would serve the top 20 U.S. cities. Cities further apart than 200 miles would send all traffic via satellite. The cost per video channel mile in this case would be \$255 -- slightly higher than the minimum cost of \$243, which occurs with a 500-mile crossover. This difference is offset in the year 2000, when the cost per mile would be \$112 with a 200-mile crossover, rather than \$137 per mile at 500 miles. The same 20-city network with additional satellites and earth stations would be near optimal in the year 2000. Other cities could be added in response to demand, however, resulting in further improvements in the cost per video channel mile.

A large question still remains regarding traffic that is not included in the 20-city satellite network. Table 2-3 shows that a 20-city system carries only 96.4 Gbps out of a total 398.3 Gbps offered in the busy hour. None of the networks considered in this study, however, were designed to carry the full intercity demand; the largest of the 40-city networks would carry no more than 43 percent of the total demand. In an actual network, it is probable that most of this traffic would be carried at least partially by a terrestrial system. If very long distances were involved, the traffic might be routed through the nearest cities served by satellite. This should ultimately decrease the cost per video channel mile carried by satellite.

APPENDIX A

TRAFFIC MATRICES

The tables in this appendix were furnished by NASA Lewis Research Center for use in the satellite trunking system analysis. The matrices contain the voice, data, and video traffic between each city pair for 10-, 20-, and 40-city networks. The numbers represent percentages of total intercity traffic between the top 275 standard metropolitan statistical areas. These data were compiled by Western Union Telegraph Company under separate contract with NASA.

Table A-1. TEN-CITY TRAFFIC MATRIX

1980 (BASE YEAR) FRACTION OF TOTAL CIRCUITS FOR 275 SMSA'S		NEW YORK	LOS ANGELES	CHICAGO	DETROIT	WASHINGTON, D.C.	SAN FRANCISCO	BOSTON	CINCINNATI	ATLANTA	HOUSTON
NEW YORK	V		0.00655	0.00659	0.00366	0.00312	0.00263	0.00337	0.00223	0.00515	0.00243
	D		0.00187	0.00188	0.00105	0.00089	0.00075	0.00096	0.00064	0.00147	0.00069
	V		0.00093	0.00094	0.00052	0.00045	0.00038	0.00048	0.00032	0.00073	0.00035
LOS ANGELES	V	0.00655		0.00459	0.00297	0.00160	0.00326	0.00166	0.00189	0.00218	0.00203
	D	0.00187		0.00131	0.00066	0.00046	0.00093	0.00047	0.00054	0.00062	0.00058
	V	0.00093		0.00065	0.00035	0.00023	0.00047	0.00024	0.00027	0.00032	0.00030
CHICAGO	V	0.00659	0.00655		0.00277	0.00165	0.00184	0.00163	0.00162	0.00222	0.00173
	D	0.00188	0.00187		0.00079	0.00047	0.00053	0.00047	0.00046	0.00063	0.00049
	V	0.00094	0.00093		0.00039	0.00024	0.00026	0.00023	0.00024	0.00032	0.00011
DETROIT	V	0.00366	0.00230	0.00277		0.00092	0.00092	0.00090	0.00080	0.00123	0.00086
	D	0.00105	0.00066	0.00079		0.00026	0.00026	0.00026	0.00023	0.00035	0.00025
	V	0.00052	0.00032	0.00039		0.00014	0.00014	0.00012	0.00011	0.00018	0.00012
WASHINGTON, D.C.	V	0.00312	0.00160	0.00165	0.00092		0.00064	0.00074	0.00055	0.00115	0.00060
	D	0.00089	0.00046	0.00047	0.00026		0.00018	0.00020	0.00016	0.00033	0.00017
	V	0.00045	0.00023	0.00024	0.00014		0.00010	0.00010	0.00008	0.00016	0.00009
SAN FRANCISCO	V	0.00263	0.00326	0.00184	0.00092	0.00064		0.00067	0.00074	0.00088	0.00080
	D	0.00075	0.00093	0.00053	0.00026	0.00018		0.00019	0.00021	0.00025	0.00023
	V	0.00038	0.00047	0.00026	0.00014	0.00010		0.00010	0.00011	0.00012	0.00011
BOSTON	V	0.00337	0.00166	0.00163	0.00090	0.00070	0.00067		0.00056	0.00104	0.00061
	D	0.00096	0.00047	0.00047	0.00026	0.00020	0.00019		0.00016	0.00030	0.00017
	V	0.00048	0.00024	0.00023	0.00012	0.00010	0.00010		0.00008	0.00015	0.00009
CINCINNATI	V	0.00223	0.00189	0.00162	0.00080	0.00055	0.00074	0.00056		0.00075	0.00089
	D	0.00064	0.00054	0.00046	0.00023	0.00016	0.00021	0.00016		0.00021	0.00025
	V	0.00032	0.00027	0.00024	0.00011	0.00008	0.00011	0.00008		0.00011	0.00013
ATLANTA	V	0.00515	0.00218	0.00222	0.00123	0.00115	0.00088	0.00104	0.00075		0.00082
	D	0.00147	0.00062	0.00063	0.00035	0.00033	0.00025	0.00030	0.00021		0.00023
	V	0.00073	0.00032	0.00032	0.00018	0.00016	0.00012	0.00015	0.00011		0.00012
HOUSTON	V	0.00243	0.00203	0.00173	0.00086	0.00060	0.00080	0.00061	0.00089	0.00082	
	D	0.00069	0.00058	0.00049	0.00025	0.00017	0.00023	0.00017	0.00025	0.00023	
	V	0.00035	0.00030	0.00011	0.00012	0.00009	0.00011	0.00009	0.00013	0.00012	

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Table A-2. TWENTY-CITY TRAFFIC MATRIX

1980 (BASE YEAR) % CKTS X 10^5		NEW YORK	LOS ANGELES	CHICAGO	DETROIT	WASH., D.C.	SAN FRANCISCO	BOSTON	CINCINNATI	ATLANTA	HOUSTON	PHILADELPHIA	DALLAS	MINNEAPOLIS	BALTIMORE	CLEVELAND	PITTSBURGH	ST. LOUIS	DENVER	SAN JOSE	NEWARK
NEW YORK	V		654	659	366	312	263	337	264	171	243	515	223	180	216	186	175	146	137	114	325
	D		187	188	105	089	075	096	075	051	069	147	064	051	062	053	050	042	039	033	093
	V		093	094	052	045	038	075	038	031	035	073	032	026	031	026	025	020	020	016	046
LOS ANGELES	V	654		459	230	160	326	166	127	122	204	218	189	138	107	112	099	107	130	144	090
	D	187		131	066	046	094	047	036	035	058	062	054	039	031	032	028	031	037	041	026
	V	093		065	032	023	046	024	018	017	029	032	027	020	015	016	015	015	019	016	012
CHICAGO	V	659	459		166	165	134	163	089	122	173	222	162	146	110	128	109	121	101	080	091
	D	188	131		047	047	053	047	025	035	049	063	046	042	031	037	031	035	029	023	026
	V	094	065		024	024	026	023	013	017	025	032	028	020	016	018	015	017	014	011	013
DETROIT	V	366	230	166		092	092	090	045	062	086	123	080	069	062	084	064	056	049	040	050
	D	105	066	047		026	026	026	013	018	025	035	023	020	018	024	019	016	014	011	014
	V	052	032	024		014	014	012	006	009	012	018	011	009	048	012	009	008	007	006	008
WASHINGTON, D.C.	V	312	160	165	092		064	070	031	046	061	115	055	044	071	048	047	036	034	028	043
	D	089	046	047	026		018	020	009	013	017	033	016	013	020	014	013	010	010	008	012
	V	045	023	029	014		010	010	004	006	009	016	008	006	011	006	007	006	004	004	007
SAN FRANCISCO	V	263	326	184	092	064		067	062	048	080	088	074	056	043	045	040	043	052	087	036
	D	075	094	053	026	018		019	018	014	023	025	021	016	012	013	011	012	015	025	010
	V	038	046	026	014	014		010	009	007	011	013	011	008	006	006	006	006	007	012	006
BOSTON	V	337	166	163	090	070	067		032	043	061	104	056	046	048	045	041	036	034	029	046
	D	096	047	047	026	020	019		009	012	017	030	016	013	014	013	012	010	010	008	013
	V	075	024	023	012	010	010		005	007	009	015	008	006	006	006	006	006	005	004	007
CINCINNATI	V	264	127	089	045	031	062	032		024	039	042	037	064	021	022	042	021	025	027	018
	D	075	036	025	013	009	018	009		007	011	012	011	018	006	006	012	006	007	008	005
	V	038	018	013	006	004	009	005		003	006	006	005	009	003	003	006	003	004	004	002
ATLANTA	V	171	122	122	062	046	048	043	024		050	060	045	033	030	031	028	029	026	021	025
	D	051	035	035	018	013	014	012	007		014	017	013	009	009	009	008	008	007	006	007
	V	031	017	017	009	006	007	007	003		007	009	006	005	004	004	004	005	004	003	003
HOUSTON	V	243	204	173	086	061	080	061	039	050		062	045	033	030	031	028	029	026	021	025
	D	069	058	049	025	017	023	017	011	014		017	013	009	009	009	008	008	007	006	007
	V	035	029	025	012	009	011	009	006	007		007	006	005	004	004	004	005	004	003	003
PHILADELPHIA	V	515	218	222	123	115	088	104	042	060	062		075	060	082	063	060	049	046	038	072
	D	147	062	063	035	033	025	030	012	017	017		021	017	023	018	017	014	013	011	021
	V	035	032	032	018	016	013	015	006	009	007		011	009	012	009	009	007	006	005	010
DALLAS	V	223	189	162	080	055	074	056	037	045	045	075		047	037	039	034	041	041	032	031
	D	064	054	046	023	016	021	016	011	013	013	021		013	011	011	010	012	012	009	009
	V	032	027	028	011	008	011	008	005	006	006	011		007	005	006	005	005	006	005	004
MINNEAPOLIS	V	180	138	146	069	044	056	046	064	033	033	060	047		029	033	028	032	031	024	025
	D	051	039	042	020	013	016	013	018	009	009	017	013		008	009	008	009	009	007	007
	V	026	020	020	009	006	008	006	009	005	005	005	007		005	005	004	004	005	003	003
BALTIMORE	V	216	107	110	062	071	043	048	021	030	030	082	037	029		032	031	025	022	019	030
	D	062	031	031	018	020	012	014	006	009	009	023	011	008		009	009	007	006	005	009
	V	031	015	016	008	011	006	006	003	004	004	012	005	005		004	004	003	004	003	004
CLEVELAND	V	186	112	128	084	048	045	045	022	031	031	063	039	033	032		035	027	024	020	026
	D	053	032	037	024	014	013	013	006	009	009	018	011	009	009		010	008	007	006	007
	V	026	016	018	012	006	006	006	003	004	004	009	006	005	004		005	003	003	002	004
NEWARK	V	325	090	091	050	043	036	046	018	025	025	072	031	025	030	026	024	020	019	015	
	D	093	026	026	014	012	010	013	005	007	007	021	009	007	009	007	007	006	005	004	
	V	046	012	013	008	007	006	007	002	003	003	010	004	003	004	004	003	002	003	003	
PITTSBURGH	V	175	099	109	064	047	040	041	042	028	028	060	034	028	031	035		024	021	018	024
	D	050	028	031	019	013	011	012	012	008	008	017	010	008	009	010		007	006	005	007
	V	025	015	015	009	007	006	006	006	004	004	009	005	004	004	005		003	003	002	003
ST. LOUIS	V	146	107	121	056	036	043	036	021	029	029	049	041	032	025	027	024		024	018	020
	D	042	031	035	016	010	012	010	006	008	008	014	012	009	007	008	007		007	005	006
	V	020	015	017	008	016	006	006	003	005	005	007	005	004	003	003	003		003	003	002
DENVER	V	137	130	101	049	034	052	034	025	026	026	046	041	031	022	024	021	024		022	019
	D	039	037	029	014	010	015	010	007	007	007	013	012	009	006	007	006	007		006	005
	V	020	019	014	007	004	007	005	004	004	004	006	006	005	004	003	003	003		004	003
SAN JOSE	V	114	144	080	040	028	087	025	027	021	021	038	032	024	019	020	018	018	023		015
	D	033	041	023	011	008	025	007	008	006	006	011	009	007	005	006	005	005	006		004
	V	016	016	011	006	004	012	004	004	003	003	005	005	003	003	002	002	003	003		003

Table A-3. FORTY-CITY TRAFFIC MATRIX

1980 (BASE YEAR) Σ CKTS x 10^5		NEW YORK	LOS ANGELES	CHICAGO	PHILADELPHIA	DETROIT	SAN FRANCISCO	HOUSTON	WASHINGTON	BOSTON	DALLAS	MINNEAPOLIS	CLEVELAND	ATLANTA	BALTIMORE	NEWARK	ANAHEIM	PITTSBURGH	ST. LOUIS	DENVER	SAN JOSE
NEW YORK	V D V		654 187 93	659 188 94	515 147 73	366 105 52	263 75 38	243 69 35	312 89 45	337 96 48	223 64 31	180 51 26	186 53 26	177 51 25	216 62 31	325 93 46	127 36 18	175 50 25	146 42 20	137 39 20	114 33 16
LOS ANGELES	V D V			459 131 65	218 62 32	230 66 32	326 93 47	204 58 29	160 46 23	166 47 24	189 54 27	138 39 20	112 32 16	122 32 17	107 31 15	90 26 12	264 75 38	99 28 15	107 31 15	130 37 19	144 41 21
CHICAGO	V D V				222 63 32	277 79 39	184 53 26	173 49 25	165 47 24	163 47 23	162 46 24	146 42 20	128 37 18	122 35 17	110 31 16	91 26 13	89 29 13	109 31 15	121 35 17	101 29 14	80 23 11
PHILADELPHIA	V D V					124 35 18	88 35 18	82 23 12	115 33 16	104 30 15	75 21 11	60 17 9	63 18 9	60 17 9	82 23 12	72 21 10	42 12 6	60 17 9	49 14 7	42 12 6	38 11 5
DETROIT	V D V						92 26 14	86 25 12	92 26 14	90 26 12	80 23 11	69 20 9	84 24 12	62 18 9	62 18 8	50 14 8	45 13 6	64 18 10	56 16 8	49 14 7	40 11 6
SAN FRANCISCO	V D V							80 23 11	64 18 10	67 19 10	74 21 11	56 16 8	45 13 6	48 14 7	43 12 6	36 10 6	62 18 9	40 11 6	43 12 6	52 15 7	87 25 12
HOUSTON	V D V								61 17 9	61 17 9	89 25 13	50 14 7	42 12 6	50 14 7	41 12 5	34 10 4	39 11 6	38 11 5	42 12 6	43 12 6	34 10 5
WASHINGTON	V D V									71 20 10	55 16 8	44 13 6	48 14 6	46 13 6	71 20 11	43 12 7	31 9 4	47 13 7	36 10 6	34 10 4	28 8 4
BOSTON	V D V										56 16 8	46 13 6	45 13 6	43 12 7	[illegible] 14 5	46 13 7	32 9 5	41 12 6	36 10 6	34 10 5	29 8 4
DALLAS	V D V											47 13 7	39 11 6	45 13 6	37 11 5	31 9 4	37 11 5	34 10 5	41 12 5	41 12 6	32 9 5

(continued)

Table A-3. (continued)

1980 (BASE YEAR) 2 CKTS x 10^5		MIAMI	CINCINNATI	MILWAUKEE	KANSAS CITY	SAN DIEGO	SEATTLE	NEW ORLEANS	PHOENIX	INDIANAPOLIS	COLUMBUS'	TAMPA	NASSAU	BUFFALO	PORTLAND	MEMPHIS	LOUISVILLE	HARTFORD	OKLAHOMA CITY	FT. LAUDERDALE	SALT LAKE
NEW YORK	V	125	118	109	104	92	95	95	86	92	95	88	138	88	68	71	68	96	60	64	56
	D	36	34	31	30	26	27	27	25	26	27	25	39	25	19	20	19	27	17	18	16
	V	17	16	16	15	14	14	13	12	13	13	12	20	12	10	10	10	14	8	10	8
LOS ANGELES	V	89	77	76	83	141	95	74	102	62	59	63	44	48	70	53	46	41	51	46	60
	D	25	22	22	24	40	27	21	29	18	17	18	13	14	20	15	13	12	14	13	17
	V	13	11	11	12	21	14	10	15	9	8	9	6	7	10	8	7	6	7	6	8
CHICAGO	V	81	90	111	83	64	67	67	61	79	69	57	44	53	48	53	53	41	44	41	40
	D	23	26	32	24	18	19	19	17	23	20	16	13	15	14	15	15	12	13	12	11
	V	11	13	15	12	10	9	9	9	11	9	9	6	7	6	8	8	6	6	6	6
PHILADELPHIA	V	42	40	36	35	31	32	32	29	31	32	29	34	29	22	24	23	28	20	22	19
	D	12	11	10	10	9	9	9	8	9	9	8	10	8	6	7	7	8	6	6	5
	V	6	6	6	5	4	4	5	4	4	5	5	4	5	4	3	3	4	2	3	3
DETROIT	V	41	47	46	39	32	34	34	30	38	39	29	25	32	24	26	27	23	22	21	20
	D	12	13	13	11	9	10	10	9	11	11	8	7	9	7	7	8	7	6	6	6
	V	6	7	6	6	5	4	4	4	5	6	5	3	4	3	4	3	3	3	3	2
SAN FRANCISCO	V	36	31	31	33	43	41	29	37	25	24	25	18	20	31	21	18	17	20	18	24
	D	10	9	9	9	12	12	8	11	7	7	7	5	6	9	6	5	5	6	5	7
	V	5	4	4	5	7	6	5	5	4	3	4	2	2	4	3	2	2	2	3	3
HOUSTON	V	35	30	29	32	29	28	34	28	24	22	25	16	18	20	22	18	15	21	18	17
	D	10	9	8	9	8	8	10	8	7	6	7	5	5	6	6	5	4	6	5	5
	V	5	4	4	5	4	4	5	4	3	4	4	2	2	2	4	3	3	3	3	2
WASHINGTON	V	31	31	27	26	22	23	24	21	23	25	22	20	21	17	18	18	18	15	16	14
	D	9	9	8	7	6	7	7	6	7	7	6	6	6	5	5	5	5	4	5	4
	V	4	4	4	4	4	3	3	3	3	3	4	3	3	2	3	2	3	2	2	2
BOSTON	V	31	29	27	26	23	25	24	22	22	23	22	23	21	18	18	17	25	15	16	14
	D	9	8	8	7	7	7	7	6	6	7	6	7	6	5	5	5	7	4	5	4
	V	4	4	4	4	3	3	3	3	4	3	3	3	3	2	2	2	4	2	2	2
DALLAS	V	32	28	27	32	27	26	29	26	22	21	22	15	17	18	21	17	14	22	30	30
	D	9	8	8	9	8	7	8	7	6	6	6	4	5	5	6	5	4	6	9	9
	V	4	4	3	4	3	4	5	4	4	3	4	2	2	3	3	2	2	4	4	4

(continued)

Table A-3. (continued)

1980 (BASE YEAR) % CKTS X 10^5		NEW YORK	LOS ANGELES	CHICAGO	PHILADELPHIA	DETROIT	SAN FRANCISCO	HOUSTON	WASHINGTON	BOSTON	DALLAS	MINNEAPOLIS	CLEVELAND	ATLANTA	BALTIMORE	NEWARK	ANAHEIM	PITTSBURGH	ST. LOUIS	DENVER	SAN JOSE
MINNEAPOLIS	V D V												33 9 5	33 9 5	29 8 5	25 7 3	27 8 3	28 8 4	32 9 4	31 9 4	24 7 3
CLEVELAND	V D V													31 9 4	32 9 4	26 7 4	22 6 3	35 10 5	27 8 3	24 7 3	20 6 2
ATLANTA	V D V														30 9 4	25 7 3	24 7 3	28 8 4	29 8 5	26 7 4	21 6 3
BALTIMORE	V D V															30 9 4	21 6 3	31 9 4	25 7 3	22 6 4	20 5 2
NEWARK	V D V																18 5 2	24 7 3	20 6 3	19 5 3	15 4 3
ANAHEIM	V D V																	20 6 2	21 6 3	25 7 4	28 8 3
PITTSBURGH	V D V																		24 7 3	21 6 3	18 5 2
ST. LOUIS	V D V																			24 7 3	18 5 3
DENVER	V D V																				22 6 4
SAN JOSE	V D V																				

(continued)

Table A-3. (continued)

1980 (BASE YEAR) % CKTS x 10^5		MIAMI	CINCINNATI	MILWAUKEE	KANSAS CITY	SAN DIEGO	SEATTLE	NEW ORLEANS	PHOENIX	INDIANAPOLIS	COLUMBUS	TAMPA	NASSAU	BUFFALO	PORTLAND	MEMPHIS	LOUISVILLE	HARTFORD	OKLAHOMA CITY	FT. LAUDERDALE	SALT LAKE
MINNEAPOLIS	V	22	22	25	25	20	20	19	18	18	17	16	12	14	15	15	13	11	13	11	13
	D	6	6	7	7	6	6	5	5	5	5	5	3	4	4	4	4	3	4	3	4
	V	4	4	4	3	2	3	3	3	3	2	2	2	2	2	2	2	2	1	2	1
CLEVELAND	V	20	23	21	19	16	16	16	15	18	20	15	13	16	12	13	13	12	11	11	10
	D	6	7	6	5	5	5	5	4	5	6	4	4	5	3	4	4	3	3	3	3
	V	3	3	3	3	2	2	2	2	3	3	2	1	2	2	1	2	2	1	1	1
ATLANTA	V	25	22	20	20	18	18	20	16	18	17	19	12	13	12	15	14	11	12	13	11
	D	7	6	6	6	5	5	6	5	5	5	5	3	4	3	4	4	3	3	4	3
	V	4	4	2	3	2	2	3	2	2	2	3	2	2	2	3	2	2	2	1	1
BALTIMORE	V	20	20	18	18	15	15	16	14	15	16	15	14	14	11	12	12	13	10	11	9
	D	6	6	5	5	4	4	5	4	4	5	4	4	4	3	3	3	4	3	3	3
	V	3	3	3	2	3	3	2	2	3	2	2	2	2	2	2	2	1	1	1	1
NEWARK	V	17	16	15	14	13	13	13	12	13	13	12	18	12	9	10	9	13	8	9	8
	D	5	5	4	4	4	4	4	3	4	4	3	5	3	3	3	3	4	2	3	2
	V	2	2	2	2	1	2	2	2	1	2	2	2	2	1	1	1	1	2	1	1
ANAHEIM	V	18	15	15	16	29	18	14	20	12	11	12	8	9	13	11	9	8	10	9	12
	D	5	4	4	5	8	5	4	6	3	3	3	2	3	4	3	3	2	3	3	3
	V	2	2	2	2	4	3	2	3	2	2	2	2	1	2	1	1	2	1	1	2
PITTSBURGH	V	19	20	18	17	14	15	15	13	15	18	13	12	14	11	11	11	11	9	10	8
	D	5	6	5	5	4	4	4	4	4	5	4	3	4	3	3	3	3	3	3	2
	V	3	3	2	2	2	2	2	2	3	2	2	2	2	1	2	2	1	1	1	2
ST. LOUIS	V	19	20	20	21	15	15	16	14	17	15	13	10	11	11	14	13	9	11	10	9
	D	5	6	6	6	4	4	5	4	5	4	4	3	3	3	4	4	3	3	3	3
	V	3	3	2	3	3	3	2	2	2	2	2	1	2	2	2	1	1	2	1	1
DENVER	V	18	17	17	19	18	18	15	18	13	13	13	9	11	13	12	10	8	12	9	13
	D	5	5	5	5	5	5	4	5	4	4	4	3	3	4	3	3	2	3	3	4
	V	3	2	2	3	3	3	3	3	2	1	2	1	1	2	2	1	2	2	1	1
SAN JOSE	V	15	13	13	15	18	18	13	16	11	11	11	8	8	13	9	8	7	8	8	11
	D	4	4	4	4	5	5	4	5	3	3	3	2	2	4	3	2	2	2	2	3
	V	3	2	2	2	3	2	1	2	1	1	2	1	2	2	1	1	1	2	1	1

(continued)

Table A-3. (continued)

1980 (BASE YEAR) # CKTS X 10^5	NEW YORK	LOS ANGELES	CHICAGO	PHILADELPHIA	DETROIT	SAN FRANCISCO	HOUSTON	WASHINGTON	BOSTON	DALLAS	MINNEAPOLIS	CLEVELAND	ATLANTA	BALTIMORE	NEWARK	ANAHEIM	PITTSBURGH	ST. LOUIS	DENVER	SAN JOSE
MIAMI																				
CINCINNATI																				
MILWAUKEE																				
KANSAS CITY																				
SAN DIEGO																				
SEATTLE																				
NEW ORLEANS																				
PHOENIX																				
INDIANAPOLIS																				
COLUMBUS																				

(continued)

Table A-3. (continued)

1980 (BASE YEAR) Σ CKTS X 10^5		MIAMI	CINCINNATI	MILWAUKEE	KANSAS CITY	SAN DIEGO	SEATTLE	NEW ORLEANS	PHOENIX	INDIANAPOLIS	COLUMBUS	TAMPA	NASSAU	BUFFALO	PORTLAND	MEMPHIS	LOUISVILLE	HARTFORD	OKLAHOMA CITY	FT. LAUDERDALE	SALT LAKE
MIAMI	V D V		14 4 2	13 4 2	14 4 2	13 4 1	13 4 1	14 4 2	12 3 2	11 3 2	11 3 2	16 5 2	8 2 2	9 3 1	9 3 1	10 3 1	8 2 2	8 2 1	8 2 2	18 5 3	8 2 1
CINCINNATI	V D V			15 4 2	13 4 2	11 3 2	11 3 2	12 3 2	11 3 1	15 4 2	15 4 2	11 3 1	8 2 1	9 3 1	8 2 1	9 3 1	11 3 2	7 2 1	8 2 1	8 2 1	6 2 1
MILWAUKEE	V D V				14 4 2	11 3 1	11 3 2	11 3 2	11 3 1	12 3 2	11 3 2	9 3 1	7 2 1	8 2 2	8 2 1	8 2 2	8 2 2	7 2 1	7 2 1	7 2 1	7 2 1
KANSAS CITY	V D V					12 3 2	12 3 2	12 3 2	11 3 2	11 3 2	10 3 1	10 3 1	7 2 1	8 2 1	8 2 2	10 3 1	8 2 2	6 2 1	9 3 1	7 2 1	7 2 1
SAN DIEGO	V D V						13 4 2	11 3 1	15 4 2	9 3 1	8 2 2	9 3 1	6 2 1	7 2 1	10 3 1	8 2 1	6 2 1	6 2 0	7 2 1	6 2 1	8 2 2
SEATTLE	V D V							11 3 1	12 3 2	9 3 1	8 2 2	9 3 1	6 2 1	7 2 1	14 4 2	8 2 1	6 2 1	6 2 1	7 2 1	6 2 1	8 2 2
NEW ORLEANS	V D V								10 3 1	9 3 1	9 3 1	11 3 1	6 2 1	7 2 1	7 2 1	9 3 1	7 2 1	6 2 1	7 2 1	7 2 1	6 2 1
PHOENIX	V D V									8 2 2	8 2 1	8 2 2	5 2 1	6 2 1	8 2 2	7 2 1	6 2 1	5 2 1	7 2 1	6 2 1	8 2 1
INDIANAPOLIS	V D V										11 3 1	8 2 2	6 2 1	7 2 1	6 2 1	8 2 1	9 3 1	5 2 1	6 2 1	5 2 1	5 2 1
COLUMBUS	V D V											8 2 1	6 2 1	8 2 1	6 2 1	7 2 1	8 2 1	5 2 1	5 2 1	5 2 1	5 1 1

(continued)

Table A-3. (continued)

1980 (BASE YEAR) % CKTS X 10^5	NEW YORK	LOS ANGELES	CHICAGO	PHILADELPHIA	DETROIT	SAN FRANCISCO	HOUSTON	WASHINGTON	BOSTON	DALLAS	MINNEAPOLIS	CLEVELAND	ATLANTA	BALTIMORE	NEWARK	ANAHEIM	PITTSBURGH	ST. LOUIS	DENVER	SAN JOSE
TAMPA																				
NASSAU																				
BUFFALO																				
PORTLAND																				
MEMPHIS																				
LOUISVILLE																				
HARTFORD																				
OKLAHOMA CITY																				
FT. LAUDERDALE																				
SALT LAKE																				

(continued)

Table A-3. (continued)

1980 (BASE YEAR) ½ CKTS X 10^5		MIAMI	CINCINNATI	MILWAUKEE	KANSAS CITY	SAN DIEGO	SEATTLE	NEW ORLEANS	PHOENIX	INDIANAPOLIS	COLUMBUS	TAMPA	NASSAU	BUFFALO	PORTLAND	MEMPHIS	LOUISVILLE	HARTFORD	OKLAHOMA CITY	FT. LAUDERDALE	SALT LAKE
TAMPA	V D V												5 2 1	6 2 1	6 2 1	7 2 1	6 2 1	5 2 1	5 2 1	8 2 2	5 2 1
NASSAU	V D V													5 2 1	4 1 1	5 1 1	4 1 1	6 2 1	4 1 1	4 1 1	3 1 1
BUFFALO	V D V														5 1 1	5 2 1	5 1 1	5 2 1	4 1 1	5 1 1	4 1 1
PORTLAND	V D V															5 2 1	5 1 1	4 1 1	5 1 1	4 1 1	6 2 1
MEMPHIS	V D V																5 2 1	4 1 1	5 2 1	5 1 1	4 1 1
LOUISVILLE	V D V																	4 1 1	4 1 1	4 1 1	4 1 1
HARTFORD	V D V																		3 1 1	4 1 1	3 1 1
OKLAHOMA CITY	V D V																			4 1 1	3 1 1
FT. LAUDERDALE	V D V																				3 1 1
SALT LAKE	V D V																				

APPENDIX B

SATELLITE CONFIGURATION MODEL

This appendix describes a computer model used to estimate the number of satellites and earth stations required for each scenario.

Inputs to the model consist of (1) the number of spot beams per satellite, (2) the maximum capacity of a spot beam (one direction), and (3) half of the satellite switch throughput. All data rates are expressed as a percentage to minimize the number of conversions required in the program. The relationship used for this purpose is:

$$\frac{\text{Beam or switch capacity (Gbps)}}{\text{Total busy-hour traffic (Gbps)}}$$

The model begins by reading the demand between the first two cities in the traffic matrix. It then determines if any spot beams on the first satellite are assigned to either of the cities or if there are any unassigned beams on the satellite. If not, each subsequent satellite is checked until either a match can be found or it is determined that a new satellite must be added to the system. Once the assignment is made, half of the traffic is assigned to the spot beam for the first city; the other half is assumed to originate in the second city and is assigned to its spot beam.

If demand exceeds the capacity remaining on either spot beam, the model fills the beam and searches for a new satellite to carry the excess traffic. The model simultaneously determines when the on-board switch capacity has been reached and routes all subsequent traffic to a different satellite.

After all demand has been satisfied, the total number of satellites required is tallied. The number of earth stations required is equal to the total number of spot beams assigned. Figure B-1 illustrates the general flow of the model. Table B-1 shows an example of the way 1990 traffic was assigned in the 10-city network.

The same model, with slight modification, was also used to design C- and Ku-band satellite systems. No restriction was placed on the amount of traffic to any particular city, but the total demand carried by the satellite was not permitted to exceed a specified throughput. The number of earth stations required was computed from the total number of all cities served by all satellites.

Sensitivity runs were performed to determine if the order in which cities were assigned to satellites affected the number of satellites and earth stations required. Three methods were tried: (1) city pairs in order of highest demand to lowest demand, (2) city pairs in order of lowest demand to highest demand, and (3) cities in order of highest demand to lowest demand. In most cases, the difference between methods 1 and 3 was not large. Method 2 was clearly less efficient than the others. It is apparent from the examples in Table B-2, however, that optimizing efforts can have a significant and unpredictable impact on satellite system design.

A complete FORTRAN IV listing of the model is included at the end of this appendix. The program was developed and run on PDP 11/34.

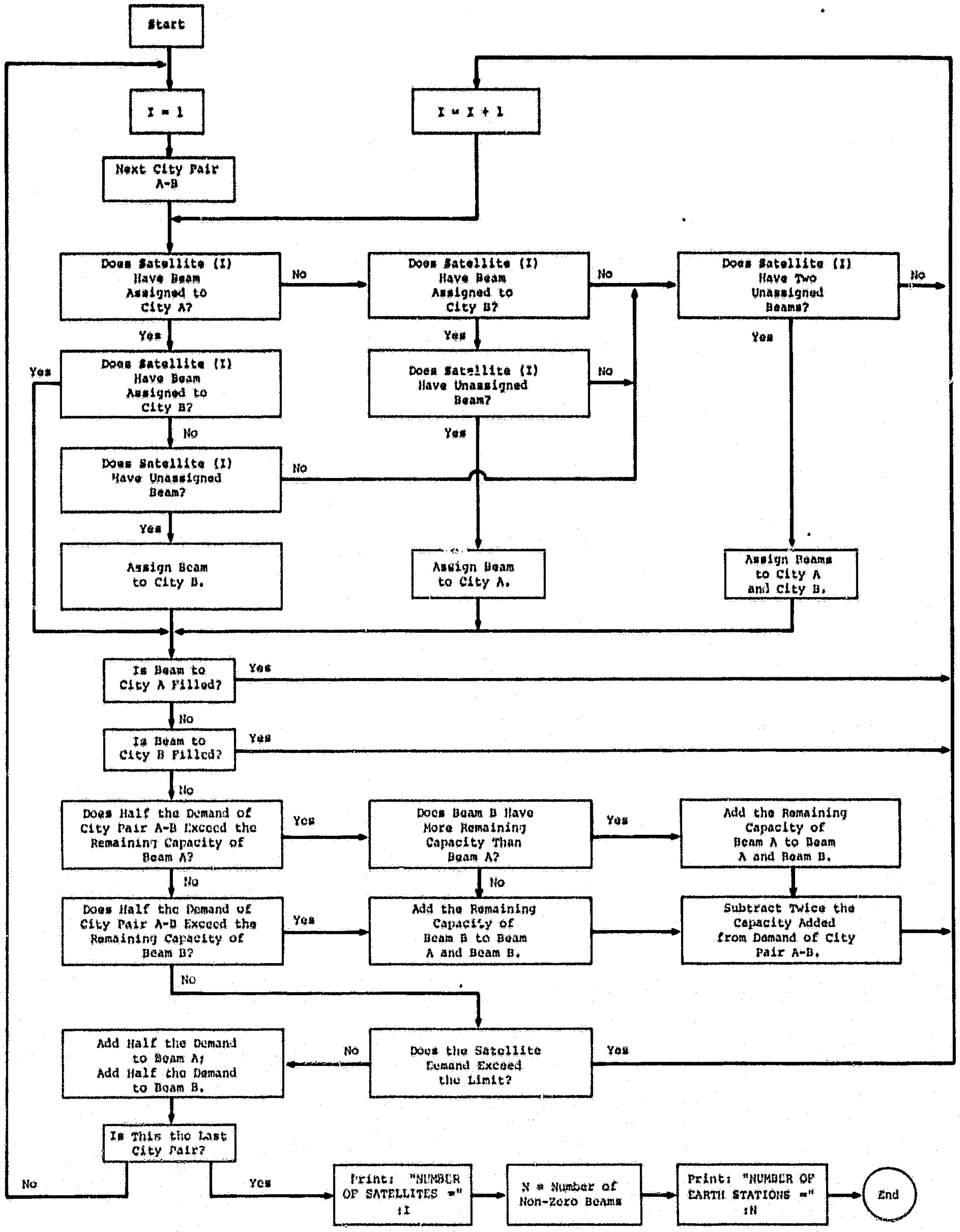

Figure B-1. ALGORITHM TO DETERMINE THE NUMBER OF EARTH STATIONS AND SATELLITES

Table B-1. ANALYSIS OF A 10-CITY 30/20 GHZ SATELLITE CONFIGURATION (1990)

Spot Beam Number	Satellite Number 1	2	3	4	5	6
1 City	NYC*	NYC	NYC	NYC	NYC	NYC
Utilization	1.00	1.00	1.00	1.00	1.00	0.64
2 City	LAX	LAX	CHI	DET	HOU	BOS
Utilization	1.00	1.00	1.00	0.14	0.09	0.25
3 City	CHI	CHI	PHL	SFO	WDC	DAL
Utilization	1.00	1.00	0.58	0.42	0.35	0.38
4 City	PHL	PHL	DET	HOU	BOS	--
Utilization	1.00	0.79	0.35	0.71	0.56	
5 City	DET	DET	LAX	LAX	LAX	--
Utilization	0.99	0.25	1.00	1.00	0.21	
6 City	SFO	SFO	SFO	WDC	DAL	--
Utilization	1.00	0.24	0.30	0.55	0.21	
7 City	HOU	BOS	HOU	BOS	--	--
Utilization	0.73	0.19	0.25	0.69		
8 City	WDC	DAL	--	DAL	--	--
Utilization	0.68	0.16		0.38		
9 City	BOS	--	--	CHI	--	--
Utilization	0.74			0.89		
10 City	DAL	--	--	--	--	--
Utilization	0.56					

*NYC = New York City
LAX = Los Angeles
CHI = Chicago
PHL = Philadelphia
DET = Detroit
SFO = San Francisco
HOU = Houston
WDC = Washington, D.C.
BOS = Boston
DAL = Dallas

Table B-2. EFFECTS OF SORTING ON SYSTEM DESIGN

Number of Cities	Year	Number of Beams	Beam Capacity (Gbps)	City Pairs From High to Low		City Pairs From Low to High		Cities From High to Low	
				Number of Satellites	Number of Earth Stations	Number of Satellites	Number of Earth Stations	Number of Satellites	Number of Earth Stations
40	1990	12	0.5	28	335	37	387	33	386
40	2000	12	0.5	46	547	67	578	46	543
40	1990	20	0.5	13	248	20	283	12	239
40	2000	20	0.5	41	602	52	535	41	591
40	1990	12	1.0	28	331	31	356	30	358
40	2000	12	1.0	41	462	46	446	37	417
40	1990	20	1.0	12	214	14	232	14	254
40	2000	20	1.0	30	482	34	432	30	475

APPENDIX C

FORTRAN LISTING OF COMPUTER MODEL

```
      PROGRAM EARSTA
C
C        THE PROGRAM EARSTA DETERMINES THE NUMBER OF SATELLITES AND
C        EARTH STATIONS REQUIRED AS DICTATED BY DEMAND FOR COMMUNI-
C        CATION LINES.
C
C     *DECLARE VARIABLES
C
      INTEGER NCITY,FIRST,TNSAT,TBEAMS,BEAMS,YEAR,EXCEED,BDIST(5)
      INTEGER VERT(40),HORZ(40),CITA(780),CITB(780),COUNT
      REAL CITIES(780),SATELL(100,40),CAPAC,DEMAND,RECAPA,RECAPB
      REAL SATLIM,SATUSE,DIST(780),BFILL(6,2),LMILES,LIMIT
      LOGICAL*1 SFILE(16),ANS,SORT,FIVE
      DATA SFILE/'S','Y','0',':',6*'X','.','D','A','T',0,0/
      DATA CITA/780*0/,CITB/780*0/,DIST/780*0.0/,SATELL/4000*0.0/
      DATA LMILES/0.0/,LIMIT/0.0/,PERCNT/0.0/,PCNTMI/0.0/
      DATA BDIST/5*0/,BFILL/0.00000,0.00058,0.00113,0.00227,0.00453,
     +     0.00907,0.00000,0.00016,0.00031,0.00063,0.00126,0.00251/
C
      WRITE(1,*) '------EARTH STATION-SATELLITE DETERMINATION-------'
      WRITE(1,*) '  '
      WRITE(1,*) '  '
10    WRITE(1,*) 'ENTER NAME OF CITY PAIR MATRIX TO BE EVALUATED:'
      READ(1,1001) (SFILE(I),I=5,10)
      WRITE(1,*) '  '
4     WRITE(1,*) 'YEAR IN WHICH EVALUATION IS TO TAKE PLACE?'
      READ(1,*) YEAR
      WRITE(1,*) '  '
      M = 0
      IF (YEAR .EQ. 1990) M = 1
      IF (YEAR .EQ. 2000) M = 2
      IF (M .NE. 0) GO TO 1
      WRITE(1,*) 'INVALID YEAR. VALID YEARS ARE 1990 AND 2000.'
      WRITE(1,*) '  '
      GO TO 4
1     WRITE(1,*) 'NUMBER OF BEAMS AVAILABLE PER SATELLITE?'
      READ(1,*) NBEAMS
      WRITE(1,*) '  '
      IF (NBEAMS .LE. 20) GO TO 2
      WRITE(1,*) 'PROGRAM ALLOWS FOR A MAXIMUM OF 20 BEAMS'
      GO TO 1
2     WRITE(1,*) 'CAPACITY PER BEAM?'
      READ(1,*) CAPAC
      WRITE(1,*) '  '
      SATLIM = NBEAMS*CAPAC             !MAXIMUM SATELLITE CAPACITY
      WRITE(1,*) 'DO YOU WISH TO SPECIFY A SATELLITE CAPACITY LIMIT?'
      READ(1,1001) ANS
      WRITE(1,*) '  '
      IF (ANS .NE. 'Y') GO TO 3
      WRITE(1,*) 'ENTER CAPACITY LIMIT LESS THAN OR EQUAL TO',SATLIM
      READ(1,*) SATLIM
      WRITE(1,*) '  '
3     WRITE(1,*) 'DO YOU WISH TO SORT THE CITY PAIR MATRIX ACCORDING'
      WRITE(1,*) 'TO TRAFFIC LOAD?'
      READ(1,1001) SORT
      WRITE(1,*) '  '
      WRITE(1,*) 'DO YOU WISH TO IMPOSE A LIMIT ON TRANSMISSION LINES?'
      READ(1,1001) FIVE
      WRITE(1,*) '  '
      IF (FIVE .NE. 'Y') GO TO 11
      WRITE(1,*) 'ENTER DESIRED TRANSMISSION DISTANCE LIMIT, USING'
      WRITE(1,*) 'DECIMAL POINT (E.G. 500.)'
      READ(1,*) LIMIT
      WRITE(1,*) '  '
C
11    BEAMS = NBEAMS*2
      EXCEED = 0
C
C     *OPEN INPUT FILE AND READ DATA
C
```

```
      OPEN(UNIT=2,NAME=SFILE,TYPE='OLD',READONLY,ERR=901)
      READ(2,1002) NCITY
      COUNT = NCITY*(NCITY-1)/2
      N = 1
      DO 25 I = 1, NCITY
        READ(2,1003)                    !CITY NAME NOT USED IN ANALYSIS
        IF (I .EQ. NCITY) GO TO 22
        DO 20 J = I+1, NCITY
          READ(2,1004) CITIES(N)
          CITA(N) = I
          CITB(N) = J
          N = N + 1
20      CONTINUE
22      READ(2,1005) VERT(I),HORZ(I)
25    CONTINUE
C
C    *COMPUTE DISTANCE BETWEEN CITY PAIRS
C
      N = 1
      DO 27 I = 1, NCITY-1
        V1 = FLOAT(VERT(I))
        H1 = FLOAT(HORZ(I))
        DO 26 J = I+1, NCITY
          V2 = FLOAT(VERT(J))
          H2 = FLOAT(HORZ(J))
          V0 = (V1-V2)**2
          H0 = (H1-H2)**2
          DIST(N) = SQRT((V0 + H0)/10.)
          N = N + 1
26      CONTINUE
27    CONTINUE
C
C    *SORT MATRIX AS REQUIRED
C
      IF (SORT .NE. 'Y') GO TO 28
      WRITE(1,*) 'DO YOU WISH TO DO A FORWARD (MAX TO MIN) OR A REAR'
      WRITE(1,*) '(MIN TO MAX) SORT?'
      WRITE(1,*) 'ENTER 1 FOR FORWARD, 0 FOR REAR'
      READ(1,*) L
      WRITE(1,*) '  '
C
      CLESS1 = COUNT - 1
      DO 8 I = 1, CLESS1
        IPLUS1 = I + 1
        DO 7 J = IPLUS1, COUNT
          IF (L .EQ. 1) GO TO 5
          IF (CITIES(I) .LT. CITIES(J)) GO TO 7
          GO TO 6
5         IF (CITIES(I) .GT. CITIES(J)) GO TO 7
6         TEMP1 = CITIES(I)
          CITIES(I) = CITIES(J)
          CITIES(J) = TEMP1
          TEMP2 = DIST(I)
          DIST(I) = DIST(J)
          DIST(J) = TEMP2
          NTEMP1 = CITA(I)
          CITA(I) = CITA(J)
          CITA(J) = NTEMP1
          NTEMP2 = CITB(I)
          CITB(I) = CITB(J)
          CITB(J) = NTEMP2
7       CONTINUE
8     CONTINUE
28    CONTINUE
C
C    *BEGIN COMPUTATIONS
C
      DO 100 I = 1, COUNT
        IF ((FIVE.EQ.'Y').AND.(DIST(I).LT.LIMIT)) GO TO 92
          NSAT = 1                      !NSAT = SATELLITE INDEX
```

```
C
C       *DETERMINE IF BEAMS ARE ALREADY ASSIGNED TO CITIES A AND B
C
30       NBA = 0                          !INDEX OF BEAM ASSIGNED TO CITY A
         NBB = 0                          !INDEX OF BEAM ASSIGNED TO CITY B
         NBFR = 0                         !NUMBER OF UNUSED BEAMS ON NSAT
         SATUSE = 0.0                     !NSAT CAPACITY ALREADY CONSUMED
         DO 35 K = 1, BEAMS, 2
           IF (SATELL(NSAT,K) .EQ. CITA(I)) NBA = K + 1
           IF (SATELL(NSAT,K) .EQ. CITB(I)) NBB = K + 1
           SATUSE = SATUSE + SATELL(NSAT,K+1)
           IF (SATELL(NSAT,K) .NE. 0) GO TO 35
           IF (NBFR .EQ. 0) FIRST = K
           NBFR = NBFR + 1
35       CONTINUE
C
C       *ASSIGN BEAMS TO CITIES A AND B AS NECESSARY
C
         IF (SATUSE .GE. SATLIM) GO TO 90     !NEED NEW SATELLITE
         IF (NBA .NE. 0) GO TO 40       !CITY A ALREADY ASSIGNED A BEAM
         IF ((NBB.EQ.0).AND.(NBFR.LT.2)) GO TO 90      !NEW SATELLITE
         IF (NBB .EQ. 0) GO TO 37
         IF (SATELL(NSAT,NBB) .EQ. CAPAC) GO TO 90     !FULL BEAM
37       IF (NBFR .EQ. 0) GO TO 90     !NEED NEW SATELLITE
         SATELL(NSAT,FIRST) = CITA(I)     !ASSIGN FIRST FREE BEAM TO A
         NBFR = NBFR - 1
         NBA = FIRST + 1
         FIRST = FIRST + 2              !INDEX OF NEXT FREE BEAM
40       IF (SATELL(NSAT,NBA) .EQ. CAPAC) GO TO 90     !BEAM FULL
         IF (NBB .NE. 0) GO TO 45       !CITY B ALREADY ASSIGNED A BEAM
         IF (NBFR .EQ. 0) GO TO 90     !NEED NEW SATELLITE
         SATELL(NSAT,FIRST) = CITB(I)     !ASSIGN FIRST FREE BEAM TO B
         NBB = FIRST + 1
45       IF (SATELL(NSAT,NBB).EQ.CAPAC) GO TO 90     !BEAM FULL
C
C       *BOTH BEAMS HAVE CAPACITY TO ACCEPT ADDITIONAL DEMAND
C       *COMPUTE DEMAND BETWEEN CITIES I AND J
C
         DEMAND = CITIES(I)/2.       !DEMAND PER BEAM
C
C       *DETERMINE IF BEAM CAPACITY WILL BE EXCEEDED
C
         RECAPA = CAPAC - SATELL(NSAT,NBA)      !REMAINING CAPACITY - A
         RECAPB = CAPAC - SATELL(NSAT,NBB)      !REMAINING CAPACITY - B
         IF (DEMAND .LE. RECAPA) GO TO 55       !A HAS ADEQUATE CAPACITY
C
C       *DEMAND EXCEEDS REMAINING CAPACITY ON BEAM A
C
         IF (RECAPA .GT. RECAPB) GO TO 50
         SATELL(NSAT,NBA) = SATELL(NSAT,NBA) + RECAPA      !FILL BEAM A
         SATELL(NSAT,NBB) = SATELL(NSAT,NBB) + RECAPA
         CITIES(I) = CITIES(I) - (2*RECAPA)
         GO TO 90                         !NEED NEW SATELLITE FOR REMAINDER
C
C       *DEMAND EXCEEDS REMAINING CAPACITY ON BEAM B
C
50       SATELL(NSAT,NBA) = SATELL(NSAT,NBA) + RECAPB
         SATELL(NSAT,NBB) = SATELL(NSAT,NBB) + RECAPB      !FILL BEAM B
         CITIES(I) = CITIES(I) - (2*RECAPB)
         GO TO 90                         !NEED NEW SATELLITE FOR REMAINDER
55       IF (DEMAND .GT. RECAPB) GO TO 50
C
C       *DEMAND DOES NOT EXCEED REMAINING BEAM CAPACITIES
C
         SATELL(NSAT,NBA) = SATELL(NSAT,NBA) + DEMAND
         SATELL(NSAT,NBB) = SATELL(NSAT,NBB) + DEMAND
         GO TO 94
C
C       *ADD NEW SATELLITE AND RE-EVALUATE CITY PAIR
C
90       NSAT = NSAT + 1
```

```
      IF (NSAT .GT. TNSAT) TNSAT = NSAT
      IF (TNSAT .GT. 100) EXCEED = 1
C
C    *CONTINUE TO EVALUATE NEW CITY PAIRS IN ORDER TO FILL SATELLITE
C
      IF (EXCEED .EQ. 0) GO TO 30
      WRITE(1,1010)
      WRITE(1,*) ' '
92    IF (DIST(I) .GE. LIMIT) GO TO 94
      LMILES = LMILES + DIST(I)
      PERCNT = PERCNT + CITIES(I)
      PCNTMI = PCNTMI + DIST(I)*CITIES(I)
94    CONTINUE
100  CONTINUE
C
C   *PRINT RESULTS
C
     WRITE(3,1009) (SFILE(I),I=5,10),YEAR
     WRITE(3,1006) TNSAT,NBEAMS,CAPAC
     WRITE(3,1015) SATLIM
C
C   *DETERMINE TOTAL NUMBER OF BEAMS USED AND TOTAL DEMAND
C
     TBEAMS = 0
     TDEM = 0.0
     DO 120 I = 1, TNSAT
       DO 110 J = 2, BEAMS, 2
         SATEMP = SATELL(I,J)
         IF (SATEMP .EQ. 0) GO TO 110
         TBEAMS = TBEAMS + 1
         TDEM = TDEM + SATEMP
C
C        *DETERMINE BEAM DISTRIBUTION
C
         DO 105 K = 1, 5
           IF ((SATEMP .GE. BFILL(K,M)).AND.(SATEMP .LT. BFILL(K+1,M)))
     +       BDIST(K) = BDIST(K) + 1
105      CONTINUE
110    CONTINUE
120  CONTINUE
     WRITE(3,1007) TBEAMS
     DO 130 K = 1, 5
       WRITE(3,1016) BDIST(K),BFILL(K,M),BFILL(K+1,M)
130  CONTINUE
     WRITE(3,1008) TDEM
     WRITE(3,1017) LIMIT,LMILES,PERCNT,PCNTMI
     IF (EXCEED .NE. 0) WRITE(3,1010)
C
     WRITE(1,*) 'DO YOU WISH TO PRINT THE SATELLITE MATRIX?'
     READ(1,1001) ANS
     WRITE(1,*) ' '
     IF (ANS .NE. 'Y') GO TO 125
     WRITE(3,1013)
     WRITE(3,1014)
C
C   *PRINT SATELLITE MATRIX
C
     DO 122 I = 1, TNSAT
       WRITE(3,1011) I
       K = 0
       DO 121 J = 1, BEAMS, 2
         K = K + 1
         NB = INT(SATELL(I,J))
         WRITE(3,1012) K, NB, SATELL(I,J+1)
121    CONTINUE
122  CONTINUE
C
125  CLOSE (UNIT=2,ERR=902)
     WRITE(1,*) 'ARE THERE MORE CITY PAIR MATRICES TO BE EVALUATED?'
```

```
      READ(1,1001) ANS
      WRITE(1,*) '  '
      IF (ANS .NE. 'Y') STOP
C
C    *REINITIALIZE ARRAYS TO ZERO
C
      DO 140 I = 1, COUNT
          CITIES(I) = 0.0
140   CONTINUE
      DO 160 I = 1, 100
        DO 150 J = 1, 40
          SATELL(I,J) = 0.0
150     CONTINUE
160   CONTINUE
      DO 170 K = 1, 5
        BDIST(K) = 0
170   CONTINUE
      TNSAT = 0
      LMILES = 0.0
      PERCNT = 0.0
      PCNTMI = 0.0
      LIMIT = 0.0
      GO TO 10
C
C    *FORMAT STATEMENTS
C
1001  FORMAT(10A1)
1002  FORMAT(I2)
1003  FORMAT(40Y)
1004  FORMAT(F7.5)
1005  FORMAT(I4,2X,I4)
1006  FORMAT(1X,//,10X,'NUMBER OF SATELLITES  ',I3,' EACH HAVING ',I2,
     1        ' BEAMS OF CAPACITY ',F7.5)
1007  FORMAT(1X,//,10X,'NUMBER OF EARTH STATIONS =',I5,' BROKEN DOWN AS
     +FOLLOWS:')
1008  FORMAT(1X,//,10X,'TOTAL DEMAND = ',F10.5)
1009  FORMAT(1H1,//,10X,'EARTH STATION-SATELLITE EVALUATION FOR ',6A1,
     1        ' MATRIX IN THE YEAR ',I4)
1010  FORMAT(1X,//,10X,'***WARNING*** MAXIMUM NUMBER OF SATELLITES HAS
     1BEEN EXCEEDED. NOT ALL CITY PAIRS HAVE BEEN EVALUATED.')
1011  FORMAT(1X,/,10X,I3)
1012  FORMAT(23X,I2,10X,I2,10X,F7.5)
1013  FORMAT(1H1,////,7X,'SATELLITE',6X,'BEAM',8X,'CITY',8X,'CAPACITY')
1014  FORMAT(7X,'---------',6X,'----',8X,'----',8X,'--------')
1015  FORMAT(1X,//,10X,'TOTAL SATELLITE CAPACITY: ',F7.5)
1016  FORMAT(20X,I3,' EARTH STATIONS OF CAPACITY ',F7.5,' TO ',F7.5)
1017  FORMAT(1X,//,10X,'TOTAL NUMBER OF MILES FOR TRANSMISSIONS UNDER
     + THE LIMIT OF ',F5.0,' MILES IS ',F10.0,/,10X,'FOR A TOTAL OF ',
     + F8.5,' PERCENT OF THE TRAFFIC FLOW.',/,10X,'THE SUM TOTAL OF THE
     + MILES-PERCENT PRODUCT IS ',F12.5)
C
C    *ERROR STATEMENTS
C
901   WRITE(1,*) 'ERROR IN OPENING CITY-PAIR DATA FILE. PLEASE'
      WRITE(1,*) 'CHECK THE FILE NAME AND TRY AGAIN.'
      WRITE(1,*) '  '
      GO TO 10
C
902   WRITE(1,*) 'ERROR IN CLOSING CITY-PAIR DATA FILE. COMPUTATIONS'
      WRITE(1,*) 'ARE COMPLETE; PROGRAM TERMINATED'
      STOP
C
      END
```