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COMSAT

INTERSATELLITE LINK (ISL) APPLICATION TO COMMERCIAL COMMUNICATIONS SATELLITES

VOLUME II
TECHNICAL FINAL REPORT

COMMUNICATIONS SATELLITE CORPORATION
SPACE COMMUNICATIONS DIVISION
950 L'ENFANT PLAZA, S.W.
WASHINGTON, D. C. 20024

PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
NASA LEWIS RESEARCH CENTER
CLEVELAND, OH 44135

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16. Abstract

Based on a comprehensive evaluation of the fundamental intersatellite link systems characteristics, potential applications of ISLs to domestic, regional, and global commercial satellite communications were identified, and their cost-effectiveness and other systems benefits quantified wherever possible. Implementation scenarios for the cost-effective communications satellite systems employing ISLs were developed for the first launch in 1993-94 and widespread use of ISLs in the early 2000's. Critical technology requirements for both the microwave (60 GHz) and optical (0.85 um) ISL implementations were identified, and their technology development programs, including schedule and cost estimates, were derived in the study.

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Table of Contents

Table of Contents (Cont.)

Table of Contents (Cont.)

List of Illustrations

List of Illustrations (Cont.)

List of Illustrations (Cont.)

List of Illustrations (Cont.)

List of Tables

List of Tables (Cont.)

List of Tables (Cont.)

1. INTRODUCTION

1.1 NASA'S ISL APPLICATION STUDY PROGRAM

This report presents the results of a study on "Intersatellite Link (ISL) Application to Commercial Communications Satellites" performed under the NASA-Lewis Research Center contract with Communications Satellite Corporation (Contract No. NAS3-24884). The study was conducted for a 10-month period from March 1986 through December 1986.

An ISL is a "missing" link in the existing commercial satellite network. ISL applications can improve and expand communications satellite services in a number of ways. As the demand for orbital slots within prime regions of the geostationary arc increases, attention is becoming focused on ISLs as a method to utilize this resource more efficiently and circumvent saturation. ISLs can effectively conserve the spectral resources allocated for fixed-satellite services by replacing the up-link/down-link bandwidth of the relay station with the ISL frequency band. An ISL replacing the multiple-hopping system also provides reduced signal propagation delay and improved quality of signal transmission.

An ISL providing a link between a domestic satellite network and an international network allows international traffic from small remote terminals in a country to be directly transmitted through the nearest domestic earth station to the domestic satellite and then carried via ISL to the satellite providing international services.

ISLs between domestic satellites and/or regional satellites could support completely new satellite network architectures to be evolved for future satellite communications.

For the implementation of an ISL, two technology approaches have been developed: microwave and optical ISLs. Both ISL system approaches have distinct, different attributes, making the choice between the two application-oriented. ISL technology issues have been well defined, and solutions to most of the remaining technological issues are anticipated in the near future.

NASA has identified that "with ISL technology being at the stage of development it is, the crucial question that must be answered to move ahead is: Can the use of intersatellite links enable cost-effective alternatives to existing satellite communication systems?" The study addressed this question from a rather broad systems perspective of ISL applications, network architectures, and their associated cost analysis and benefit evaluations, based on the future service demands and traffic projections for domestic regional and international communications.

1.2 STUDY OBJECTIVES AND TASKS

The objectives of the ISL Application Study are as follows:

- To define potential applications of intersatellite links to commercial communication satellites and their benefits.

- To define implementation scenarios for commercial communications satellite systems employing intersatellite links.
- To define technology requirements for ISL systems.

The following three technical tasks defined in the Statement of Work were performed to achieve the above specific objectives:

- Task 1: Determination of ISL Applications,
- Task 2: Network Architectures and Cost Analyses,
- Task 3: Implementation Scenarios and Technology Issues.

Figure 1-1 shows the Work Flow Chart for performance of the three tasks.

Task 1 determined various GEO-to-GEO applications that ISLs may provide potential benefits over existing communication systems. A set of criteria was developed to assess the potential applications. Six major ISL applications were selected for further study in Task 2 and Task 3. Upon completion of Task 1, the first interim briefing was presented to NASA-Lewis on June 30, 1986.

Task 2 developed ISL traffic models, network systems architectures, and payload configurations. For each of the chosen ISL applications, ISL versus non-ISL satellite systems architectures were derived. The non-ISL system provides the same services as the corresponding ISL system. Both microwave (60 GHz) and optical (0.85 μm) ISL implementation approaches were evaluated for payload sizing and cost analyses. Cost models were developed in the study. The overall systems cost analysis is based on "add-on" systems cost comparisons between the ISL systems and the corresponding non-ISL systems. For each

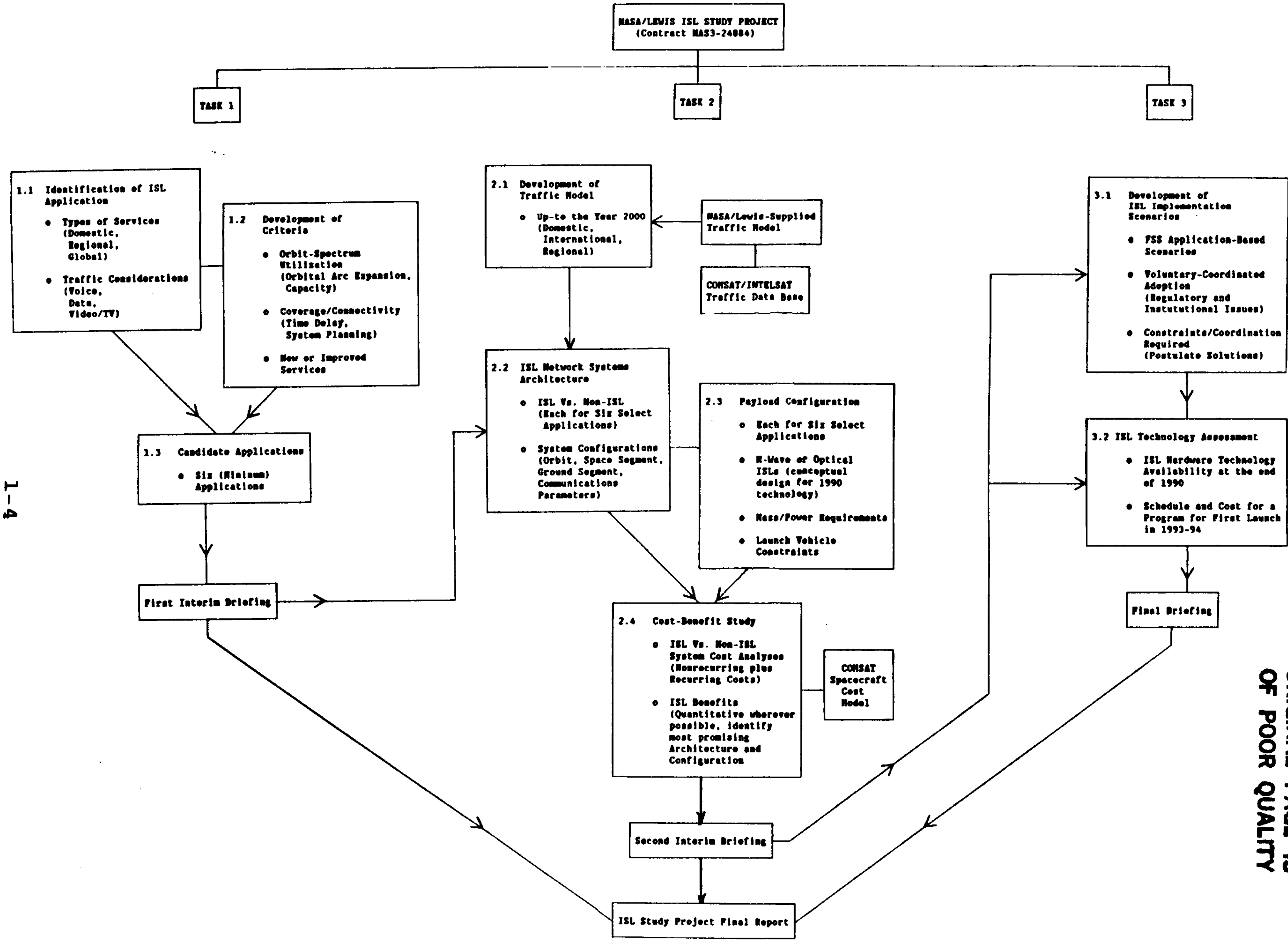

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Figure 1-1. Work Flowchart

of the ISL systems applications, the benefits and costs of the ISL were quantified, along with some qualitative assessments. Task 2 study results were presented to NASA-Lewis at the Second Interim Briefing on October 29, 1986.

Task 3 developed implementation scenarios for each of the ISL system architectures derived in Task 2 for the following time frame:

- The state-of-the-art technology at the end of 1990.
- First launch in 1993-94.
- Widespread use of ISLs in 2000.

The technological availability for ISL implementations was assessed. Critical subsystems technology areas were identified, and an estimate of the schedule and cost to advance the technology to the required state of readiness was made. The final briefing was presented to NASA-Lewis on December 15, 1986.

1.3 GUIDELINES AND CONSTRAINTS

The scope of the ISL applications study was restricted to GEO-to-GEO commercial satellite communications in accordance with the Statement of Work for this study.

Some of the major NASA-directed and contractor-recommended guidelines and constraints for the study are the following:

- ISL applications for various fixed-satellite services (FSS).
- ISL traffic models for the year 2001.

- The ISL network architectures to be based on a 100-percent capture of the satellite-addressable traffic.
- 4,500 half-voice circuits per 36-MHz equivalent transponder technology assumed for space segment sizing for the year 2000 time frame.
- The SOA technology at the end of 1990 to be used for ISL implementations with the first launch taking place in 1993-94.
- 12-year design life of satellites.
- All costs in 1986 dollars.

In order to identify potential ISL applications for which an ISL can play a major role beyond the limited supporting function of the existing systems, no specific constraints related to any existing satellite network systems were imposed for this study.

The cost-effectiveness of ISLs were addressed in comparison to the corresponding non-ISL satellite communication systems.

1.4 ORGANIZATION OF FINAL REPORT

The Final Report consists of two volumes. Volume I, Executive Summary, provides a brief overview of the study results. Volume II, Final Technical Report, presents the detailed description of the performance of the study on three tasks.

Section 2 of this technical report describes the identification and selection of candidate ISL applications under Task 1.

The results of Task 2 are contained in three sections. Section 3 provides ISL traffic models for various applications. Section 4 includes network architectures and payload configurations for each of the selected ISL applications. The systems cost analyses and benefit evaluations are summarized in Section 5.

Section 6 describes the Task 3 study results on implementation scenarios and technology issues.

Finally, Section 7 provides conclusions and recommendations of the study. Some of the specific technical data and analyses are given in the appendices.

2. DETERMINATION OF ISL APPLICATIONS

Based on a comprehensive review of the background and analysis of fundamental systems characteristics of ISLs, various potential applications were identified. ISL figure of merit factors were developed as a part of the criteria which were used to assess and determine promising applications of ISLs. Finally, six candidate ISL applications were selected for further study in Task 2.

2.1 BACKGROUND DESCRIPTION

The intersatellite link concept, in fact, was originated by A. C. Clarke as early as in 1945 [1]. With reference to Figure 2-1, Clarke observed that:

> "Three (geostationary earth orbit) satellite stations would ensure complete coverage of the globe. The (satellite) stations would be linked by radio or optical beams, and thus any conceivable beam or broadcast service could be provided."

It is interesting to see that both microwave (i.e., radio beam) and optical ISL implementations were envisioned in his historical concept.

As the international communications satellite technology matured, ISL technologies have been under study for over a decade, since late 1970, by many organizations such as

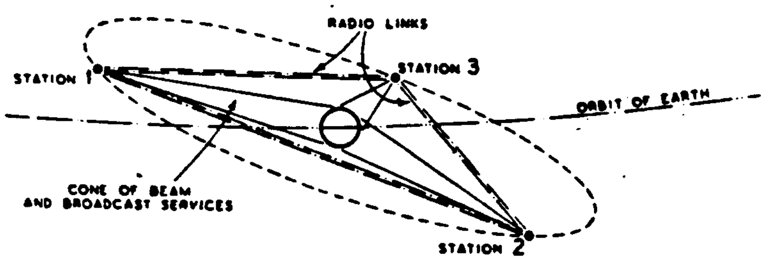


Figure 2-1. A. C. Clarke's Concept
of GEO Communications Satellites
and Intersatellite Links

NASA, the Department of Defense (the Air Force), COMSAT, INTELSAT, and the European Space Agency (ESA).

Experimental microwave ISLs have been demonstrated in space by the Lincoln Experimental Satellites (LES-8 and LES-9) at 40-/50-GHz bands [2]. Implementation of an ISL in the 33-/23-GHz bands was investigated for international satellite communications, and key hardware components were developed for space applications [3]-[4]. Detailed ISL payload configurations onboard INTELSAT VI spacecraft was also defined [6],[7]. However, INTELSAT VI's ISL flight program was canceled due to economic reasons.

Various laser sources (i.e., Nd:YAG, CO_2, and semiconductor diode lasers) have been developed for the applications to optical ISLs. Optical ISLs using diode lasers are an emerging technology and provide potential advantages in space applications. Leading R&D organizations worldwide, including NASA Goddard Space Flight Center (GSFC), have been conducting studies on optical ISL technologies. NASA's Advanced Communications Technology Satellite (ACTS) Lasercom flight program, under a joint effort by NASA and the Air Force, is currently in progress for the proof-of-concept flight operation of optical ISLs in the early 1990s.

The ISL technology issues are well defined, and solutions to most of the remaining issues are anticipated in the near future.

Recently, the commercial satellite communications community is facing serious competition from the fiber-optic cable industry. The need to search for more cost-effective means of satellite communications has, thus, been increased. New satellite network systems architectures employing ISLs may provide more cost-competitive communications services than the existing conventional satellite systems to cope with future market demands. The motivation of this study is based on this need, as part of NASA's advanced definition studies of the future commercial satellite communications systems.

2.2 STUDY APPROACH

A number of previous reports [2]-[6] addressed ISL applications on how to improve and expand the existing conventional communications satellite systems. The conventional satellite network system has, however, been developed without intersatellite links. The role of ISLs in those reports was limited to supporting functions of the conventional network systems.

This study explores various ISL systems applications without any constraints that may be imposed by the existing systems. Figure 2-2 shows the methodology used for performing the Task 1 study on Identification of ISL Applications.

Fundamental systems characteristics were evaluated for all generic categories of ISLs. Those results, along with the satellite-addressable traffic and transponder requirements of various types of services, were used to identify potential ISL applications.

Table 2-1 shows major systems applications of ISLs and their potential impact on FSS communications systems planning and network implementation.

Regarding those applications, "figure-of merit" factors were derived as part of the development of ISL systems criteria and used to quantify ISL systems advantages. In addition, other nonquantifiable systems operational/planning aspects related to each of the systems applications were considered also in the selection of candidate ISL applications.

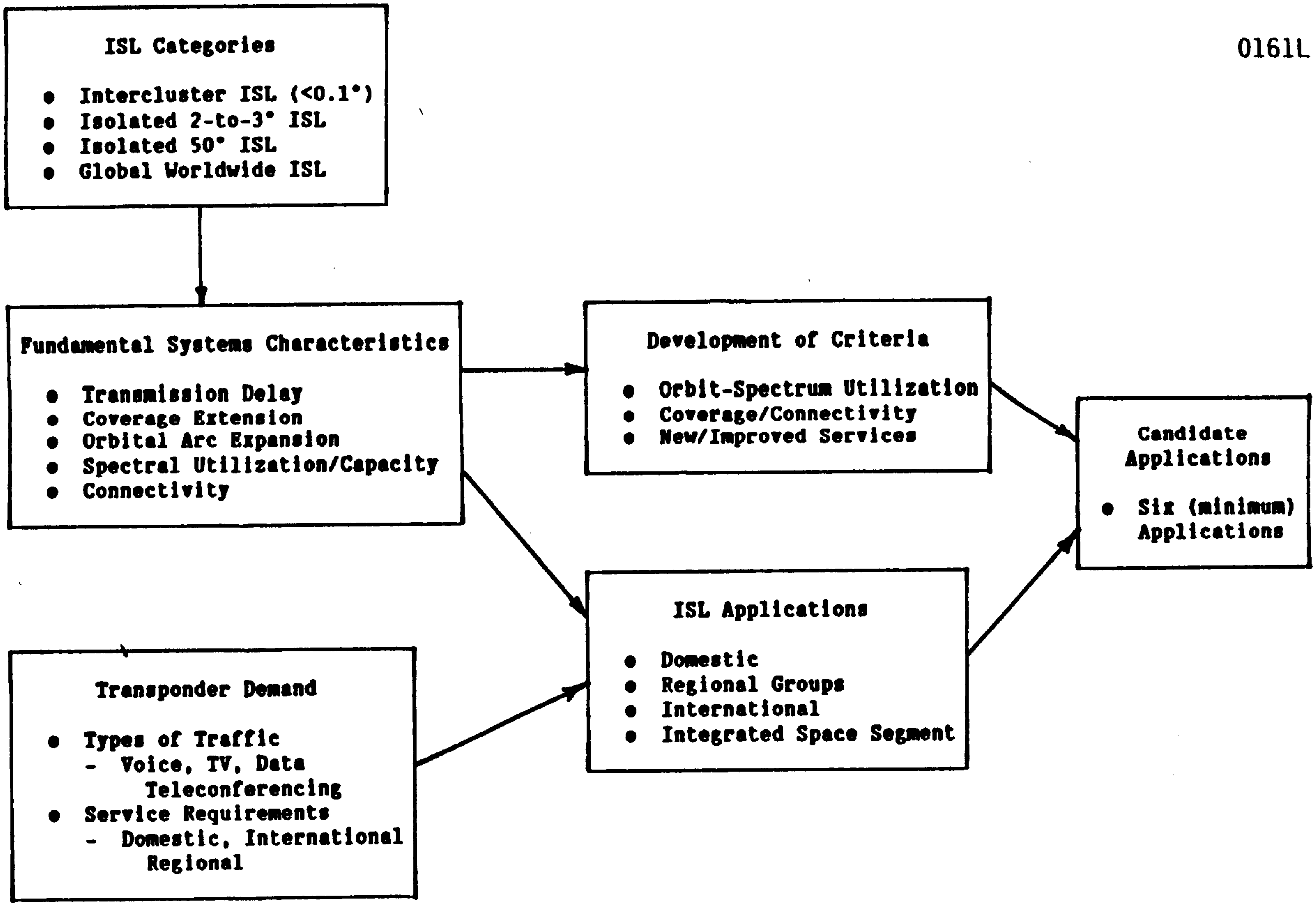


Figure 2-2. Determination of ISL Applications (Task 1)--Study Methodology

Table 2-1. Potential ISL Systems Applications

No.	ISL Systems Applications	Systems Impact
1	Orbital Arc Expansion	Increased number of useful prime slots
2	K_u/K_a-Band Utilization	Improved services for small on-the-premise earth stations
3	Coverage Extension	Improvement in existing system
4	Transmission Time Delay Reduction	Better quality service for voice traffic to more users by avoiding double hop
5	Efficient Bandwidth Utilization	Reduced intersystem interference and more efficient FSS spectrum utilization
6	N-Fold Orbital Arc Utilization	New system with a "super" satellite
7	Integrated Space Segment	New system, ISDN with satellites

Four generic categories of ISLs were identified according to the orbital separation between two adjacent satellites that can be connected by an ISL:

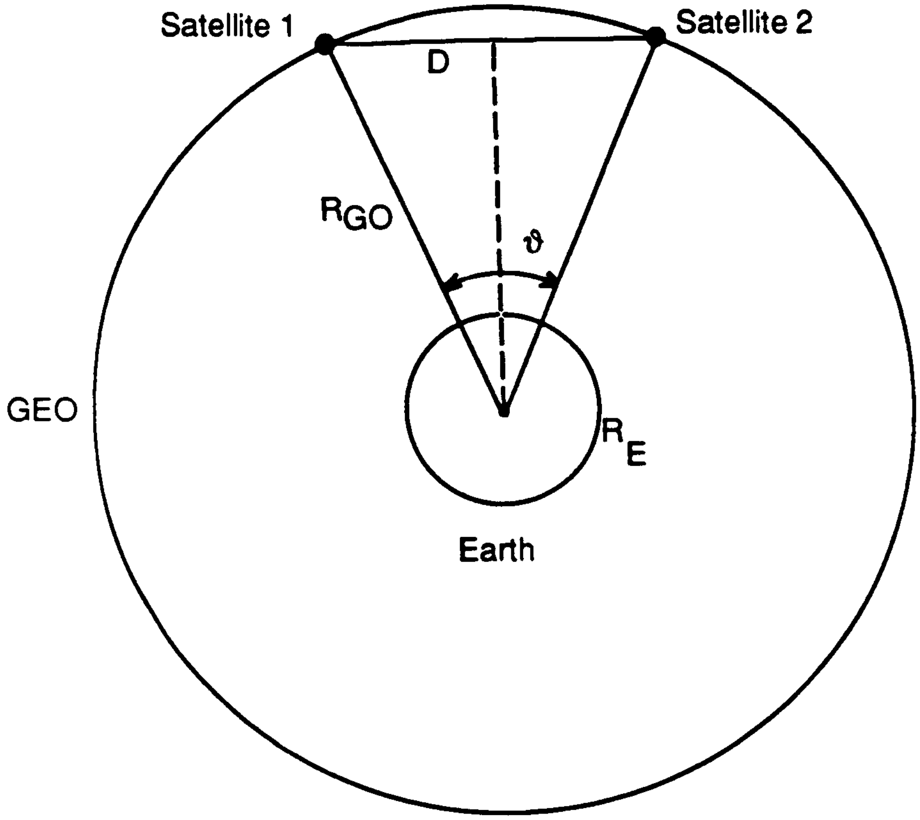
a. Intercluster ISL for which the orbital spacing is less than 0.1°.
b. Isolated short-range (2° ~ 3° nominal) ISL for which each satellite provides a common or separate coverage area(s).
c. Isolated medium-range (50° nominal) ISL which can replace double-hop links mostly for international or interregional satellite communications.
d. Complete global, worldwide coverage ISL for which the network of satellites are interconnected to provide complete worldwide traffic interconnectivity. ITU interregional ISLs belong to this category.

2.3 FUNDAMENTAL ISL SYSTEMS CHARACTERISTICS

The fundamental systems characteristics of ISLs were identified and quantified wherever applicable. This section describes the ISL's time delay characteristics, orbital arc expansion capability, coverage extension, space segment capacity utilization improvement, and others.

2.3.1 TIME DELAY

The transmission time delay is determined by the simple geometry shown in Figure 2-3. The total one-way time delay of signals originating from a transmit earth station and



R_E = Earth radius, 6.375×10^6 m

R_{GO} = Geostationary orbit distance from the center of the earth, 4.216×10^7 m

ϑ = ISL longitudinal separation in degrees

D = ISL distance between two satellites

Figure 2-3. Basic Geometry of ISL

received by another in any location within the coverage areas of two ISL satellites includes three path delays consisting of up-link, ISL, and down-link propagation times. The up- and down-link delays are actually dependent on the elevation angle requirement of the transmit or receive earth stations involved.

Figure 2-4 shows the total one-way transmission delay versus ISL distance in longitudinal degrees. Also shown in Figure 2-4 are single-hop and double-hop delays of the conventional satellite network. The lower bound of delay corresponds to transmit and receive earth stations located near the subsatellite points, while the upper bound corresponds to earth stations having 5° elevation angles within the coverage areas.

Figure 2-4 shows a clear advantage of ISL in reduced delay performance over a corresponding double-hop network. The delay characteristics of ISL indicate that:

a. ISLs between satellites spaced by about 50° (in longitudinal degrees) can meet the 400-ms criterion of one-way transmission delay, which is the CCITT recommended network performance objective for voice traffic.
b. A corresponding double-hop network requires a longer delay ranging from 477 ms to 555 ms, and cannot meet the CCITT criterion.
c. The time delay advantage of ISLs can provide improved telephony services to more users in the extended coverage areas, resulting in increased satellite-addressable traffic.

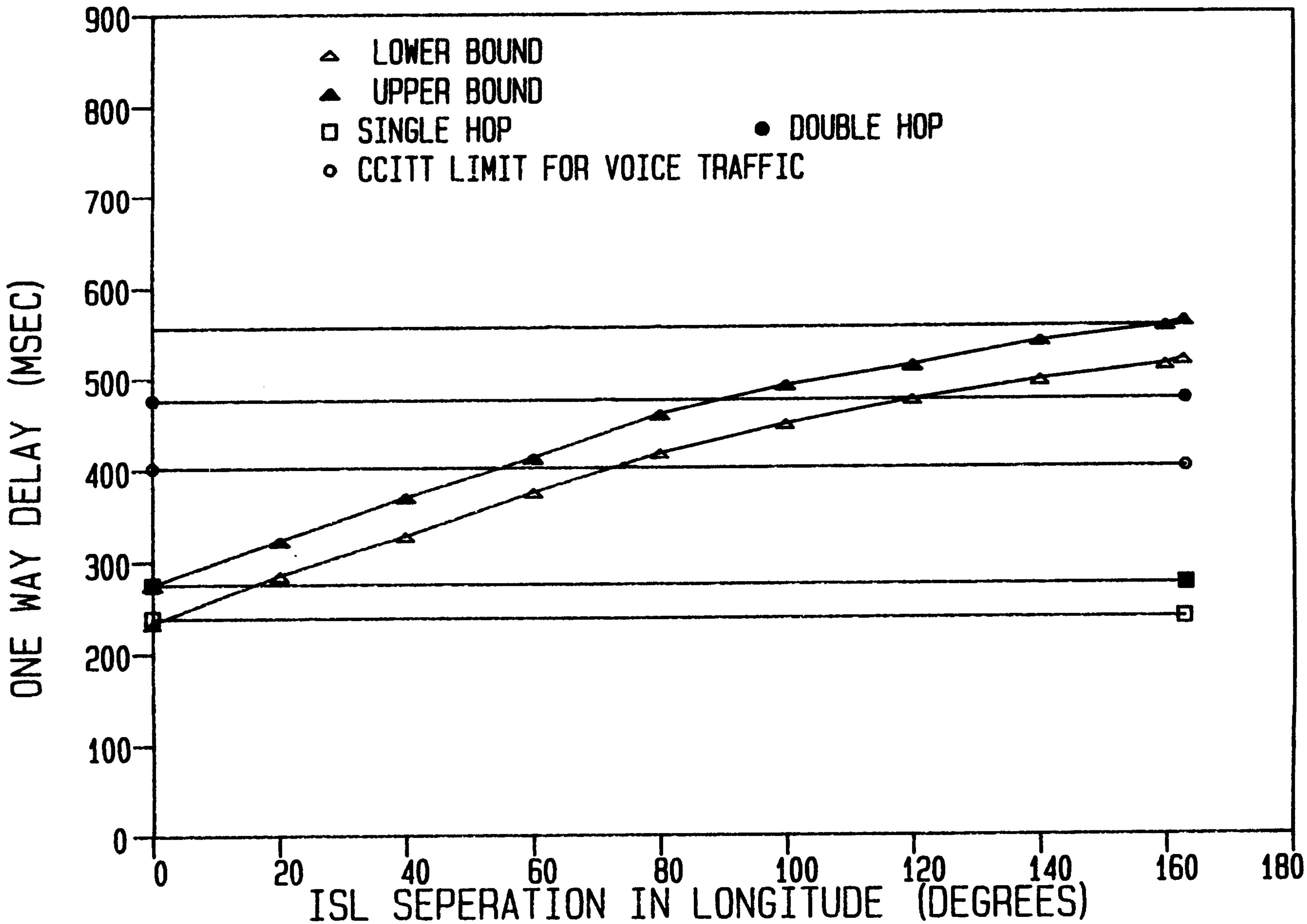


Figure 2-4. Transmission Delay of ISL System

2.3.2 ORBITAL ARC EXPANSION CAPABILITY

The useful geostationary orbital arc length that can accommodate FSS satellites can be increased substantially by employing ISLs. This capability of ISLs was investigated previously by Ponchak and Spence for applications to domestic satellite systems [8].

The arc expansion capability of ISLs was investigated further in this section for the continental United States (CONUS) satellite coverages to alleviate the congestion problem of prime orbital locations. In the analysis, the following three cases were considered:

a. A single CONUS area coverage.
b. Double area coverages of CONUS:
   East- and West-half geographical coverages defined by 96°W longitude line.
c. Four time zone coverages: Pacific, Mountain, Central, and Eastern time zone areas.

For each case the useful geostationary orbital locations of each satellite were computed for C-, K_u-, and K_a-band FSS communications services. The minimum elevation angle of earth station was defined to be 5°, 10°, and 30° for C-, K_u-, and K_a-band, respectively. The NASA-supplied satellite-addressable CONUS traffic matrix (i.e., 316 x 316 standard metropolitan statistical areas (SMSAs) and 84 x 84 traffic matrix) was used in the analysis: Subsection 3.1 describes the traffic model. The Arc Expansion Analysis Program developed for this work is described in Subsection 3.2.2. Figure 2-5 shows the 84 SMSAs and various cases of CONUS

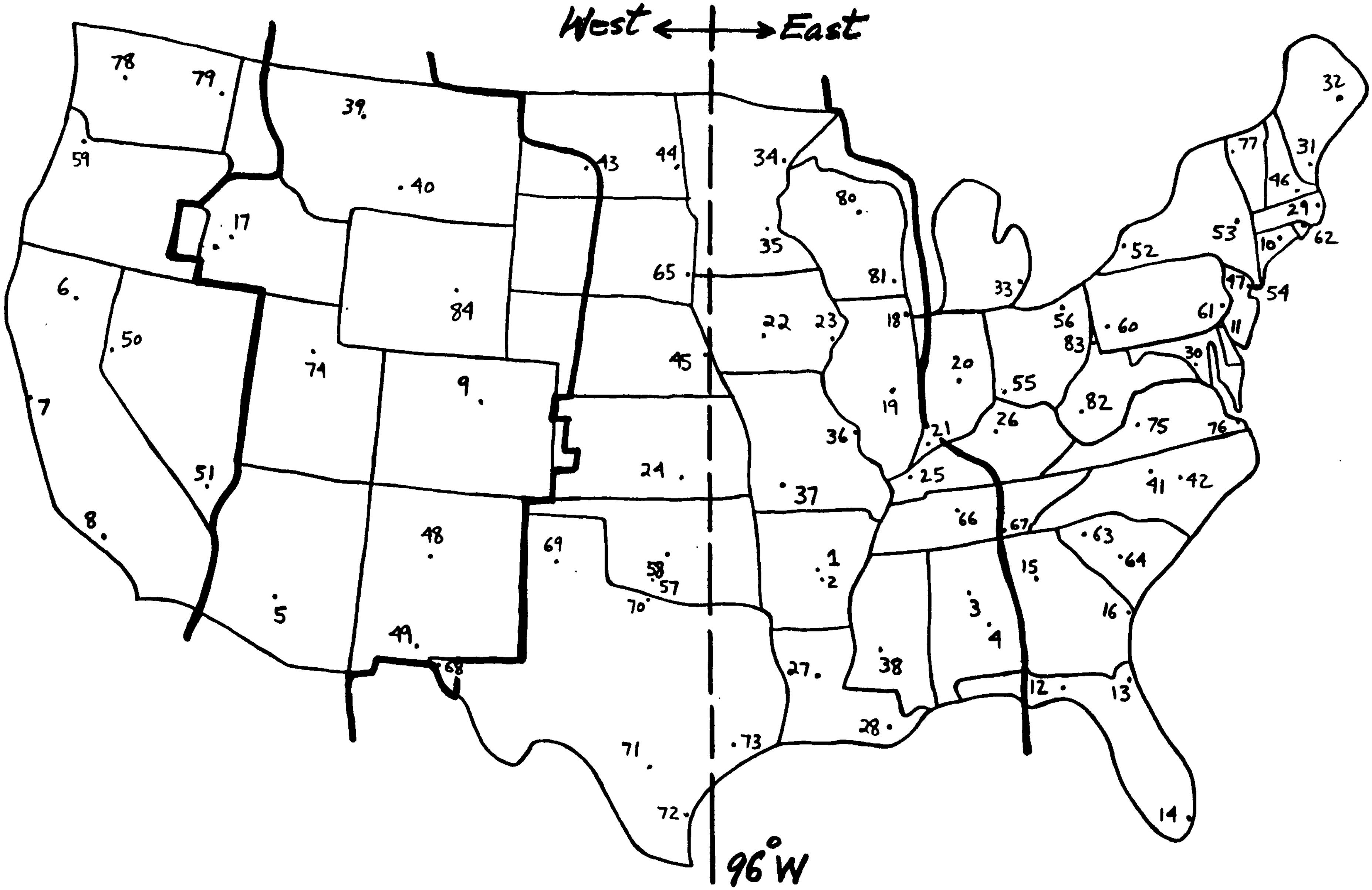


Figure 2-5. 84 SMSAs and Various CONUS Geographical Coverages

coverage. The location and traffic of earth node is listed in Table 2-2.

The percentage of satellite traffic accessible with a minimum specified earth station elevation angle within a coverage is shown in Figures 2-6 through 2-8 for various various satellite orbital locations. The percentage of satellite traffic was defined as the ratio of visible traffic to the total amount of traffic within the prescribed area.

Table 2-3 shows a summary of the useful orbital arc length that can provide 100-percent traffic coverage for CONUS. The ISL orbital arc expansion capability is determined from the arc length that is useful to accommodate 100-percent CONUS traffic with ISLs compared to the single coverage case without ISL.

The ISL application to CONUS increases the total useful arc length significantly as follows:

Frequency Band	Two Coverages with ISLs	Four Time Zones with ISLs
C-Band	1.68	1.89
K_u-Band	1.86	2.29
K_a-Band	11.8	18.8

Therefore, ISL provides an increased number of useful orbital slots for FSS satellites. For K_a-band satellites, the ISL arc expansion capability is very significant.

Table 2-2. CONUS 84 SMSAs

No.	SMSA	Location: Longitude (° East)	Location: Latitude (° North)	Traffic (Thousand Half-Voice Circuits)
1	Little Rock, AK	-92.17	34.42	84.698
2	Pine Bluff, AK	-92.0	34.13	21.498
3	Birmingham, AL	-86.55	33.3	179.295
4	Montgomery, AL	-86.2	32.22	69.118
5	Phoenix, AZ	-112.03	33.3	103.88
6	Redding, CA	-122.24	40.35	48.901
7	San Francisco, CA	-122.27	37.45	311.256
8	Los Angeles, CA	-118.15	34.0	390.484
9	Denver, CO	-105.0	39.45	188.297
10	Hartford, CT	-72.42	41.45	247.829
11	Wilmington, DE	-75.31	39.46	32.57
12	Tallahassee, FL	-84.19	30.26	96.85
13	Jacksonville, FL	-81.4	30.2	92.838
14	Miami, FL	80.15	25.45	411.315
15	Atlanta, GA	-84.23	33.45	133.594
16	Savannah, GA	-81.07	32.04	107.288
17	Boise City, ID	-115.3	43.38	21.715
18	Chicago, IL	-87.45	41.5	309.752
19	Decatur, IL	-88.57	39.51	21.801
20	Indianapolis, IN	-86.1	39.45	308.336
21	Evansville, IN	-87.33	38.0	25.303
22	Des Moines, IA	-93.35	41.35	34.84
23	Davenport, IA	-90.34	41.3	114.165
24	Wichita, KS	-97.2	37.43	97.504
25	Owensboro, KY	-87.05	37.45	19.843

Table 2-2. CONUS 84 SMSAs (Cont.)

No.	SMSA	Location		Traffic (Thousand Half-Voice Circuits)
		Longitude (° East)	Latitude (° North)	
26	Louisville, KY	-85.48	38.13	74.282
27	Alexandria, LA	-92.29	31.19	78.053
28	New Orleans, LA	-90.03	30.0	157.146
29	Boston, MA	-71.05	42.2	249.971
30	Washington, DC/MD	-77.0	38.55	177.262
31	Portland, ME	-70.18	43.41	34.179
32	Bangor, ME	-68.47	44.49	17.463
33	Detroit, MI	-83.05	42.23	418.394
34	Duluth, MN	-92.1	46.45	26.432
35	Minneapolis, MN	-93.15	45.0	152.006
36	St. Louis, MO	-90.15	38.4	178.631
37	Springfield, MO	-93.19	37.11	52.28
38	Jackson, MS	-90.11	32.2	77.481
39	Great Falls, MT	-111.6	47.3	18.906
40	Billings, MT	-108.3	45.47	21.148
41	Burlington, NC	-79.27	36.05	204.806
42	Raleigh, NC	-78.39	35.46	120.212
43	Bismarck, ND	100.48	46.5	20.17
44	Fargo, ND	-96.49	46.52	46.216
45	Omaha, NE	-96.0	41.15	107.674
46	Nashua, NH	-71.28	42.44	55.173
47	Newark, NJ	-74.11	40.44	252.26
48	Albuquerque, NM	-106.38	35.05	40.504
49	Las Cruces, NM	-106.47	32.18	19.511
50	Reno, NV	-119.49	39.32	19.386

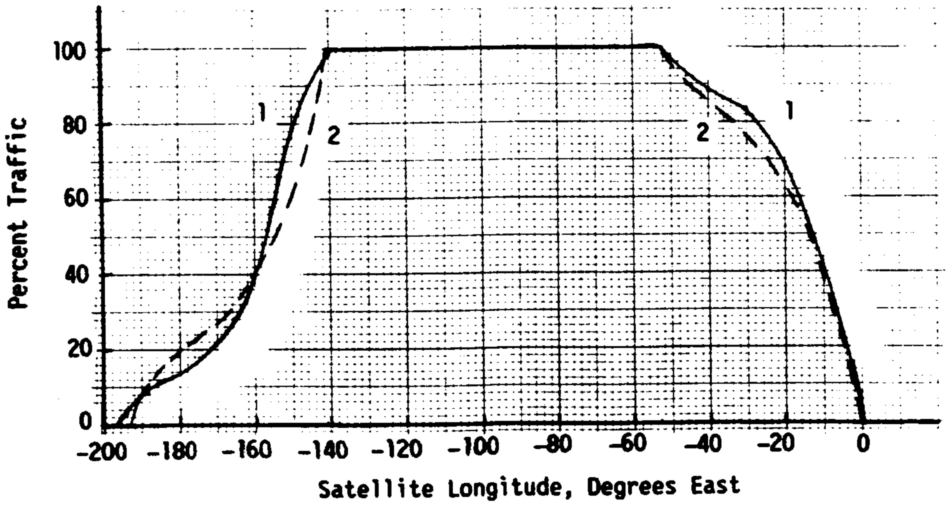
Table 2-2. CONUS 84 SMSAs (Cont.)

No.	SMSA	Location		Traffic (Thousand Half-Voice Circuits)
		Longitude (° East)	Latitude (° North)	
51	Las Vegas, NV	-115.1	36.1	36.593
52	Buffalo, NY	-78.55	42.52	109.402
53	Albany, NY	-73.49	42.4	177.074
54	New York, NY	-73.5	40.4	278.811
55	Cincinnati, OH	-84.3	39.1	281.808
56	Cleveland, OH	-81.41	41.3	207.306
57	Lawton, OK	-98.25	34.36	42.956
58	Oklahoma City, OK	-97.33	35.28	113.546
59	Portland, OR	-122.4	45.32	96.395
60	Pittsburgh, PA	-80.0	40.26	137.582
61	Philadelphia, PA	-75.1	40.0	268.814
62	Providence, RI	-75.53	39.42	36.888
63	Greenville, SC	-82.25	34.52	85.226
64	Columbia, SC	-81.0	34.0	112.969
65	Sioux Falls, SD	-96.42	43.34	24.399
66	Nashville, TN	-86.5	36.1	139.123
67	Chattanooga, TN	-85.18	35.02	123.849
68	El Paso, TX	-106.3	31.45	36.096
69	Amarillo, TX	-101.5	35.14	25.673
70	Wichita Falls, TX	-98.3	33.55	70.943
71	San Antonio, TX	-98.3	29.25	215.452
72	Corpus Christi, TX	-97.26	27.47	88.581
73	Houston, TX	-95.25	29.45	335.9
74	Salt Lake City, UT	-111.55	40.45	70.755
75	Roanoke, VA	-79.58	37.15	58.969

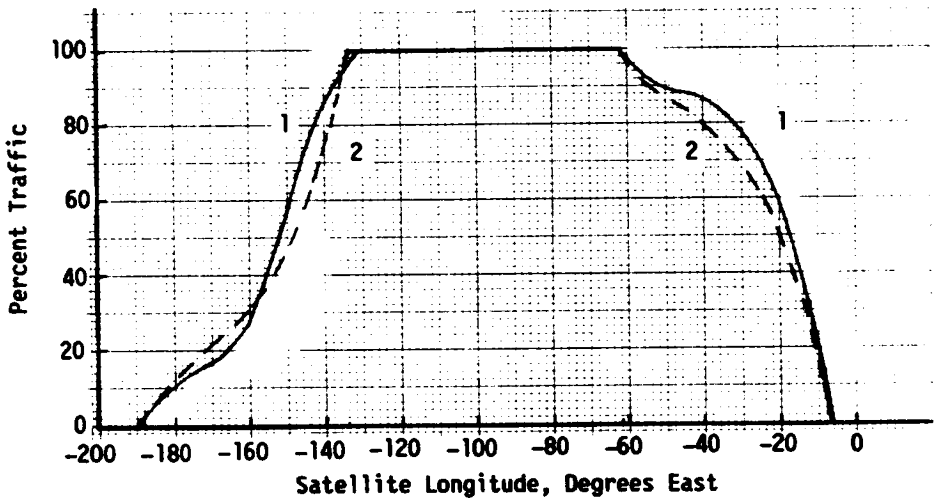
Table 2-2. CONUS 84 SMSAs (Cont.)

No.	SMSA	Location		Traffic (Thousand Half-Voice Circuits)
		Longitude (° East)	Latitude (° North)	
76	Norfolk, VA	-76.18	36.54	144.707
77	Burlington, VT	-73.14	44.28	17.273
78	Seattle, WA	-122.2	47.35	123.685
79	Spokane, WA	-117.25	47.4	58.93
80	Wausau, WI	-89.4	44.58	42.112
81	Milwaukee, WI	-87.56	43.03	245.487
82	Charleston, WV	-81.4	38.23	63.529
83	Wheeling, WV	-80.43	40.05	15.581
84	Casper, WY	-106.2	42.5	19.322

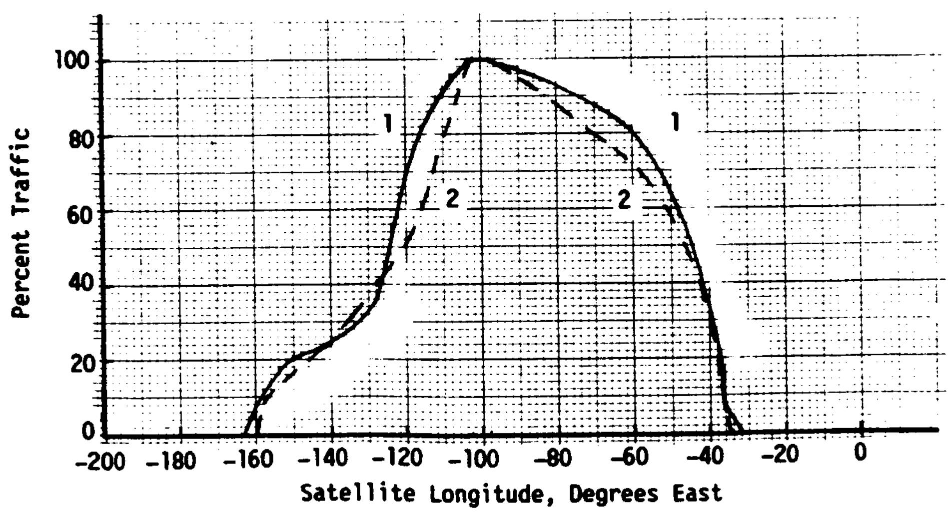
Curve 1: Current Result with 84 Nodes
Curve 2: Previous Result with 45 Nodes by Ponchak [8]



A. Elevation Angle 5°, C-Band

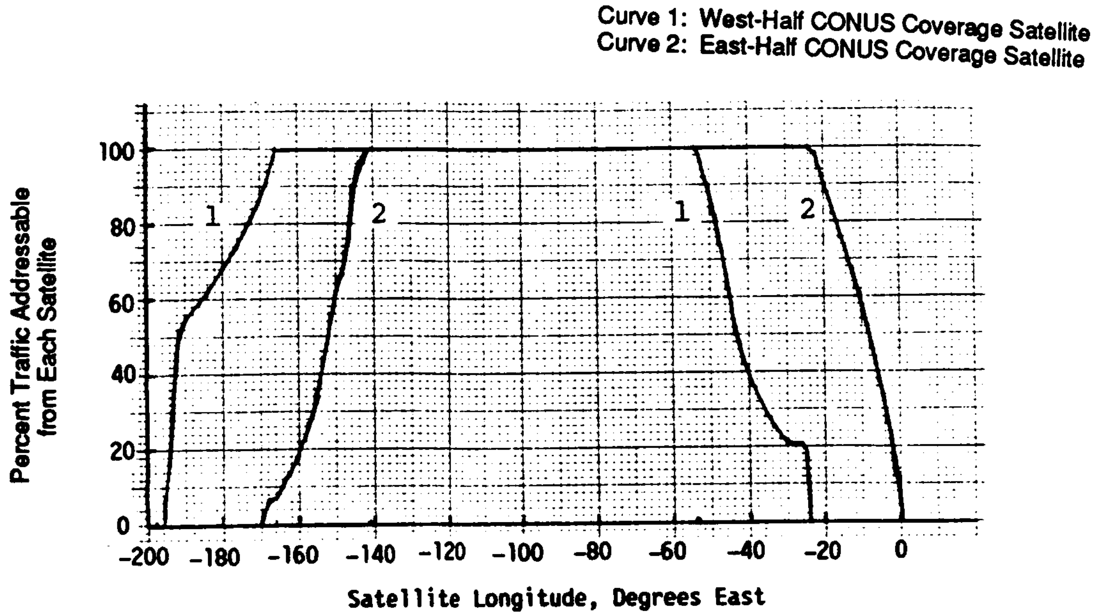


B. Elevation Angle 10°, K_u-Band

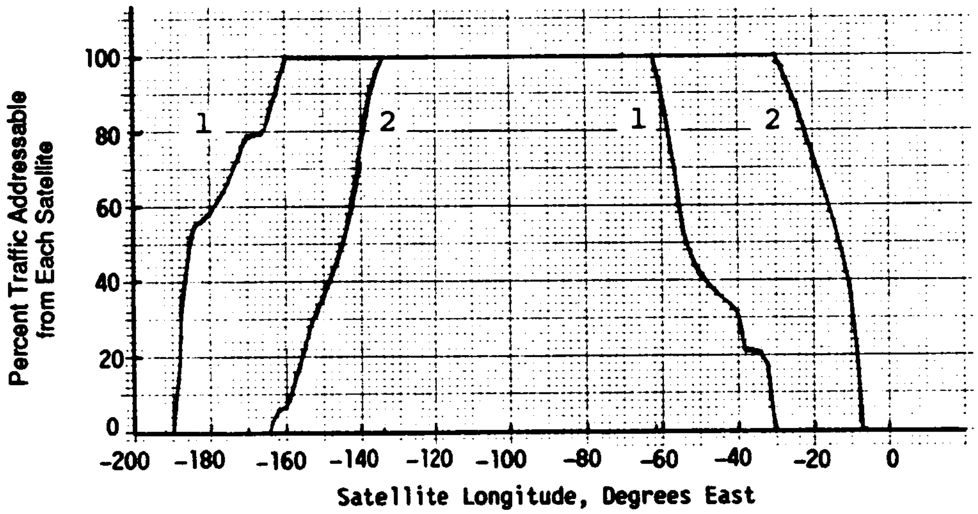


C. Elevation Angle 30°, K_a-Band

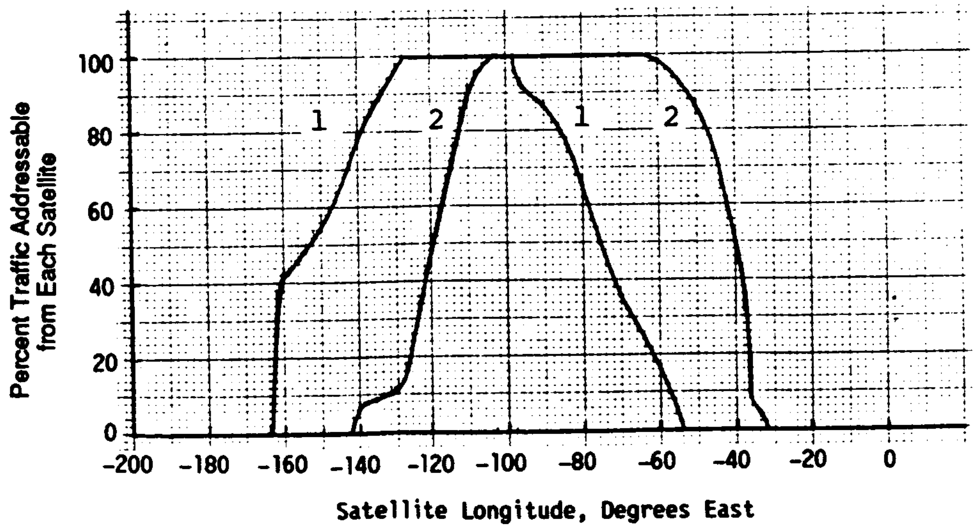
Figure 2-6. A Single CONUS Coverage Satellite Orbital Arc Requirement



A. Elevation Angle 5°, C-Band



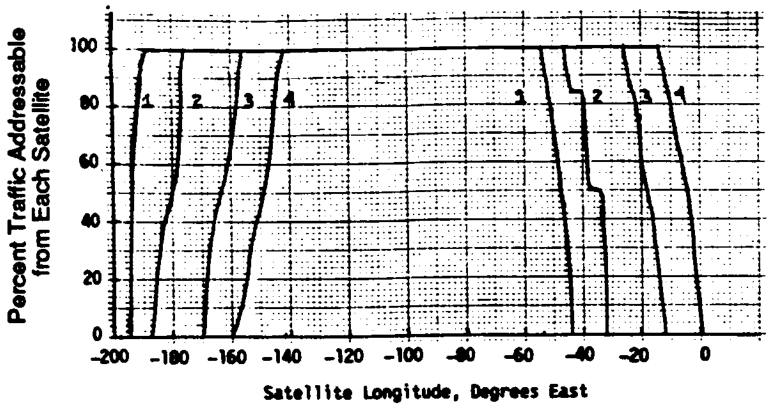
B. Elevation Angle 10°, K_u-Band



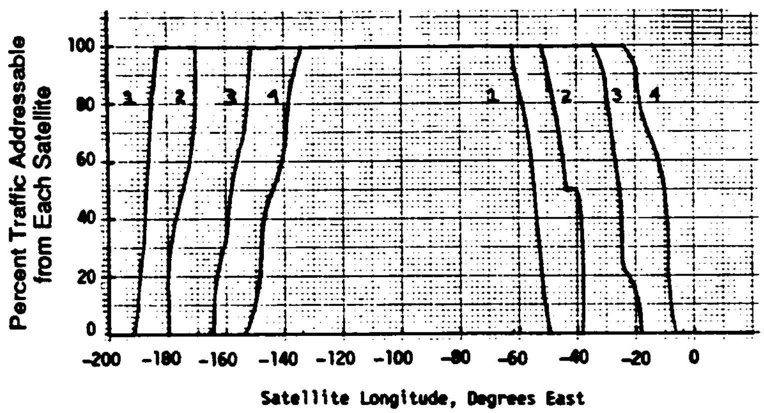
C. Elevation Angle 30°, K_a-Band

Figure 2-7. CONUS East- and West-Half Coverage ISL Orbital Arc Expansion

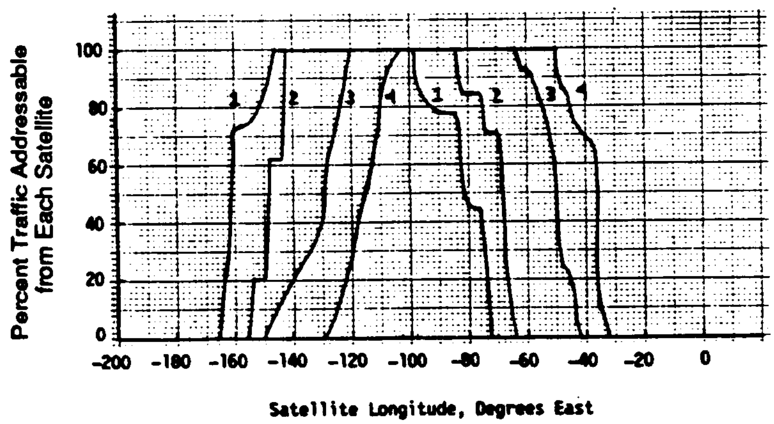
Curve 1: Pacific Zone Coverage Satellite
Curve 2: Mountain Zone Coverage Satellite
Curve 3: Central Zone Coverage Satellite
Curve 4: Eastern Zone Coverage Satellite



A. Elevation Angle 5°, C-Band



B. Elevation Angle, 10°, K_u-Band



C. Elevation Angle 30°, K_a-Band

Figure 2-8. Four Time Zone Coverage Orbital Expansion Capability of ISL

Table 2-3. ISL Orbital Arc Expansion Capability for CONUS

Frequency	Arc Length Total[a] for CONUS Coverage		
	Case 1 Single Coverage without ISLs	Case 2 Two Coverages with ISLs	Case 3 4 Zones with ISLs
C-Band	85°	143°	160°
K_u-Band	69	128	158
K_a-Band	5	59	94

[a]GEO orbital arc centered around 100°W longitude.

2.3.3 COVERAGE EXTENSION

Increased geographical coverage and traffic interconnectivity are achieved with the ISL. Individual satellite orbital locations can be selected to provide coverage of high traffic areas.

For two satellites located at 10°W longitude and 60°W longitude, Figure 2-9a shows constant elevation angle contours from 5° to 30° in a 5° increment. A 50° ISL between these two satellites can provide full traffic interconnectivity for all users in the extended joint coverage areas including CONUS, South America, Europe, the Middle East, and Africa.

A number of other ISL coverage extension applications were considered initially in connection with the FSS traffic model described in Section 3. Figure 2-9b shows the extended coverages achievable with three ITU regional ISL satellites positioned at 15°E, 125°E, and 250°E, respectively.

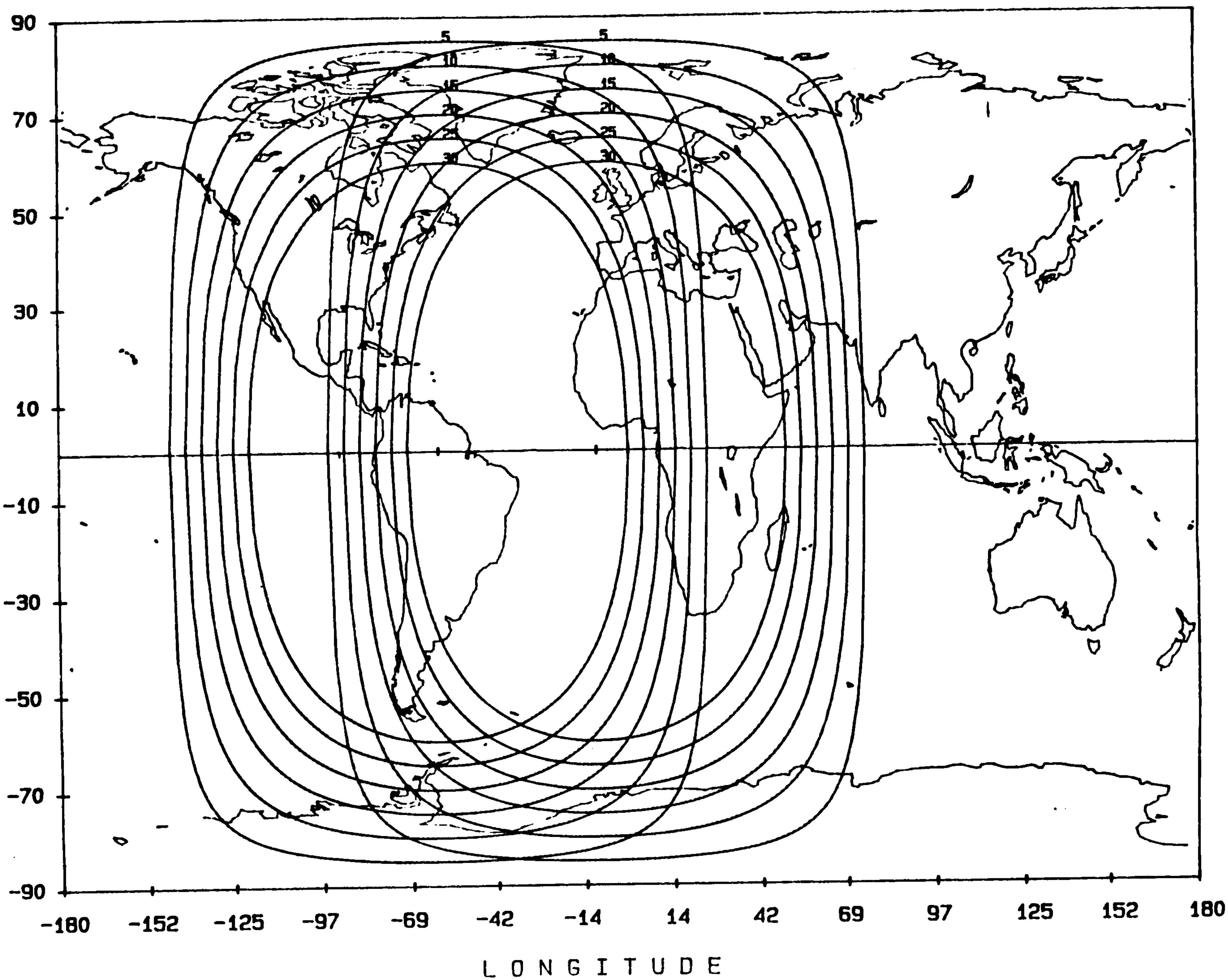


Figure 2-9a. Elevation Angle Contours for Satellite Locations at 10°W Longitude and 60°W Longitude

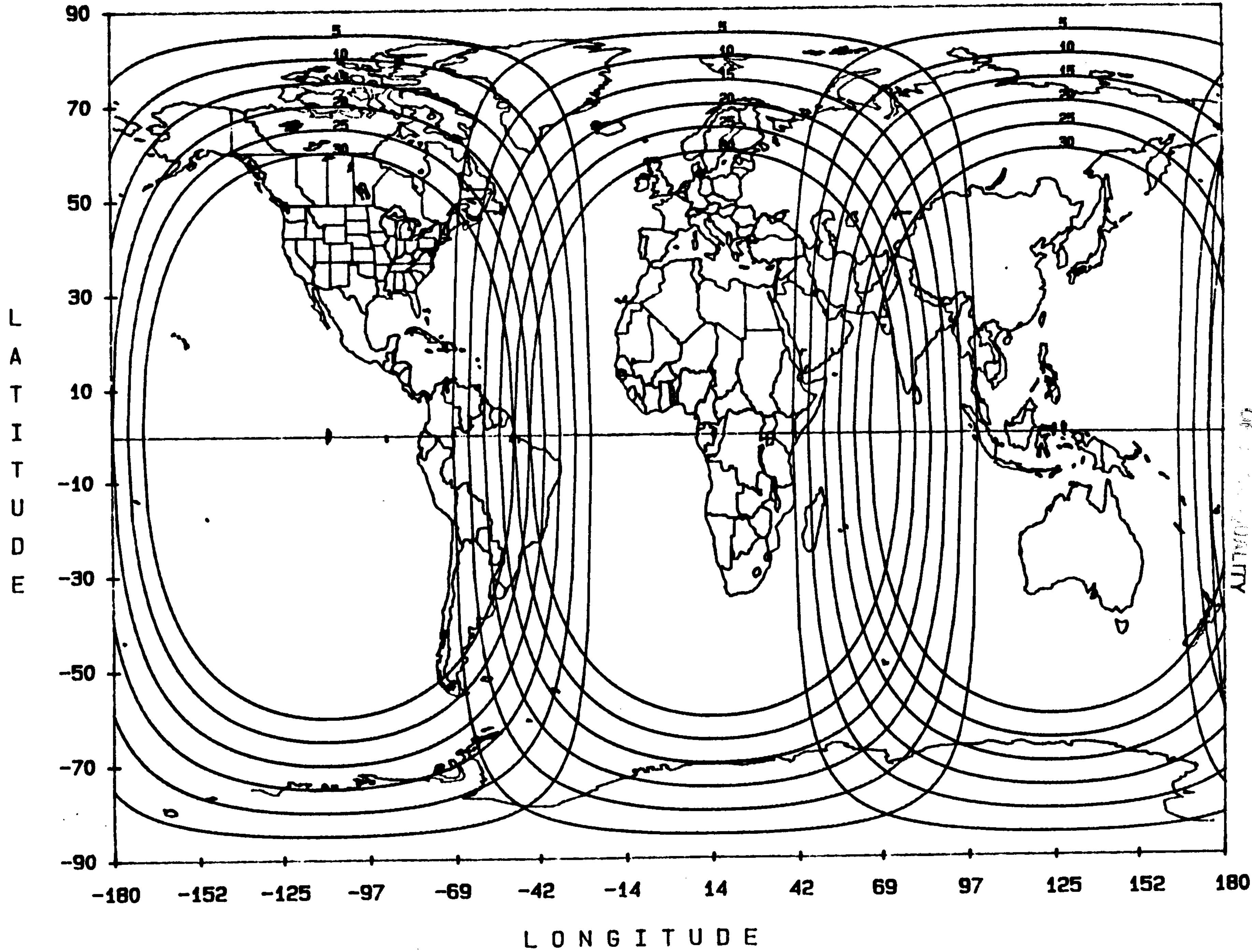


Figure 2-9b. Extended Coverage with Three ISL Satellites at 15°E, 125°E, and 250°E

2.3.4 SPACE SEGMENT CAPACITY UTILIZATION

The bandwidth needed for up- and down-links of the double-hop relay earth station is replaced by the ISL frequency band. Frequency bands that are characterized by high atmospheric attenuation and, thus, not useful for up- or down-link transmissions, are dedicated for ISL. Table 2-4 lists microwave ISL frequencies allocated by ITU [9].

The released bandwidths are then available for carrying useful traffic. Therefore, an ISL replacing double-hop transmission provides an effective increase of the available space segment capacity. In addition, it can reduce intersystem interference, allowing more effective utilization of spectral resources.

For video/TV carriers which require relatively large bandwidth per carrier, the potential increase of space segment capacity utilization is significant. In the limiting case of

Table 2-4. ISL Frequency Allocation (ITU)

Frequency Band [GHz]	Bandwidth Total[a] [GHz]
22.55-23.55	1.00
32.0-33.0	1.00
54.25-58.20	3.95
59.0-64.0	5.00
116-134	18.00
170-182	12.00
185-190	5.00
Total	45.95

[a]To be shared with other radio services in most of the bands.

full transponder TV, the effective spectral utilization can be almost doubled when ISL is used to replace double hopping.

Further discussions are provided in Subsection 2.4.2.

2.3.5 CONNECTIVITY

ISL provides a space segment link for flexible traffic interconnectivity between ISL satellites. In the conventional satellite network, traffic interconnectivity between two satellites is provided through the ground stations. ISL is a "missing link" in the existing system.

Considerable flexibility in satellite systems network planning is possible with ISL. Integrated space segment for domestic, regional, and international communications [10,11] can be achieved only through efficient use of ISLs. Subsection 2.5 provides further discussion.

2.4 DEVELOPMENT OF CRITERIA

2.4.1 CRITERIA

Initial considerations for the development of criteria on the benefits of ISL network systems included a broad range of issues. There are several aspects for which criteria need to be developed:

a. Technical criteria,
b. Operation criteria,

c. Economic criteria,

d. Regulatory criteria.

Operational, economic, and regulatory aspects are rather uncertain to handle in the early definition study of ISL systems applications. For this reason, technical criteria were considered primarily for the derivation of "figure-of-merit" factors of ISL systems.

Various alternative formulations of possible figure-of-merit factors were evaluated for each category of ISL applications.

Table 2-5 shows possible systems advantages of ISLs over the corresponding non-ISL counterparts.

Based on the fundamental ISL systems characteristics described in Subsection 2.3, the following major technical factors were included in the development of the ISL systems advantage measure (i.e., figure-of-merit):

- Orbital arc expansion capability of ISL.
- Improved frequency bandwidth (i.e, spectrum) utilization of ISL by avoiding double-hopping channels and reduced intersystem interference.
- Reduced ISL time delay.
- Reduced number of earth stations by use of ISL traffic interconnectivity in space rather than on the ground.

In addition, the ISL traffic requirement and new services potential were also evaluated and included in the selection of potential ISL applications. The development of an ISL traffic model is described in Section 3.

Table 2-5. Potential ISL Systems Advantages

System Advantages	Intercluster ISLs (<0.1°)	2°-to-3° ISLs	50° (and Longer) ISLs	All Combined ISLs
Time Delay Improvement (Over Double Hop)		X	X	X
Orbital Arc Expansion		X		X
Coverage Extension		X	X	X
Capacity Increase and Spectral Utilization	X	X	X	X
Flexible Interconnectivity	X	X	X	X
Reduced Number of Earth Station Antennas		X	X	X
Distributed Smaller Earth Station	X	X	X	X
Space Segment Implementation - Modular	X	X	X	X
Improved or New Services	X	X	X	X

2.4.2 FIGURE-OF-MERIT FACTORS

The "figure-of-merit (M)" of an ISL network system, with reference to a corresponding non-ISL system, was formulated as the following:

$$M = M_{\theta} \bullet M_{B} \bullet M_{T} \bullet M_{E} \tag{2-1}$$

where
M_{θ} = Orbital arc expansion factor
M_{B} = Transponder bandwidth utilization improvement factor
M_{T} = Time delay reduction factor
M_{E} = Reduction factor of the number of earth station antennas

Each of these factors is defined below.

2.4.2.1 Orbital Arc Expansion Factor

The orbital arc expansion factor, M_{θ}, is defined as the ratio of the total useful arc length of the ISL system to that of the corresponding non-ISL system. As discussed in Subsection 2.3.2, M_{θ} is determined from numerical computations as a function of the following system parameters:

- Satellite orbital location,
- Coverage area(s),
- Geographical distribution of traffic nodes (i.e., earth stations) within the coverage area, and

- Minimum elevation angle of earth station, which is determined by frequency band and communications link availability (i.e., rain statistics).

The Orbital Arc Expansion Analysis Computer Program is a tool that was developed to quantify this factor (see Subsection 3.2.2). The results of analysis for CONUS ISL applications were presented in Subsection 2.3.2.

The potential applications of ISL orbital arc expansion capability are the following:

a. Alleviation of congested prime orbital slot allocation problem (for CONUS and Europe, in particular),
b. Increased number of small K_a-band satellites for FSS communications services.

2.4.2.2 Bandwidth Utilization Improvement Factors

The space segment bandwidth saving (i.e., for up- and down-links) that can be achieved with an ISL by avoiding double-hopping transmissions is shown in Figure 2-10. The transponder bandwidth needed by the cross traffic (T_{12} and T_{21}) between coverage areas C_1 and C_2 is indicated each for (a) the double-hop system and (b) the ISL system in Figure 2-10.

The ISL system provides an effective space segment capacity increase directly proportional to the ISL traffic, because ISL frequency bandwidth is traded for recovering the double bandwidth. The released bandwidth is then available for additional up- and down-link traffic.

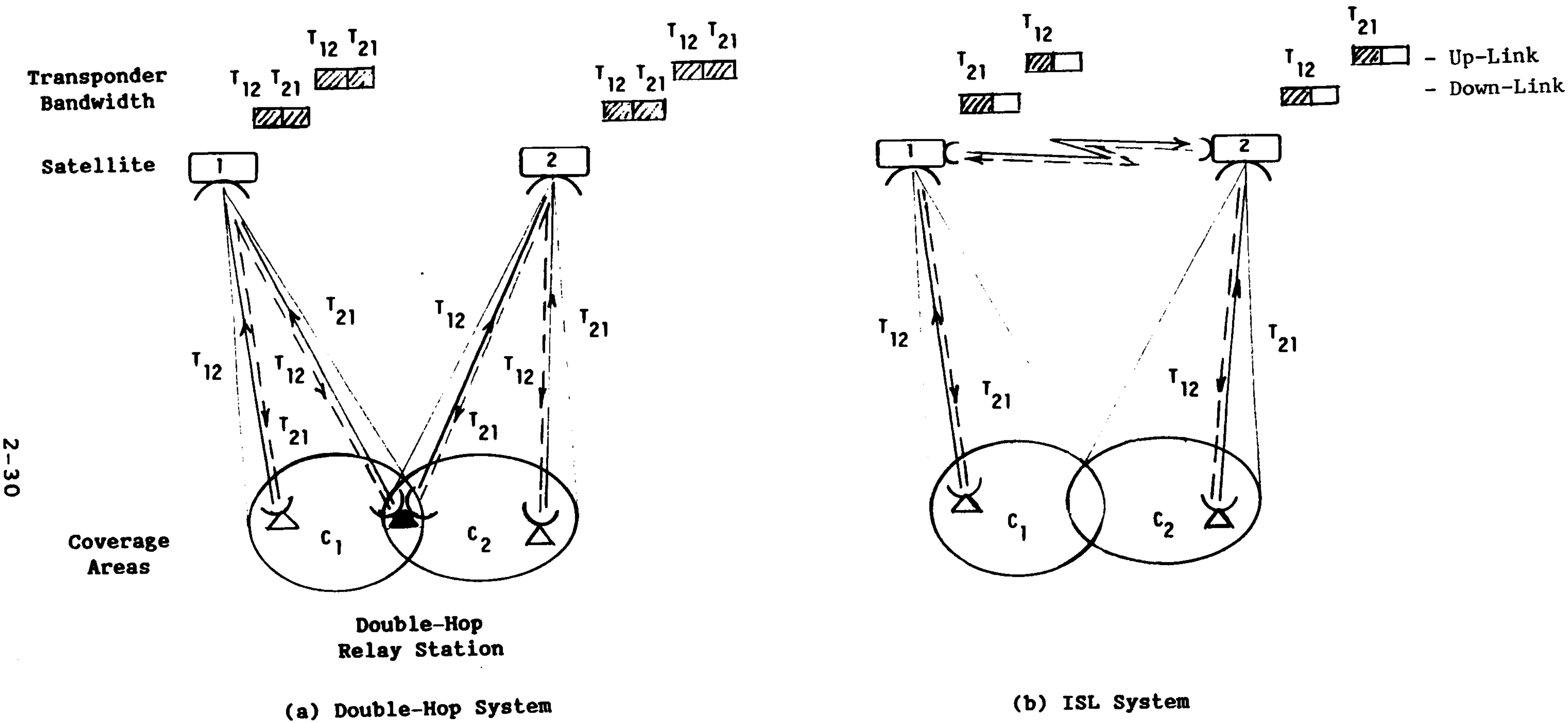


Figure 2-10. Bandwidth Utilization Improvement with ISL

The bandwidth utilization improvement factor, M_B, is defined as the ratio of total traffic between non-ISL to ISL systems. For a large service area encompassing N satellite coverages, M_B is given by

$$M_B = \frac{\text{Total Bandwidth of Non-ISL System}}{\text{Total Up- and Down-Link Bandwidth of ISL System}}$$

$$= 1 + \frac{\sum\limits_{\substack{i,j=1 \\ (i \neq j)}}^{N} T_{ij}}{\sum\limits_{i,j=1}^{N} T_{ij}} \qquad (2\text{-}2)$$

where T_{ij} represents a traffic matrix element between service areas i and j. The numerator in the second term represents the additional bandwidth required for double hopping.

For the case of four-time zone CONUS coverage with four ISL satellites (one each per zone), M_B is quanitified as follows:

- CONUS traffic total,

$$\sum_{i,j=1}^{N=4} T_{ij} = 10 \times 10^6$$

- ISL traffic (off-diagonal matrices total),

$$\sum_{\substack{i,j=1 \\ (i \neq j)}}^{N=4} T_{ij} = 6.408 \times 10^6$$

- The factor $M_B = 1.641$.

A total of a 64-percent saving in the space segment transponder bandwidth can, thus, be achieved in this case for CONUS coverage with ISLs.

The development of an ISL traffic model for various applications is described in Section 3.

2.4.2.3 Time Delay Reduction Factor

Transmission time delay over the link provides impact on commercial satellite communications with the following effects:

a. A user's convenience in carrying out the conversation is inversely proportional to the mean of the end-to-end delay in the satellite communications system [12]. Therefore, increased delay in a double-hop transmission, for example, discourages voice circuit users, resulting in a decrease of traffic.

b. The transmission efficiency in a data transmission system is related to the waiting factor which is proportional to $1/(1+d)$, where d is the round trip delay time in blocks for Stop and Wait ARQ error control [13]. The transmission efficiency decreases rapidly when the delay is significant relative to the block duration.

c. Video/TV and other types of one-way video traffic is not affected by the delay. However, those constitute only about 10 percent or less of the total international traffic.

The end-to-end delay reduction factor of an ISL is defined as

$$M_T = \frac{\text{Transmission Delay in Non-ISL System}}{\text{Transmission Delay in ISL System}} \tag{2-3}$$

M_T quantified completed for each ISL application, using the results contained in Subsection 2.3.1.

2.4.2.4 Earth Station Antenna Number Reduction Factor

Multiple earth station antennas are needed for traffic interconnectivity between satellites in the conventional satellite network system. On the other hand, one earth station antenna per traffic node is adequate for the ISL satellites.

The ISL advantage factor associated with the reduced number of earth station antennas is defined as

$$M_E = \frac{\text{N in Non-ISL System}}{\text{N in ISL System}} \tag{2-4}$$

where N represents total number of earth stations.

When a multiple number of isolated satellites provide FSS communications services for a single common coverage, it can be shown that:

$$M_E = 1 + \frac{\Theta_s}{\Delta\Theta} \tag{2-4a}$$

where Θ_s = total orbital arc length used and $\Delta\Theta$ = orbital arc spacing between adjacent satellites. $\Delta\Theta$ ranges from 2° to 3° in accordance with recent licensing policy by the FCC [14].

The total number of earth stations in the ISL vs non-ISL network systems is a rather difficult parameter to quantify, because it strongly depends on the systems architecture and traffic model. For example, if each one of the multiple isolated satellites provides a subdivided coverage, the corresponding ISL network will eliminate the double-hop relay earth stations only. In this case, M_E is given by

$$M_E = 1 + \frac{1}{N_{E/S}} \sum_{i=1}^{N_s-1} N_{Ri} \tag{2-4b}$$

where N_s = number of isolated satellites, $N_{E/S}$ = total number of earth stations in the ISL network system, and N_{Ri} = number of relay stations for double hopping between adjacent, i-th, and (i+1)-th coverages.

Equation (2-4a) provides the upper bound of M_E as a limiting case of ISL applications. The total useful orbital arc length in equation (2-4a) was quantified for ISL applications to CONUS in Subsection 2.3.2. The analytical methodology developed in Subsection 3.2.2 can be applied to all applications.

2.4.2.5 Figure-of-Merit of CONUS ISLs

The figure-of-merit factors were quantified for ISL applications to CONUS. Table 2-6 contains a summary for two (East- and West-half CONUS) coverages as well as four time zone coverages employing ISLs. The traffic models are described in

Section 3. The total figure-of-merit factor is large for higher frequency bands (i.e., K_a-band). Four time zone coverage ISLs provide higher figure-of-merit than two coverage ISLs.

Table 2-6 also shows some of the other considerations. The up- and down-link traffic capacity requirement per satellite is not excessively high for the four time zone coverage approach.

2.5 CANDIDATE ISL APPLICATIONS

2.5.1 POTENTIAL APPLICATIONS

Various applications of ISLs were identified through a comprehensive evaluation of ISL systems characteristics and their impact on the overall FSS communications network when ISL is introduced. Subsections 2.3 and 2.4 provided the basis of these evaluations.

Major systems characteristics of ISLs are summarized in Table 2-7. The systems impact associated with these characteristics are also shown in this table.

The potential ISL applications are related to relevant systems characteristics in Table 2-8.

Relative ranking of various ISL applications was derived, based on a set of criteria including the following factors:

- Total ISL traffic capacity requirement,
- Orbital arc expansion applicability,
- Improved space segment bandwidth utilization,
- Reduced number of earth station antennas,

Table 2-6. CONUS ISL Figure-of-Merit Factors and Other Considerations

Factors	CONUS ISL Applications	
	Two (East-/West-Half) Coverages	Four Time Zone Coverages
• Orbital Arc Expansion Factor		
C-Band	1.68	1.89
K_u-Band	1.86	2.29
K_a-Band	11.8	18.8
• Bandwidth Utilization Improvement Factor	1.35	1.64
• Time Delay Factor	1.3 to 1.4 (1.35 average)	1.3 to 1.4 (1.35 average)
• Earth Station Antenna Reduction Factor	2 Maximum	4 Maximum
• Total "Figure of Merit"		
C-Band	6.12	16.74
K_u-Band	6.78	20.28
K_a-Band	43.0	166.5
• Other Considerations		
- Up-Link/Down-Link Capacity/Satellite	Exceeding 1,000 x 2 tranponders	Not exceeding 500 x transponders
- Satellite Spare	One	One (minimum)
- Operational Complexity	Moderate	Increased

Table 2-7. ISL Systems Characteristics and Applications

No.	ISL Systems Characteristics	Systems Impact	Potential Applications
a	Orbital Arc Expansion	Increased number of useful prime slots	CONUS and European region
b	K_u-Band Utilization	Improved services for small on-the-premise earth stations	Domestic, regional, and international
c	Coverage Extension	Improvement in existing system	Interregional, worldwide
d	Transmission Time Delay Reduction	Better quality service for more users by avoiding double hop	Interregional, international
e	Efficient Bandwidth Utilization	Reduced intersystem interference and more efficient FSS spectrum utilization	Worldwide
f	N-Fold Orbital Arc Utilization	New system with a "super" satellite	CONUS, ITU 3 Regions
g	Integrated Space Segment	New system, ISDN with satellites	Worldwide

Table 2-8. Potential ISL Applications

No.	Applications	ISL Category	Relevant System Characteristics[a]
1	CONUS	2°-3° ISL (for isolated satellites)	a, b, e
2	European Region	2°-3° ISL	a, b, c
3	CONUS/Region 2	Intercluster ISL	b, f
4	European/Region 1	Intercluster ISL	b, f
5	CONUS to International (AOR and IOR)	50° ISL	b, c, d, e
6	Region 1 to International (AOR and POR)	50° ISL	b, c, d, e
7	Region 3 to International (POR and IOR)	50° ISL	b, c, d, e
8	Three ITU Regions	>50° ISL	b, c, e, f, g
9	Integrated, Worldwide	All combined	b, c, d, e, f, g

[a]Refer to Table 2-7 for the alphabetical item numbers.

- Reduced transmission delay, and
- New services potential.

ISL traffic models are described in Section 3 for various applications for the year 2001.

Table 2-9 shows the result of relative grading of potential ISL applications. Grading is referenced to a corresponding non-ISL system for each ISL application. A lower score corresponds to a higher grading level.

Based on the overall ranking in Table 2-9, the following six candidate applications were recommended for further study to NASA-LeRC at the First Interim Briefing:

<u>Preliminary Candidate ISL Applications</u>

1. CONUS, 4-Zone Coverage Domestics Services
2. CONUS-European Region
3. CONUS-International (AOR/POR)
4. N. America-European Region
5. ITU Region 1-International (AOR/IOR)
6. ITU Regions 1-2-3 Regional/International

2.5.2 SELECTED CANDIDATE ISL APPLICATIONS

Even though the CONUS Intercluster ISL Application shows a low relative ranking when a large platform payload is taken for comparison, it has unique ISL characteristics (being less than 0.1° ISL) when compared with conventional payloads. Therefore, at the briefing NASA LeRC requested it to be included in the candidate applications by combining CONUS-Europe and North America-Europe applications.

Table 2-9. Relative Grading of Potential ISL Applications

Criteria / ISL Application (ISL Distance)	ISL Capacity Total	Orbital Arc Expansion Applicability	Improved FSS Bandwidth Utilization	Reduced Number of Earth Station Antennas	Reduced Time Delay	New Services Potential	Score Total[a]	Overall Ranking
1. CONUS, Intercluster (<0.1°)[b]	1	8	6	7	4	1	27	H
2. CONUS, 4-Zone Coverage (≲30°)	1	1	1	1	1	1	6	A
3. CONUS-Europe (50°)	5	2	4	5	3	2	22	E
4. N. America-Europe (50°)	4	2	5	5	3	2	21	D
5. Europe-Asia (60°)	8	5	5	6	3	2	29	I
6. CONUS-International, AOR/POR (50°)	3	3	3	3	2	3	17	B
7. Region I-International, AOR/IOR (50°)	6	4	4	4	2	3	23	F
8. Region III-International, POR/IOR (60°)	7	6	4	4	2	3	26	G
9. Region I-II-III, Regional and International (120°)	2	7	2	2	4	1	18	C

[a]Grading is referenced to an equivalent non-ISL system for each ISL application. Score 1 corresponds to the highest ranking.
[b]A platform payload is taken for comparison.

Therefore, the candidate ISL applications finally selected for further study in Task 2 are shown in Table 2-10.

Network architectures of the selected ISL applications are described in Section 4, following the development of ISL traffic models in Section 3.

Table 2-10. Selected ISL Applications

1. CONUS, 4-Zone Coverage Domestic Services

2. a. CONUS-European Region
   b. N. America-European Region

3. CONUS-International
   a. CONUS-POR
   b. CONUS-AOR

4. ITU Region 1-International
   a. Region 1-AOR
   b. Region 1-IOR

5. ITU Region 1-2-3
   a. Region 1-Region 2
   b. Region 2-Region 3
   c. Region 3-Region 1

6. Intercluster ISL for CONUS

3. DEVELOPMENT OF ISL TRAFFIC MODELS

Satellite-addressable FSS traffic forecast data through the year 2000 was used for the development of ISL traffic models. Relevant transponder requirements for the 1990s technology were identified, based on the traffic models for domestic (CONUS), regional, and international fixed-satellite communications services.

3.1 FSS TRAFFIC MODELS

The following FSS traffic data bases were available for the ISL traffic model development:

a. NASA-supplied U.S. domestic traffic model for the year 2000 [15]-[17],
b. INTELSAT's international traffic data base [18], and
c. FCC Space WARC 1985 Advisory Committee's Traffic Forecast and Others for non-U.S. domestic data [19]-[21].

NASA's CONUS traffic model was made available to this Contract Study [15]. The traffic data consisted of: (a) updated 316 x 316 SMSA Satellite Addressable Matrix. The updated matrix was based on the original 316 x 316 SMSA Traffic Matrix, by eliminating all traffic demands between two locations less than 400 miles apart. The data entries were renormalized to a total sum of 10,000,000 half-voice circuits; (b) a reduced

84 x 84 traffic matrix. The 84 SMSAs were shown in Table 2-2 of Subsection 2.3.2.

The international traffic forecast for the countries in three Ocean regions is based on the INTELSAT Traffic Data Base of 1984 [18]. The INTELSAT Traffic Data Base provides 15 years of international FSS traffic model until 1998.

Other traffic forecast models of ITU Region 2, Europe, and other regions were derived, wherever applicable, from available documents [19]-[21].

3.2 TRAFFIC ANALYSIS PROGRAMS

Computer programs were developed to quantify the space segment and ISL capacity requirements from the FSS traffic models described in Subsection 3.1. A description of the traffic analysis programs is given in this section.

3.2.1 TRAFFIC GROUPING PROGRAM

A large NxN-sized traffic matrix needs to be reduced to a small MxM matrix for a set of M constituent groups of traffic nodes. The reduced matrix defines:

a. intergroup traffic by the off-diagonal matrix elements, and
b. intragroup traffic by the diagonal elements.

The intergroup traffic is equivalent to ISL traffic between two coverage areas defined by the corresponding two groups of nodes.

As an example, Figure 3-1 illustrates a simplified ISL traffic model consisting of two satellites, each of which has an independent coverage area. The NxN traffic matrix of the overall network (N-node system) can be reduced into a 2x2 matrix for the two coverage areas #1 and #2 as follows:

Traffic Matrix of N-Node System

$$
T = \left[\begin{array}{cccc|ccc}
T_{11} & T_{12} & \cdots & T_{1K} & T_{1\ K+1} & \cdots & T_{1N} \\
T_{21} & T_{22} & \cdots & T_{2K} & T_{2\ K+1} & \cdots & T_{2N} \\
\vdots & & \ddots & & & & \vdots \\
T_{K1} & T_{K2} & \cdots & T_{KK} & T_{K\ K+1} & \cdots & T_{KN} \\
\hline
T_{K+1\ 1} & T_{K+1\ 2} & \cdots & T_{K+1\ K} & T_{K+1\ K+1} & \cdots & T_{K+1\ N} \\
\vdots & & & & & \ddots & \vdots \\
T_{N1} & T_{N2} & \cdots & T_{NK} & T_{N\ K+1} & \cdots & T_{NN}
\end{array}\right]
$$

$$
= \begin{bmatrix} T_{G11} & T_{G12} \\ T_{G21} & T_{G22} \end{bmatrix}
$$

(Matrix Reduction into Groups 1 and 2)

In the reduced matrix, the off-diagonal elements T_{G12} and T_{G21} represent ISL traffic between satellites 1 and 2.

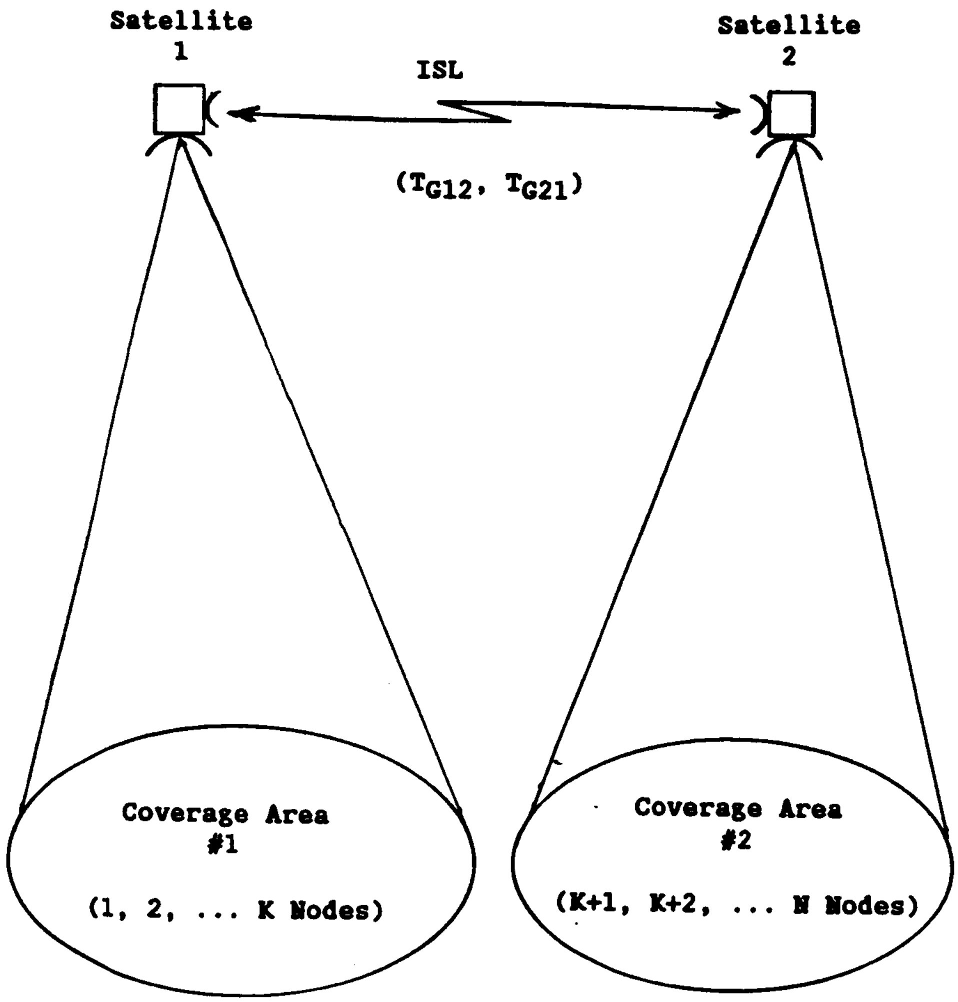


Figure 3-1. A Basic ISL Traffic Model

A generalized traffic grouping algorithm of this approach was implemented in a computer program. The functional flowchart of the program is shown in Figure 3-2. A detailed description of the programs and a sample output is contained in Appendix A.

The traffic grouping program was used extensively to derive a comprehensive data package of ISL traffic models that can be applied to all potential ISL applications. Typical results of the traffic model analyses are contained in Appendix B.

These results were used in the determination of ISL traffic models and transponder requirements for the selected ISL applications.

3.2.2 ORBITAL ARC ANALYSIS PROGRAM

The satellite location in longitudes that can provide 100-percent traffic accessibility within a prescribed coverage area, with and without ISLs, was determined from the output of the computer program developed for ISL orbital arc expansion analysis. The traffic matrix data are part of the input parameters.

The functional flowchart of the orbital arc analysis program is shown in Figure 3-3. Appendix C describes the formulation of the analysis and a sample output.

Based on the analysis result of this program, the orbital arc expansion capability of ISLs for CONUS coverages was quantified in Subsection 2.3.2.

Input:

- Number of earth stations (E/S), N
- NxN traffic matrix for traffic (in number of equivalent voice circuits) from E/S I to J, for I, J = 1 to N
- Number of E/S groups, M(M < N), and earth stations in each group

Computation:

- Algorithm generates the elements of reduced MxM grouping maxtrix, T.G. TG(K,L) is the traffic among E/S groups K and L.

Output:

- Table of reduced traffic matrix, T.G.

Figure 3-2. Functional Flowchart of the Traffic Grouping Program

Input:

- Number of earth stations (E/S)
- E/S location (latitude, longitude) and traffic (in number of equivalent voice circuits) for each E/S
- Minimum elevation angle
- A range of satellite orbit locations (longitude)

↓

Computation:

- Earth stations accessible from the given orbit locations with greater or equal to the minimum value specified
- Total earth station traffic and the percentage of E/S traffic for the visible earth stations

↓

Output:

- Percentage of visible E/S traffic versus the satellite orbital location
- Table of satellite location, E/S, and the elevation angle if below the minimum specified

Figure 3-3. Functional Flowchart of the Orbital Arc Program

3.3 CONUS ISL TRAFFIC MODEL

U.S. domestic telecommunications demand for satellite services through the year 2000 has been investigated by many researchers [22]. The previous NASA study, based on the results of two contracts NASA LeRC had with ITT and Western Union, provides a U.S. Domestic Fixed Satellite Services Traffic Model [16],[17].

Table 3-1 shows a CONUS FSS traffic forecast for the year 1990 and the year 2000 for various types of traffic: Voice in half-voice circuits (HVC), video including TV broadcasting and videoconferencing in channels, and data in peak-hour megabits per second [16]. The corresponding transponder requirement expressed in number of 36-MHz equivalent transponder channels is shown in Table 3-2. The capacity per 36-MHz transponder is identified for each traffic in the last column of Table 3-2.

Recently NASA has revised the original CONUS FSS Traffic Model. The revised 316 x 316 SMSA traffic matrix was derived under a criterion of a satellite-addressable FSS traffic requirement between two nodes greater than 400 miles apart. This 400-mile criterion reduces the FSS traffic requirement by a factor of about 0.8 for voice, videoconferencing, and data services. TV broadcasting remains approximately the same.

Tables 3-3 shows a summary of the satellite-addressable total traffic forecast. The total traffic is expressed in numbers of equivalent half-voice circuits and the corresponding number of 36-MHz equivalent transponders. The transponder demand for the year 2000 is about 1,738 transponders, which shows an annual traffic growth rate of 7.6 percent from the year 1990.

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Table 3-1. CONUS Fixed-Satellite Services Traffic Model[a]

	Year 1990	Year 2000	Remarks
Voice	1,833,000	6,851,000	Half-Voice Circuits (HVC)
Video:			
TV	158	233	Broadcasting Channels
Conferencing	1,971	8,225	Video Channels
Data	12,687	26,945	Peak-Hour Mbit/s

[a]Based on the NASA Traffic Model by Stevenson et al.

Table 3-2. CONUS Fixed-Satellite Services Transponder Requirement

	Year 1990	Year 2000	Capacity per 36 MHz Transponder
Voice	655[a]	1,523[b]	a: 2,800 HVC* b: 4,500 HVC
Video:			
TV	79[c]	78[d]	c: 2 TV Channels d: 3 TV Channels
Conferencing	56[e]	176[f]	e: 35 Video Channels f: 46.7 Video Channels
Data	235[g]	374[h]	g: 54 Mbit/s h: 72 Mbit/s
Total	1,025	2,151	

*HVC: Half-Voice Circuit.

Table 3-3. CONUS Satellite-Addressable Total Traffic

Total Number	Year 1990	Year 2000	Remarks
Transponders*	835.8	1,737.2	Annual Growth Rate, 7.6%
Equivalent Half-Voice Circuits**	2,340,240[a]	7,817,400[b]	a: 2,800 HVC/Transponder b: 4,500 HVC/Transponder

*Excluding SMSA traffic less than 400 miles, a reduction factor of 0.8 was applied to voice, videoconferencing, and data.
**8,371,200 HVCs for the year 2001 (with 7.1% annual growth).

The total satellite-addressable traffic of about 10-million equivalent half-voice circuits could be reached by the year 2004 if a 7.1-percent annual growth rate is applicable.

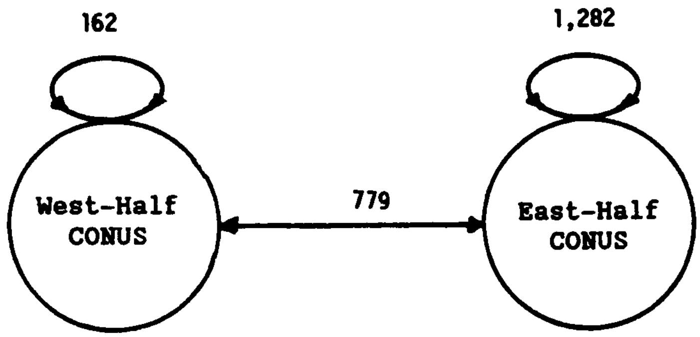
Traffic grouping analyses of the CONUS traffic model provides the ISL traffic models. Figure 3-4 depicts East- and West-half CONUS coverage traffic model and transponder requirement. The ISL capacity requirement between the two half-CONUS coverage satellites is 389.2 transponders each for transmit and receive ISL terminals, yielding a total two-way ISL capacity of 779 transponders.

For four time zone coverage CONUS satellites, Figure 3-5 depicts the traffic model and corresponding transponder requirement. The total two-way ISL capacity requirement between any two of the time zone coverage satellites is shown in Figure 3-5.

The CONUS ISL traffic model provides a basis for the development of ISL network architecture and payload configurations. Section 4 describes the details.

3.4 REGIONAL AND GLOBAL ISL TRAFFIC MODELS

The international and regional/non-U.S. domestic traffic data described in Subsection 3.1 were used to derive basic ISL traffic models of various regional/international FSS applications. A summary of the ISL traffic models is contained in this section.

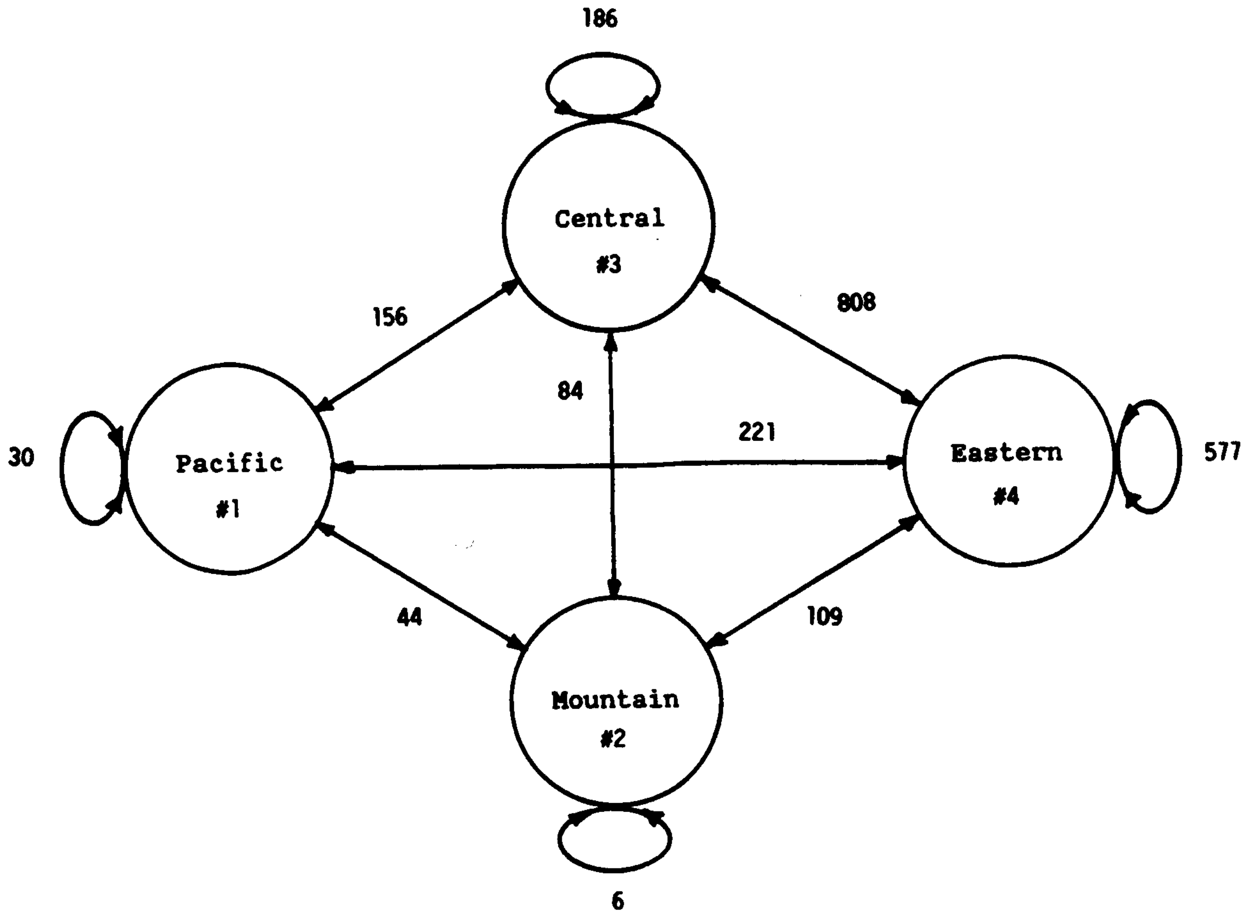


(a) Transponder Requirement

To / From	WEST CONUS	EAST CONUS
West CONUS	728,410	1,751,460
East CONUS	1,751,460	5,768,914
Total	10,000,252	

(b) Traffic Matrix in Number of Equivalent Half-Voice Circuits

Figure 3-4. East- and West-Half CONUS Coverage Traffic Model and Transponder Requirement



(A) TRANSPONDER REQUIREMENT

FROM \ TO	PACIFIC	MOUNTAIN	CENTRAL	EASTERN
PACIFIC	134,346	99,335	355,445	497,504
MOUNTAIN	99,335	27,214	189,134	244,621
CENTRAL	355,445	189,134	836,138	1,818,191
EASTERN	497,504	244,621	1,818,191	2,594,094
TOTAL	10,000,252			

(B) TRAFFIC MATRIX IN NUMBERS OF EQUIVALENT HALF-VOICE CIRCUITS

Figure 3-5. Four Time Zone CONUS Coverage
Traffic Model and Transponder Requirement

3.4.1 INTERNATIONAL SATELLITE TRAFFIC MODEL

The INTELSAT Traffic Data Base contains international FSS traffic data based on the estimated requirements for the next five years, and projected forecast for the following 10 years. A total of 15 years' traffic forecast reflects international carriers and INTELSAT Signatories' best projection.

The 1984 INTELSAT Traffic Data Base was used for the development of international ISL traffic models [18]. The latest 1986 Global Traffic Meeting of INTELSAT forecasted a somewhat higher traffic growth for the next five years on the INTELSAT system: The projections show substantial growth in the Pacific Ocean Region (POR) and in the Indian Ocean Region (IOR). However, the traffic forecast for the Atlantic Ocean Region (AOR) is somewhat lower than the previous one. However, the 1986 INTELSAT Traffic Data Base was proprietary to INTELSAT and not available for this study.

The telephony traffic data in the three operating modes (FDM/FM, SCPC, and companded FM) were collected and processed as part of the traffic grouping analyses (see Subsection 3.2.1). The traffic matrices of various geographical groups of countries are contained in Appendix B. The 1995 and 1998 traffic models of international FSS Communications, shown in Appendix B, were used as the bases of the development of regional and international ISL traffic models.

3.4.2 SEVEN-GROUP REGIONAL TRAFFIC MODEL

The geographical regional ISL traffic models were derived from the 1984 INTELSAT Traffic Data Base with additional modifications for the following considerations:

a. Ten percent of the telephony traffic was added to account for TV broadcasting, videoconferencing, and other data traffic in international satellite communications.
b. An 8-percent annual growth rate was used to extrapolate the traffic forecast to the year 2001.
c. Domestic satellite traffic requirements were derived from various available sources and incorporated into the intraregional group traffic.

Table 3-4 shows the seven-group geographical worldwide satellite traffic model for the year 2001. The intraregional traffic is shown by the diagonal elements of the traffic matrix. The off-diagonal elements represents interregional ISL traffic for a seven-group regional satellite network implementation approach.

Table 3-4 shows very small traffic between (a) South America and South Pacific countries, (b) South America and Africa, (c) South Pacific and Mideast countries, and (d) South Pacific and Africa. This is a consequence of the double-hop requirement in the existing non-ISL satellite system. Interregional ISLs can provide full connectivity among these groups, introducing new services and more users in these regions.

Figure 3-6 represents the 36-MHz equivalent transponder requirements of the seven-group regional ISL system. Interregional ISL traffic capacity constitutes only 5.2 percent of the total traffic requirement. Intraregional traffic is clearly dominant.

A bar chart representation of the seven regional ISL transponder requirement in Table 3-5 shows what the potential ISL applications associated with a large ISL traffic requirement

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Table 3-4. Seven-Group Regional Satellite Traffic Model for the Year 2001[a]

From \ To	N. America	S. America	Asia	S. Pacific	Europe	Mideast	Africa	Subtotal
N. America	9,102,703	18,424	15,782	5,020	42,358	8,084	3,695	9,196,066
S. America	18,424	188,097	1,329	112	11,262	723	222	220,169
Asia	15,782	1,329	546,966	3,709	20,430	6,047	746	595,039
S. Pacific	5,020	112	3,709	37,161	7,882	318	479	54,681
Europe	42,358	11,262	20,430	7,882	792,046	17,212	14,077	905,267
Mideast	8,084	723	6,047	318	17,212	202,337	503	235,224
Africa	3,695	222	746	479	14,077	503	305,920	325,642
Total	11,532,088 (HVC)							

[a]The total traffic model for the year 1998 was extrapolated to the year 2001, assuming an 8% annual growth rate.

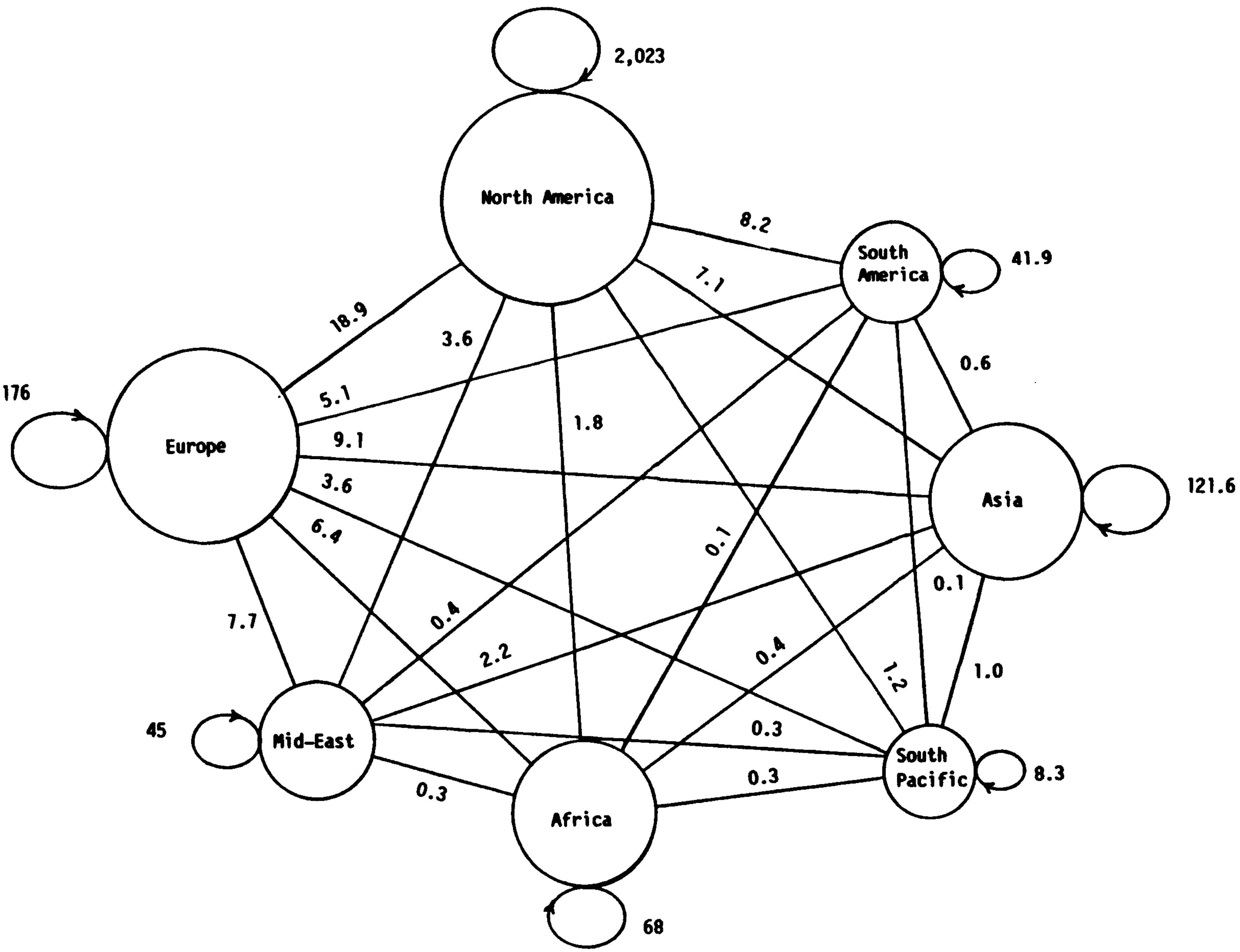


Figure 3-6. Seven-Group Regional ISL Transponder Requirement for the Year 2001

Table 3-5. Seven-Group Regional ISL Transponder Requirement for the Year 2001

ISL	Number of ISL Transponders
N. America-S. America	8.2
-Asia	7.1
-S. Pacific	1.2
-Europe	18.9
-Mideast	3.6
-Africa	1.8
S. America-Asia	0.6
-S. Pacific	0.1
-Europe	5.1
-Mideast	0.4
-Africa	0.2
Asia-S. Pacific	1.0
-Europe	9.1
-Mideast	2.8
-Africa	0.4
S. Pacific-Europe	3.6
-Mideast	0.3
-Africa	0.3
Europe-Mideast	7.7
-Africa	6.4
Mideast-Africa	0.3

Potential ISLs: 1. N. America-Europe
2. Asia-Europe

are for the regional satellites between (a) North America and Europe and (b) Europe and Asia.

3.4.3 ITU REGIONAL TRAFFIC MODEL

The seven regional traffic matrices were reduced further to obtain an ITU regional traffic model for the year 2001. Table 3-6 shows the traffic model. It should be noted that the traffic requirements of Communist block countries were not available for this study and were not included in the traffic model.

Table 3-6. Three ITU Regions Traffic Model for the Year 2001

From \ To	Region 1	Region 2	Region 3
Region 1	1,363,887	66,344	35,902
Region 2	66,344	9,327,648	22,243
Region 3	35,902	22,243	591,575
Total	11,532,088 (HVC)		

Region 1: Europe, Mideast, Africa

Region 2: North America, South America

Region 3: Asia, South Pacific

Listed below are the ISL transponder requirements for 4,500 HVCs per 36-MHz transponder:

Interregional ISL	Number of ISL Transponders (2-Way Capacity)
Region 2-Region 1	29.5
Region 2-Region 3	10.0
Region 1-Region 3	16.0

Figure 3-7 shows the intraregional as well as the interregional ISL transponder requirements.

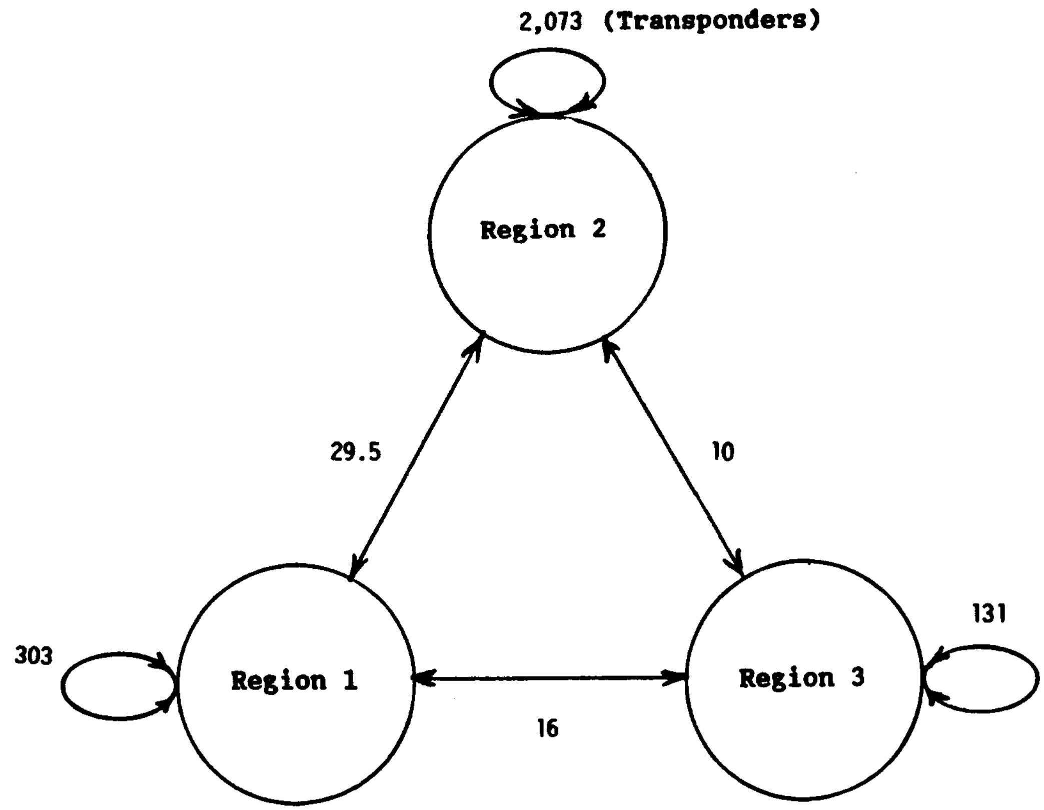


Figure 3-7. ITU Regional Transponder Requirement for the Year 2001

4. NETWORK ARCHITECTURE AND PAYLOAD CONFIGURATIONS

The network architectures of each selected ISL application described in Subsection 2.5.2 and the corresponding non-ISL systems were defined to meet the ISL traffic requirement for the year 2001. The study methodology and basic ISL system parameters that were used in the development of the network architectures are highlighted in Subsection 4.1. A summary of the network architectures is described in Subsection 4.2. For each ISL application, microwave vs optical ISL payload configurations were derived and mass and power requirements were determined. The network systems architectures and payload configurations are used in Section 5 to quantify the add-on system costs.

4.1 STUDY METHODOLOGY AND ISL SYSTEM PARAMETERS

An evolving ISL system was considered initially. It would lead eventually to fully mature ISL applications for the three ITU regional ISL satellite network.

Figure 4-1 shows the existing international communications satellites (INTELSAT) and major domestic/regional satellites. The orbital locations of INTELSAT spacecraft and their roles are indicated on the inner circle as a clear distinction from the other satellites.

The orbital locations of ISL satellites for the applications selected in Table 2-10 (Subsection 2.5.2) were determined from the following factors:

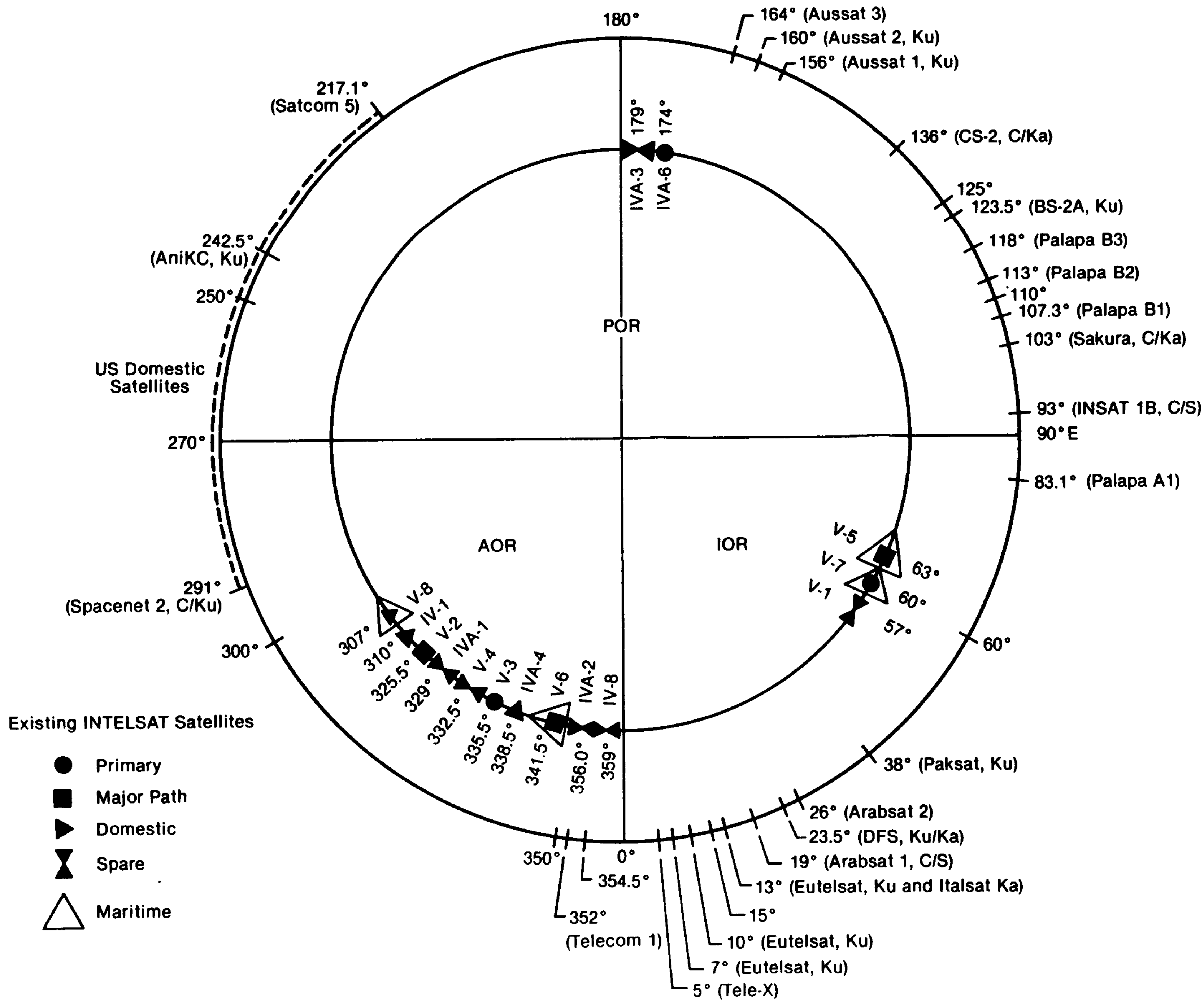


Figure 4-1. Existing Satellite Systems

- Coverage requirement per each application,
- High elevation angle exceeding 10° of any earth station within the coverage,
- ISL distance not to exceed 50° in longitudinal degrees for voice traffic wherever possible,
- ISL between regional and international satellites to be compatible with the existing INTELSAT system, and
- ITU regional satellites for the mature global applications of ISLs.

For each candidate ISL application, Figure 4-2 shows the methodology of the Task 2 study for the development of network architectures and cost analysis. Some of the highlights are as follows:

a. Both microwave (60 GHz) and optical (0.85 μm) ISL payload configurations were evaluated for sizing the mass and power requirements of each application. ISL payload sizing algorithms were developed and used for the analysis.

b. The host spacecraft sizing was based on a statistical design approach. A number of design data of advanced commercial communications satellites for C-, K_u-, and K_a-band services were collected and analyzed to derive a statistical spacecraft "figure of merit" which characterizes the space segment normalized cost per 36-MHz equivalent transponder per year. This "figure of merit" was used in the systems "add-on" cost analysis (see Section 5).

c. ISL payload cost models were developed to quantify nonrecurring and recurring costs of microwave vs optical ISL systems implementations.

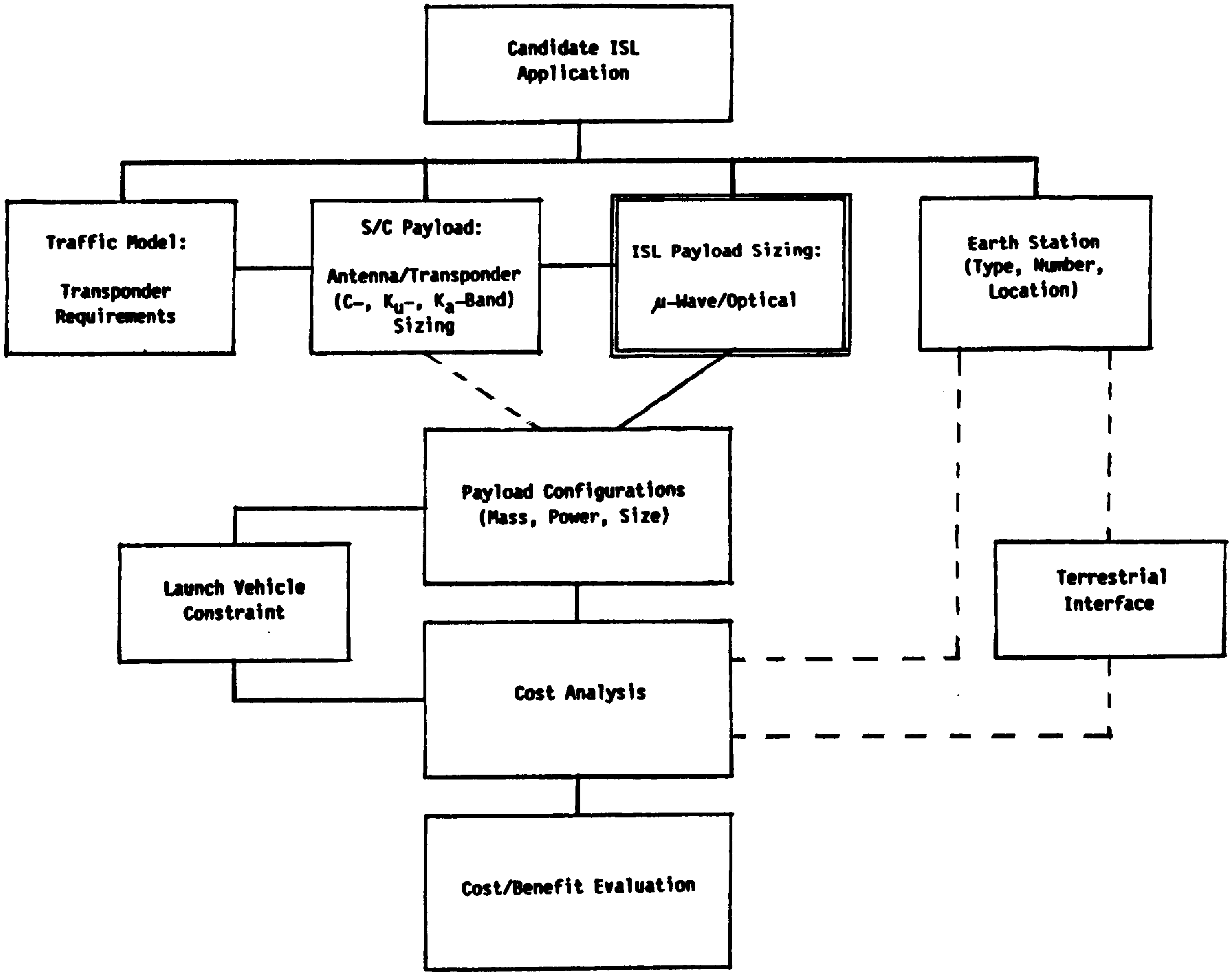


Figure 4-2. Methodology of Task 2 Study

d. The earth station requirements were included for the "add-on" systems cost comparison between ISL and the corresponding non-ISL systems (see Section 5).

4.2 ISL NETWORK ARCHITECTURE

Network architectures were derived for each ISL vs the corresponding non-ISL satellite applications. The non-ISL system provides the same services as the corresponding ISL system. CONUS ISL network architectures are described in Subsection 4.2.1, followed by a summary of the other ISL systems architectures in Subsection 4.2.2.

4.2.1 CONUS NETWORK ARCHITECTURES

4.2.1.1 CONUS ISL Networks

CONUS ISL applications for the four time zone coverage satellites, based on the discussions provided in Subsection 2.4.2.5, were selected for further investigation.

The orbital arc expansion capability of ISLs allows four time zone CONUS satellites for K_a-band services to be placed anywhere within the following arc segments:

CONUS Time Zone Satellite	Orbital Location[a]
Pacific	49°W to 99°W
Mountain	66°W to 119°W
Central	86°W to 128°W
Eastern	97°W to 143°W

[a]Under a 30° elevation angle criterion for K_a-band services

Figure 4-3 shows the ISL application for CONUS. The coverage maps of Eastern and Pacific time zone satellites positioned at 302°E (i.e, 58°W) and 229°E (131°W), respectively, are illustrated.

In comparison, non-ISL entire CONUS coverage satellites have a very limited number of orbital slots for K_a-band services, between 98°W and 103°W. K_a-band up- and down-links are considered a major utilization for CONUS fixed-satellite services in the year 2000. The useful orbital arc can accommodate only three CONUS satellites under a 2° spacing requirement between two adjacent satellites.

Table 4-1 lists key parameters of the CONUS ISL requirements for two possible ISL constellations, i.e., mesh and string connectivity configurations. Based on the CONUS ISL traffic model (Subsection 3.3), the capacity requirement of each ISL payload terminal was determined:

- From 0.8 Gbit/s to 14.6 Gbit/s for Mesh Configuration.
- From 7.6 Gbit/s to 20.5 Gbit/s for String Configuration.

An 8-kbits/s per half-voice circuit transmission technology in the 1990s was assumed in the ISL capacity estimation.

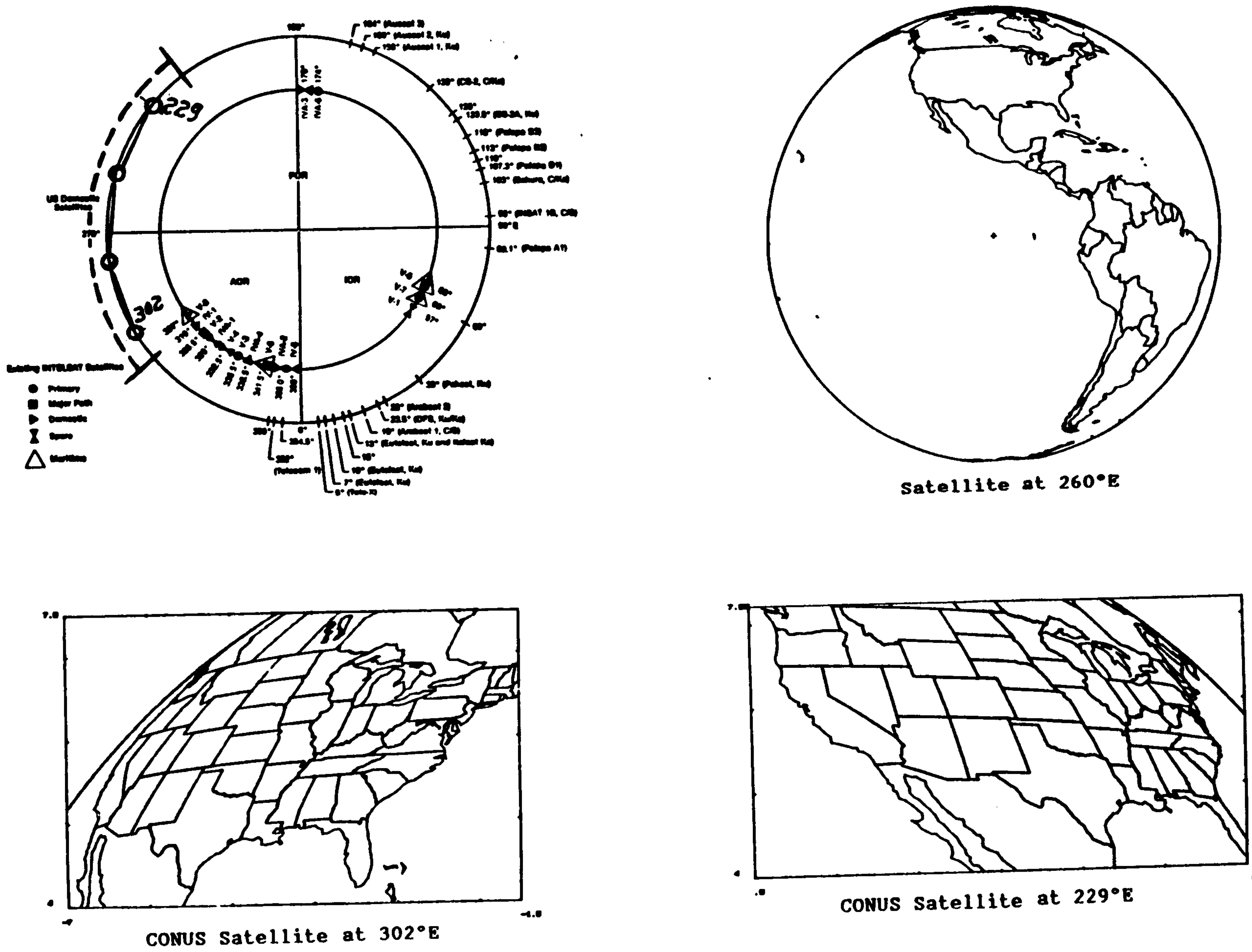
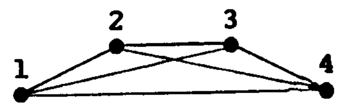


Figure 4-3. ISL Application (No. 1) for CONUS

Table 4-1. CONUS ISL Applications

Parameters	CONUS ISL Applications (Isolated S/C ISLs <50°)	
	Four Time Zone Coverages	
	Mesh	String
• ISL Constellation		
• Number of ISL Transponders[a,b]	22 x 2 for 1-2, 78 x 2 for 1-3, 111 x 2 for 1-4 42 x 2 for 2-3, 55 x 2 for 2-4, 404 x 2 for 3-4 Total: 712 x 2	211 x 2 for 1-2, 286 x 2 for 2-3 569 for 3-4 Total 1,066 x 2
• ISL Terminal Capacity	0.8 Gbit/s rate to 14.6 Gbit/s	7.6 Gbit/s to 20.5 Gbit/s
• Up-/Down-Link Transponder Requirement	241 for 1, 125 for 2, 711 for 3 1,145 for 4	241 for 1 125 for 2 711 for 3 1,145 for 4

[a]CONUS total traffic for 10 million HVCs.
[b]Based on 4,500 half-voice circuits per 36-MHz transponder.

The total up- and down-link capacity requirement in number of 36-MHz equivalent transponders of each satellite is also defined in Table 4-1. It ranges from 125 transponders for the Mountain time zone satellite to 1,145 transponders for the Eastern time zone satellite.

Figure 4-4 illustrates the CONUS ISL system architecture. The ISL capacity given here corresponds to the string connectivity configuration.

Each time zone satellite (i.e., host spacecraft) is characterized by the coverage and traffic capacity requirements. Extensive frequency reuses with a number of spatially isolated spot beams as well as dual polarizations in the C-, K_u-, and K_a-bands can be used to meet the FSS requirements for the year 2000 and beyond.

A complete traffic interconnectivity within CONUS is provided via ISL in space in this network architecture.

4.2.1.2 Non-ISL CONUS Satellite Network

The corresponding non-ISL satellite network for CONUS was derived for two different system architectures:

Architecture I: Double-Hopping Network
Architecture II: Multiple Colocated Earth Station Network

Figure 4-5 illustrates non-ISL Architecture I. A centralized double-hop earth station concept for traffic switching and signal processing is shown here. ISLs are replaced by the double-hop relay links in this architecture.

The double-hopping traffic capacity of each satellite is shown in Table 4-2. The number of double-hop beams for each

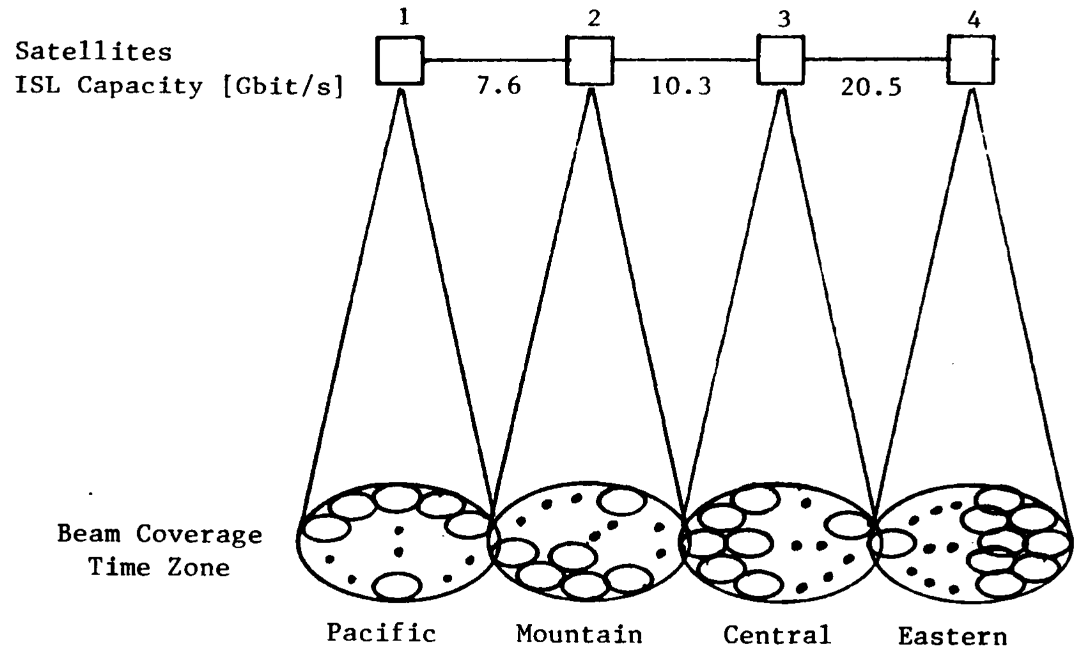


Figure 4-4. CONUS ISL System Architecture

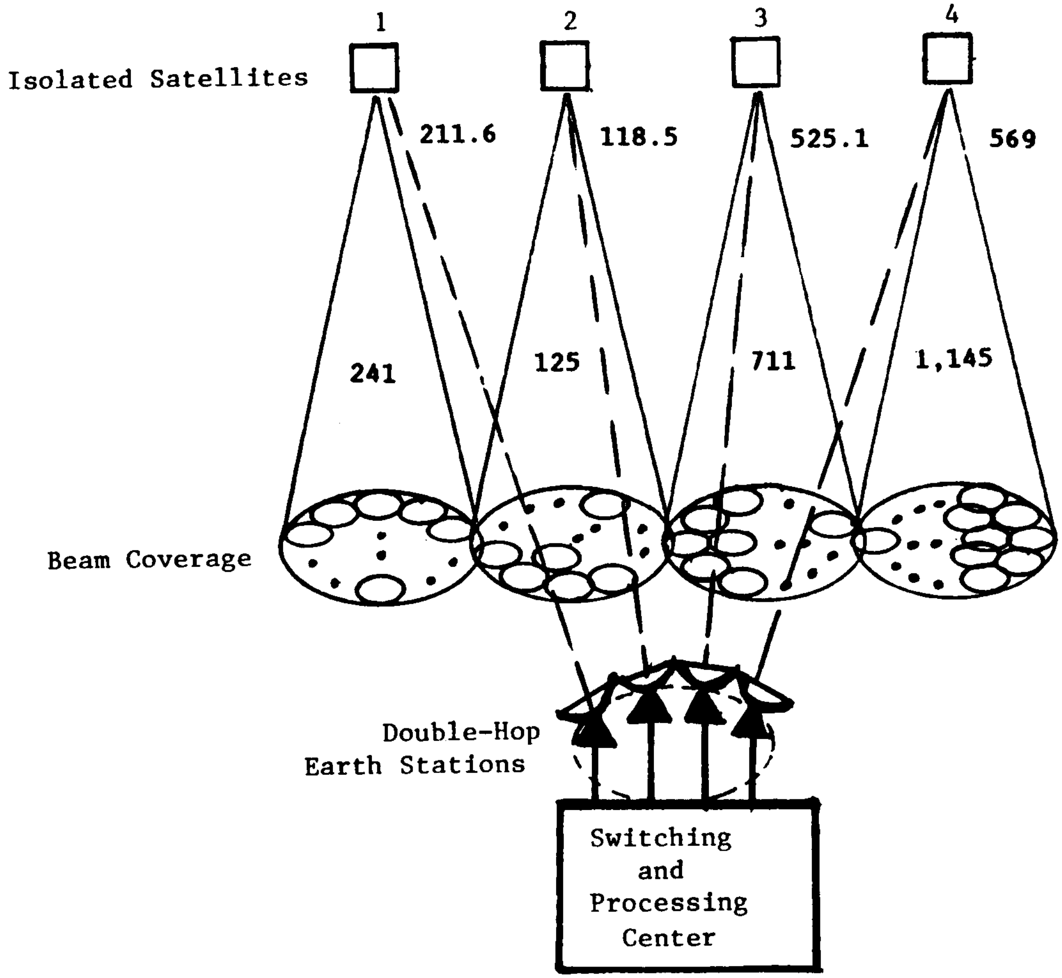


Figure 4-5. CONUS Non-ISL System Architecture I

Table 4-2. CONUS Non-ISL System Architecture I--
Capacity Requirement

Parameters	Time Zone Satellites: Pacific 1	Mountain 2	Central 3	Eastern 4
Double-Hop Transponder Requirement[a]	211.6	118.5	525.1	569
Number of Double-Hop Beams[b]	2	1	5	5

[a] 36-MHz equivalent transponder.
[b] K_a-band for 120 transponders per beam.

satellite is also given in this table, assuming a 120 36-MHz equivalent transponder capacity of a K_a-band spot beam. Interconnectivity of the double-hop spot beams to the central switching station could be provided additionally by terrestrial links.

Non-ISL CONUS System Architecture II is shown in Figure 4-6. Each satellite provides entire CONUS coverage using multiple spot beams. However, the space segment capacity of each spacecraft is the same as the host spacecraft of the CONUS ISL satellites (Figure 4-4).

Each location of major ground segment nodes in Architecture II requires multiple colocated earth station antennas, as many as the number of isolated spacecraft (four in this case) for full interconnectivity of traffic within CONUS.

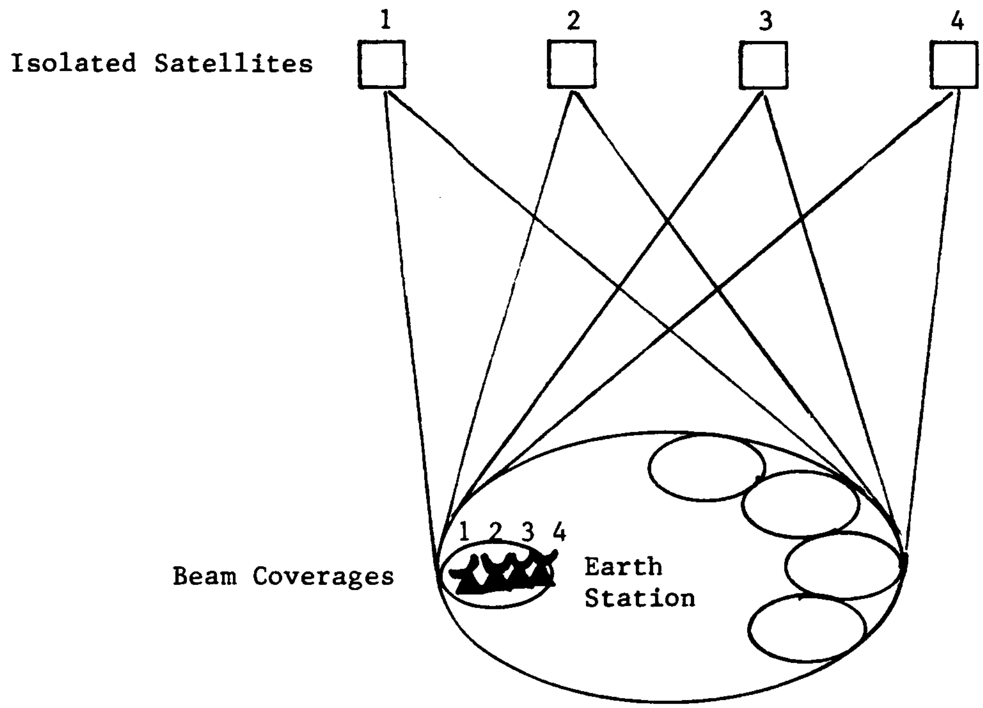


Figure 4-6. CONUS Non-ISL System Architecture II

4.2.2 SELECTED ISL NETWORK ARCHITECTURES

ISL network architectures of the selected ISL applications were derived. The result is shown in Table 4-3, including nominal ISL range, ISL terminal capacity, and satellite orbital locations. The CONUS ISL network was described in a previous subsection (Subsection 4.2.1).

ISL Application No.2, (a) between CONUS and Europe and (b) between N. America and Europe, is shown in Figure 4-7. A 50°-ISL between a CONUS satellite located at 302°E (58°W) and a European satellite at 352°E (8°W) provides full traffic interconnectivity. The ISL traffic capacity requirement is 618 Mbit/s and 677 Mbit/s, respectively, for Applications No. 2a and No. 2b.

For other ISL applications, elevation angle contours and orthographic maps of earth coverage from each satellite orbital location were used extensively to determine the ISL satellite orbital locations identified in Table 4-3.

For mature ISL systems, a three ITU regional satellite network architecture (Application No. 5) is shown in Figure 4-8. The visible coverage area of each regional satellite, located at 15°E, 125°E, and 250°E, is also shown in Figure 4-8.

A simplified representation of ISL vs non-ISL satellite constellations for each application is illustrated in Figure 4-9. Satellites for domestic, regional, and international services are shown in the constellation as needed. The ISL constellations were identified in Table 4-3. Intercluster ISL satellites, shown in Figure 4-8, represent a revolving star configuration. A simpler string or other alternative configurations can be used.

Table 4-3. Selected ISL Network Architectures

No.	ISL Application	ISL Range Nominal	ISL Payload Capacity [Mbit/s]	Orbital Locations
1	CONUS-4 Zone Coverage	30°	7,600; 10,300; 20,500	49°W to 143°W
2a	CONUS-Europe	50°	618	58°W, 8°W
2b	N. America-Europe	50°	677	58°W, 8°W
3	CONUS-International			
	a. CONUS-POR	50°	317	131°W, 177°E
	b. CONUS-AOR	30°	1,220	58°W, 24.5°W
4	ITU Region 1-International			
	a. Region 1-AOR	70°	845	15°E, 53°W
	b. Region 1-IOR	70°	200	15°E, 81°E
5	ITU Region 1-2-3			
	a. Region 1-Region 2	125°	1,430	15°E, 110°W
	b. Region 2-Region 3	125°	360	110°W, 125°E
	c. Region 3-Region 1	110°	576	125°E, 15°E
6	Intercluster ISL for CONUS	0.1°	50 to 10,300 (Configuration-dependent)	98°W to 103°W

C-2

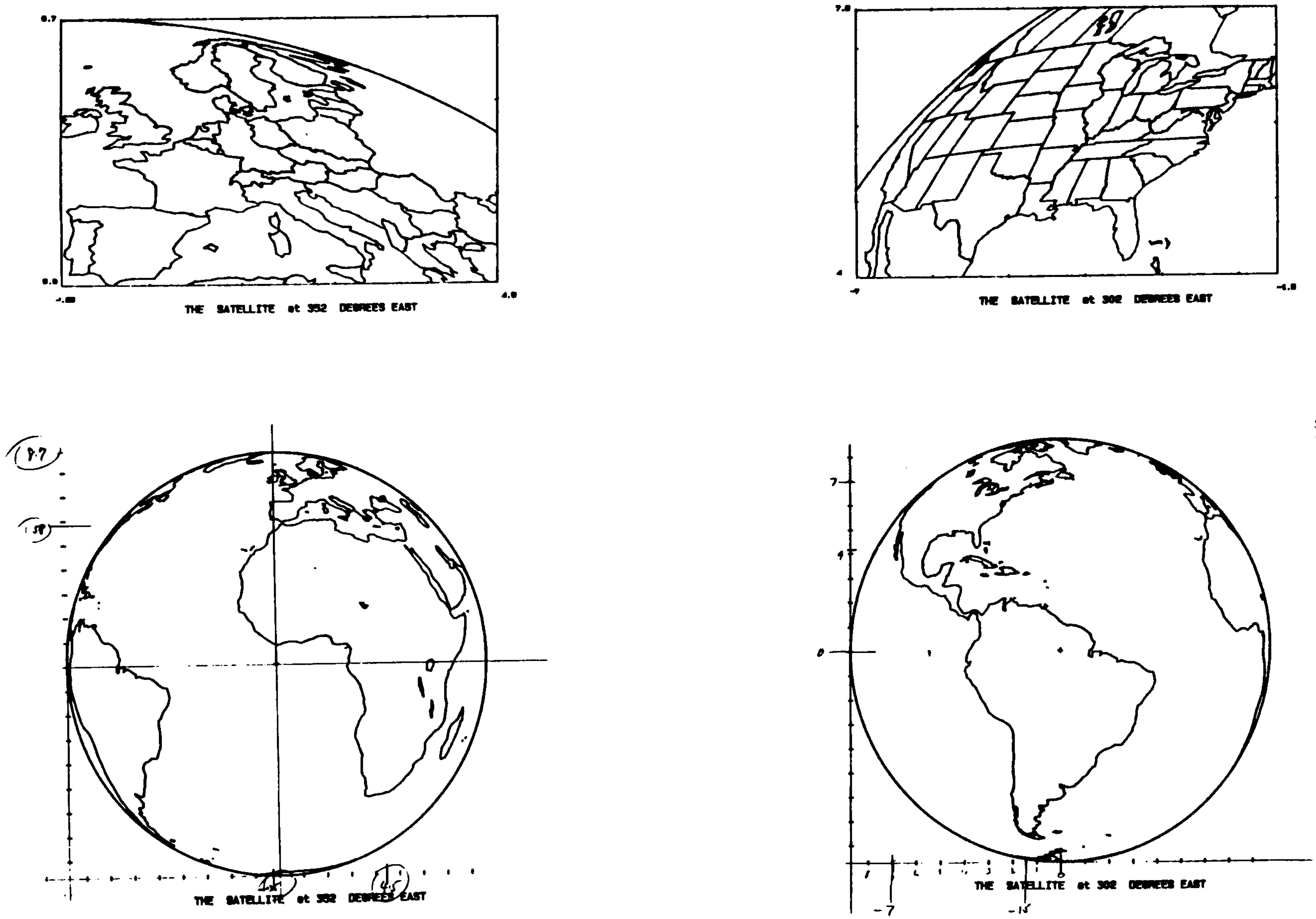


Figure 4-7. 50° ISL Connectivity Between CONUS and Europe

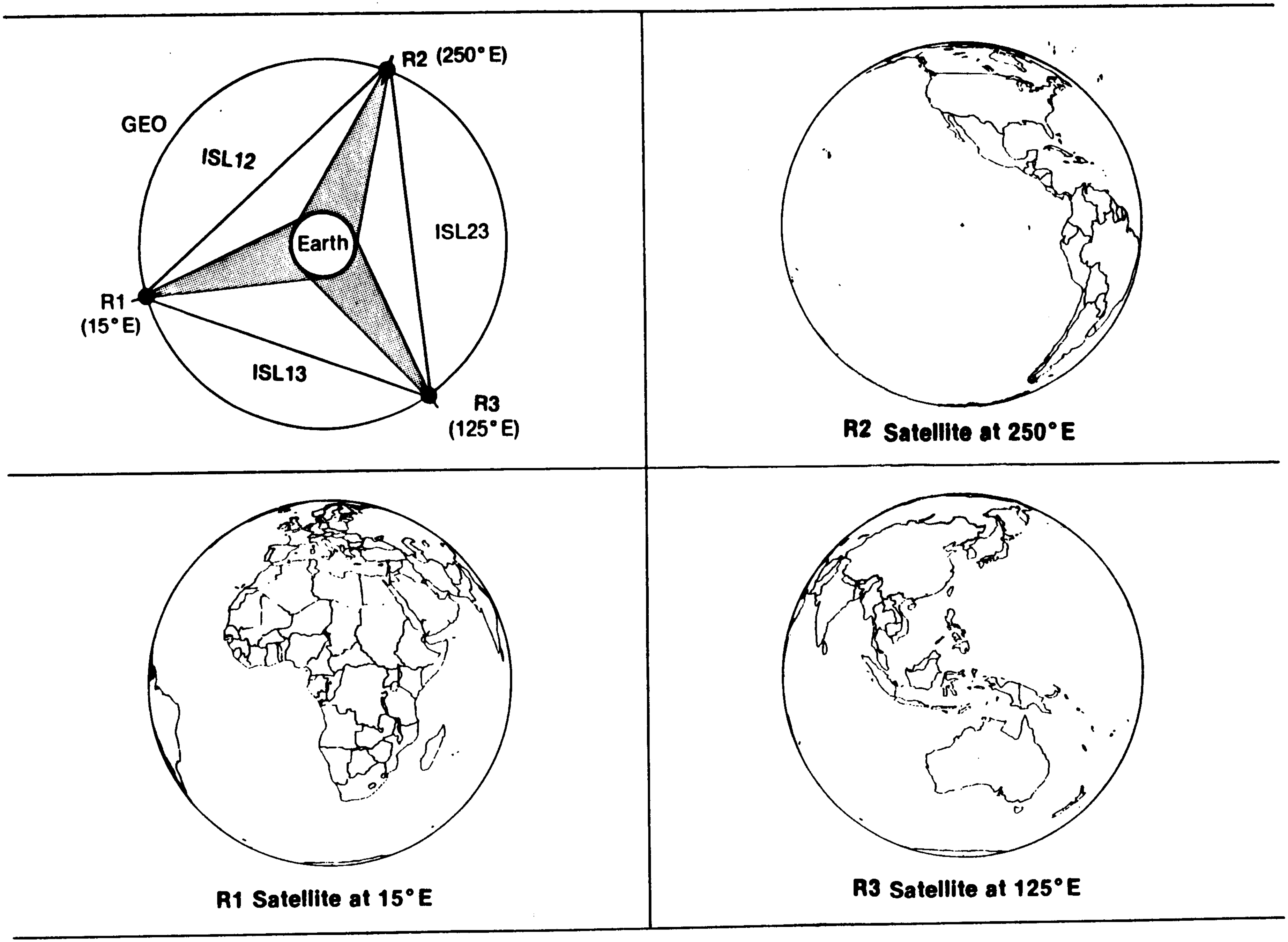


Figure 4-8. Three ITU Regional ISL Satellite System

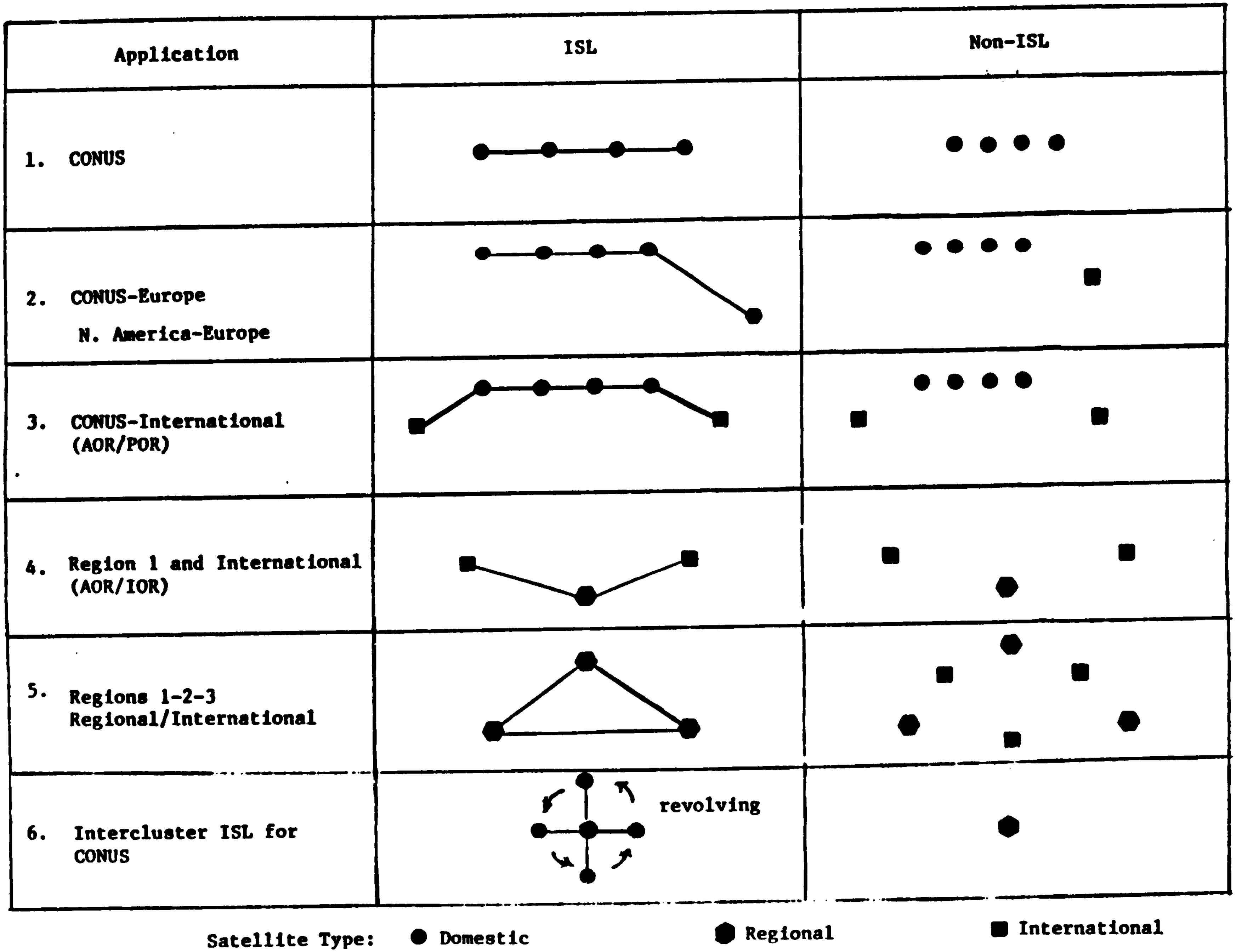


Figure 4-9. ISL vs Non-ISL Satellite Constellations

The corresponding non-ISL satellite constellations, shown in Figure 4-9, provide the same services as the ISL system of each application using double-hop relay configurations. An exception to it is Application No. 6 where a large single spacecraft is taken as the corresponding non-ISL system.

Figure 4-10 illustrates a simplified representation of the existing three ocean region international satellite (INTELSAT) system. The earth coverage orthographic map for each ocean region satellite, located at 60°E, 174°E, and 335.5°, is given in Figure 4-10.

A comparison of the three ITU regional ISL system (Figure 4-8) and the corresponding non-ISL INTELSAT system (Figure 4-10) shows that the mature ISL system could provide increased coverage of the world land mass. From the elevation angle contours, Figure 4-11 presents the percentage coverage of the land mass. The ISL system provides more coverage by about 15 percent under a 20° elevation requirement and by about 10 percent under 20° elevation criterion. The USSR is excluded in this land mass estimate, considering the fact that the USSR is not covered by the existing INTELSAT system.

4.3 PAYLOAD CONFIGURATIONS

For each network system architecture developed in Subsection 4.2, ISL payload configurations and spacecraft sizing was determined. Microwave (60 GHz) vs optical (0.85-μm diode laser) implementation approaches of the ISL payload were evaluated comparatively for their mass, power, and size requirements. Cost analyses are presented in Section 5.

A generic satellite block diagram is shown in Figure 4-12. The baseline (non-ISL) payload includes

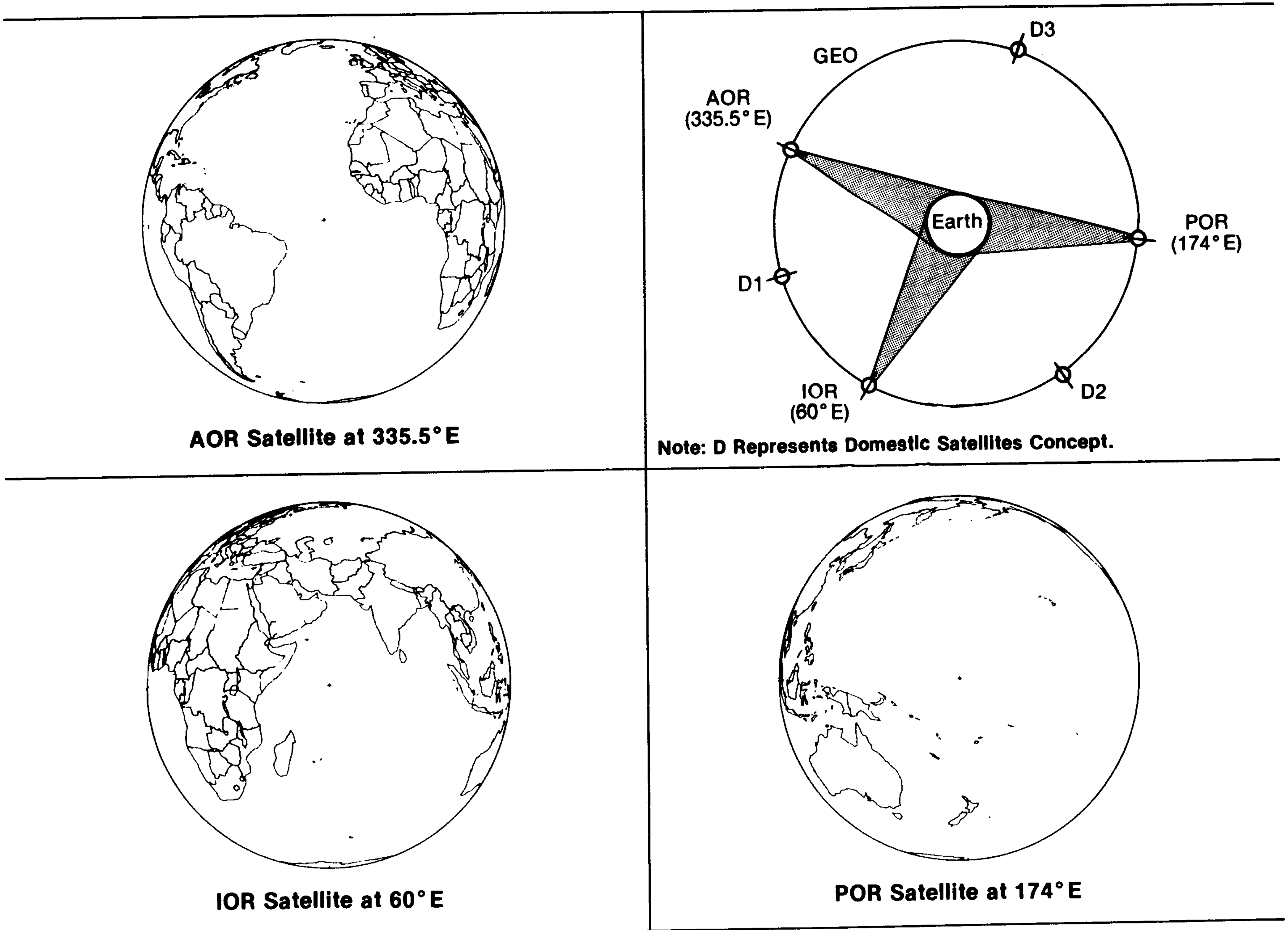


Figure 4-10. Existing Three Ocean Region International Satellite (INTELSAT) System

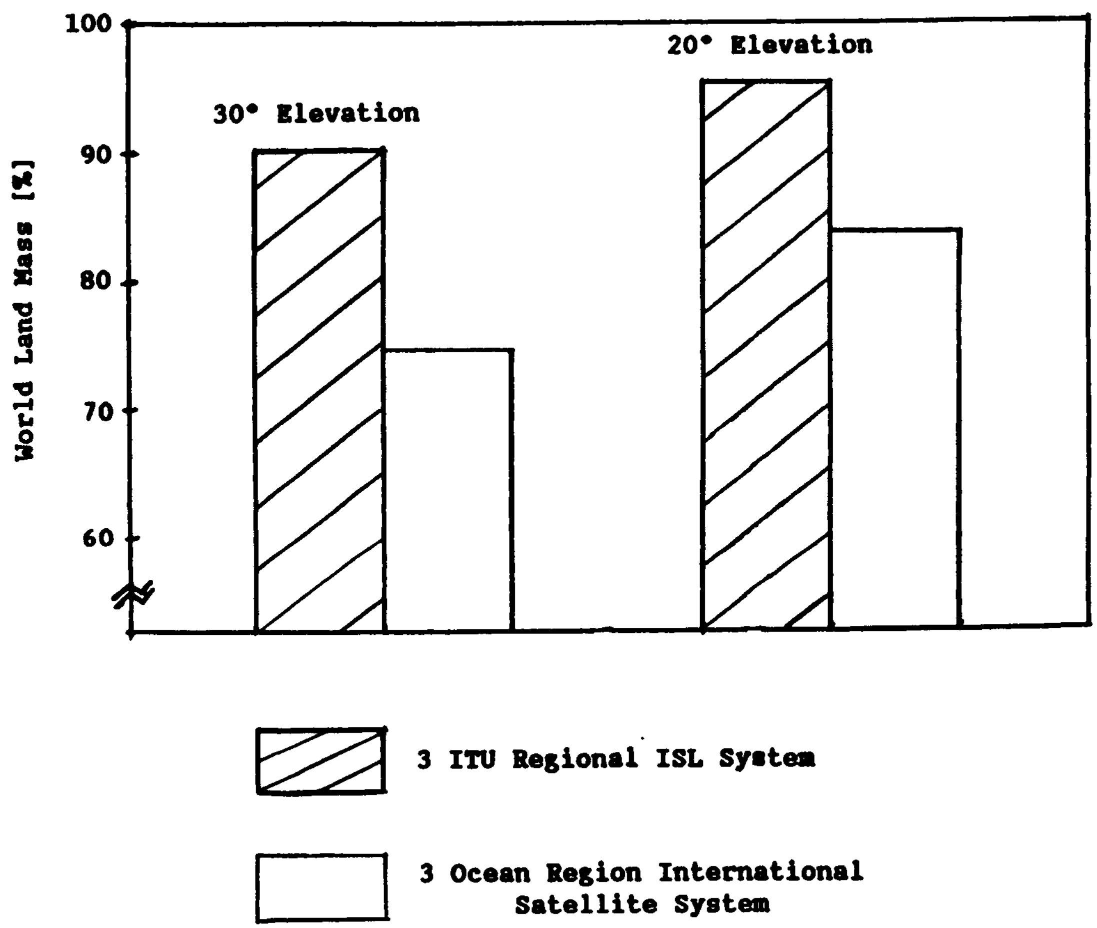


Figure 4-11. Percentage Coverage of World Land Mass

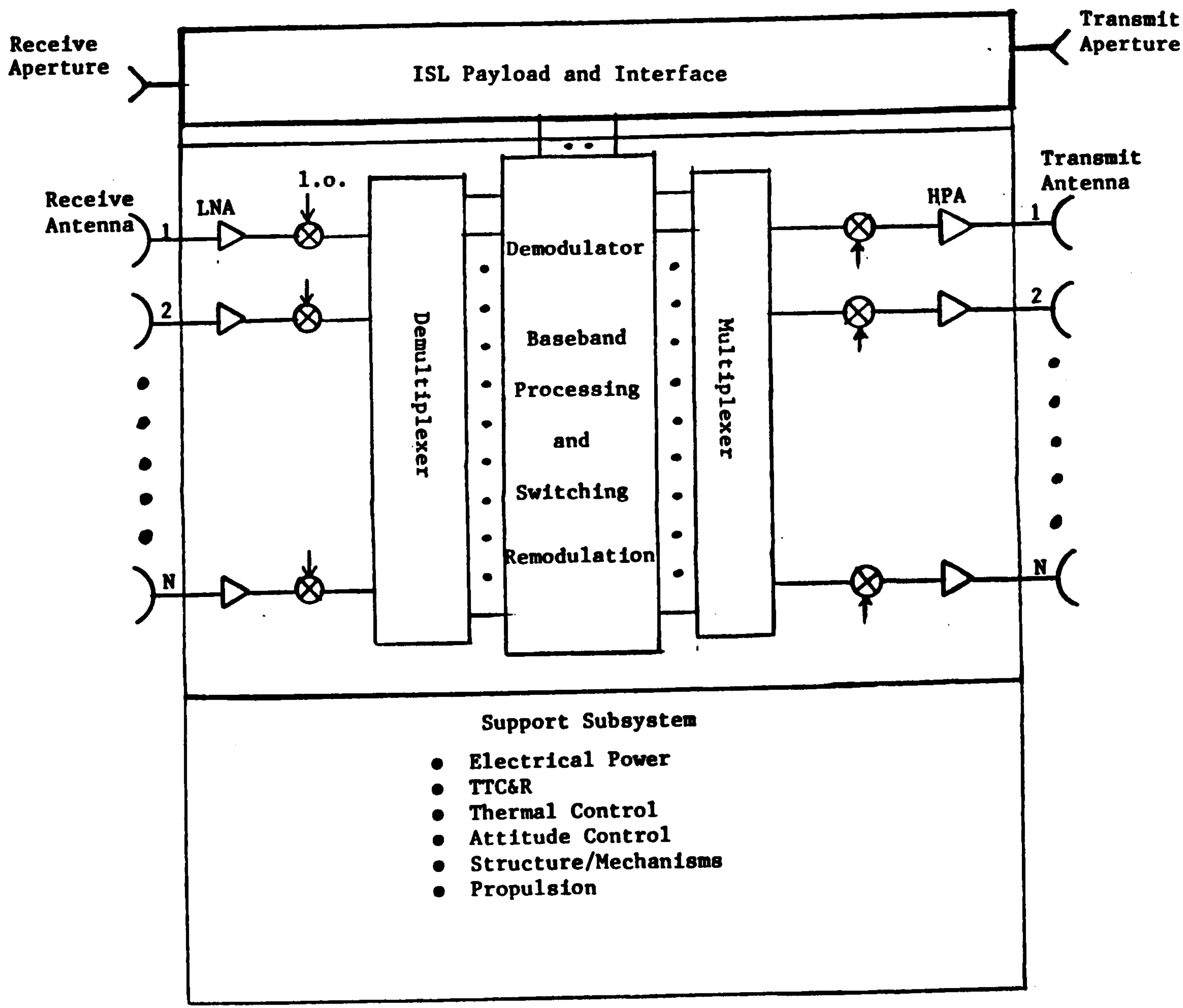


Figure 4-12. Generic Satellite Block Diagram

multibeam receive input and transmit output channels, on-board signal processing, and switching subsystems.

An ISL payload is integrated onto the host spacecraft, as shown in Figure 4-12. The ISL interface provides ISL traffic routing and signal processing functions between the host spacecraft and the ISL payload. Further discussions are given in Subsection 4.3.3.

The spacecraft support (bus) subsystem provides various functions for spacecraft operation:

- Electric Power,
- Telemetry, Tracking, Command, and Ranging (TTC&R),
- Thermal Control,
- Attitude Control,
- Structure and Mechanisms,
- Propulsion.

Basic ISL system parameters used in the payload sizing of microwave and optical ISLs are listed in Table 4-4. The ISL distance and the transmission data rate requirement of each application were defined in Table 4-3. The ISL design criterion was set for a transmission performance of bit error rate (BER) $\leq 10^{-7}$. Other key parameters of the ISL link design are shown in Table 4-4.

Table 4-4. Basic ISL System Parameters

- ISL Distance and Transmission Data Rate: Per Selected Application
- Bit Error Rate $\leq 10^{-7}$
- Parameters

Parameters	Microwave (60 GHz)	Optical (0.85 μm)
- Modulation	Uncoded QPSK	Diode Laser PPM, Uncoded
- Antenna Aperture Size	$\leq$ 2 m	$\leq$ 60 cm
- Transmit Power	10 W to 75 W	100 mW to 300 mW
- Receive Characteristics	Noise Figure = 8 dB (HEMT Device)	Photodetector Optical Receive Power $\geq$ -70 dBW at 1-Gbit/s Rate

4.3.1 60-GHz ISL PAYLOADS

4.3.1.1 Payload Configurations

A simplified microwave ISL payload block diagram is shown in Figure 4-13. It consists of two major subsystems:

- o Antenna subsystem, including gimballed reflector antenna, gimbal drive electronics and acquisition, and tracking processors.
- o Repeater subsystem, including receive and transmit subsystems, and electronic power subsystems.

The antenna size and RF output power are the key design parameters of the ISL payload. The 60-GHz ISL payload design trade-off for a nominal 1 GHz RF bandwidth is shown in Figure 4-14. The ISL antenna size is limited to 2 m as a design choice. The ISL link performance is specified by a 17-dB carrier-to-noise ratio and a link margin of 2.2 dB.

Table 4-5 shows the 60-GHz link budget. RF circuit loss of 0.5 dB is included for each transmit output and receive input circuit. An 8-dB noise figure of the 60-GHz LNA (i.e., High Electron Mobility Device) is used in the calculation. For 1-GHz noise bandwidth, the carrier-to-noise power ratio is 19.2 dB including the link margin under normal black-sky background. It could be reduced to 12.8 dB during solar conjunction.

The antenna size and RF power requirement of each ISL application were determined through similar link calculations. Table 4-6 lists the HPA RF output power requirement per ISL payload terminal (i.e., facing only one direction) for each application. A 2-m ISL antenna was selected in the link

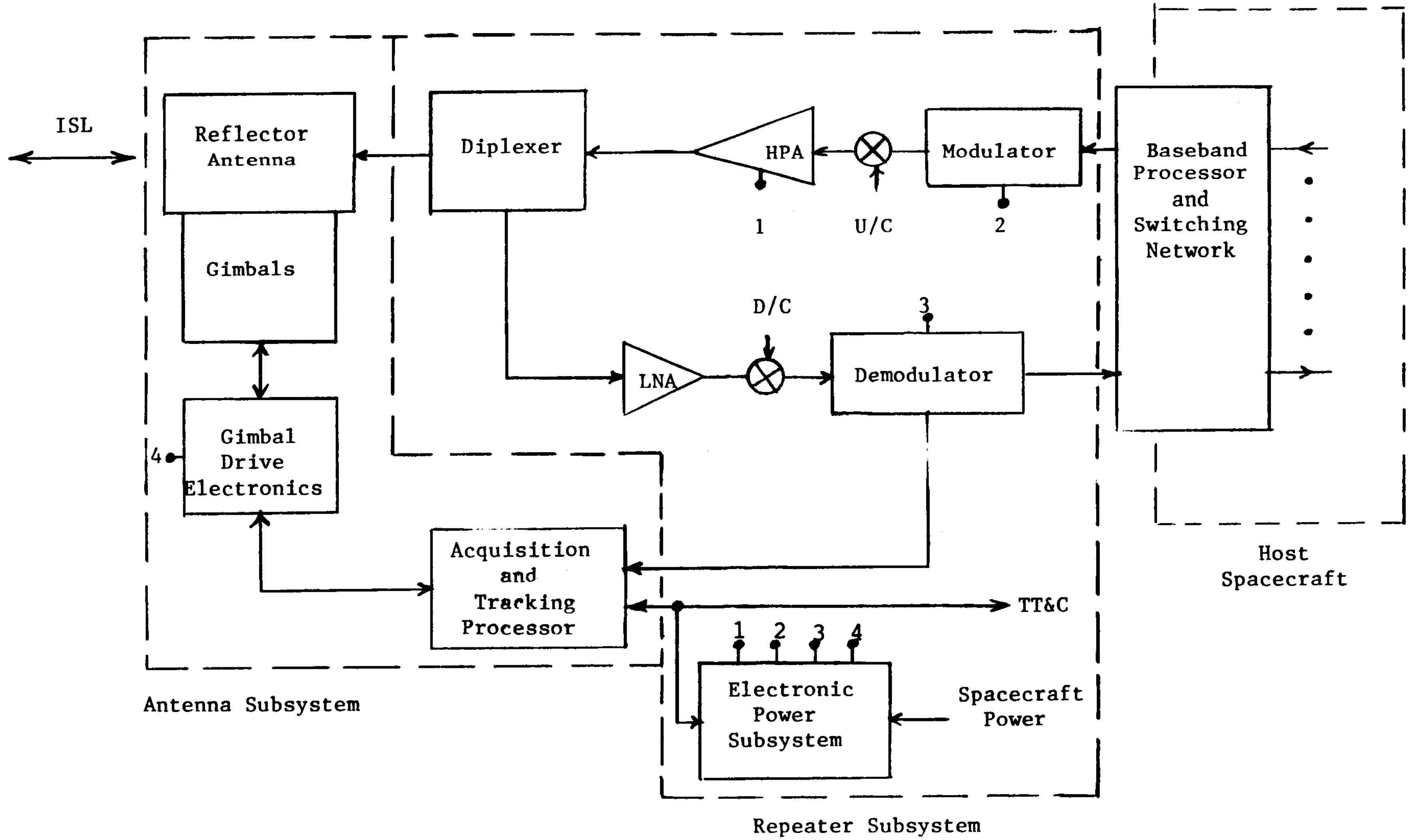


Figure 4-13. Microwave Payload Block Diagram

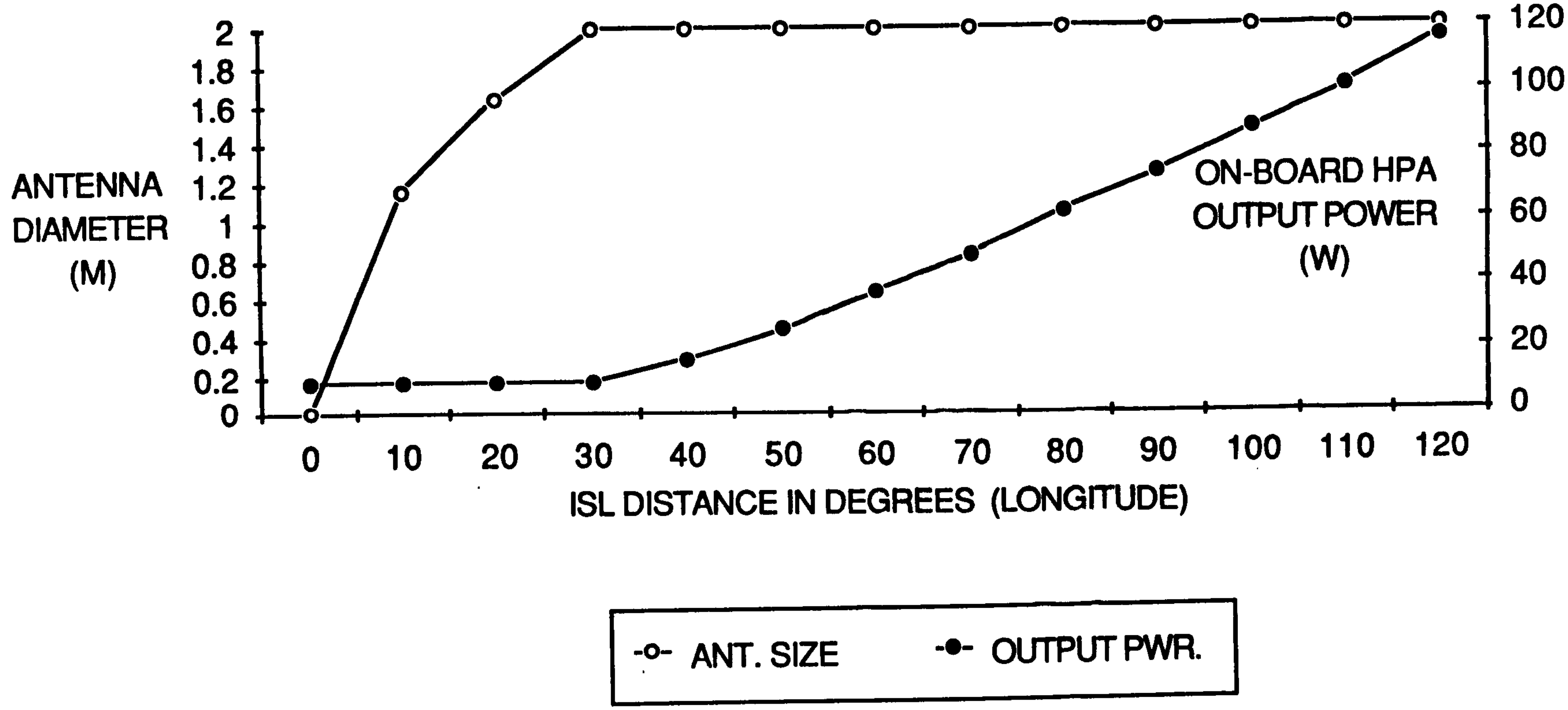


Figure 4-14. 60-GHz ISL Payload Design Trade-Off

Table 4-5. 60-GHz ISL Link Budget, 30° Orbital Spacing

Parameters	Unit	Black-Sky Background	Sun Background
Transmit Power	dBW	10.0	10.0
Antenna Gain (2 m, 55% efficiency)	dBi	59.3	59.3
RF Circuit Loss	dB	0.5	0.5
e.i.r.p.	dBW	68.8	68.8
Free Space Path Loss (22,000 km)	dB	214.8	214.8
Receive Antenna Gain (2 m)	dBi	59.3	59.3
Receive Circuit Loss	dB	0.5	0.5
Carrier Power, C	dBW	-87.4	-87.4
Noise Power Density, N_O (kT_{system})	dBW/Hz	-196.6	-190.2
o k = -228.6 dBW/HzK			
o Receiver Temperature = 1,540°K (8-dB Noise Figure)			
o System Noise Temperature, T_{sys}*	dBK	32.0 (1,571°K)	38.4 (6,919°K)
C/N_O	dB-Hz	109.2	102.8
Noise Bandwidth (1 GHz)	dB-Hz	90	90
C/N	dB	19.2	12.8

*$T_{sys} = \alpha T_A + (1 - \alpha) T_O + T_R$; α = loss factor, T_A = 6,000°K for solar background, T_R = receive temperature.

Table 4-6. 60-GHz ISL Payload per Terminal Sizing

ISL Applications Number	ISL Range Nominal	ISL Payload Capacity [Mbit/s]	Repeater/HPA Requirement per ISL Terminal with a 2-m ISL Antenna			
			HPA RF Output Power [W]	TWTA Units (Power Rating)	TWTA Mass* [kg]	Total DC Power* [W]
1 (a)	30°	7,600	76; 103; 205	60 W, 16 W; 60 W,	5.01; 5.55; 11.0	168.7, 228.7, 455.1
(b)		10,300		43 W; 50 W (3),***		
(c)		20,500**		25 W		
2a	50°	618	6.2	6.2 W	1.72	13.8
2b	50°	677	6.8	6.8 W	1.8	15.1
3a	50°	317	3.2	3.2 W	1.5	7.1
3b	30°	1,220	12.2	12.2 W	2.0	27.1
4a	70°	845	8.5	8.5 W	1.9	18.9
4b	70°	200	2.0	2.0 W	1.4	4.5
5a	125°	1,430	14.3	14.3 W	2.1	31.8
5b	125°	360	3.6	3.6 W	1.52	8.0
5c	110°	576	5.8	5.8 W	1.7	12.9

*Two-for-one standby redundancy for TWTAs.

**Exceeds allocated ISL bandwidth.

***Number of active units; otherwise one (1).

design. The mass and power estimates are given in the following subsection.

Figure 4-15 shows a 60-GHz intercluster ISL (0.1°) payload terminal design nomograph. The trade-off between antenna size and transmit RF power for a number of transmission data rates is shown in the graph.

4.3.1.2 Mass and Power Estimate

The ISL payload sizing algorithm was developed, employing statistical techniques, to estimate mass and power requirements. The antenna and repeater HPA characteristics are used as basic input parameters.

The 60-GHz ISL tracking antenna subsystem model was based on an INTELSAT development model in the 33-/23-GHz band [23]. Table 4-7 shows a mass data of the gimballed 2-m antenna subsystem, shown in Figure 4-16. A future flight model is expected to have a mass total reduced by about 22 percent, yielding 34.6 kg. The prime power requirement of the antenna tracking/driver subsystem is 27 W.

The mass and power estimate of a 60-GHz TWTA is based on the following statistically derived equations:

a. Mass:

$$M_{TWTA} = 0.4\ P_{RF}^{0.227}\ N(1 + 0.84\ Rd) \qquad (4\text{-}1)$$

where P_{RF} = RF output power at saturation,
N = Number of TWTAs,
R_d = TWT redundancy factor (≤ 1).

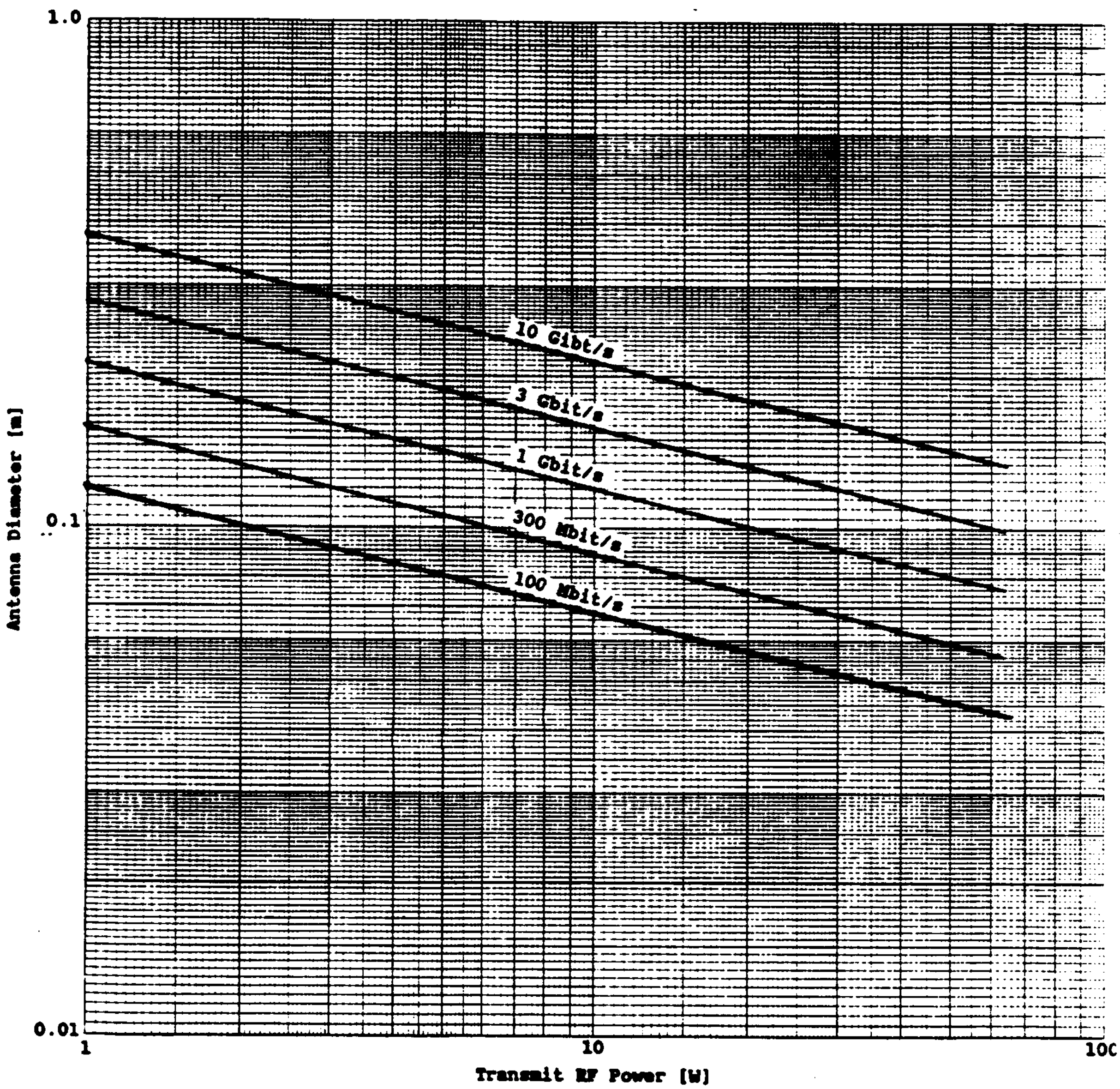


Figure 4-15. 60-GHz Intercluster ISL ($\leq$0.1°) Payload Terminal Design Nomograph

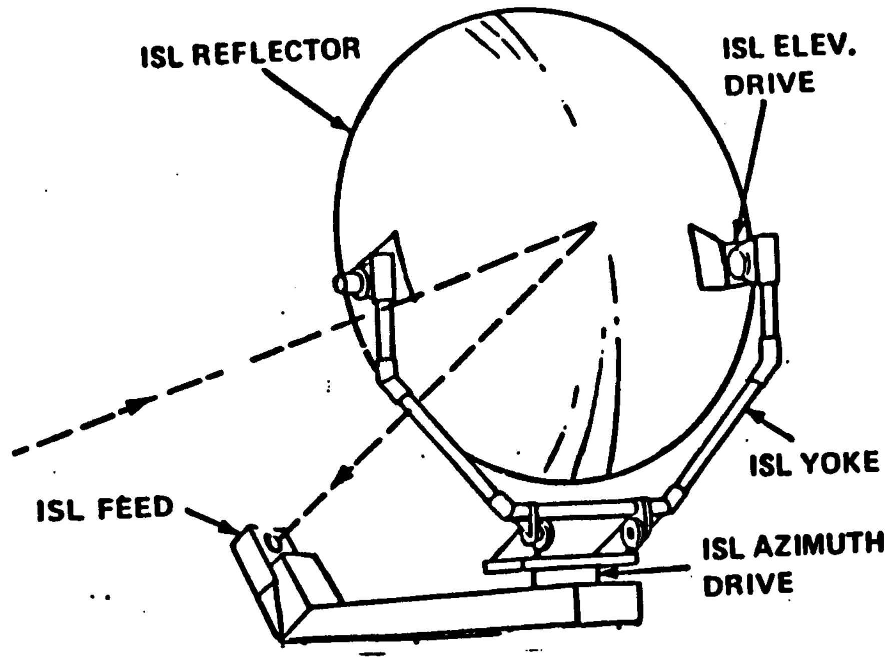


Figure 4-16. A 2-m Microwave (33/23 GHz) ISL Antenna
(GE Developmental Model for INTELSAT)

Table 4-7. Gimballed Microwave Antenna Subsystem Mass Data

Item	INTELSAT Demonstration Model Mass Data [kg]
Reflector (2 m)	9.1
Feed/Support Assembly	8.2
Actuator Turntable	5.7
Antenna Yoke/Power Hinge	13.5
Support Assembly	7.9
Total	44.4

- ISL P/L Sizing Model.
  Mass of a 2-m Antenna Subsystem: 34.6 kg.
  Mass reduction by 22% for future flight model.

b. DC Power:

$$P_{DC} = 2.22 \, P_{RF} N_A \qquad (4\text{-}2)$$

where N_A = Number of active operating TWTAs under full loading condition.

The above statistical equations were obtained from a previous COMSAT study [24]. The mass and power of TWTAs for each ISL payload terminal in Table 4-6 were computed from these equations.

The antenna size and TWTA mass/power are basic input parameters in the ISL payload sizing. The ISL mass and power estimating algorithm was developed based on COMSAT's ten commercial spacecraft program data base. Appendix D shows the summary of mass, power, and costs of the 10 spacecraft programs.

Table 4-8 shows the mass and power estimating equations of a 60-GHz ISL payload. The input to this ISL payload sizing model are:

Table 4-8. 60-GHz ISL Payload: Mass and Power Estimating Equations

1. Antenna Subsystem Mass (M_{ANT})

- Reflector Mass (M_R) in Kilograms

$$M_R = 0.547 + 2.332 * A_T^{1.1}$$

where A_T = Antenna aperture area in m^2

- Feed Mass (M_F)

$$M_F = 7.015 + 0.016\ N_B^3 + 7.163 \times 10^{-4} NF^{1.8}$$

where N_B = Number of beams

N_F = Number of feeds

- Antenna Tracking Gimbal Driver Mass (M_{TD})

$$M_{ATD} = 1.2\ M_R$$

- Antenna Subsystem Total Mass

$$M_{ANT} = 6.196 + 1.124\ M_R + 1.127\ M_F + M_{ATD}$$

Table 4-8. 60-GHz ISL Payload: Mass and Power Estimating Equations (Cont.)

2. Repeater Mass (M_{REP})

$$M_{REP} = 14.615 + 2.497\ M_{PA}$$

where M_{PA} = HPA mass

3. Electrical Power Conditioner (EPC) Mass (M_{ECP})

$$M_{EPC} = 0.50 + 0.0833\ P_{ISL}$$

where P_{ISL} = ISL payload power

4. Total Mass (M_{ISL})

$$M_{ISL} = M_{ANT} + M_{REP} + M_{EPC}$$

5. Antenna Tracking/Driver Power (P_{ATD}) in Watts

$$P_{ATD} = 17 + 1.04\ M_{ATD}$$

where M_{ATD} = Antenna tracking/gimbal drive mass

Table 4-8. 60-GHz ISL Payload: Mass and Power Estimating Equations (Cont.)

6. Repeater Power (P_{REP})

$$P_{REP} = 11.244 + 1.075\ P_{PA}$$

where P_{PA} = HPA DC power

7. Total Power (P_{ISL})

$$P_{ISL} = P_{ATD} + P_{REP}$$

a. Antenna size (aperture area in square meters),
b. Number of ISL beams (one typical),
c. Number of feeds (one transmit and receive feed typical),
d. Mass (in kg) of on-board HPAs, and
e. Power (in watts) of on-board HPAs.

Based on the 60-GHz ISL sizing data contained in Table 4-6, the payload mass and power requirement per ISL payload terminal was computed for each ISL application. Table 4-9 contains the result. The letters a, b, and c under ISL Application No.1 correspond to ISL terminal capacity of 7.6 Gbit/s, 10.3 Gbit/s, and 20.5 Gbit/s, respectively. Other applications were identified previously in Table 4-3.

The ISL payload total mass and power per spacecraft for each application can be readily obtained from the results in Table 4-9 by counting the corresponding ISL terminals per spacecraft. Further discussion is provided in Subsection 5.1.

4.3.2 OPTICAL ISL PAYLOADS

4.3.2.1 Payload Configurations

A simplified block diagram of the optical ISL payload is illustrated in Figure 4-17. The pointing, acquisition, and tracking (PAT) subsystem includes gimballed telescope assembly, gimbal drive and acquisition/tracking electronics, imaging optics, and photodetector assembly. The repeater subsystem contains modulator/driver and diode laser assembly for the

Table 4-9. 60-GHz ISL Payload: Mass and Power Requirements per ISL Terminal

ISL Applications Number	Mass (kg)			Power (W)	
	Repeater	EPC	Payload*	Repeater	Payload**
1a	27.1	18.9	80.6	192.6	220.5
1b	28.5	24.2	87.3	257.1	285.0
1c	43.1	44.5	121.2	500.5	528.4
2a	18.9	5.0	58.5	26.1	54.0
2b	19.1	5.1	58.8	27.5	55.4
3a	18.4	4.4	57.3	18.9	46.8
3b	19.6	6.2	60.4	40.4	68.3
4a	19.4	5.5	59.4	31.6	59.5
4b	18.1	4.2	56.9	16.1	44.0
5a	19.9	6.6	61.1	45.4	73.4
5b	18.4	4.5	57.5	19.8	47.8
5c	18.9	4.9	58.4	25.1	53.0

*Antenna (2 m) Subsystem Mass = 34.6 kg.
**Antenna Tracking/Driver Power = 28 W.

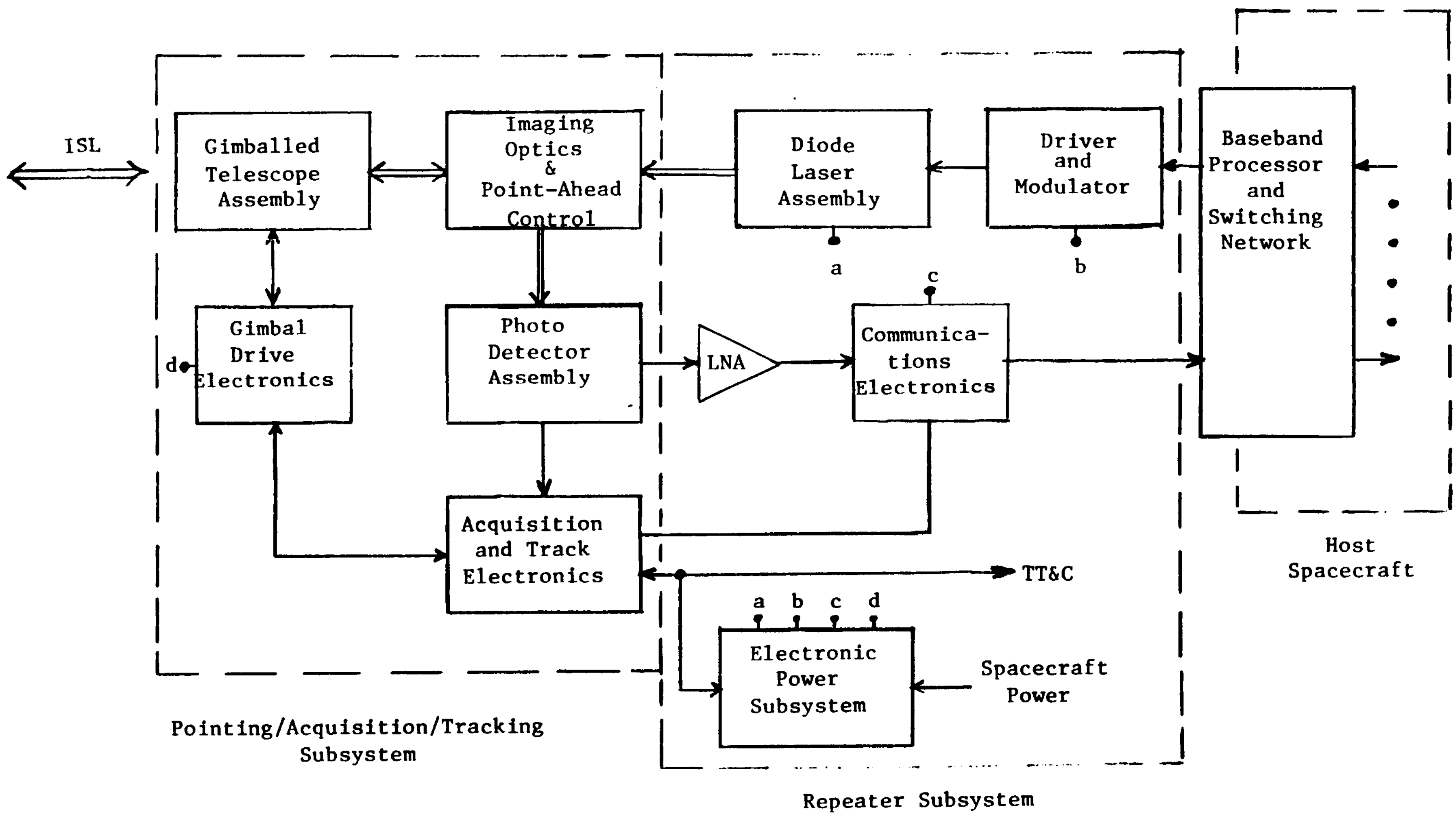


Figure 4-17. Optical ISL Payload Block Diagram

transmit channels, and LNA and communications electronics for the receive channels.

A specific example of an optical payload configuration is shown in Figure 4-18. It shows the NASA/AF's ACTS Lasercom System Payload Schematic for direct detection laser transmitter (DDLT) employing GaAlAs diode lasers and DDLT receivers. The MIT Lincoln Laboratories laser transmitter employing a coherent modulation technique can be operated also through the Flip Mirror in the transmit chain [25].

The ISL payload design trade-off between aperture size and optical transmit power was analyzed using the link equation:

$$P_R = P_T \bullet L_T \bullet G_T \bullet L_P \bullet \left(\frac{\lambda}{4\pi R}\right)^2 \bullet G_R \bullet L_R \qquad (4\text{-}3)$$

where P_R = Optical power received at the detector.

P_T = Laser output power.

L_T = Transmitter optics transmission loss factor.

G_T = Transmit aperture gain.

L_P = Antenna pointing loss.

λ = Optical wavelength.

R = ISL range.

G_R = Receive aperture gain.

L_R = Receiver optics transmission loss factor.

The aperture gain is given by

$$G = \eta \left(\frac{\pi D}{\lambda}\right)^2 \qquad (4\text{-}4)$$

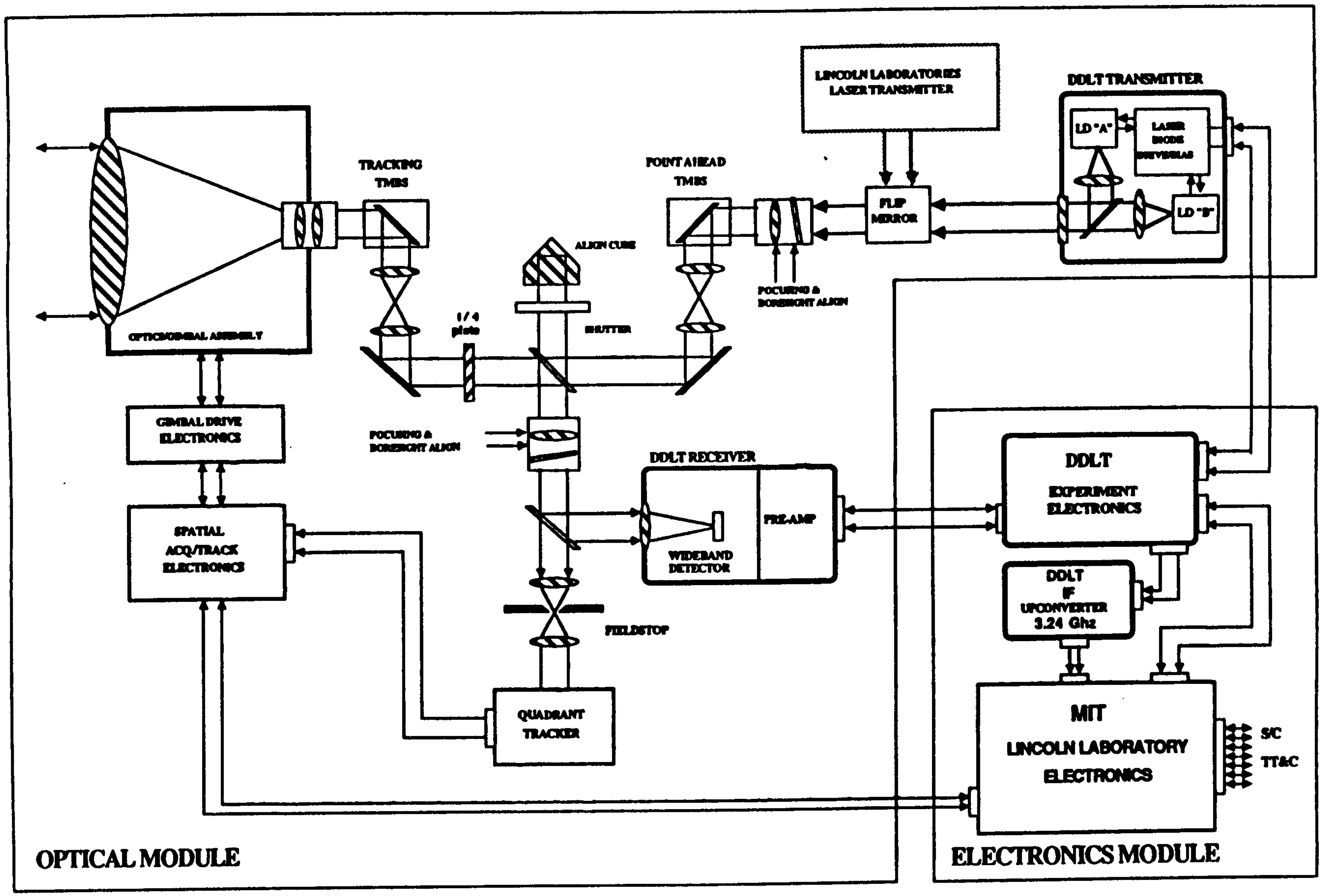


Figure 4-18. ACTS Laser Communications System--Direct Detection Configuration

where η = Antenna efficiency (50 percent typical).
D = Aperture diameter.

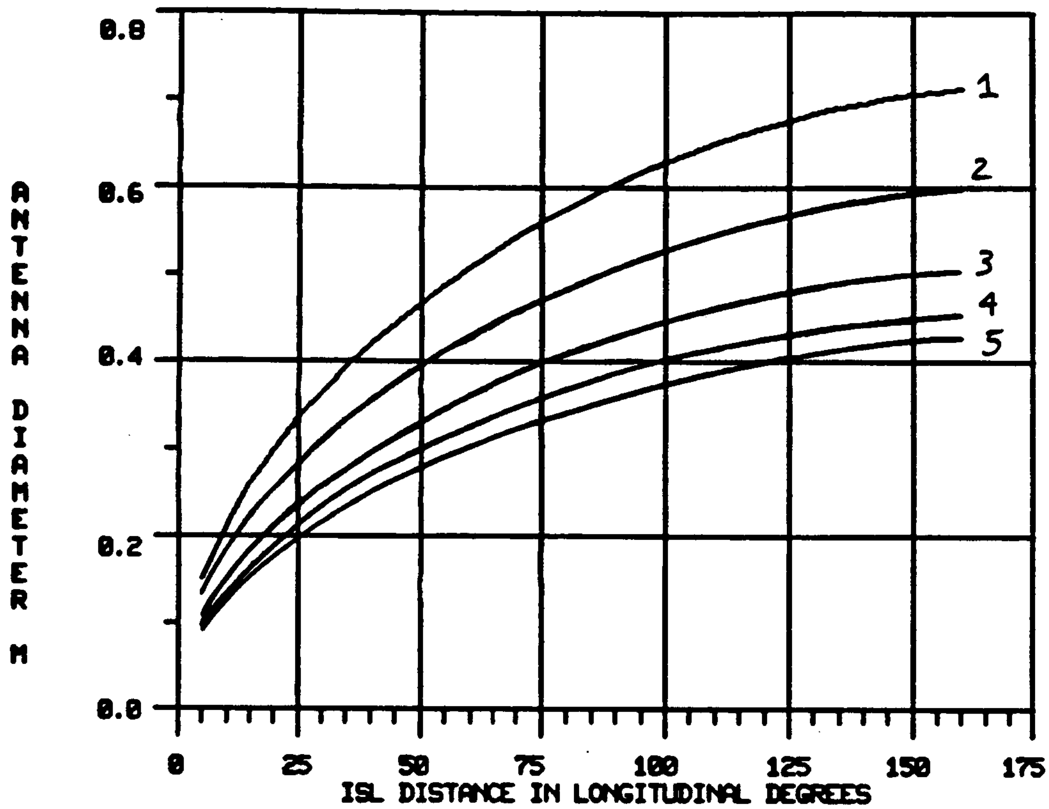
The diplexing optics loss is about 1 dB on both transmit and receive optical channels. A typical narrowband optical filter has a transmission loss of about 1 dB. The pointing loss is estimated to be 1 dB each for transmit and receive optical antennas.

For equal sized transmit and receive antennas of aperture diameter D, equations (4-3) and (4-4) provide optical ISL design parameter trade-offs. Figure 4-19 presents diode laser (0.85 µm) ISL design trades for a 1-Gbit/s transmission capacity: aperture size versus ISL distance with laser output power as a parameter. A laser diode efficiency of 10 percent was used for laser output power ranging from 50 mW to 400 mW. Optical power received at the photodetector was required to be -70 dBW to provide BER $\leq 10^{-7}$ in the state-of-the-art avalanche photodiode detector (APD) receivers. Either on-off keying (OOK) or low-order pulse position modulation (PPM) formats are applicable for the ISL link implementation [26].

4.3.2.2 Mass and Power Estimate

Significant revisions to the previous COMSAT algorithms of optical ISL mass and power models were made by incorporating recent input data obtained through industry contact.

The state-of-the-art optical pointing, acquisition, and tracking (PAT) subsystem, which consists of gimballed telescope (Material: Be) and control electronics assemblies, indicates the following mass requirement:



Curve	Laser Power, mW
1	50
2	100
3	200
4	300
5	400

Data Rate = 1 Gbit/s
η = 10%
λ = 0.85 μm

Figure 4-19. Optical ISL Payload Design: Parameter Trade-Offs

Aperture Diameter (in Inches)	Mass [kg]
6	9.1
12	27.3
18	54.6

The PAT subsystem mass can, thus, be estimated from:

$$M_{GT}\ [kg] = 1.747 + 216.1\ D^{1.8} \tag{4-5}$$

where D is the aperture diameter in meters.

The mass estimate of control electronics subsystems, excluding thermal and structure items, is shown below:

Components	Mass [kg]
Acquisition and Tracking Array Electronics	2.2
Point-Ahead Compensator Electronics	0.9
Servo Control	2.7
Microprocessor/Driver Electronics	2.4
Subtotal	8.2

The mass/power estimating equations for the electronics and other items were derived, based on available COMSAT models. Table 4-10 lists a summary of the optical ISL payload mass and power equations.

Table 4-10. Optical ISL Payload: Mass and Power Estimating Equations

1. Primary Optics and Acquisition/Tracking Subsystem

- Gimballed Telescope Mass (M_{GT})

$$M_{GT} = 1.747 + 216.1\ D^{1.8}$$

where D is the aperture size in meters

- Control Electronics Mass (M_{CE})

$$M_{CE} = 8.18$$

- Total Mass (M_{GTC})

$$M_{GTC} = M_{GT} + M_{CE}$$

2. Repeater Mass (M_{REPS}) including EPCs

$$M_{REPS} = 12.331 + 15.314\ PL^{1.3} + 0.0833\ P_{TOT}$$

where PL is the laser optical output power in watts, and P_{TOT} is ISL payload power total.

Table 4-10. Optical ISL Payload: Mass and Power Estimating Equations (Cont.)

3. Thermal/Structural Mass ($M_{T/S}$)

$$M_{T/S} = 0.1\ P_{TOT}$$

4. ISL Payload Dry Mass Total (M_{ISL})

$$M_{ISL} = M_{GTC} + M_{REPS} + M_{T/S}$$

5. Tracking/Gimbal Drive Power (P_{TR}) in Watts

$$P_{TR} + 39.66 + 20.3\ D^{1.3}$$

where D is the aperture diameter in meters

6. Laser Diode Power (P_{LP})

$$P_{LP} = 1.25 + 2 \times 10^2\ PL/EF,$$

where EF is the diode laser efficiency in percent

7. Repeater Power (P_{REP})

- Transmitter and Control Electronics

Table 4-10. Optical ISL Payload: Mass and Power Estimating Equations (Cont.)

$$P_{TX} = 11.8 + 5 \times 10^{-3} R_b$$

where R_b is data rate in Mbit/s

- Receiver Electronics

$$P_{RX} = 2.1 + 1 \times 10^{-3} R_b$$

- $P_{REP} = P_{TX} + P_{RX}$

8. ISL Payload Power Total (P_{TOT})

$$P_{TOT} = P_{TR} + P_{LP} + P_{REP}$$

The input parameters to the mass/power model are:

- Optical aperture diameter in meters,
- Laser output power in watts,
- Data rate in Megabits/sec., and
- Diode laser efficiency in percentage.

Those parameters are determined from the link design described in Subsection 4.3.2.1.

The computed result of optical ISL payload terminal sizing for the selected application (re: Table 4-3) is shown in Table 4-11. The aperture size requirement was determined for a 100 mW laser optical output power with a 10-percent laser efficiency at 0.85 µm. The prime power and mass estimates per ISL terminal for each ISL application are given in Table 4-11. Table 4-12 contains the mass and power breakout for PAT, repeater, and thermal subsystems.

The ISL payload total mass and power per spacecraft can be obtained from Table 4-11, by adding the corresponding number of ISL terminals. Section 5 provides further discussion.

4.3.3 ISL INTERFACE AND INTEGRATION TO HOST SPACECRAFT

A general configuration of the ISL interface to the host spacecraft is illustrated in Figure 4-20, with reference to two, East-facing and West-facing ISLs for SS-TDMA transmissions. The microwave interface, which consists of the following major components, is functionally the same for optical and microwave ISLs:

a. SS-TDMA switch matrix to provide traffic interconnectivity between ISLs and the host spacecraft channels.
b. Regenerators to generate baseband data bit streams from the incoming signals of the host spacecraft and/or the other ISL channels.

Table 4-11. Optical ISL Payload Terminal Sizing for Selected ISL Applications

No.	ISL Applications	Optical ISL Payload Sizing*		
		Aperture [cm]	DC Power [W]	Mass [kg]
1a	CONUS-4 Zone Coverage	51	110.9	107.6
1b		54.6	127.9	119.1
1c		65.3	191.5	158.4
2a	CONUS-Europe	34.8	65.7	67.4
2b	N. America-Europe	35.6	66.2	68.8
3	CONUS-International			
3a	CONUS-POR	29.4	62.8	58.4
3b	CONUS-AOR	32.3	68.8	63.9
4	ITU Region 1-International			
4a	Region 1-AOR	43.8	68.9	84.5
4b	Region 1-IOR	30.6	62.4	60.1
5	ITU Region 1-2-3			
5a	Region 1-Region 2	62.1	76.3	128.7
5b	Region 2-Region 3	44.0	66.0	84.4
5c	Region 3-Region 1	47.6	68.0	92.3
6	Intercluster ISL for CONUS	1 to 3.2	57.2 to 118.9	23.6 to 34.9

*For 100-mW laser output with 10 percent efficiency at a 0.85-μm wavelength.

Table 4-12. Mass/Power Requirement of Optical ISL Payload Subsystems

ISL Application Number	Aperture Diameter [m]	Subsystem Mass [kg]				Power [W]		
		PAT	Repeater and EPC	Thermal	Total	PAT	Repeater and EPC	Total*
1a	0.510	74.2	22.3	11.1	107.6	48.1	59.5	110.9
1b	0.546	82.6	23.7	12.8	119.1	48.9	75.7	127.9
1c	0.653	110.3	29.0	19.1	158.4	51.3	136.9	191.5
2a	0.348	42.2	18.6	6.6	67.4	44.8	17.6	65.7
2b	0.356	43.6	18.6	6.6	68.8	45.0	18.0	66.2
3a	0.294	33.8	18.3	6.3	58.4	43.8	15.8	62.8
3b	0.323	38.2	18.8	6.9	63.9	44.3	21.2	68.7
4a	0.438	58.8	18.8	6.9	84.5	46.6	19.0	68.8
4b	0.306	35.6	18.3	6.2	60.1	44.0	15.1	62.4
5a	0.621	101.6	19.5	7.6	128.7	50.6	22.5	76.3
5b	0.440	59.2	18.6	6.6	84.4	46.6	16.1	66.0
5c	0.476	66.7	18.8	6.8	92.3	47.4	17.4	68.0

*Including power for laser diodes.

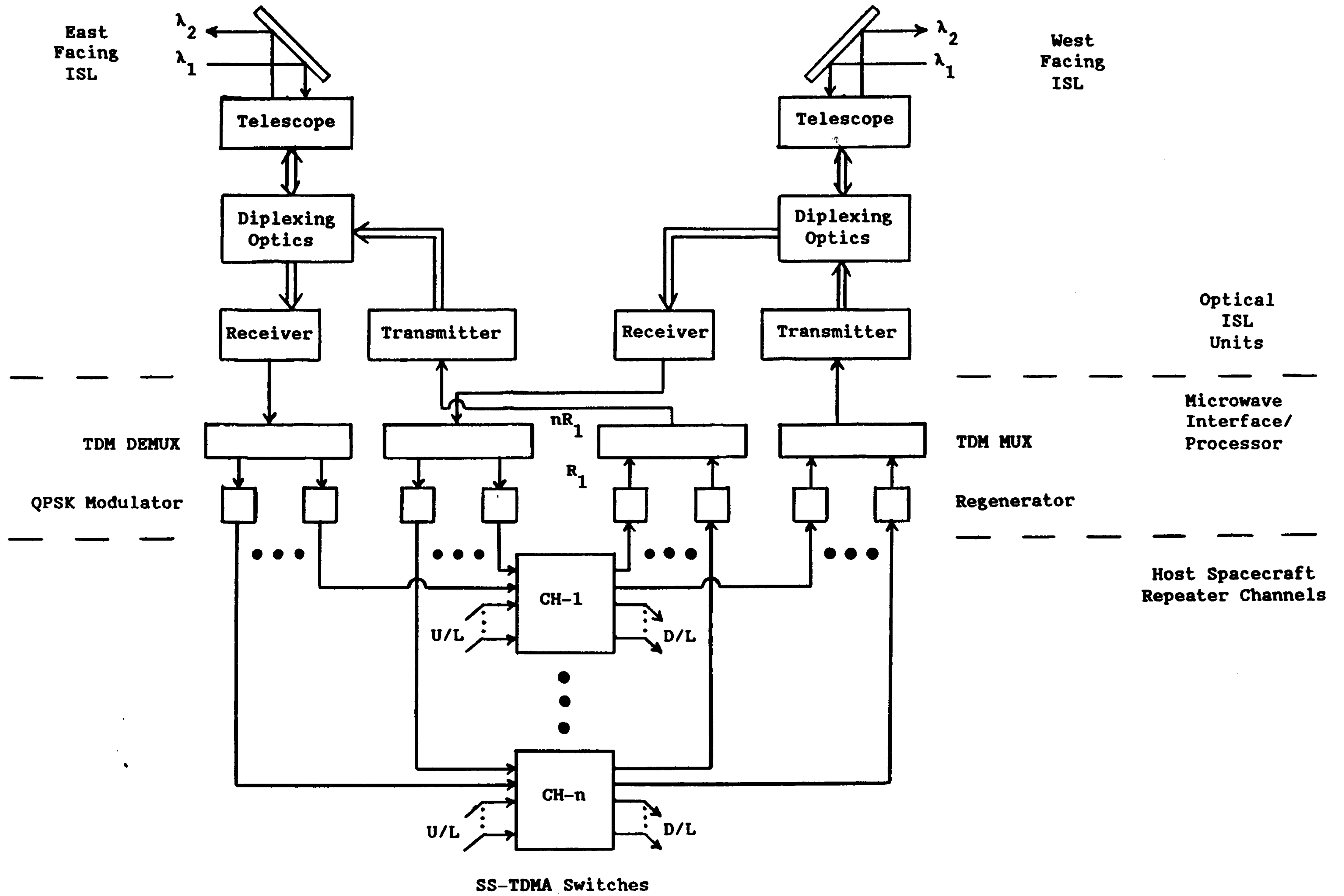


Figure 4-20. ISL Interface to Host Spacecraft

c. TDM multiplexers to provide specified transmission rate signals to the ISL transmitter.

d. TDM demultiplexers to demultiplex the incoming ISL high rate data signal into multiple lower rate data channels.

e. QPSK modulators to provide modulated carriers that are compatible with the host spacecraft transmission specifications.

In addition, buffer memories in the baseband data processor need to be incorporated into the interface. The design of the ISL host spacecraft interface subsystem needs detailed consideration for specific network and signal design requirements, which is beyond the scope of this study.

Figure 4-21 shows a conceptual approach of a modularized optical ISL payload assembly. An estimate of the size of a 30-cm aperture ISL payload is about 60 cm x 60 cm x 100 cm in dimension.

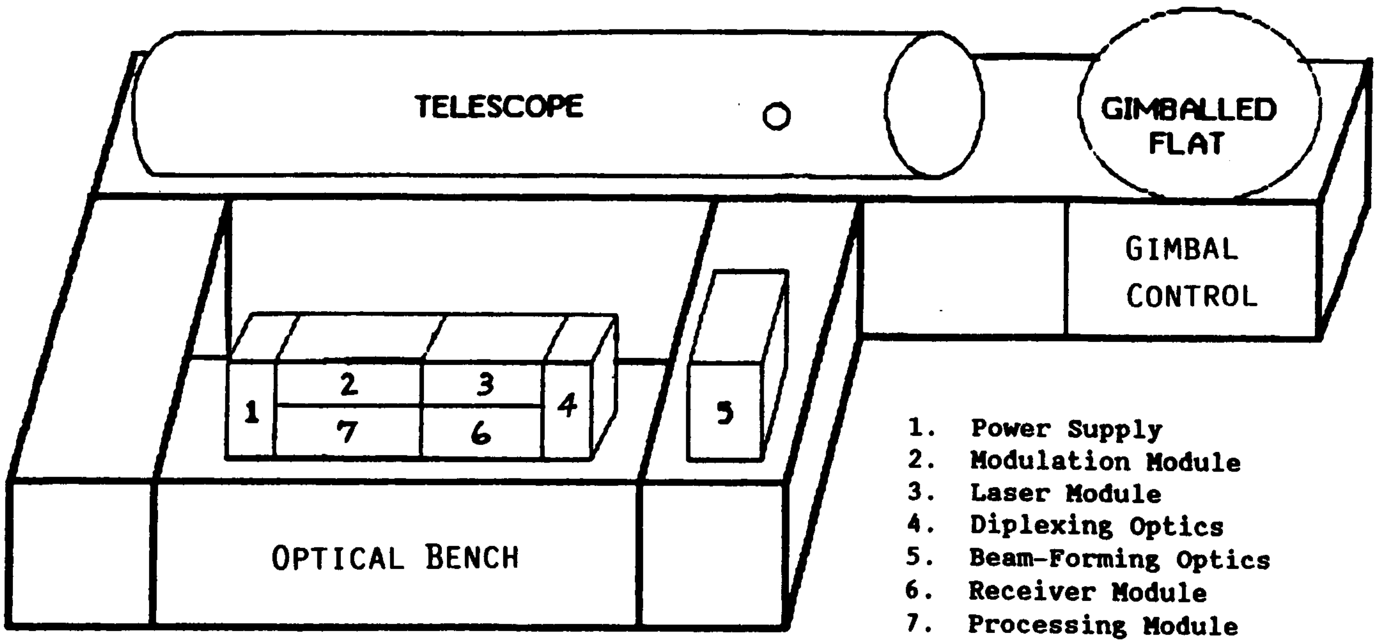
Integration of an ISL payload with a spacecraft requires various system-interface considerations as follows:

- Mass impact on the host spacecraft mass margin budget,
- Power impact on end-of-life and battery power budget,
- Payload thermal control and heat dissipation designs,
- Physical mounting space availability, and
- Antenna deployment and stowage configurations and field-of-view clearance in azimuth and elevation.

Figure 4-22 illustrates microwave ISL payload integration to a conventional host spacecraft for (a) Spinner- and (b) body-stabilized spacecraft. Large 2-m sized microwave

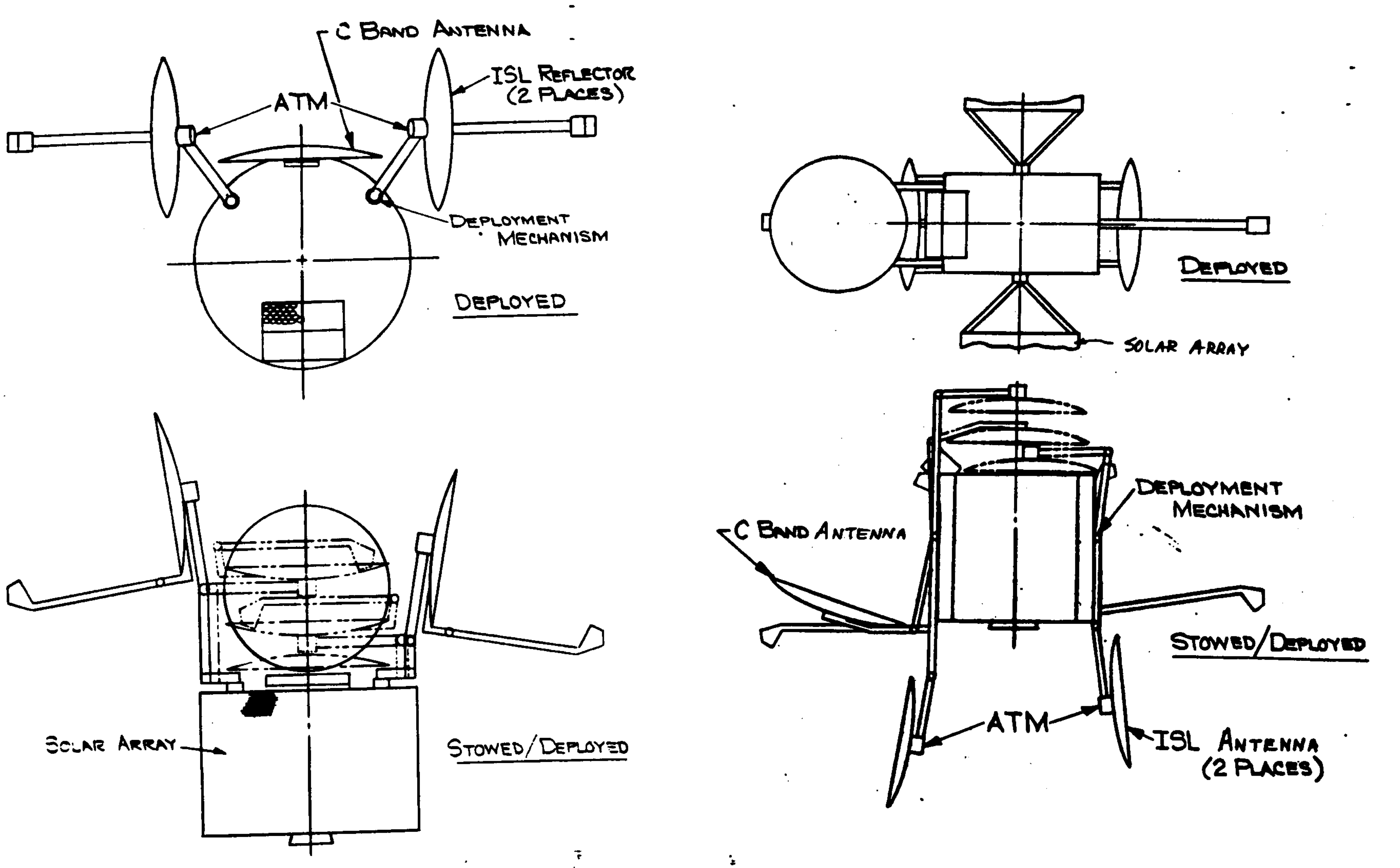
Nominal

±10° Elevation
±70° Azimuth



1. Power Supply
2. Modulation Module
3. Laser Module
4. Diplexing Optics
5. Beam-Forming Optics
6. Receiver Module
7. Processing Module

Figure 4-21. Optical ISL Payload Schematic



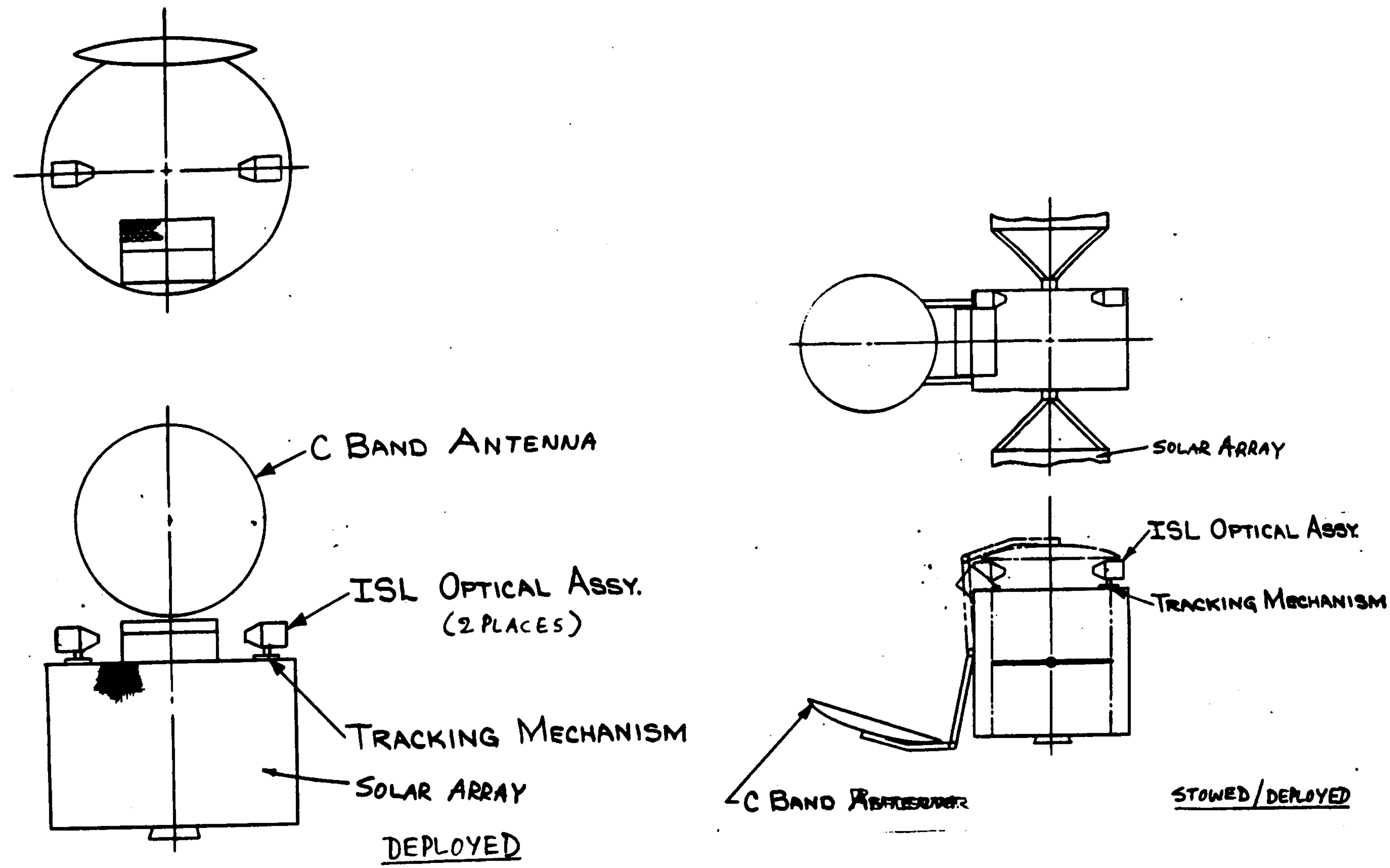
(A) SPINNER

(B) BODY STABILIZED

Figure 4-22. Microwave ISL Integration to Host Spacecraft

ISL antennas provide serious real-estate problems on the host spacecraft.

A rather compact integration is possible with an optical ISL. Figure 4-23 shows the corresponding optical ISL integration to the host spacecraft. The smaller real-estate requirement to the host spacecraft provides a clear advantage for the implementation of an optical ISL.



(A) SPINNER

(B) BODY STABILIZED

Figure 4-23. Optical ISL Integration to Host Spacecraft

5. COST ANALYSIS AND BENEFIT EVALUATION

The payload configuration and network systems architectures derived in Section 4 were used to quantify the cost requirement of ISL vs non-ISL systems. Cost models were developed for microwave (60 GHz) and optical (0.85 μm) ISL payloads. Cost advantages of the selected ISL applications were identified in the cost analysis. ISL applications to CONUS services could provide the largest systems cost benefit in future commercial satellite communications.

5.1 SYSTEM COST ANALYSIS

5.1.1 APPROACH

The comparative cost evaluation between ISL and corresponding non-ISL systems was made from the analysis of relevant "add-on" systems costs. Table 5-1 shows the major cost factors of the space segment and ground segment.

The ISL payload and its launch costs constitute the "add-on" systems cost of the ISL. As for the corresponding non-ISL system, a double-hopping network requires both additional host spacecraft capacity and relay earth station(s) for the double-hop traffic. The additional space segment charge is called a transponder double charge, because it is associated with the up- and down-link capacity required only by the double-hop traffic interconnectivity. Another equivalent conventional network architecture of some applications (i.e.,

Table 5-1. ISL vs Non-ISL Add-On Systems Cost Factors

Category	ISL System	Non-ISL System	
		Double-Hopping Network	Multiple-Collocated Earth Stations
Space Segment	• ISL payload • Add-on launch cost	• Host spacecraft transponder double charge	
Ground Segment		• Relay earth station installation cost	• Collocated earth stations as many as the spacecraft per major node.

CONUS services) includes multiple colocated earth stations, as many as the number of spacecraft per major node.

Microwave vs optical ISL payload costs, including both nonrecurring design and engineering costs and recurring costs, were computed for each application.* The development of cost models is described in Subsection 5.1.2. The ISL payload terminal cost estimate of each application is contained in Subsection 5.1.3.

The add-on space segment cost of a double-hop network was estimated from the "figure of merit" of the host spacecraft. The figure of merit was defined as the statistical cost per 36-MHz equivalent transponder per year. A number of advanced commercial satellite programs, currently existing and planned, were reviewed and used to derive the spacecraft "figure of merit" as a function of the total number of transponders per spacecraft. Subsection 5.1.4 describes the statistical space segment sizing and cost estimate.

The ground segment cost estimate was based on available earth station cost models. The K_a-band earth station cost model was derived from the K_u-band model. Appendix E shows the earth station cost models.

The result of the ISL systems cost analysis is provided in Subsections 5.1.5 and 5.1.5. Subsection 5.2 describes the ISL systems cost-effectiveness and other systems benefits.

*Nonrecurring cost includes all developmental costs which occur only once during the program, such as design, engineering, and space-qualification testing of the prototype model. Recurring cost is the procurement cost of the flight model after the prototype development.

5.1.2 ISL PAYLOAD COST MODELS

Cost models were developed to estimate ISL payload per terminal costs for optical and microwave technology implementations. The cost model flow diagram common to both technologies is shown in Figure 5-1.

The model employs statistical techniques to calculate the model sizing, cost drivers, and the subsystem cost estimates. The statistical algorithms were developed from data bases assembled as part of this effort, but much of it was obtained from relevant in-house data bases assembled for the COMSAT spacecraft cost model. The model operates based on cost-estimating relationships (CERs) which were developed using normalized costs as the dependent variable in a multiregression analysis with candidate cost drivers as independent variables. Typically, the cost drivers are payload characteristics, such as the aperture diameter or area, mass and power quantities. The model provides the nonrecurring and recurring cost estimations for the following subsystems:

- Antenna,
- Repeater,
- Bus or Support Subsystems,
- Management/Engineering Functions.

The input and output parameters of the ISL cost models are shown in Figure 5-2. The input parameters are determined for each application from the payload configurations described in Subsection 4.3.

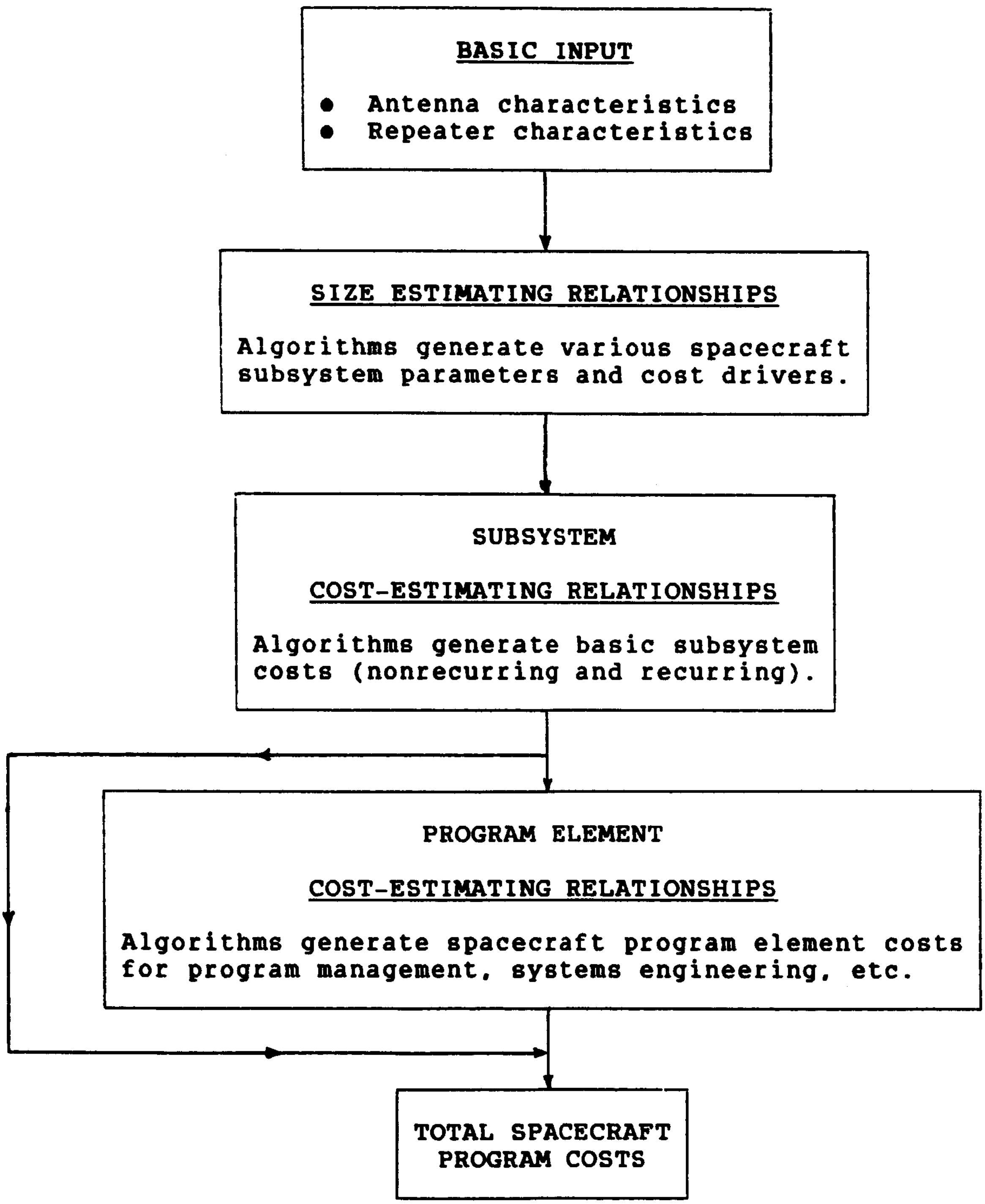


Figure 5-1. The Overall Cost Model Flow Diagram

Optical

Input Parameters

- Aperture Diameter
- Optical Power
- Data Rate
- Diode Efficiency

Subsystem Sizing

- Mass and Power Estimate
- Optical PAT Assy.
- Repeater
- Thermal Cont.
- Total Mass/Power

Cost Estimate of Subsystems
(Recurring and Nonrecurring)

- Optical Assy.
- Repeater
- Thermal Cont.
- Management and Engineering
- Total

Microwave

Input Parameters

- Reflector Aperature Area
- Number of Feeds/Coverages
- Mass of Power Amplifier
- Power of Power Amplifier

Subsystem Sizing

- Mass and Power Estimate
- Antenna
- Repeater/EPC
- Total Mass/Power

Cost Estimate of Subsystems
(Recurring and Nonrecurring)

- Antenna
- Repeater including EPC
- Management and Engineering
- Total

Figure 5-2. ISL Payload Cost Model: Input and Output Parameters

5.1.2.1 Microwave ISL Payload

The 60-GHz model sizing and cost-estimating programs were developed based on data and algorithms used in the COMSAT Spacecraft Cost Model due to close similarity between the two. The COMSAT Spacecraft Cost Model was developed using data of 10 commercial spacecraft programs. Summary information of those programs is contained in Appendix D.

The 60-GHz tracking antenna subsystem model was based on an INTELSAT development model in the 33-/23-GHz band. The cost calculation was accordingly normalized for (a) complexity in the system design or technology used and (b) technology carry-over factor corresponding to the production year 1992.

The COMSAT Spacecraft Cost Model, which is based on the original SAMSO model, describes the effects of complexity in subsystem design and of technology carry-over (industry-wide learning) through the introduction of a normalization factor; NF, given by

$$NF = (TCF) \times (TCW) + (CDF) \times (CDW) + (OF) \times (OW)$$

where
TCF = Technology carry-over factor,
TCW = Technology carry-over factor weighting,
CDF = Complexity design factor,
CDW = Complexity design factor weighting,
OF = "Other" factor (= 1.0),
OW = "Other" factor weighting.

The factor NF is employed to provide a normalized cost:

$$\text{Normalized Cost (Base Year \$)} = \frac{\text{Raw Cost (Base Year \$)}}{\text{NF}}$$

which, in principle, is thereby adjusted to remove the effects of complexity and technology carry-over. All CERs are constructed to estimate normalized cost. Consequently, all data base costs must be divided by NF before CERs are generated. When CERs are applied in the use of the model, the resulting normalized cost must be multiplied by NF to obtain the estimate of actual cost.

Presently the ISL payload cost models use the same basic normalizing factor equation as the COMSAT cost model; however, the CDF and TCF values have been appropriately adjusted from the data provided in the COMSAT cost model.

The equation form, the complexity design factors, and the technology carry-over factor values used in the ISL payload cost model for the antenna and repeater subsystems are provided below.

TCF Values [1992 Production Year]

Subsystem	Nonrecurring	Recurring
Antenna	0.8185	0.8185
Repeater	0.7867	0.7867

CDF Values for 60 GHz ISL

Subsystem	Nonrecurring	Recurring
Antenna	2.585	2.585
Repeater	2.374	1.800

The normalization factor equation is of the form:

$$NF = 0.35 \times CDF + 0.53 \times TCF + 0.12$$

The above form is obtained from the COMSAT cost model and incidentally happens to be the same for both antenna and repeater subsystems. The NF values thus calculated using the TCF and CDF already stated are:

NF Values

Subsystem	Nonrecurring	Recurring
Antenna	1.459	1.459
Repeater	1.368	1.167

Table 5-2 lists a summary of the 60-GHz ISL cost model. The basic parameters are identified from the mass and power estimating equations in Table 4-8. The nonrecurring and recurring costs are all in millions of dollars for the year 1986.

The program management cost estimate includes management and engineering costs. The cost factors were derived as the average value of the ratios between management/engineering cost and payload cost of the 10 commercial spacecraft programs.

5.1.2.2 Optical ISL Payload

The optical ISL payload cost model estimates the cost of a fully gimballed telescope, repeater subsystem, thermal control/structural, and program/engineering management.

The portion of the model algorithm which estimates the telescope subsystem cost was based on data collected through industry contact. The cost data for a fully gimballed,

Table 5-2. 60-GHz ISL Payload Cost Model
(Cost in Millions of Dollars
for the Year 1986)

---

a. Antenna Subsystem

- Nonrecurring Cost (CANR)

$$CANR = 1.6049\ (-1.227 + 0.788\ M_{ANT}^{0.5})$$

- Recurring Cost (CAR)

$$CAR = 1.6049\ (1.708 + 5.333 \times 10^{-5} \times M_{ANT}^{2})$$

b. Repeater Subsystem (including EPC)

- Nonrecurring Cost (CRNR)

$$CRNR = 1.5048\ (0.626\ M_{REPS}^{0.65}),$$

where $M_{REPS} = M_{REP} + M_{EPC}$

- Recurring Cost (CRR)

$$CRR = 1.2837\ (0.012\ M_{REPS}^{1.3})$$

c. ISL Payload Cost

- Nonrecurring Cost (CPNR)

$$CPNR = CANR + CRNR$$

- Recurring Cost (CPR)

$$CPR = CAR + CRR$$

Table 5-2. 60-GHz ISL Payload Cost Model
(Cost in Millions of Dollars
for the Year 1986) (Cont.)

d. Upper Bound of Program Management Cost

- Nonrecurring Cost (PGNR)

$$PGNR = 0.4939\ (CANR + CRNR)$$

- Recurring Cost (PGR)

$$PGR = 0.4884\ (CAR + CRR)$$

space-qualified telescope subsystem, including necessary control electronics assembly, are shown below:

Aperture Size Diameter [cm]	Gimballed Telescope Subsystem Cost [$M, 1986]
30	3.0
20	2.0
5	1.0

The recurring cost of the optical antenna subsystem is then given by the following equation:

$$CAR = 0.847 + 13.06\ D^{1.5}$$

where D = aperture size in meters.

Considering the optical technology development status and possible flight system implementation using the existing design with minor improvement, the nonrecurring cost of the optical antenna subsystem is estimated to be about twice the recurring cost. Reference 27 provides the basis for this estimate, as shown below:

Nonrecurring-to-Recurring Cost Ratio Estimate [27]

Ratio ($ Nonrec./Rec.)	Criteria
1.5-2.0	• Adaptation of an existing design with minor improvement
2.5-2.75	• About 80% of new design involved
3.0	• For a 100% new design within the state-of-the-art technology
>3.5	• New improvement of the state of the art

The cost estimating relationships (CERs) for the repeater and other subsystems were obtained from the COMSAT Spacecraft Cost Model.

Table 5-3 presents the 0.85-µm optical ISL payload cost model. Costs are in millions of 1986 dollars. The basic parameters were identified in the mass/power estimating equations of Table 4-10.

The management/engineering cost factors are the same as for the microwave ISL payload.

The spacecraft bus subsystem cost estimate was attempted also to obtain the nonrecurring and recurring costs as a function of the payload cost which includes antenna subsystem and repeater subsystem costs. A multiplication factor was developed using the data base of 10 commercial spacecraft programs. Based on engineering judgement, the "mean value" of

Table 5-3. Optical (0.85 μm) ISL Payload Cost Model (Cost in Millions of Dollars for the Year 1986)

---

a. Optical Antenna Subsystem

- Recurring Cost (CAR)

$$CAR = 0.847 + 13.06\ D^{1.5}$$

where D is the optical aperture size in meters

- Nonrecurring Cost (CANR)

$$CANR = 2\ CAR$$

b. Repeater Subsystem

- Recurring Cost (CRR)

$$CRNR = 0.0132\ M_{REPS}^{1.3}$$

- Nonrecurring Cost (CRNR)

$$CRNR = 0.6886\ M_{REPS}^{0.65}$$

c. Thermal Control/Structural

- Recurring Cost (CTR)

$$CTR = 0.0187\ M_{T/S}^{0.95}$$

- Nonrecurring Cost (CTNR)

$$CTNR = 0.0034\ M_{T/S}^{1.5}$$

Table 5-3. Optical (0.85 μm) ISL
Payload Cost Model
(Cost in Millions of Dollars
for the Year 1986) (Cont.)

d. Optical ISL Payload Cost

- Recurring Cost (CPLR)

  CPLR = CAR + CRR + CTR

- Nonrecurring Cost (CPLNR)

  CPLNR = CANR + CRNR + CTNR

e. Upper Bound of Program Management Cost

- Recurring Cost (PGR)

  PGR = 0.444 CPLR

- Nonrecurring Cost (PGNR)

  PGNR = 0.449 CPLNR

the factors were derived and included in the following bus subsystem cost-estimating relationship:

Bus Subsystem:

Nonrecurring Cost = 1.725 x (Total Payload Nonrecurring Cost)
Recurring Cost = 1.144 x (Total Payload Recurring Cost)

The above estimate provides an upper bound of bus subsystem costs, because the multiplication factor is derived from the entire spacecraft systems data base. The bus requirement for the integration of an ISL payload varies substantially depending on the host spacecraft characteristics. Therefore, the bus subsystem costs were not included in the ISL payload system cost analysis, due to the large uncertainty involved in the bus subsystem design approach.

5.1.3 ISL PAYLOAD TERMINAL COST ESTIMATE

For each of the selected ISL network architectures and payload configurations described in Subsection 4.3, the ISL payload per terminal costs were estimated with the cost models developed in Subsection 5.1.2. Table 5-4 shows the results for optical vs microwave ISLs. Nonrecurring and recurring cost estimates of each ISL payload terminal are listed in this table.

The cost breakdown of major subsystems for (a) nonrecurring costs and (b) recurring costs is shown in Tables 5-5a and 5-5b for optical and microwave, respectively. Program management costs are also included in Tables 5-5a and 5-5b. The program management costs are about 44.7 percent of the ISL payload terminal costs.

The averaged total cost ratio between optical ISL and microwave ISL of each application from Table 5-4 is 1.075. The optical ISL payload terminal costs about 7.5 percent more than the corresponding microwave ISL payload.

For this reason, the ISL network system cost estimate in the subsequent section are provided mainly with reference to the optical ISLs.

Table 5-4. ISL Payload Terminal Analysis* [Cost in $M, 1986]

No.	Application	Optical ISL			Microwave (60 GHz) ISL		
		Non-Rec.	Rec.	Total	Non-Rec.	Rec.	Total
1a	CONUS	16.519	6.536	23.055	16.815	5.078	21.893
1b	CONUS	17.785	7.137	24.922	17.866	5.511	23.377
1c	CONUS	21.914	9.101	31.015	-	-	-
2a	CONUS - Europe	11.713	4.229	15.942	12.885	3.798	16.683
2b	N.A. - Europe	11.906	4.324	16.230	12.948	3.814	16.762
3a	CONUS - POR	10.473	3.615	14.088	12.651	3.739	16.390
3b	CONUS - AOR	11.191	3.961	15.152	13.261	3.897	17.158
4a	R1 - AOR	13.968	5.349	19.317	13.066	3.845	16.911
4b	R1 - IOR	10.723	3.742	14.465	12.552	3.714	16.266
5a	R1 - R2	19.289	7.993	27.282	13.392	3.933	17.325
5b	R2 - R3	13.978	5.361	19.339	12.678	3.746	16.424
5c	R3 - R1	14.963	5.848	20.811	12.858	3.791	16.649

*Note: Program management costs are given in Tables 5-5a and 5-5b.

Table 5-5a. Subsystem Cost of Optical ISL Payload Terminal

Application No.	Optical Antenna	Repeater	Thermal	Payload Total	Management	Program Total
			(a) Nonrecurring Cost [$M, 1986]			
1a	11.207	5.186	0.126	16.519	7.417	23.936
1b	12.232	5.397	0.156	17.785	7.985	25.770
1c	15.477	6.152	0.286	21.914	9.840	31.754
2a	7.056	4.599	0.057	11.713	5.259	16.972
2b	7.242	4.606	0.058	11.906	5.346	17.252
3a	5.858	4.561	0.054	10.473	4.702	15.175
3b	6.489	4.641	0.062	11.191	5.025	16.216
4a	9.266	4.641	0.062	13.968	6.272	20.240
4b	6.115	4.555	0.053	10.723	4.815	15.538
5a	14.476	4.741	0.072	19.289	8.661	27.950
5b	9.317	4.603	0.058	13.978	6.276	20.254
5c	10.272	4.630	0.060	14.963	6.718	21.681
			(b) Recurring Cost [$M, 1986]			
1a	5.604	0.749	0.184	6.536	2.902	9.438
1b	6.116	0.811	0.210	7.137	3.169	10.306
1c	7.738	1.053	0.309	9.101	4.041	13.142
2a	3.528	0.589	0.112	4.229	1.878	6.106
2b	3.621	0.591	0.113	4.324	1.920	6.244
3a	2.929	0.579	0.107	3.615	1.605	5.220
3b	3.244	0.600	0.117	3.961	1.759	5.720
4a	4.633	0.600	0.117	5.349	2.375	7.724
4b	3.058	0.578	0.106	3.742	1.661	5.403
5a	7.238	0.626	0.129	7.993	3.549	11.542
5b	4.659	0.590	0.112	5.361	2.380	7.741
5c	5.136	0.597	0.116	5.848	2.597	8.445

Table 5-5b. Subsystem Cost of Microwave ISL Payload Terminal

Application No.	Antenna	Repeater	Payload Total	Program Total*
		(a) Nonrecurring Cost [$M, 1986]		
1a	5.470	11.345	16.815	25.120
1b	"	12.396	17.866	26.690
1c	"	17.117	22.587	33.743
2a	"	7.415	12.885	19.249
2b	"	7.479	12.948	19.344
3a	"	7.181	12.651	18.900
3b	"	7.791	13.261	19.810
4a	"	7.596	13.066	19.520
4b	"	7.082	12.552	18.751
5a	"	7.922	13.392	20.001
5b	"	7.208	12.678	18.939
5c	"	7.389	12.858	19.209
		(b) Recurring Cost [$M, 1986]		
1a	2.844	2.234	5.078	7.558
1b	"	2.667	5.511	8.203
1c	"	5.086	7.930	11.803
2a	"	0.954	3.798	5.653
2b	"	0.971	3.814	5.677
3a	"	0.895	3.739	5.565
3b	"	1.054	3.897	5.801
4a	"	1.002	3.845	5.723
4b	"	0.871	3.714	5.528
5a	"	1.089	3.933	5.854
5b	"	0.902	3.746	5.575
5c	"	0.948	3.791	5.643
6a	"	0.805	3.649	5.431

*Including Program Management Total.

5.1.4 HOST SPACECRAFT SIZING

Statistical characteristics of the commercial communications spacecraft were examined to obtain relevant systems design and costing information for the host spacecraft sizing. Existing advanced commercial satellites and NASA-sponsored future geostationary platform payload concepts [28,29] were reviewed. The figure of merit of space segment cost was derived as the on-station cost per equivalent 36-MHz transponder per year.

Figure 5-3 presents the space segment cost per transponder year as a function of the number of 36-MHz equivalent transponders per spacecraft. The figure of merit of each spacecraft includes the payload total and their launch costs. Nonrecurring and recurring costs of the spacecraft were all included in the payload cost data. The cost is given in 1986 millions of dollars. INTELSAT Series IV through VI and two major domestic satellites (i.e., SBS and COMSTAR series spacecraft) were part of the COMSAT spacecraft data base.

The figure of merit of platform payload is based on representative advanced payload concept design:

- Payload Concept PL1:
  - FACC Payload Scenario V for High Capacity CONUS FSS Application [28]
  - Number of Transponders (36-MHz equivalent): 998
  - Figure of Merit: $29,000 per transponder year

- Payload Concept PL2:
  - RCA Payload Concept 2 for FSS under 20 Percent Capacity of 1998 [29]

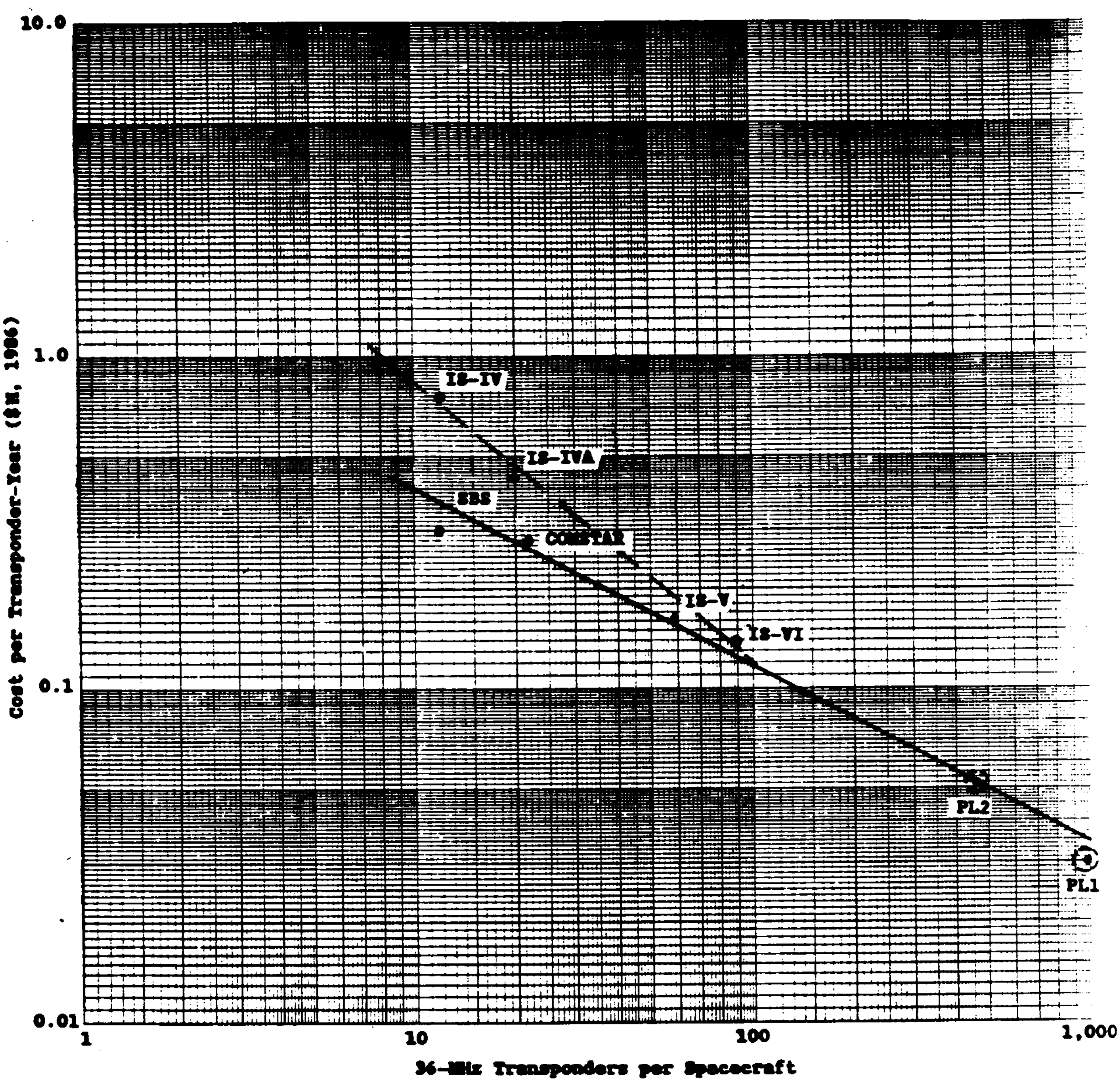


Figure 5-3. Figure of Merit of Space Segment Cost

- Number of Transponders (36-MHz equivalent): 466
- Figure of Merit: $51,000 per transponder year

Table 5-6 shows the two payload designs. The payload design included advanced spacecraft technologies employing a high degree of frequency reuses for multiband (i.e., C-, K_u-, and K_a-band) services. Dual-polarization and spatially isolated multibeams were used extensively in the payload design. Therefore, the platform payload figure-of-merit factors should be representative of the 1990 technology.

Figure 5-3 shows that the space segment cost per 36-MHz equivalent transponder per year is lower as the payload total capacity increases. A platform payload having a 1,000 transponder capacity would provide a low figure-of-merit factor, $30,000 per transponder year.

5.1.5 CONUS ISL SYSTEMS

For CONUS ISL applications, the four time zone coverage satellite systems network was investigated in detail (i.e., Application No. 1). This ISL application has been characterized in Subsection 4.2.1.1.

The CONUS ISL system architecture, shown in Figure 4-4, can be implemented with add-on ISL payloads integrated into the host spacecraft. A host spacecraft per time-zone coverage using a number of spot beams in K_u-band should be able to provide the up- and down-link capacity requirements given in Table 4-1. A complete interconnectivity of traffic within CONUS is provided via ISL in space. The four zone satellites can be interconnected with either a mesh configuration or a string configuration, as shown in Table 4-1.

Table 5-6. Platform Payload Figure of Merit

Item	Payload Concepts	
	PL1[a]	PL2[b]
Payload Mass [kg]	2,261	2,244
Recurring Cost Total [$M]	288	237
Design Lifetime	10	10
Number of 36-MHz Equivalent Transponders	998	466
Cost Per Transponder per Year [$K]	29	51

[a]FACC P/L Scenario V--High Capacity CONUS FSS [28].
[b]RCA/COMSAT P/L Concept 2-FSS, 20% capacity of 1998 [29].

A detailed incremental cost analysis of the CONUS four zone coverage ISL system was conducted for both configurations of ISL interconnectivity. Tables 5-7a and 5-7b show the analysis results of the string configuration and the mesh configuration, respectively. Optical ISLs were taken as representative of the ISL implementation in accordance with discussions in Subsection 5.1.3.

The ISL systems incremental cost includes:

a. Nonrecurring and recurring costs of ISL payload terminals plus associated program management for about 45 percent each of the payload costs.
b. Incremental launch cost, based on $35,000 per kilogram of add-on dry mass.

Table 5-7a. ISL Application 1.
CONUS - 4-Zone Coverage ISL System Incremental Cost [$M]
Optical ISLs - String Configuration

ISL Transmission Rate [Gbit/s]	Number of ISL Payloads*1	ISL Payload Cost*2			Incremental Launch Cost	
		Nonrecurring	Recurring	Total+	Dry Mass++ [Kg]	Launch Cost**
7.6	3	23.936	9.438	52.250	107.6 x 2	7.532
10.3	3	25.770	10.306	56.688	119.1 x 2	8.337
20.5	3	31.754	13.142	71.18	158.5 x 2	11.095
Subtotal				180.118		26.964
System Total					207.082	

*1 Including one spare ISL terminal each.
*2 Payload Cost including Program Management/Engineering Costs.
+ Total = Nonrecurring + 3 x Recurring Costs per unit.
++ Dry mass per ISL payload.
** Based on $35K per Kg of add-on payload dry mass.

Table 5-7b. ISL Application 1.
CONUS - 4-Zone Coverage ISL System Incremental Cost [$M]
Optical ISLs - Mesh Configuration

ISL Transmission Rate [Gbit/s]	Number of ISL Payloads*1	ISL Payload Cost*2			Incremental Launch Cost	
		Nonrecurring	Recurring	Total+	Dry Mass++	Launch Cost**
.792	3	15.111	5.180	30.651	58.3 x 2	4.081
2.808	3	18.968	7.055	40.133	78.6 x 2	5.502
3.996	3	20.488	7.788	43.852	87.0 x 2	6.090
1.512	3	16.816	6.012	34.852	67.0 x 2	4.690
1.980	3	17.694	6.438	37.008	71.7 x 2	4.977
14.544	3	28.633	11.667	63.634	137.5 x 2	9.625
Subtotal				250.130		34.965
System Total					285.095	

*1 Including one spare ISL terminal each.
*2 Payload Cost including Program Management/Engineering Costs.
+ Total = Nonrecurring + 3 x Recurring Costs.
++ Dry mass per ISL payload.
** Based on $35K per Kg of add-on payload dry mass.

The cost analysis is based on the ISL terminal cost estimates in Subsection 5.1.3. The number of ISL payloads include one flight-qualified, on-ground spare terminal each. Some of the parameters were noted in Tables 5-7a and 5-7b.

The string configuration of ISL interconnectivity is actually more cost-effective than the alternative mesh configuration. The CONUS four zone coverage ISL system in the string configuration costs about $207 million. It is approximately 38 percent lower than the cost of the mesh configuration, as a result of trades between PAT subsystems and repeater subsystems of the two configurations. For this reason the string configuration was selected for the CONUS ISL application.

The corresponding non-ISL network systems Architectures I and II, derived in Subsection 4.2.1.2 (Figures 4-5 and 4-6), were analyzed. The following systems add-on costs were quantified:

a. Double-Hopping Systems Network (Architecture I)

- Host spacecraft transponder double charge needed for double hopping,
- Relay earth stations and switching/processing central station on the ground,
- Associated terrestrial facilities such as fiber-optic cable installation.

b. Conventional System with Multiple Colocated Earth Station Antennas per Major Node for Trunk Line Services (Architecture II)

- Four antennas (maximum) per earth station for complete flexibility in traffic interconnectivity with the four zone satellites.
- The number of major nodes treated as a parameter in the range of 17 to 500.

The add-on ground segment cost of the double-hopping systems network is estimated in Table 5-8. K_a-band relay stations with 7-m antennas are included in the cost analysis. The earth station cost model includes antenna, HPA, LNA, modem, multiplex and interface equipment, power subsystem for thin installation and testing (re: Appendix E). In addition, a $0.3 million per year for the relay station operation and maintenance (O&M) cost was included for a period of 12 years.

Assuming about 200-km distance between individual relay station per double-hop beam, a total of $28.8 million is estimated for the fiber-optic installation cost for the central switching/processing station. Twelve thousand dollars per km is assumed for the fiber-optic installation.

The total add-on ground segment cost of non-ISL system Architecture I is, thus, estimated to be $153.6 million, as shown in Table 5-8.

As for conventional systems Architecture II, each of the major ground segment nodes requires three add-on earth station antennas compared with the corresponding ISL systems ground segment. A single torus antenna earth station for a cost of $10.5 million, including a 12-year O&M cost, is selected in the cost estimate instead of individual parabolic antennas, because of its cost-effectiveness.

Table 5-9 lists a sample comparison of the total add-on system costs between ISL and corresponding non-ISL systems networks for CONUS services. Some of the key parameters

Table 5-8. Add-On Ground Segment Cost for CONUS 4-Zone Satellite Double-Hop Network

Parameters	Satellites			
	1	2	3	4
Number of 36-MHz transponders for traffic Interconnectivity	211.6	118.5	525.1	569
Number of double-hop beams (K_a-band for 120 transponders per beam)	2	1	5	5
Double-hop earth station Cost [$M]	12	6	30	30
12-year O&M cost [$M]	7.2	3.6	18	18
Terrestrial fiber-optic installation cost[a] for central switching station	28.8			
Total cost [$M]	153.6			

[a]$12K per km is assumed for this estimate.

Table 5-9. CONUS ISL vs Non-ISL Systems
Add-On System Cost Comparison
Cost in 1986 Dollars [$M]

Item	ISL System (Application No. 1)	Non-ISL System: Architecture 1	Non-ISL System: Architecture II
Space Segment:			
• ISL Payload/Program	180.118	-	-
• Incremental Launch Cost	26.964	-	-
• Transponder (Host Spacecraft) Double Charge	-	1,914.124	-
Ground Segment:			
• Double-Hop Relay Stations	-	153.6	-
• Earth Stations	-	-	304.5 (a) to 5,250(b)
System Total	207.1	2,067.7	304.5 to 5,250
Remarks	• Design lifetime at 12 years	• Total number of double-hop transmission capacity $\simeq$ 1,424 transponders • 36-MHz transponder cost at $.112M • For a period of 12 years • Cost per Ka-band relay earth station at $6M plus $3.6M for O&M over 12 years.	• (a): For 29 major nodes (b): For 500 major nodes • Cost of add-on antennas per earth station at $10.5M including a 10% O&M expenses for 12 years

used in the cost estimate are noted also in Table 5-9. The transponder double charge under non-ISL system Architecture I is based on a $0.112 million per 36-MHz equivalent transponder per year (nominal).

A comparison of the total system cost in Table 5-9 shows that the ISL system for CONUS is more cost-effective than the corresponding non-ISL systems. Major cost driving parameters in Table 5-9 were treated further in a parametric form in Figures 5-4 and 5-5.

Figure 5-4 presents the total add-on systems cost of non-ISL network Architecture I (double hop) as a function of the cost per 36-MHz transponder year. The corresponding ISL systems cost ($207.1 million) is shown for comparison. The limiting case of systems cost dependence on estimated parameter tolerances is indicated for:

a. $\pm$50-percent tolerance from the nominal cost of the double-hop ground segment given in Table 5-8, and
b. $\pm$25-percent tolerance from the nominal ISL space segment cost estimate (Table 5-7a).

As the most conservative estimate corresponding to a lower relay earth station cost by 50 percent and a higher ISL system cost by 25 percent than the nominal, the cost break-even point is about $0.02 million per 36-MHz transponder per year in the double-hop system. Therefore, the ISL application for CONUS is more cost-effective than the double-hop system if the figure of merit of the host spacecraft exceeds about $0.01 million (nominal) to $0.02 million (worst case).

Currently, a U.S. domestic 36-MHz equivalent transponder (on-station) cost is approximately $0.2 million per year (launch plus satellite costs). This indicates that the ISL

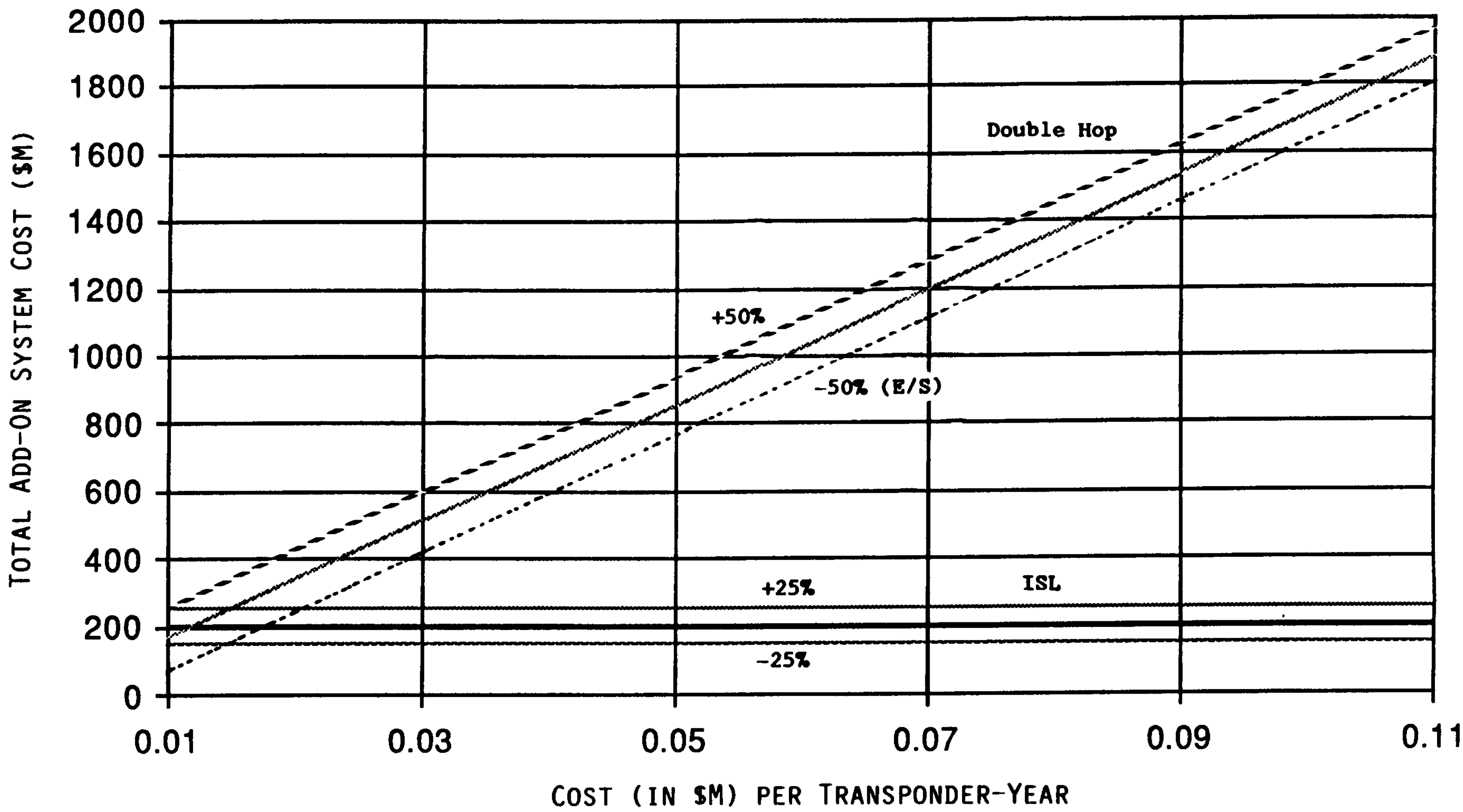


Figure 5-4. ISL vs Double-Hop Systems Incremental Cost [$M, 1986]

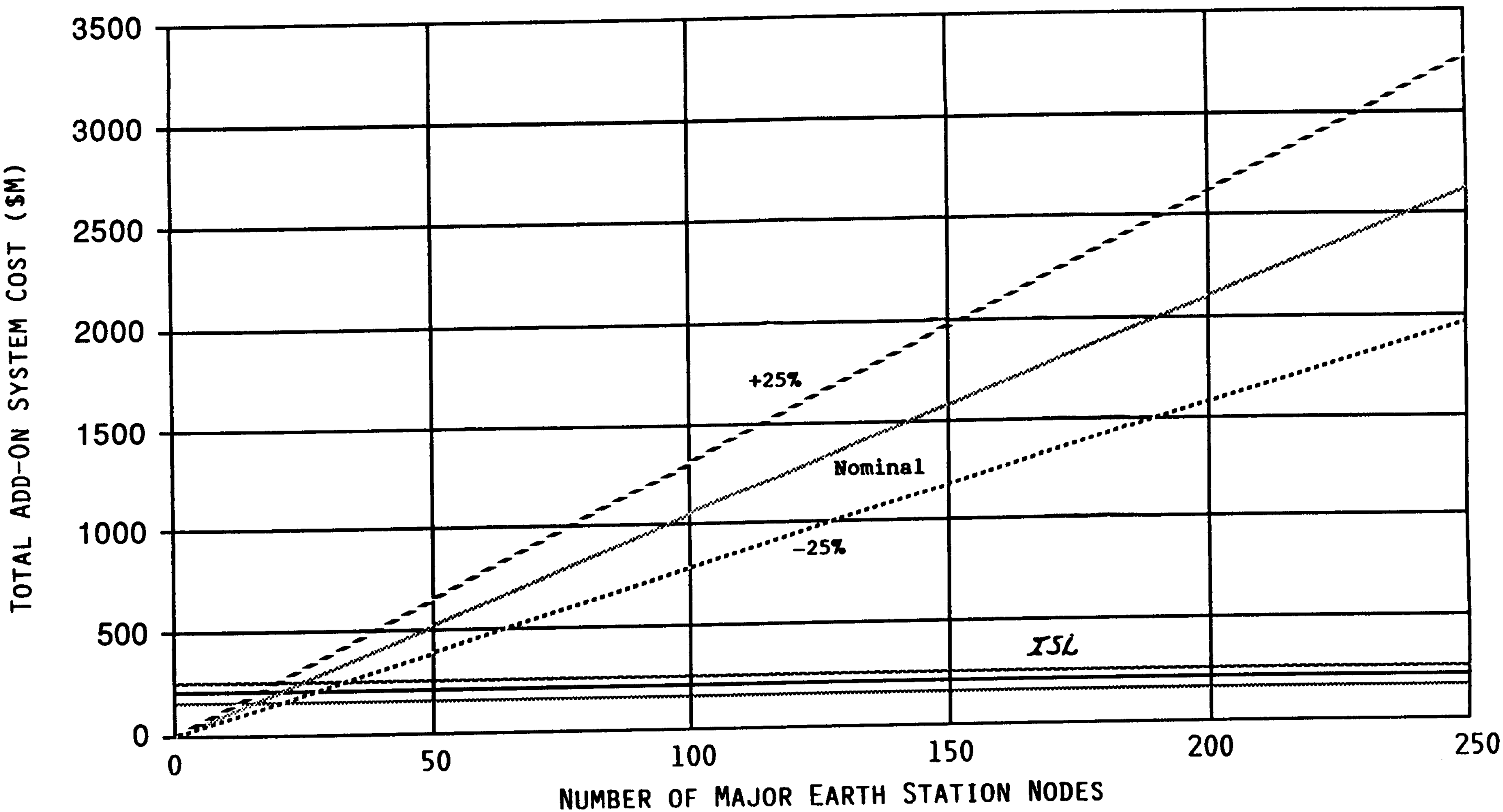


Figure 5-5. ISL vs Conventional Multiple Earth Station Antenna Systems Incremental Cost [$M, 1986]

system is more cost-effective than the non-ISL system unless the space segment cost is reduced to about 1/20 of current cost.

Figure 5-5 plots the total add-on system costs of ISL vs conventional non-ISL systems (Architecture II). Tolerances up to ±25 percent were considered from the nominal cost estimates for ISL as well as non-ISL systems. The cost break-even point ranges from 13 to 27 (i.e., 20 ± 7) major nodes.

Assuming one major ground segment node per 400 miles in diameter circular area, which requires complete traffic interconnectivity for all four CONUS satellites, the total CONUS area (3,615,122 square miles) can be covered with 29 major earth stations as a minimum. In addition, less-than-full connectivity to two or three CONUS satellites may be needed for some other earth stations. The population of transmit and receive carrier (licensed) earth stations is currently exceeding 550 within the U.S. Therefore, it is obvious that the ISL application for CONUS FSS services is more cost-effective than the corresponding non-ISL domestic satellite systems approach.

5.1.6 OTHER ISL SYSTEMS

ISL vs corresponding non-ISL systems total add-on costs were computed each for selected ISL Applications No. 2 through No. 5. Table 5-10 shows the cost estimates.

The space segment cost is based on

- ISL payload terminal costs, nonrecurring and recurring costs of PAT, repeater, thermal/structural, and program management costs given in Table 5-4 (Section 5.1.3),
- 12 years' on-station lifetime of the spacecraft for all applications, and

Table 5-10. ISL vs Non-ISL Systems Cost Estimate (All Costs in $M for Year 1986)

No.	ISL Application	ISL System Space Segment--ISL Payload Cost				Non-ISL System Double-Hop Relay Network Systems Add-On Cost				
		Non-Recurring	Recurring	No. of P/L	Total	No. of Tran-sponders	Relay Earth Stations	Transponder Double Charge*	Relay Station Cost**	Total
2a	CONUS-Europe	16.972	6.106	2	29.184	17.2	15-m/C-band and 8-m/K_u-band	23.117	22.969	46.086
2b	N. America-Europe	17.252	6.244	2	29.740	18.9	15-m/C-band and 8-m/K_u-band	25.402	22.969	48.371
3a	CONUS-POR	15.175	5.220	2	25.615	8.8	15-m/C-band	11.828	13.369	25.197
3b	CONUS-AOR	16.216	5.720	2	27.656	33.9	15-m/C-band and 8-m/K_u-band	45.562	22.969	68.531
4a	Region 1-AOR	20.240	7.724	2	35.688	23.6	15-m/C-band and 8-m/K_u-band	31.719	22.969	54.688
4b	Region 1-IOR	15.538	5.403	2	26.344	5.5	15-m/C-band	7.392	13.369	20.761
5a	Region 1-2	27.950	11.542	2	51.034	39.5	15-m/C-band and 8-m/K_u-band	53.088	22.969	76.057
5b	Region 2-3	20.254	7.741	2	35.736	10.0	15-m/C-band	13.440	13.369	26.809
5c	Region 3-1	21.681	8.445	2	38.571	16.0	15-m/C-band	21.504	13.369	34.873

*$0.112 million per 36-MHz equivalent transponder year for 12 years of spacecraft lifetime.

**Including E/S installation and O&M costs (10%) for 12 years.

- A constant figure of merit of the spacecraft at $0.112 million per 36-MHz equivalent transponder per year.

The earth station cost, including new installation and O&M for 12 years is estimated from:

- A C-band relay earth station with two 15-m class antennas for $13.369 million, and
- A K_u-band station with two 8-m class antennas for $9.6 million.

The non-ISL system, each for Applications No. 2a through No. 5c, corresponds to a conventional double-hop network. Figure 5-6 illustrates a simplified comparison of ISL vs the corresponding non-ISL system for these applications.

Application No. 2a or 2b (i.e, CONUS-to-Europe or North America-to-Europe services) requires ISLs for traffic connectivity between CONUS or North America and European regional satellites. The corresponding non-ISL network for double hopping can be derived with relay earth stations located in an overlapping coverage area of the two satellites. However, the two separate regional satellites may not provide any overlapping coverage. Figure 5-7 illustrates this case: An international AOR satellite is used, as an evolutionary configuration, for double hopping in the conventional non-ISL network. The previous non-ISL satellite constellations for Applications No. 2 and No. 5 in Figure 4-8 (Subsection 4.2.2) showed this evolutionary network including international satellites. Additional terrestrial link would be needed in the non-ISL network to avoid a triple-hop transmission. Triple hopping is more expensive due to doubled add-on costs, and excessive transmission time delay in triple hopping makes it

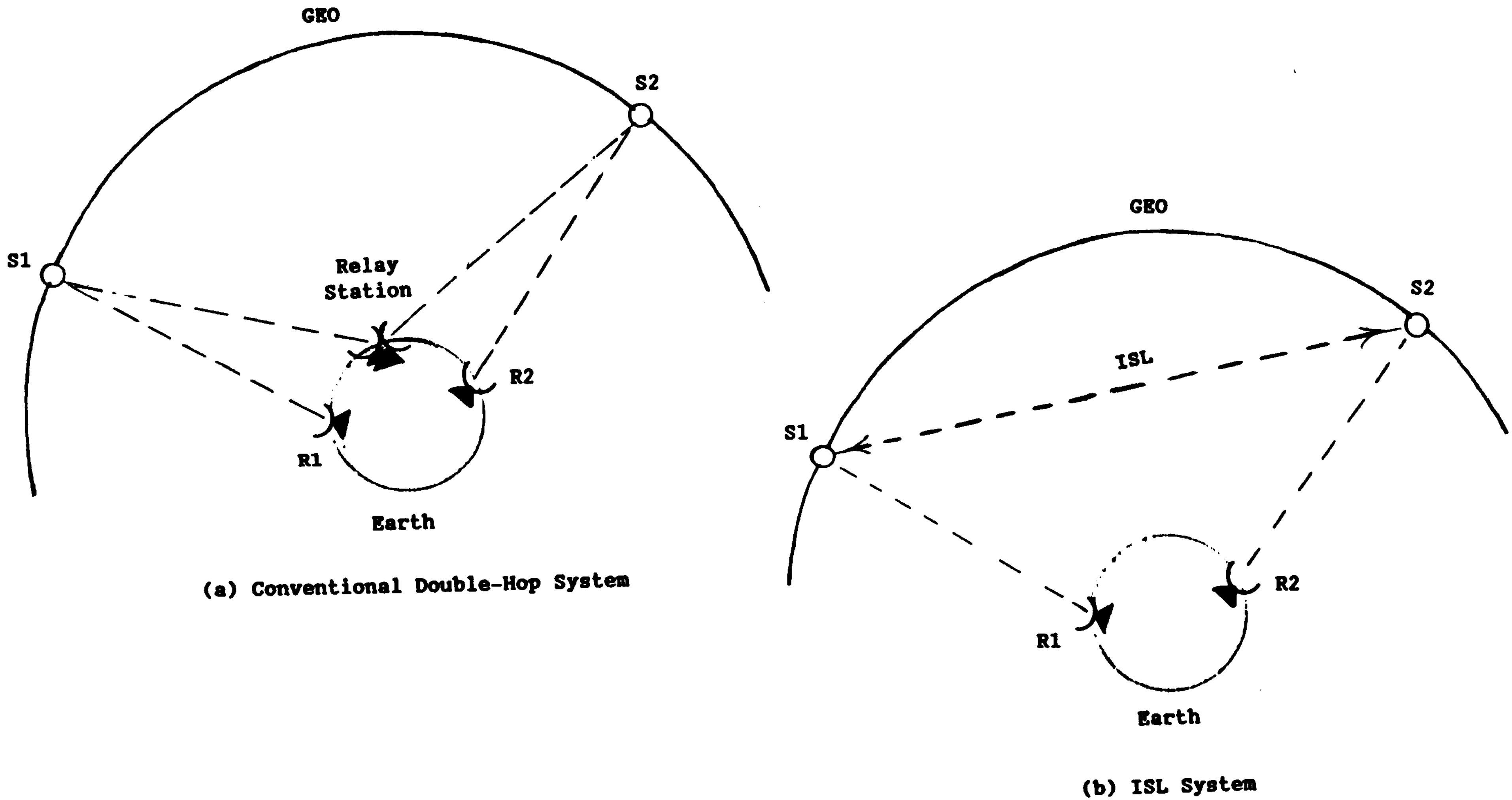


Figure 5-6. Connectivity Between Earth Stations Located in Two Disjoint Service Areas

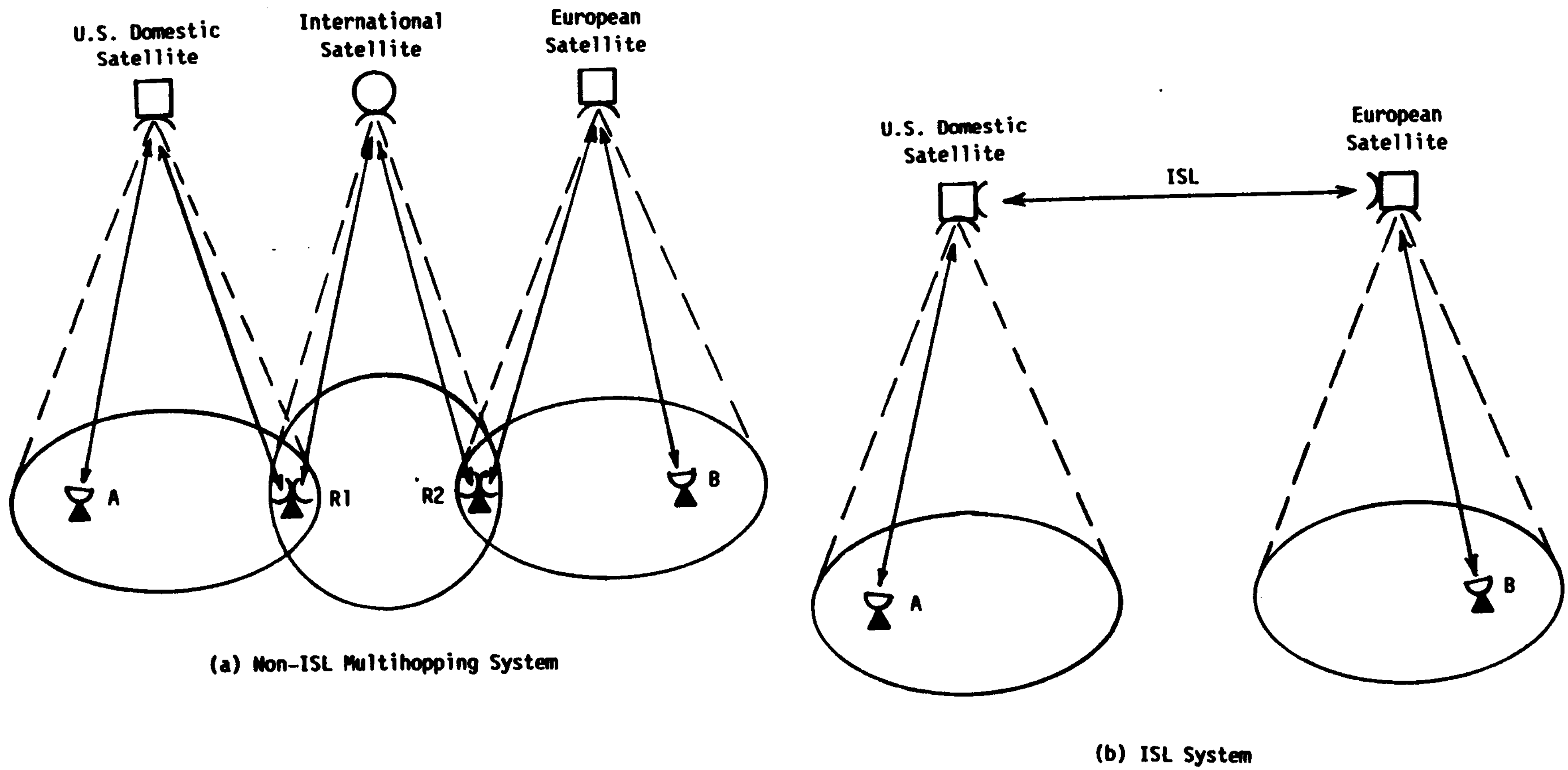


Figure 5-7. Connectivity Between Domestic and Regional Satellites

unacceptable for voice traffic (re: Subsection 2.3.1). However, terrestrial link facility was not included in the cost analysis. The result of the cost estimate is thus considered to provide a lower bound of the ISL system cost advantage over the corresponding non-ISL system.

As for Application No. 6 on intercluster ($\leq 0.1°$) ISLs, a cost analysis is provided in Table 5-11. A sample ISL application was considered for interconnecting five colocated satellites, providing a total of 8-Gbit/s ISL capacity. A star network connectivity of ISLs with a 2-Gbit/s capacity per ISL payload terminal was evaluated in the cost analysis.

A 60-GHz ISL implementation is more favorable due to its technological maturity than an optical implementation approach for the intercluster ($\leq 0.1°$) ISLs. The total cost for eight 2-Gbit/s ISL payload terminals of the 60-GHz intercluster ISLs is $68.6 million.

The corresponding non-ISL systems were derived in two categories:

a. A single large "super" satellite which is capable of complete on-board traffic inteconnectivity.
b. The same number of colocated ($\leq 0.1°$) smaller satellites (five satellites in this case) without ISLs.

The colocated cluster of satellites, with or without the ISL, functions as a single large satellite in the assigned orbital slot. When the single "super" satellite is not feasible mainly due to launch vehicle limitation, colocated multiple smaller satellites provide a possible alternative to it. Each satellite performs a part of the "super" satellite mission. Functional divisions of individual satellites are possible through:

Table 5-11 60-GHz Intercluster ($\leq 0.1°$) ISL Cost

5 Colocated Satellites with ISLs (0.1° Max.)	
ISL Capacity 2-Gbit/s per Terminal	
ISL Terminal:	
Mass [kg]	37.6
Nonrecurring Cost [$M]	15.008
Recurring Cost [$M]	5.387
Number of ISL Terminals	8
Total Program Cost [$M] for 8 Terminals	58.104
Incremental Launch Cost [$M]	10.528
Add-On Cost Total [$M]	68.632
Cost Advantage	None

- Frequency band division, and/or
- Time division (for TDMA system).

Colocated satellites without ISLs could be used if the need for a functionally equivalent super satellite space segment is to be met in the near-term requirement. The ultimate solution to it is the implementation of a single super satellite, minimizing the spacecraft housekeeping functions and multiple launch costs. Then the add-on ISL payload costs can be avoided. Further discussion is included in Subsection 5.2.2.

5.2 ISL SYSTEMS BENEFIT

ISL systems benefits are very significant and wide ranging in the overall systems aspects of commercial satellite communications. Quantifiable benefits are the ISL cost advantage over the corresponding non-ISL systems of the selected applications.

The following ISL systems figure-of-merit factors could provide substantially improved or new services in the FSS:

- Orbital arc expansion capability,
- Space segment bandwidth utilization improvement,
- Transmission delay reduction,
- Number of earth station antenna reduction.

The improved or new services potential is semiquantifiable with the ISL systems figure-of-merit factors.

Systems operational and planning/regulatory aspects of ISLs were not quantified at this time. However, qualitative discussions are included in this section.

5.2.1 COST-EFFECTIVENESS

A measure of ISL systems cost-effectiveness is defined as the ratio of the add-on systems cost of the corresponding non-ISL system to that of the ISL system. A summary of the add-on systems cost is given in Table 5-12. The non-ISL to ISL systems cost ratio is also shown in the last column of the table.

A graphical presentation of the cost ratio for each ISL application is provided in Figure 5-8. The CONUS ISL application was compared with the corresponding non-ISL Architecture I (double hopping) and Architecture II (multiple colocated earth station antennas). Applications I and II in Figure 5-8 denote the CONUS ISL Application (No. 1) compared to non-ISL systems Architectures I and II, respectively.

Table 5-12. Total System Incremental Cost Comparison
(Cost in $M, 1986)

No.	ISL Applications	ISL System	Non-ISL System[a]	Non-ISL/ISL Cost Ratio
1	CONUS - 4 Zone Coverage	207.1	2,067.6 (Architecture I) 304.5-5,250 (Architecture II) 29-500 E/S	10 1.5 to 25
2a	CONUS - Europe	29.2	46.10	1.6
2b	N. America - Europe	29.8	48.371	1.7
3a	CONUS - POR	25.615	25.20	≃ 1
3b	CONUS - AOR	27.656	68.531	2.5
4a	Region 1 - AOR	35.688	54.688	1.6
4b	Region 1 - IOR	26.344	20.761	0.8
5a	Region 1 - Region 2	51.034	76.057	1.5
5b	Region 2 - Region 3	35.736	26.809	0.7
5c	Region 3 - Region 1	38.571	34.873	0.9

[a]Space segment cost at $0.112 million per 36-MHz transponder per year for 12 years.

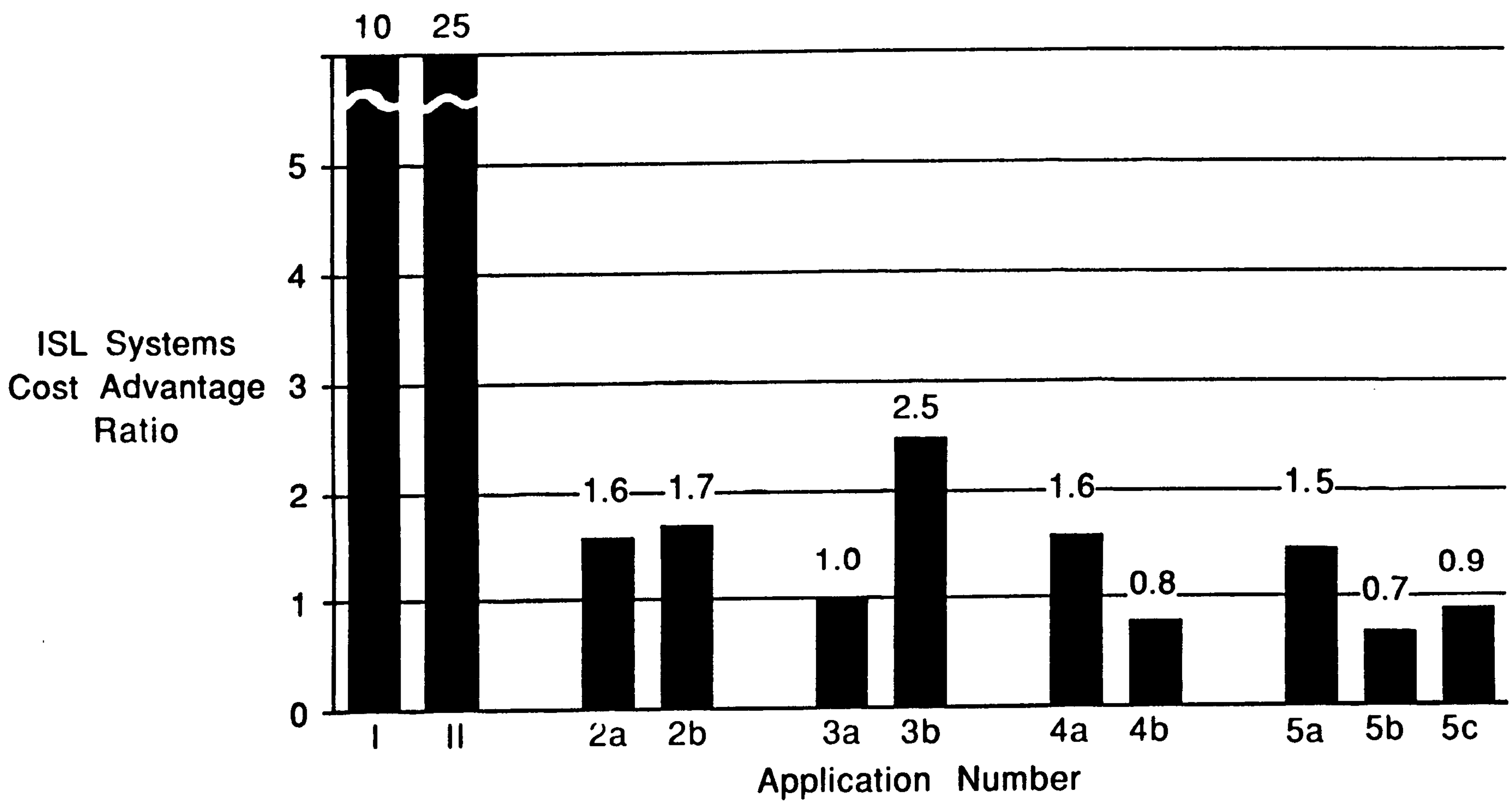


Figure 5-8. ISL Systems Incremental Cost Advantage Ratio with Respect to Non-ISL Systems

The ISL cost advantage over the corresponding non-ISL system is identified by the cost ratio when it exceeds unity (1). Most of the selected applications provide a systems cost advantage. The ISL application for CONUS shows the largest potential of a systems cost advantage. Marginal cases are the ISL applications for ITU Region 1-IOR international (Application No. 4b), Region 2-Region 3 (Application No. 5b), and Region 3-Region 1 (Application No. 5c).

Cost-effective ISL applications are:

- U.S. Domestic (CONUS),
- CONUS-Europe,
- North America-Europe,
- CONUS-AOR,
- CONUS-POR,
- Region 1-AOR,
- Region 1-Region 2.

Figure 5-9 shows the ISL cost advantage ratio as a function of capacity requirement for 30° to 70° ISLs. The range of cost-effective ISLs, in a statistical sense, is indicated by a shaded area in Figure 5-9. It shows that the ISL is cost-effective when ISL traffic is large. The break-even point is in the range from 300 Mbit/s to 360 Mbit/s. It corresponds to 8.4 to 10 36-MHz equivalent ISL transponders, assuming an 8-kbit/s per half-voice circuit and 4,500 half-voice circuits per transponder technology.

The three ITU Regional Application (110-125° ISLs) appears to have a break-even point at about 700 Mbit/s. However, if the full systems improvement or new services potential that fully matured ISLs could provide is taken into account, the break-even point could be shown to be low.

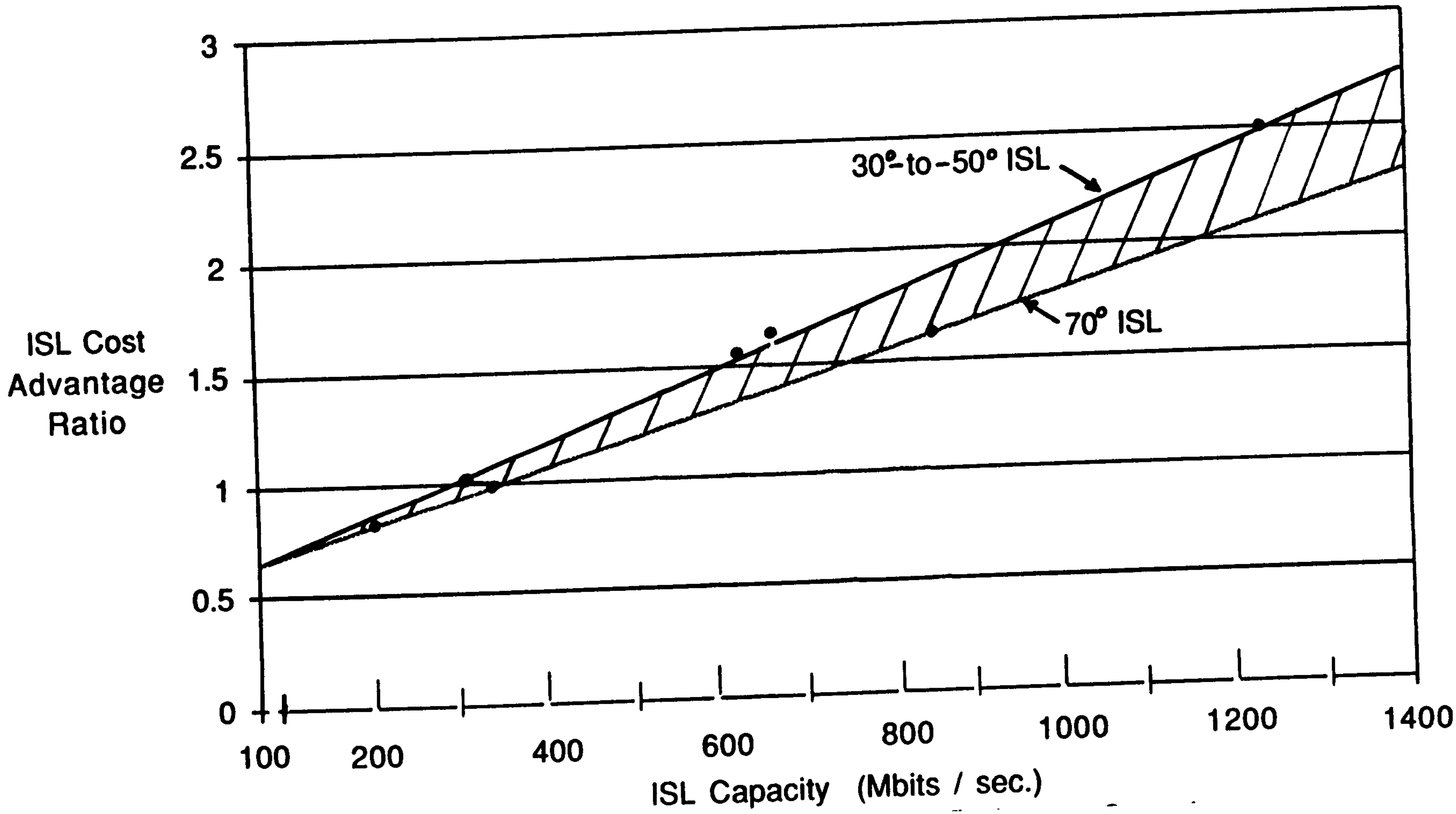


Figure 5-9. ISL Cost Advantage Ratio vs Capacity Requirements

In addition to the quantified cost-effectiveness, ISL systems provide other potential advantages. The subsequent subsection highlights some of the qualitative systems advantages of ISLs for future commercial satellite communications.

5.2.2 OTHER SYSTEMS BENEFITS

ISL applications provide the following systems planning and operational benefits:

- To achieve improved utilization of orbit and spectrum resources for FSS communications,
- To improve and expand the existing commercial satellite communications services, and
- To evolve eventually to new, mature integrated services satellite networks based on domestic and regional satellites.

As discussed in Section 2, efficient utilization of orbit/spectrum resources is possible with ISL applications due to the fundamental systems characteristics of ISLs:

- The expansion capability of useful orbital arc,
- An effective conservation of the FSS spectral bandwidth by avoiding multiple hopping wherever possible, and
- Improved service offerings with an increased number of K_a-band satellites as needed.

The orbital arc expansion capability of ISL applications is most significant for K_a-band satellites. For

CONUS ISL applications the useful arc length centered around 100°W is expanded from 5° (for non-ISL satellites) to

94° for CONUS 4-zone satellites,
59° for CONUS 2-half (East/West) coverage satellites.

The orbital slot allocation problem for prime service regions, such as CONUS, Europe, and other congested regions, can be alleviated with the introduction of ISLs. Subsection 2.4.2 described the formulation of figure-of-merit factors that can be used to quantify those ISL characteristics.

FSS services of the existing systems can be improved and expanded with ISL applications. The ISL systems characteristics that can be utilized for the supporting role of the existing systems are:

- Coverage extension,
- Propagation time delay reduction,
- Improved orbit/spectrum utilization,
- Reduced number of earth station antennas,
- Improved transmission quality, and
- Continued service cost reduction.

The extension of coverage allows more users direct access to the satellite network, and improved quality services for various traffic (voice traffic, in particular) can be provided as the benefits of time delay reduction and the elimination of excess atmospheric transmission loss that could be encountered in multiple-hopping transmission. As a result, ISL applications will increase the effectiveness of satellite communications, providing more cost-competitive services.

A large space segment approach provides N-fold orbital arc utilization and a higher degree of frequency reuses with a large number of smaller spot beams. Also large cost advantages are expected due to the high ratio of payload to spacecraft housekeeping requirements.

ISLs interconnecting colocated ($\leq$ 0.1°) satellites can be used to provide a functionally equivalent large satellite. Each satellite functions as part of the large spacecraft through frequency band divisions or time divisions (i.e., portions). Actually, colocated partitioned satellites without ISLs also provide a functionally equivalent large satellite to earth stations within the coverage, provided that adequate stationkeeping can be maintained.

A comparison of intercluster ISL satellites, colocated satellites without ISLs, and a single large platform payload concept is shown on the following page. Intercluster ISLs ($\leq$ 0.1°) do not provide any significant advantage over the partitioned small satellites.

Looking far ahead into the future, completely new satellite systems can be evolved with full utilization of the ISL systems as follows:

- Coverage of world land masses increased by about 15 percent for K_a-band services employing domestic and regional satellites,
- Integrated space segment for domestic, regional, and global services, and
- Global satellite coverage for integrated services digital networks (ISDN).

Parameters	Intercluster ISLs	Colocated Satellites	Single Large Platform Payload
• Satellite traffic cross-strapping	ISL	Ground station	On-board switching network
• TT&C and stationkeeping	Complex	Difficult	Simple
• Technology involved	ISL payload	Existing bus and S/C technology	New platform payload
• Launch vehicle limitation	None	None	Yes (space assembly may be needed)
• Introduction	Phased time introduction	Phased time introduction	Future space segment
• Initial investment	Moderate	Small	Large
• Growth flexibility	Only planned buildup possible	Gradual buildup	No flexibility
• Cost benefit	Small	Small	Large
• Application	Mid-term	Near-term	Year 2000

ISL cross-linking regional/domestic satellites will provide new global satellite network architectures. The existing three ocean region INTELSAT system for global coverage could be replaced by three ITU regional satellite systems employing ISLs.

The development of ISL network implementation scenarios is described in Section 6.

6. IMPLEMENTATION SCENARIOS AND TECHNOLOGY ISSUES

Implementation scenarios of the ISL were developed for the following time frame:

- First launch in 1993-94.
- Widespread use of ISLs in 2000.

As a parallel effort in Task 3, the availability status of space hardware technology was assessed to support the implementation scenarios. Critical ISL subsystem technologies that need further development effort were identified, and technology development programs including schedule and cost/risk estimates were derived in the study.

6.1 DEVELOPMENT IMPLEMENTATION SCENARIOS

This section describes ISL implementation scenarios in two categories:

a. Technology implementation for the first flight taking place in the 1993-94 time frame.
b. Network system implementation for the applications selected in Tasks 1 and 2.

6.1.1 TECHNOLOGY IMPLEMENTATION SCENARIOS

The ISL systems cost analysis in Section 5 showed that an ISL between two isolated satellites is more cost-effective than the corresponding non-ISL network when the ISL capacity is large, exceeding 300 Mbit/s. The largest cost advantage of ISLs can be derived from the CONUS ISL applications if fully implemented. For this this reason, the CONUS ISL application was identified as the technology driver.

6.1.1.1 Critical ISL Technology

A baseline ISL payload for the CONUS applications can be defined for the following design requirements:

- Transmission capacity: 8-Gbit/s nominal.
- Pointing, acquisition, and tracking performance for a 1.7-μ radian beamwidth, corresponding to a diffraction-limited optical system with 0.85-μm diode lasers: 0.2-μ radian fine tracking accuracy at one standard deviation (1 σ_{rms}).
- Space-qualified system level performance.
- Technology readiness by the end of 1990 for the first launch in 1993-94.

This baseline ISL design requirement was evaluated to identify critical ISL technologies for both the microwave and optical implementation approaches.

The identified critical technology areas are listed below. Subsection 6-2 describes a detailed assessment of the

Critical ISL Technology

Item	60-GHz ISL	Optical ISL
• Pointing/Tracking/ Acquisition	None	Precision Tracking in Dynamic Mode
• Transmitter	TWTA/Reliability	Laser Diode
• On-Board Processor/ Interface	- High-Speed A/D (FDM/FM to Digital) Format Converter	
• In-Orbit Testing	- Test Method and Verification	

state-of-the-art (SOA) technologies. Only a brief discussion is given below.

a. <u>Pointing, Tracking, and Acquisition (PAT) Subsystem</u>:

Acceptable level of PAT performance is a prerequisite of an ISL. The fundamental limitation of a PAT subsystem is associated with fine tracking capability. Table 6-1 compares the fine tracking requirement of a 60-GHz microwave vs 0.85-µm optical ISL for the baseline design.

A 2m-sized microwave ISL tracking antenna subsystems performance has demonstrated a fine tracking accuracy (1 σ_{rms}) of about 0.025° [23]. It is adequate to meet the baseline design requirement. Additional requirements for compensation of satellite motion and antenna scanning loss can be met with minor improvement in the SOA hardware technology.

Table 6-1. Fine Tracking Requirement

Parameters	60 GHz	0.85 µm Optical ISL
Aperture Size Diameter	2 m	30 cm to 60 cm
Beamwidth[a]	0.175°	3.5-µ rad to 1.73-µ rad
rms Tracking Requirement[b]	0.0175°	0.17 ≈ 0.35-µ rad
SOA Performance (1 σ_{rms})	0.025°	0.2-µ (static-mode)
Limiting Parameters	- Satellite Motion - Scanning Loss	- Satellite Motion - Optical Subsystem Vibration/ Motion - Photodetector and Background Noise Dynamic Mode Performance
Need for NASA Development	None	Demonstration

[a] Beamwidth = $1.22 \frac{\lambda}{D}$ (radian).
[b] σ_{rms} = 0.1 beamwidth.

The optical PAT subsystem demands extremely high accuracy of pointing, typically less than 0.5-μ radian (1 σ), in order to maintain reliable communication. A closed-loop quadrant detector tracking subsystem design technique provides tracking jitter of about 0.2-μ radian [30]. However, the fine tracking performance under a dynamic spacecraft environment needs to be demonstrated. Various factors to be included are spacecraft motion, optical subsystem vibration, photodetector noise, and background noise effects.

b. <u>Transmitter Subsystem</u>

NASA Lewis Research Center has developed a 60-GHz TWTA for microwave ISL applications. The developmental TWTA showed the following output capability [31]:

- 59-to-64 GHz, 5-GHz bandwidth,
- 115-W output power,
- Efficiency up to 40 percent.

Space-qualified 60-GHz TWTAs are not yet available. Reliability performance must be demonstrated through further laboratory testing.

As for the optical ISL single-mode diode laser technology is a critical one: a highly spectrally stable single-mode laser output of about 100 mW to 300 mW and long lifetime performance up to 10 to 12 years are desirable for the flight ISL payload.

c. <u>On-Board Processors and Interface</u>

On-board processors are needed for the implementation of interface between host spacecraft and ISL payload. On-board switching for traffic rerouting, modulation/demodulation and multiplex/demultiplexing functions are provided in the interface. High-speed A/D format converters may be needed also to accommodate analog (FDM/FM) and digital (TDM) signal transmissions. Advanced satellite technology heritages such as NASA's ACTS on-board baseband processing [32] should be applied to the ISL interface implementation.

d. <u>In-Orbit Testing</u>

In-orbit tests are normally conducted to ensure that the communications payload has successfully survived the spacecraft launch into geosynchronous orbit. Additional provisions of TT&C may be needed for ISL in-orbit testing, because the ISL is transparent to the up- and down-link earth stations. One ISL includes two satellites with ISL terminals. In-orbit testing methodology should be developed for two cases:

- Testing a single ISL satellite.
- Testing a complete ISL with two satellites.

Further discussion is provided in Subsection 6.2.3.

6.1.1.2 Technology Development Scenarios

The critical technologies identified in Subsection 6.1.1.1 require further development beyond their present level of technical maturity. Additional funding is needed for technology development.

Technology development scenarios are outlined below:

1. Optical ISL

   a. Optical Pointing, Acquisition, and Tracking (PAT) Subsystem

      - Design and performance verification for in-orbit spacecraft dynamic environment.
      - Acceptable performance for solar conjunction.
      - Preparation of space-qualified PAT specifications.
      - Time frame: 1987-1989.

   b. Optical Transmitter

      - Subsystem design for 8-Gbit/s (nominal) transmission capacity with greater than 100-mW (single mode) optical output power.
      - Prototype development of space-qualified diode laser transmitter.
      - Ten-year reliability greater than 0.9.
      - Time frame: 1987-1989.

c. On-Board Processors and Interfaces

- Applications of advanced technology heritage.
- Prototype design and development (common to microwave and optical ISLs).
- Time frame: 1988-1990.

d. In-Orbit Testing Program

- Develop techniques for a single spacecraft ISL terminal as well as a complete ISL employing two ISL spacecraft.
- TT&C station requirement and associated software development.
- Time frame: 1989-1990.

e. Flight ISL Payload Development

- Prototype, fully space-qualified payload.
- Performance testing and evaluation.
- Time frame: 1990-1993.

2. <u>Microwave ISL</u>

Microwave (60 GHz) ISL technology does not need any major technical breakthrough. All subsystems are available within the SOA technology. Only one exception is the need for TWTA reliability performance verification.

In the TWTA industry, the heritage of technology is counted heavily (about 60 percent) for space qualification. A new TWTA design and assembly-related aspects constitute only about 40 percent. This consideration is based on the fact that the 60-GHz TWTAs are manufactured from modified designs of the existing lower frequency band TWTAs.

For this reason a simple thermal vacuum temperature cycling performance test of the 60-GHz TWTA is applicable. The temperature range should be -10°C to 70°C. In addition, accelerated temperature testing of TWTA cathode performance is needed.

If flight units of TWTAs are available, the simplified reliability testing can be completed within a 6-month to 1-year period. The time frame from 1987 to 1988 should be adequate for the flight program.

Table 6-2 shows a summary of the scenarios, including objectives and key technical requirements. Critical subsystems technology needs to be developed first, followed by payload system design and in-orbit testing programs. The development time frame is illustrated in Figure 6-1.

The key points of ISL technology development scenarios are the following:

- NASA should support ongoing Lasercom component R&D programs (re: Subsection 6.2.1) to obtain results by the end of 1989.
- Develop the critical subsystem technologies to meet the space-qualification level performance requirement by 1989.
- Conduct ISL payload system design and testing programs, including in-orbit operational testing, for completion by 1990.

Table 6-2. ISL Technology Development Scenarios

Priority No.	Item	Objective	Requirements	Time Frame
1.	Critical Subsystem Technology			
	a. Diode Laser Transmitter[a]	Prototype Development (8 Gbit/s Rate)	• Single-Mode Diode Laser System • 100-mW to 300-mW Optical Output • MTBF $\geq 10^6$ Hours	1987-1989
	b. PAT Subsystem[a]	Performance Verification for In-Orbit Operation	• Submicroradian Tracking Accuracy • Dynamic-Mode Environment • Solar Conjunction	1987-1989
	c. 60-GHz TWTA[b]	Reliability Performance Demonstration	• 10-Year On-Station Lifetime • Output Power Exceeding 60 W	1987-1989
2.	Payload System Design and Testing Program	Prototype P/L Design and In-Orbit Testing Program Development	• Overall ISL P/L System Design • On-Board Processor/Interface • Thermal/Mechanical Integration Model • Host S/C Bus Including TT&C • In-Orbit Testing Method	1989-1990
3.	Flight ISL Payload	Prototype Flight-Qualified P/L Development	• Prototype Manufacturing, Assembly, and Testing • Fully Space-Qualified Performance	1990-1993

[a]For Optical ISL System.
[b]For 60 GHz ISL System.

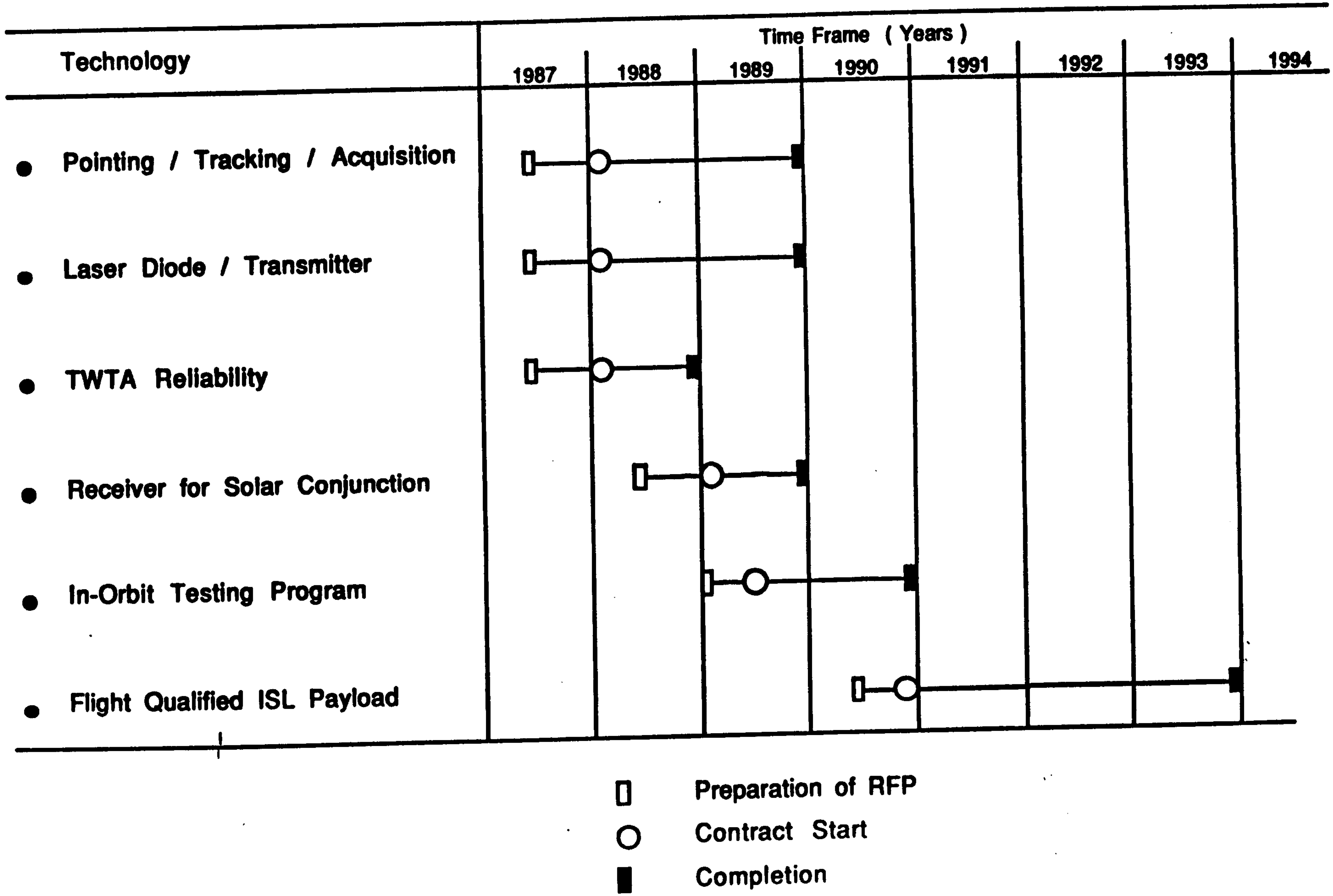


Figure 6-1. A Scenario for Critical ISL Technology Development

- o Develop prototype flight ISL payloads in the 1990-1993 time frame.
- o First launch takes place in 1993-1994.

6.1.2 NETWORK SYSTEMS IMPLEMENTATION

Based on certain assumptions, ISL network systems implementation scenarios were developed for selected ISL applications. Various issues of technical and non-technical aspects are described also in this section.

6.1.2.1 Assumptions

The following major assumptions are made for the development of scenarios of ISL network systems implementations:

a. Successful completion of the current experimental ISL space programs, including ACTS Lasercom and ESAs Data Relay Satellite (DRS) ISLs, in accordance with their projected program schedule. Those flight programs will provide a solid technical basis for future commercial ISL applications.

b. Fully space-qualified ISL technologies will be available at the end of 1990 in accordance with the technology implementation scenarios outlined in Subsection 6.1.1.2.

c. The first post-INTELSAT VI spacecraft in a 1993-94 time frame can be used for the introduction of the earliest possible ISL applications for international FSS communications.

d. Domestic and ITU regional satellites as the host spacecraft of ISL payloads could be planned and implemented within a reasonable time frame.

The in-orbit-communications experiments of the ACTS Lasercom could take place in 1991-92. On the other hand, European DRS flight ISL is projected for a 1994-95 time frame. This indicates the possibility of introducing ISLs to CONUS FSS communications (at least in the experimental phase) under NASA's leadership role for the commercial satellite community. This is consistent with the long-range mission model of NASA's communication program using laser ISLs in the year 2000 [33].

6.1.2.2 Scenarios

The following cost-effective ISL applications were considered initially for the development of network implementation scenarios:

- CONUS ISL,
- CONUS-AOR International,
- N. American-Europe or CONUS-Europe,
- ITU Region 1-AOR International,
- ITU Region 1-Region 2.

The evolving ISL networks, initiated by U.S. domestic and European applications, can be developed in a number of possible alternative paths. A simplified scenario is shown in Figure 6-2. Various institutional, economical, and political

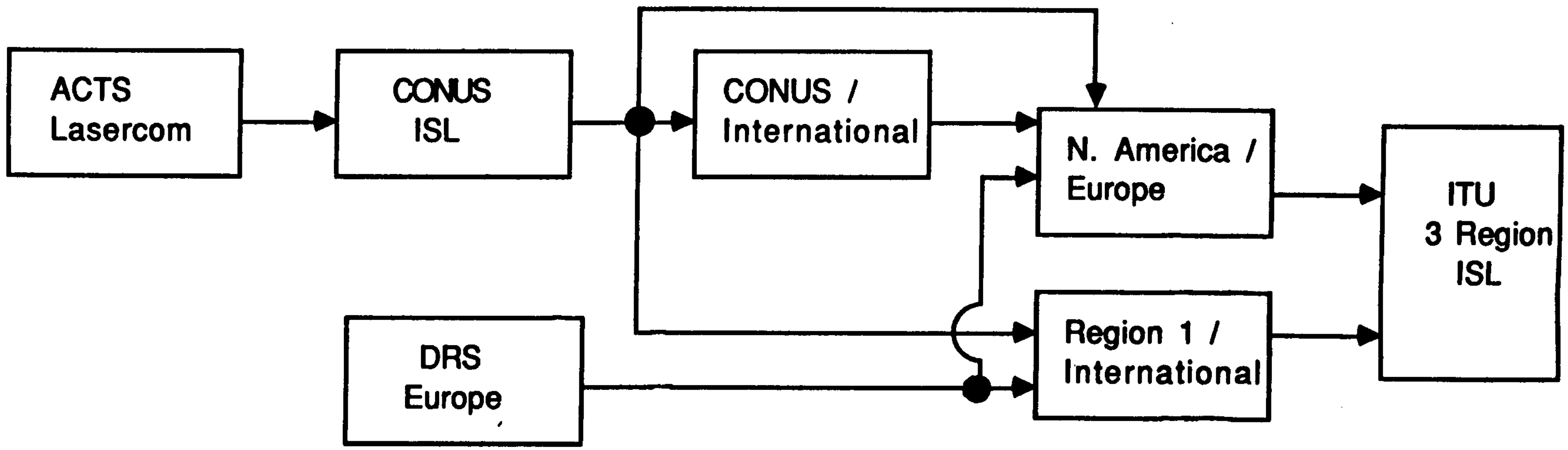


Figure 6-2. Major ISL Applications Scenario for Commercial FSS Communications

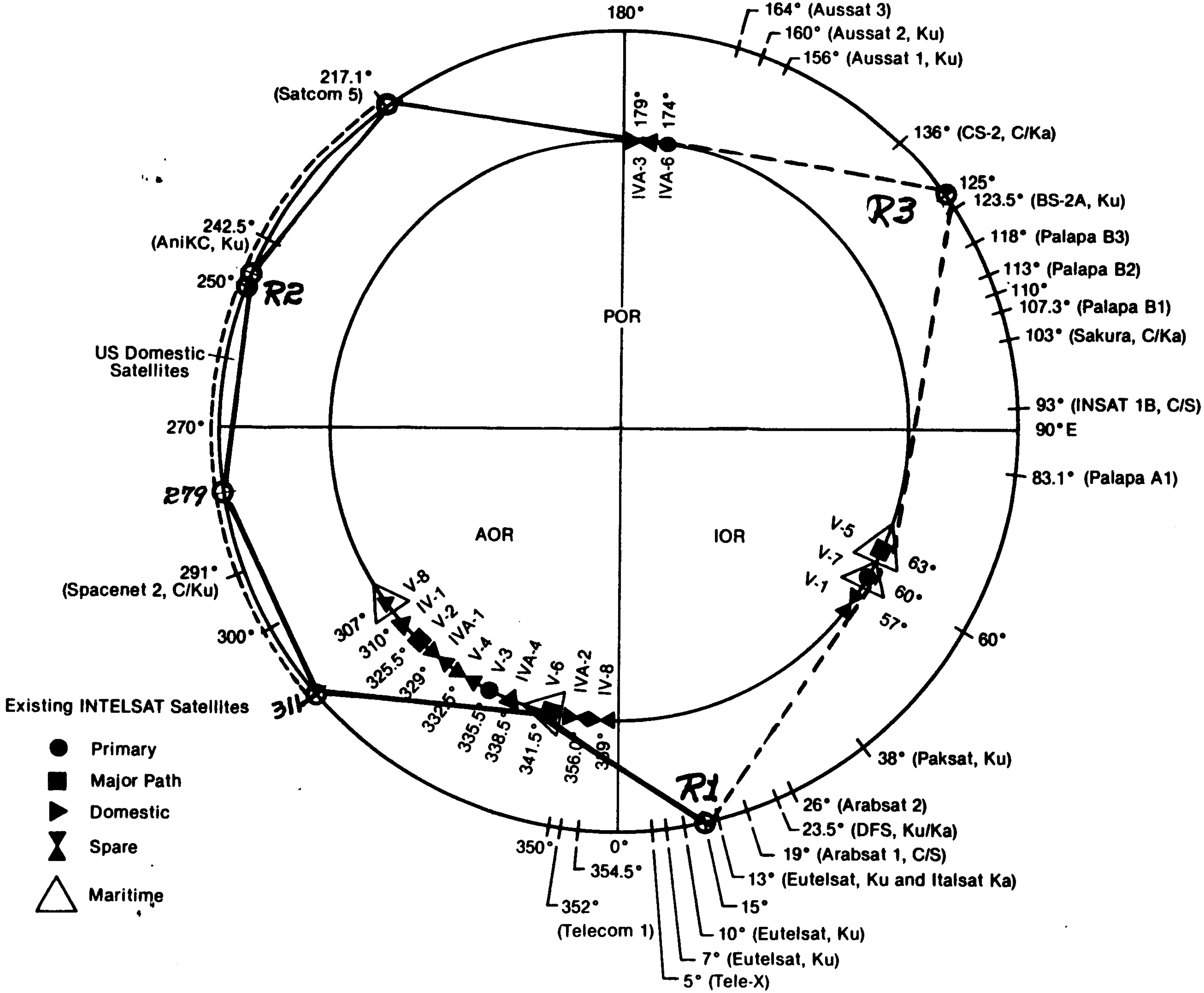
factors (rather than technical) will play a major role in determining the eventual path of ISL network development.

An evolving ISL network, such as that shown in Figure 6-3, will lead ultimately to a mature three ITU regional ISL system. Figure 6-4 shows the mature ISL network system. The ISLs, shown by solid lines in Figure 6-3, indicate more cost-effective ISL applications, based on the result of Task 2 (cost analysis). The other ISLs represented by dashed lines are marginally cost-effective. ISL applications involving international satellites may not be implemented if North America-Europe ISL is developed directly from the initial CONUS and Europe ISLs, as shown in Figure 6-2.

An attempt was made to derive a possible time frame for the introduction of each of the ISL applications selected in Task 1. Under the assumption that the first launch takes place in 1993-94, the CONUS 4-zone coverage ISL (Application No.1) could be introduced at the end of 1998. The host spacecraft will be platform communications payloads with ISLs similar to those investigated by NASA in recent studies [28,29].

Figure 6-5 illustrates a tentative time frame of the ISL network systems implementation. The ACTS-Lasercom and European DRS ISL program schedules indicated in the lower end of Figure 6-5 provide the basis of the other ISL development time frame. Other assumptions were described in Subsection 6.1.2.1.

The three ITU regional ISL network could be developed in the year 2000 as the earliest possible scenario.



180°
164° (Aussat 3)
160° (Aussat 2, Ku)
156° (Aussat 1, Ku)
136° (CS-2, C/Ka)
125°
123.5° (BS-2A, Ku)
118° (Palapa B3)
113° (Palapa B2)
110°
107.3° (Palapa B1)
103° (Sakura, C/Ka)
93° (INSAT 1B, C/S)
90°E
83.1° (Palapa A1)
60°
38° (Paksat, Ku)
26° (Arabsat 2)
23.5° (DFS, Ku/Ka)
19° (Arabsat 1, C/S)
13° (Eutelsat, Ku and Italsat Ka)
15°
10° (Eutelsat, Ku)
7° (Eutelsat, Ku)
5° (Tele-X)
0°
354.5°
352°
(Telecom 1)
350°
217.1°
(Satcom 5)
242.5°
(AniKC, Ku)
250°
R2
US Domestic
Satellites
270°
279
291°
(Spacenet 2, C/Ku)
300°
311
R1
R3
POR
AOR
IOR
IVA-3 179°
IVA-6 174°
V-5 63°
V-7 60°
V-1 57°
V-8 307°
IV-1 310°
V-2 325.5°
IVA-1 329°
V-4 332.5°
V-3 335.5°
IVA-4 338.5°
V-6 341.5°
IVA-2 356.0°
IV-8 359°
Existing INTELSAT Satellites
Primary
Major Path
Domestic
Spare
Maritime

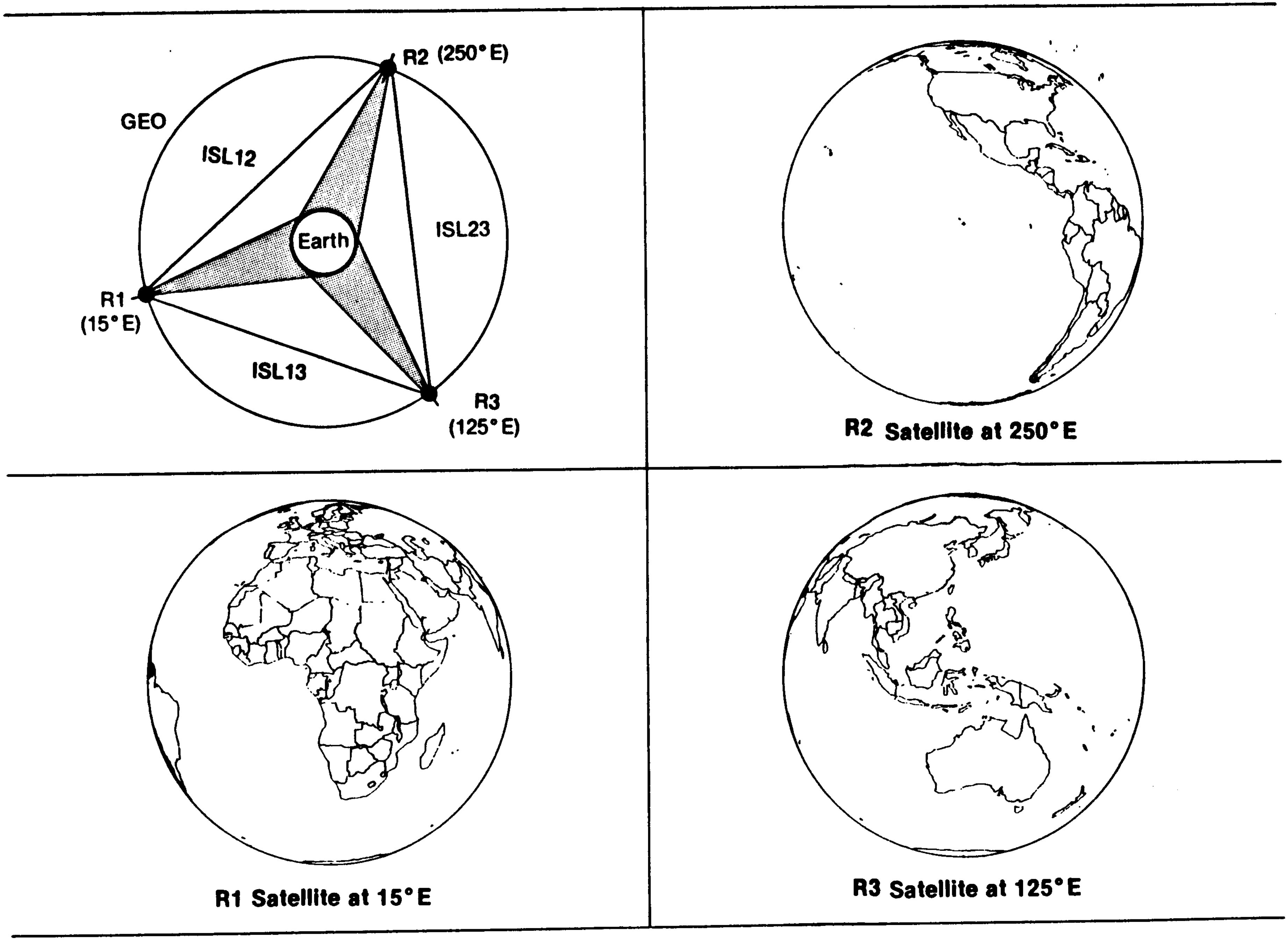


Figure 6-4. Mature ITU Regional ISL Satellite System

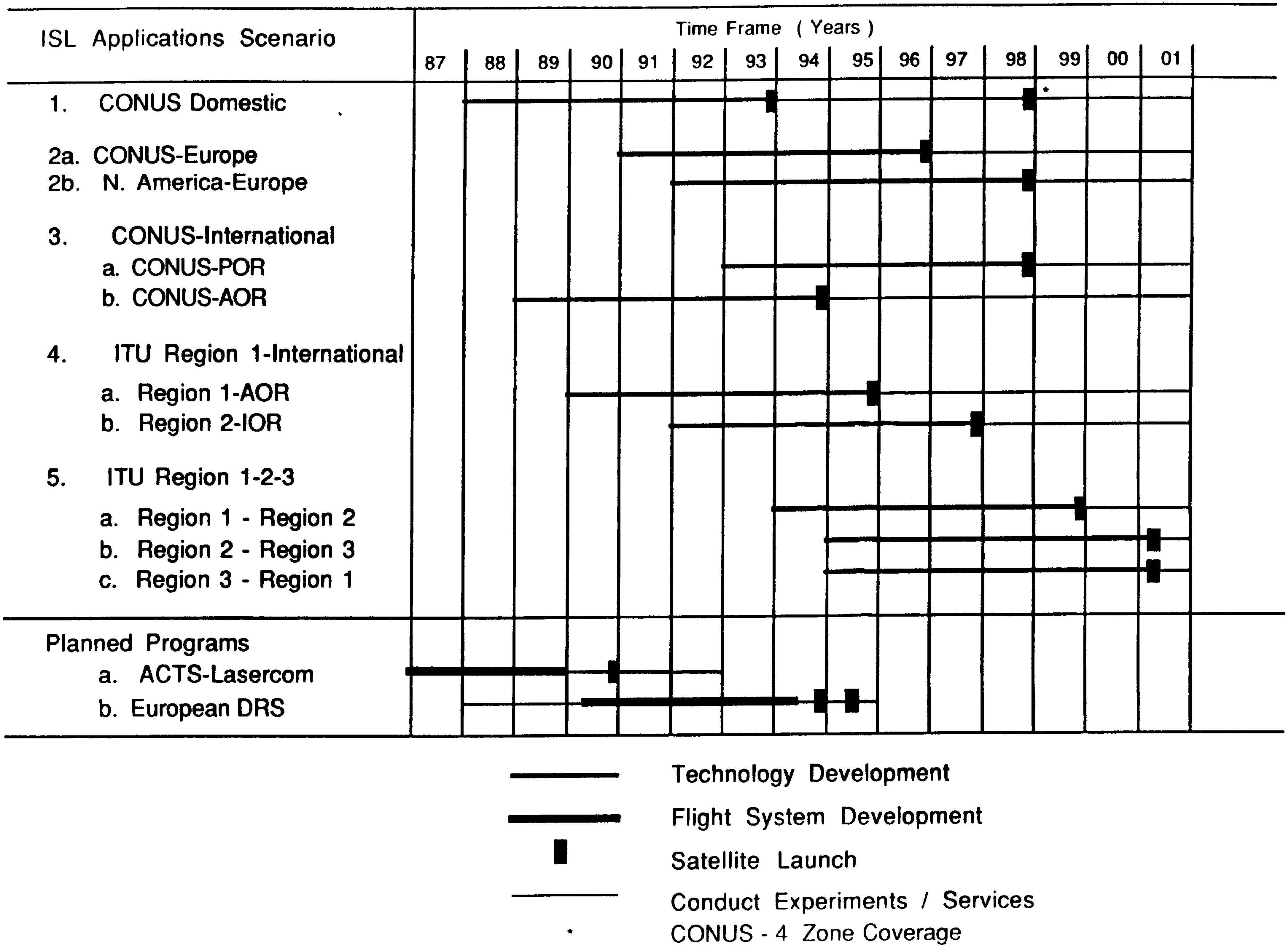


Figure 6-5. Implementation Scenario of Selected ISL Applications

6.1.2.3 Issues of Implementations

Optical and microwave ISL payload technologies are cost-competitive; optical ISL cost is only about 7.5 percent higher than the corresponding microwave ISL on a statistical basis from the cost analyses in Section 5. Large-sized tracking antennas (2 m in diameter typical) of the microwave ISL impose real-estate problems and constraints to host spacecraft integration.

There are possibilities of intersystem interference in case of microwave ISL implementation. Potentially harmful interference could occur between direct broadcasting satellite services (DBS) and ISLs in the 33-/23-GHz band. A 60-GHz ISL is less susceptible to interference, but frequency sharing with mobile services and space research applications in some portions of the band may need coordination

On the other hand, optical frequencies are completely free from interference, and optical ISL does not need any intersystem coordination. There is essentially no bandwidth limitation in the utilization of the optical wavelength band.

Prior to the introduction of the ISL for commercial communications, various institutional and systems planning issues must be fully addressed. The systems level constraints and coordinations needed are wide-ranging in many areas. Key issues are identified below:

- Host spacecraft management through consortium of systems operators or regional group of administrations involved.
- Development of standards for:
  - Systems interface,
  - Network control,
  - Protocol development.

- ISL satellite networks integrated into global ISDN.
- Fiber-optics impact on FSS communications.

Figure 6-6 shows the emerging fiber-optics technology impact on ISL applications. Actually ISL network systems will benefit the overall communications services through their competing, complementary, and unique nature of systems characteristics. Improved and new services at lower costs can be provided to users with the introduction of ISL satellite network systems.

The key issues identified above, the fiber optics impact on cost-effective ISL applications, in particular, need further study in the future.

A summary of the ISL network system implementation scenarios is the following:

- NASA's leadership role toward commercial ISL applications to FSS is indispensable.
- Investigation of the fiber-optics impact on the cost-effective ISL applications needs further study.
- The CONUS ISL network system should be developed as part of the next generation GEO platform payloads.
- Mature ISL network systems will be possible in a long-range ($\geq$ 15 years) time frame.

6.2 ISL TECHNOLOGY ASSESSMENT

Based on a review of major ongoing ISL programs, optical as well as microwave ISL subsystems technologies were assessed for their performance characteristics and space hardware availability. Payload system design and in-orbit

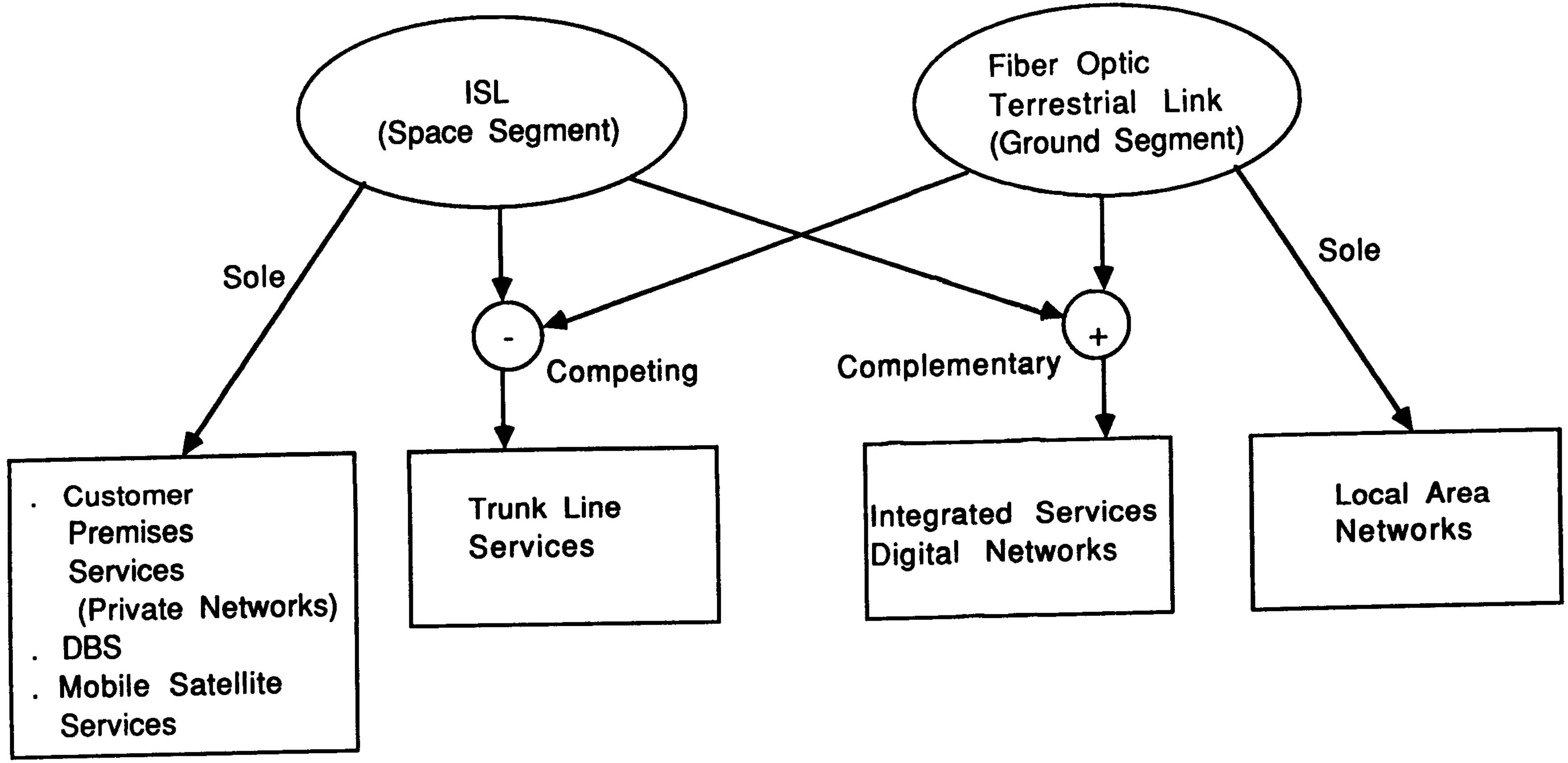


Figure 6-6. Fiber-Optics Impact on ISL Applications

testing programs were addressed. Technology program schedule, cost, and risk estimates were derived under Task 3.

6.2.1 CURRENT PROGRAMS

As a part of the assessment of hardware technology availability, major ongoing ISL programs were reviewed. They include:

a. NASA's ACTS Lasercom Program,
b. European Data Relay Satellite (DRS) System's Optical ISL Program,
c. INTELSAT R&D Programs of Microwave and Optical ISLs, and
d. Other Noncommercial Applications.

Table 6-3 shows a summary of the current optical ISL programs.

NASA and the Air Force's ACTS Lasercom program includes both direct detection diode laser technology and Lincoln Labs-developed heterodyne detection approaches using diode lasers. The Lasercom program represents SOA optical space hardware technology available today [34].

The European DRS system, which is planned by the European Space Agency (ESA) for preoperational service in 1994-95, includes two options of optical ISL technology: CO_2 laser and diode laser direct detection system [35]-[37].

The CO_2 laser system operating in the 10-micrometer range provides an advantage in somewhat relaxed requirements of pointing, acquisition, and tracking subsystem performance due to a longer wavelength involved than the diode laser operating in

Table 6-3. Ongoing Optical ISL Programs

Item	ACTS Lasercom	DRS ISLS	INTELSAT FOS	Noncommercial Applications
• Organization	NASA/AF	ESA	INTELSAT[a]	DOD
• Status Development	Flight System Hardware	Subsystem Level	Components R&D	R&D
• Key Technology				
– Source	Diode Laser	Diode vs CO_2 Lasers	TBD	Diode Laser, CO_2 Laser, Nd:YAG Laser
– Modulation Detection	Direct and Heterodyne	Direct vs Coherent	TBD	TBD
– Data Rate (Mbit/s)	220	400 to 500	TBD	TBD

[a]Developed microwave (33/23 GHz) ISL subsystems under internal R&D program.

the 0.85-µm region. The CO_2 laser requires heterodyne detection with cryogenically cooled photodetectors, making the optical system more complex. The lifetime and reliability performance of diode lasers is potentially superior to CO_2 lasers.

Previously, INTELSAT had developed microwave (22/23 GHz) ISL subsystems technology under an internal R&D program. ISL payload design studies were conducted for implementation on board INTELSAT VI spacecraft [7]. However, the flight system development program was canceled due to cost considerations. Current INTELSAT ISL programs are restricted to optical components level technology development.

Nevertheless, various optical link technologies are being sponsored by DOD for noncommercial applications. Significant technological advances are anticipated for the military Lasercom applications in the 1990s.

6.2.2 SUBSYSTEMS TECHNOLOGY

Technology assessment was performed for microwave and optical ISL subsystems. The following critical technology issues were identified for major subsystem areas:

- Pointing, acquisition, and tracking (PAT),
- Transmitter and receiver,
- Payload system,
- In-orbit testing.

6.2.2.1 PAT Subsystem

The ISL antenna subsystem performs initial search and acquisition in order to establish a link between two ISL satellites. The acquisition mode is then followed by an autotracking mode to maintain the link regardless of the spacecraft orbital motions and perturbations arising from antenna/spacecraft interaction.

In the search mode, each satellite tries to locate the other satellite without the ISL link according to the initial estimate of ground commands and search scan patterns. When each antenna receives maximum signal strength from the other, the search mode is completed.

A. Microwave PAT

Table 6-4 compares two autotrack techniques, monopulse vs step-track of microwave ISL antennas. The monopulse technique is insensitive to the signal level variation and fast responding to spacecraft motion. It has been implemented in the INTELSAT development model ISL antenna.

Some of the INTELSAT ISL antenna characteristics are given below [23]:

- 33-/23-GHz ISL antenna,
- 2-m single offset parabolic reflector system,
- Graphite fiber epoxy/aluminum honeycomb construction,
- Surface tolerance: 0.015-cm rms,
- Efficiency: 60 percent,
- Monopulse tracking system including tracking beacon/ receiver and control,

Table 6-4. Microwave ISL Monopulse vs Step-Track

Item	Monopulse	Step-Track
• Basic Concept	Error Signal Sensing Process	Signal Peaking Process
• Hardware Complexity	Sum and Difference (Δ el, Δ az) channels	Sum Channel Only
• Acquisition to Autotrack	Automatic	Ground Control Interaction
• Response to Spacecraft Motion	Fast	Slow
• Effect of Signal Level Variation	Insensitive	Sensitive
• Space History	LES 8, 9 and Others	None (Ground Station Only)

- Beam-pointing accuracy: 0.122° rss,
- Tracking accuracy: 0.025° (1 σ).

This technology is directly applicable to the 60 GHz ISL PAT implementation. Figure 6-7 shows a simplified block diagram of the ISL tracking receiver subsystem.

The SOA microwave tracking antenna technology has been well developed and there is no critical area that needs further development.

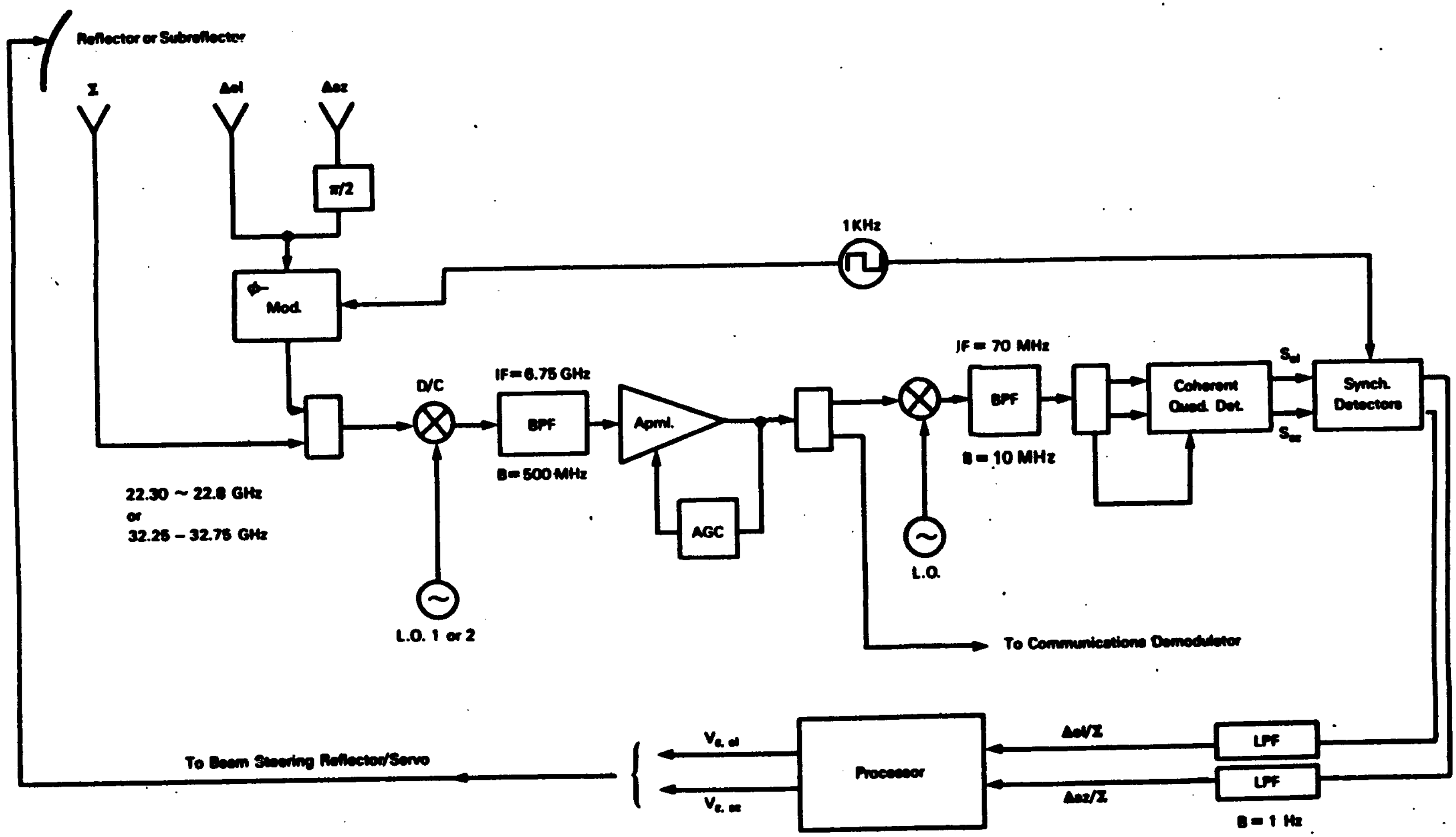


Figure 6-7. ISL Tracking Receiver System--Simplified Block Diagram

B. Optical PAT

The SOA performance of the optical PAT subsystem shows that pointing accuracies of less than 0.5-μ radian (1 σ) can be achieved [30,38,39].

Laser communication beacon signals are generally used for acquisition and pointing the laser transmitter output beam to the receive satellite. Breadboard models have been developed for GEO-GEO and GEO-LEO Lasercom links [30,39]. Acquisition time of about 10 to 60 seconds for the GEO-GEO optical link has been achieved with gimballed telescope pointing system control and scanning servo loops.

Table 6-5 shows a summary assessment of optical PAT subsystem technology. Three major items were identified for the SOA technology status and critical issues for ISL applications.

A previous study by Hughes Aircraft Co. under NASA/GSFC sponsorship [40] investigated the optical PAT performance limitation associated with its host spacecraft dynamics. LANDSAT data were used to assess the effects of vibration and disturbance on a diode laser link between the LEO satellite and a TDRSS (GEO) satellite. However, the on-station motion of a GEO satellite including stationkeeping maneuvers could provide a more severe dynamic environment than the LEO satellite. The PAT system design needs a detailed parameter sensitivity analysis and simulation study to derive various subsystem specifications:

- Gimbal assembly,
- Fine pointing, alignment, and point-ahead compensation,
- Coarse and fine tracking detector assembly and signal processor, and
- Acquisition and tracking receiver.

Table 6-5. Optical PAT Subsystem Technology--Assessment

Item	Topics	1986 SOA	Critical Issue
• PAT Performance in Dynamic Mode	- Parameter Sensitivity Analysis	Not Available	Analysis/Simulation
	- Error Budget and Specification Development		
• Subsystem Development	- Coarse Steering Gimbal; Assembly	Mature	Specialized Design
	- Fine Pointing/Alignment/ Point-Ahead Compensator	Available	Realiability/Redundancy
	- Coarse and Fine Tracking Detector Assembly/ Processor	Feasible	To Be Developed
	- Acquisition/Tracking Electronics	Feasible	Develop a Common Processor
• PAT S/S Testing and Performance Verification	- Submicroradian Tracking Accuracy Under Dynamic Mode	Not Demonstrated	Testing in Dynamic Mode
	- Adequate Performance in Solar Conjunction	To Be Demonstrated Experimentally	Stable Optical Filter
	- Flight Specifications	To Be Developed	Flight Program

The PAT subsystems flight performance specifications should be developed through appropriate testing and performance verification. Adequate link performance during solar conjunction needs to be demonstrated experimentally.

Typical optical link margin related to the PAT performance is estimated in Table 6-6. The occurrence of the real-time mispoint angle exceeding a specified value causes a link loss and bursty errors in bit error rate performance of the ISL [41]. This results in reduced transmission efficiency for digital data. Available analysis shows that the outage duration could be 0.5 ms to 1 ms. Improved design techniques for fast clock synchronization are needed to minimize the outage duration.

A 3-dB link margin attributed to pointing loss in Table 6-6 is due to combined effects of optical system vibration, satellite motion, motion of coarse pointing mechanism, and detector noise. Design improvements could reduce these effects, resulting in a 1-dB pointing loss budget in the 1990s.

Point-ahead angle is approximately 2 v_t/c where v_t is the magnitude of the tangential component of relative velocity between two satellites and C is the velocity of light (3×10^8 m/sec). The point-ahead compensation is based on orbit computation data concerning the two satellites. An error in the orbit-computation and bias between the reference frames associated with the optical system and the satellite platform causes the point-ahead compensation loss, which is about 2-dB typical. Further improvement is possible to reduce it by 1 dB in the 1990s. Table 6-6 shows that the total link margin then could be improved by 3 dB with the development of advanced PAT subsystem technology in the 1990s.

Table 6-6. Optical Link Margin Estimate

Item	Source	SOA	1990 Technology
Pointing Loss [dB]	Fine Tracking Limitation	3 dB	1 dB
Pointing-Ahead Angle Compensation[a] Loss [dB]	Orbit Compensation Errors of Two Spacecraft	2 dB	1 dB
Total		5 dB	2 dB

[a]With bias between reference frames associated with optical system and spacecraft platform.

6.2.2.2 Transmitters and Receivers

Key building block hardware components of the microwave ISL repeater have been developed for space applications [7]. The implementation of microwave (60 GHz) ISLs does not require any new development of critical components. As discussed in Subsection 6.1.1, NASA-developed 60-GHz TWTA technology can be used to produce flight units [31]. Space qualification of the flight TWTAs requires further testing, such as thermal vacuum temperature cycling performance tests. There should be no major problem in meeting the space reliability requirement, provided that the TWTAs are procured from a manufacturer who has the heritage of reliable TWTA technology in lower frequency bands (i.e., K_u-, and K_a-bands).

Some of the critical technical items of optical repeater subsystems are assessed in this section.

A. Optical Transmitters

Recent advancement of single-mode laser diode technology has demonstrated output power and reliability performances adequate for optical ISL applications. Table 6-7 shows a comparison of three optical technologies: GaAlAs diode laser, CO_2 laser, and Nd:YAG laser.

The CO_2 laser requires a cryogenic photodetector operating at about 100°K, and coherent detection adds complexity to the CO_2 laser system. The limited lifetime performance of a CO_2 laser is a serious problem for space applications. Gas refilling of the CO_2 laser will be needed to meet a 10- to 12-year in-orbit lifetime.

Nd:YAG lasers operating in the 1.064-µm wavelength or in the 0.532-µm with frequency doubling have been well developed. Diode lasers were used as the pump source for the Nd:YAG lasers, increasing the lifetime performance of the laser. However, the complexity of the Nd:YAG laser assembly, including a multiple number of pump-laser diodes and associated low efficiency and lifetime performance limitations, provides problems for commercial ISL applications.

Laser diode systems are advantageous in a number of systems aspects:

- Direct OOK or PPM modulation of the laser diode up to multigigabit rate without using external modulators,
- Direct detection receivers without special cooling requirements, and
- Potentially long lifetime and high reliability performance. Small-size laser diodes are advantageous for a redundancy design of the laser system to enhance

Table 6-7. Comparison of Optical ISL Technology

Parameter	Diode Laser	CO_2 Laser	Nd:Yag Laser
Wavelength (μm)	0.8-0.9	10.6	0.532/1.064
Output Power	Low	High	Medium
Detection Scheme	Direct or Heterodyne	Heterodyne (Cryogenic Detector)	Direct
SOA Lifetime [Hours]	1×10^6	1×10^4	2×10^4
Tracking Requirement	High Accuracy	Low	Medium
Development Status	Ongoing	Mature	Mature

the system reliability beyond the individual device reliability achievable.

The lifetime performance of GaAlAs laser diodes is estimated to be about 10^7 hours for low output power (typically less than 10-mW CW) devices at room temperature. However, a lower lifetime of 4×10^5 hours or better is projected for the SOA 50-mW CW laser diode. The upper limit of optical output in a single diode device is limited to catastrophic damage of the mirror facets caused by high optical density and saturation of output power due to self-heating.

The following SOA laser diode technology needs improvement in two areas of performance [42]:

a. Laser output power,
b. Lifetime and reliability performance of high-power laser diodes.

These technology needs have been identified in the NASA Laser Communications Component R&D effort. NASA/GSFC's GaAlAs diode laser development program calls for a single-mode laser output power of 100-mW average and multiyear lifetime performance [34].

The potentially long lifetime capability of quaternary (InGaAsP) laser diodes has been recognized for long wavelength (1.1-1.55 μm) fiber-optics application. However, the quaternary laser device technology for high-power output has not been available for space applications.

Table 6-8 shows a critical technology assessment of diode laser transmitter subsystems. High-power optical transmitters can be implemented with relatively low output

Table 6-8. Diode Laser Transmitter Technology—Assessment

Item	Topics	1986 SOA	Critical Issue
• Devices/Life Testing	- Stable Single-Mode Diodes with High Output Power (100-300 mW) - 10-Year On-Station Lifetime - Multigigabit Rate Pulse Mode Operation	Not Available	• MTBF $\geq 10^6$ Hours
• 8-Gbit/s Modulator (PQM)/Driver and Interface Processors	- MMIC TDM Mux/Demux - High-Speed A/D (FDMA/FM to TDMA) Format Converters - Baseband Switches and Memories	To Be Developed	• MMIC Implementation • Availability of Technology Heritages from Advanced Space Programs

(typically less than 50-mW average) laser diodes in two systems design approaches shown in Figure 6-8:

a. Parallel optical data channel combining technique,
b. Single-channel coherent optical power combining.

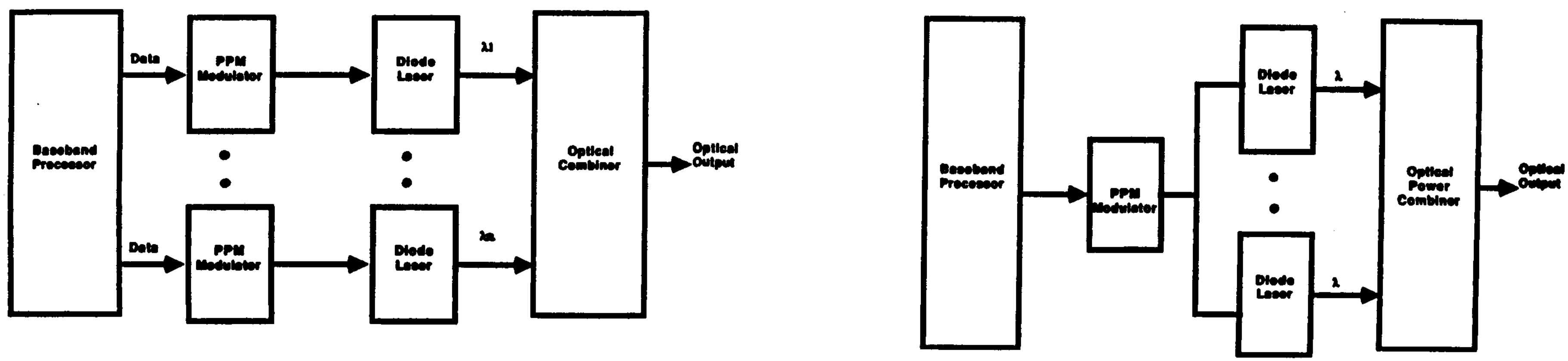
The parallel optical channel combining produces the output of several diodes into a single near diffraction-limited beam, consisting of several very closely spaced individual optical wavelengths. The increase in power can be as much as 5 to 10 times. Dichroic combining using narrowband interference filters has been demonstrated for the design of high data rate Lasercom transmitters [43,44]. Proven dichroic and grating filter technologies are suitable for these combining approaches.

The coherent optical power combining is conceptually simple, but the matched phase output from a member of individual diodes is a rather challenging problem, requiring significant technological development to make it practical.

A baseline (8 Gbit/s) laser transmitter and interface development will require substantially effort in MMIC implementation. The availability of technology heritages from advanced space programs [32] should be evaluated and utilized efficiently for this application.

B. Receivers

The state-of-the-art receiver at 60 GHz employs high electron mobility transistor (HEMT) devices. Uncooled HEMT provides a noise figure of about 8 dB at 60 GHz [45]. The microwave ISL receiver temperature of 1,600°K or lower can, thus, be achieved. The 60-GHz receiver technology is adequate for applications to an ISL payload implementation.



(a) Parallel Optical Channels

(b) Single Channel Optical Power Combining

Figure 6-8. Implementation Approaches of High-Power Optical Transmitters

The critical component in the optical receiver technology is low-noise photodetector diodes. An avalanche photodiode (APD) provides higher receiver sensitivity than PIN photodiode due to the internal multiplication gain of APD. However, the excess noise factor associated with the random avalanche process provides a fundamental limitation of the APD receiver performance.

The optical receiver performance employing a direct detection of digital (OOK as an example) signals can be described by the following carrier-to-noise power ratio as a limiting case:

$$C/N = \frac{R_o P_s}{qB_n} \bullet \frac{P_s}{4\ F(M)(P_s + P_b)} \qquad (6\text{-}1)$$

where R_o = Detector responsivity,
P_s = Received optical signal power,
q = Charge of an electron,
B_n = Noise bandwidth,
$F(M)$ = Excess noise factor of APD,
M = Average avalanche gain of APD,
P_b = Background optical noise power.

The excess noise factor of APD is given by

$$F(M) \simeq 2 - \frac{1}{M} + k_{eff}\ \frac{(M-1)^2}{M} \qquad (6\text{-}2)$$

where k_{eff} = Effective ratio of carrier ionization rates dependent on materials selection.

Equation (6-1) shows that the excess noise factor of APD must be reduced to achieve an improvement in C/N performance. Typical APD performance characteristics are listed in Table 6-9. The quarternary GaAlAsSb-based APD is suitable for long wavelength (1.1-1.55 μm) fiber-optics applications. The representative excess noise factor of GaAs APD at 0.85 μm is 10 or less. The corresponding penalty in C/N is 10 log [4 F(M)] $\leq$ 16 dB from equation (6-1).

Table 6-9. APD Performance

Parameters	Si	GaAs	GaAlAsSb
Optimum Wavelength [μm]	1.06	0.9	1.4
Responsivity [A/W]	0.65	0.45	0.9
Ionization Probabilities Ratio (k_{eff}]	<0.03	<0.02	0.3
Dark Current [pA]	20	-	1,000
Multiplication Gain	40	400	17
Excess Noise Factor	<13.9	<9.96	7.02

Recently, new device design approaches have been taken to develop staircase avalanche photodiodes for realization of a solid-state version of photomultipliers. NASA/GSFC's Lasercom components R&D program includes the solid-state photomultiplier development. The receiver performance improvement by about 6 dB is projected with this technology [34].

Other critical issues of the optical receiver technology are:

- o Design for solar conjunction,
- o Heterodyne (or coherent) detection systems options.

These issues are addressed in the subsequent subsections.

6.2.2.3 Design for Solar Conjunction

The successful operation of intersatellite links must be maintained during solar conjunction. Solar conjunction occurs during the periods of vernal and autumnal equinoxes and lasts a few minutes daily for a few days.

For the microwave ISL design, the effect of the solar conjunction can be modeled as increased sky noise temperature: The solar background temperature is about 6,000°K. The effect on overall receive system temperature (T_s) is given by

$$T_s = \alpha\, T_A + (1 - \alpha)\, T_o + T_R$$

where α = RF circuit attenuation factor for loss between antenna and receiver,

T_A = 6,000°K (sun) during solar conjunction,

T_o = 290°K (ambient temperature),

T_R = Receiver LNA temperature.

Assuming a 1-dB RF circuit loss ($\alpha \approx 0.8$) and an LNA noise figure of 8 dB, the effect of solar conjunction causes a degradation by about 6 dB in effective G/T of the ISL receive system.

The optical ISL receiver technology for solar conjunction employs narrowband optical filters to reduce the solar background noise power.

The solar background power received by diffraction-limited optics is given by [46]:

$$P_b \simeq 3.91 \times 10^{-9} \, \Delta\lambda \bullet L \, [\text{Watt}/\text{Å}] \tag{6-3}$$

where $\Delta\lambda$ is the filter bandwidth in Angstrom unit, and L is the optics loss. For 40Å filter bandwidth and a 3-dB loss for L, solar background power is

$$P_b = 7.82 \times 10^{-8} \, [\text{W}]$$

The C/N performance is degraded by a factor of 10 log $(1 + P_B/P_s)$. For the nominal design for $P_s = 1 \times 10^{-7}$ W, for a 1-Gbit/s ISL, solar background causes a degradation by about 2.5 dB in the ISL link C/N compared to a black-sky condition. The overall link performance (including the up-/ISL/down-links) could encounter a C/N loss by about 1 dB during solar conjunction. The up-/down-link C/N is 14 dB typical, and an ISL link C/N of 17 dB is assumed in this link calculation.

A decreased bandwidth of the optical filter reduces the effect of solar conjunction. However, various sources of tolerances that are imposed by device performance characteristics must be included in the selection of the optical filter. A typical spectral error budget of the optical receiver design is shown below:

- Laser diode:

Temperature Stability (1°C)	2Å
Device Aging	10
Device Selection	20

- Optical filter:

Temperature Stability (10°C)	4
Aging	4
Total	40Å

The design considerations of tracking receivers under solar conjunction are similar to those of the communications receivers.

The improvement of stability performance of single-mode laser diodes will allow a narrower optical bandwidth in the receiver design, minimizing the effect of solar conjunction in the ISL network.

6.2.2.4 Issues of Heterodyne System Using Diode Lasers

The single-mode diode laser technology has been developed primarily for fiber-optics communications using direct detection as well as heterodyne or coherent detection systems. Direct detection systems were considered in the optical ISL payload implementation in the previous subsections.

A heterodyne detection system needs an optical local oscillator to produce an intermediate frequency (heterodyne detection) or a baseband (homodyne detection) signal output from the received optical field. When the local oscillator power is high, a near quantum-limited system performance could be achieved. The quantum-limited system performance is given by [47]:

$$C/N = \frac{R_o P_s}{q B_n} \tag{6-4}$$

The parameters in equation (6-4) are the same as those identified in equation (6-1).

A comparison of equations (6-1) and (6-4) shows that a heterodyne detection system could provide an improvement in C/N by a factor of 10 log $[4\ F(M)\ (1 + P_b/P_s)]$ over a direct detection system using APDs. This indicates significant potential systems advantages of the heterodyne system [48,49]:

- At least 10-dB better theoretical performance over a direct detection system at the 0.85-μm region,
- Not limited by the background noise, P_b.

However, the disadvantages are:

- Extremely stable single frequency laser diode sources required,
- Heterodyne receiver complexity, and
- High sensitivity in performance dependence on environmental parameters such as temperature changes.

Actually, a PSK-homodyne (and FSK-heterodyne) system has demonstrated a receiver sensitivity improvement of 7.4 dB from the Si-APD detection level [50]. Lincoln Labs' Lasercom experiment on board the ACTS spacecraft should demonstrate the degree of practical advantage achievable with the heterodyne system, providing a realistic link budget of the flight system.

The selection between a direct detection and a heterodyne detection system will eventually depend on the applications and environmental effects. It should be noted that the development of noise-free avalanche photodetectors could make a direct detection system potentially near quantum-limited as well. Therefore, the advanced solid-state photomultiplier technology in the 1990s will make the simpler direct detection system quite suitable for the ISL applications.

6.2.3 PAYLOAD SYSTEM AND IN-ORBIT TESTING

A payload system design (an 8-Gbit/s ISL terminal as a baseline) is to be based on the space hardware technology available at the end of 1990. The key issues of payload subsystem technologies were discussed in Subsection 6.2.2.

The objective of the ISL payload system design will be to develop technical specifications of the flight model through a study on:

- Optimum communications payload configurations and mass/power/size requirements. A detailed design parameter trade-off study is to be performed.
- ISL interface requirements and implement strategy.
- Reliability assessment and redundancy provisions.
- Impact on the host spacecraft bus and launch vehicle requirement.

A technology and procedure to test the ISL communications subsystems when the spacecraft is launched into orbit needs to be developed. The in-orbit test provides payload performance data after it is launched into the geostationary orbit. By comparing the in-orbit test data with the corresponding prelaunch acceptance test data, acceptable performance of the ISL payload can be determined.

Major parameter to be measured include:

- e.i.r.p.,
- Carrier frequency or wavelengths,
- ISL antenna gain,
- Pointing, acquisition, and tracking performance.

The development of an ISL in-orbit testing technique can be performed in two categories:

a. A single ISL payload terminal,
b. A complete link consisting of two ISL payload terminals.

When a single spacecraft with an ISL terminal is launched into orbit, an initial in-orbit testing can be performed using a ground control station which is equipped with the corresponding ISL terminal. The ISL antenna on board the spacecraft must be steered by ground command to point toward the ground terminal. The space-to-earth link is then used for the preliminary in-orbit testing. Atmospheric effects on an optical link must be calibrated carefully to derive the free space optical link performance from the measured data.

When two spacecraft, each with east-facing and west-facing ISL terminals, are placed in-orbit, a complete ISL link performance testing can be conducted. The space-to-space link provides an actual operating environment. The ISL performance testing may require specific provisions of the ISL terminals, such as loopback channel connectivity if a single earth station access for up-link and down-link is used. The ISL in-orbit testing with two or multiple individual earth stations needs proper coordination for the testing. The in-orbit testing of an ISL actually involves indirect measurements. The ISL link performance must be derived from the overall link performance data including up-link, ISL, and down-link.

In addition, on-station performance monitoring of the ISL communications systems is required during active traffic transmissions. The performance monitoring provides information on the health of the ISL payloads.

Various techniques of in-orbit testing and on-station monitoring measurements have been developed for non-ISL satellites [51],[52]. These techniques should be refined and modified for applications to the ISL satellite network.

The Doppler effect must be calibrated in ISL frequency measurements. Relative velocity between two GEO satellites is 3-m/sec typical, resulting in a frequency shift by a factor of 1 x 10^{-8}. A 60-GHz ISL and an 0.85-µm optical ISL can encounter a Doppler shift, as shown below.

Parameter	60-GHz ISL	0.85-µm Optical ISL
Carrier Frequency f_0 [Hz]	6×10^{10}	3.53×10^{14}
Doppler Shift Frequency Δf [Hz]	6×10^{2}	3.53×10^{6}
Receiver Bandwidth Minimum	600 Hz	3.6 MHz

The Doppler effect on the ISL does not impose any restriction to the ISL receive subsystem design, provided the receiver bandwidth includes a margin given above.

6.2.4 PROGRAM COST/RISK ESTIMATE

In accordance with the technology development scenarios (Subsection 6.1.1.2) and the SOA technology assessment in Subsection 6.2, technology development programs of critical ISL subsystems were identified. Table 6-10 shows the priority, cost, and risk estimates of those programs. The cost is based on engineering manpower estimate and materials for the programs. The major test facility and the 1986 SOA hardware applicable to each of the programs were assumed available and were not included in the cost estimate. The program schedule was described in Subsection 6.1.1.2

The flight ISL payload cost estimate per terminal is based on the cost analysis described in Section 5. Table 6-11 shows the cost breakdown of major subsystems for (a) 7.6-Gbit/s ISL and (b) 1.2 Gbit/s ISL. It should be noted that additional costs related to spacecraft bus subsystems and the launch vehicle are not included in this estimate (Table 6-11).

For the ISL applications described in Sections 4 and 5, the ISL payload systems total cost is estimated in Table 6-12.

Table 6-10. Program Cost/Risk Estimate

Program	Priority	Cost [$M]	Risk
A. Microwave ISL			
● 60-GHz TWT Reliability Test	1	0.5	Very Low
B. Optical ISL			
● 8-Gbit/s Diode Laser Transmitter	1		
- Laser Diodes/Space Qualification		1.5	High
- Modulator/Baseband Processor		2.0	Medium
- Transmitter System/Interface		2.5	Low
● PAT System	2		
- Dynamic Model Performance Analysis		0.3	Low
- Critical Subsystem Implementation		2.0	Medium
- Testing and Performance Verification		1.5	Low
● Payload System Design	4	0.3	Low
● In-Orbit Testing Technique Development	3	0.5	Low
C. Flight ISL P/L Development			
● Space-Qualified Payload		34	High

Table 6-11. Optical 30° ISL Payload Cost Estimate [$M, 1986]

Subsystem	7.6-Gbit/s ISL		1.2-Gbit/s ISL	
	Nonrecurring Cost	Recurring Cost	Nonrecurring Cost	Recurring Cost
• Pointing/Acquisition/ Tracking	11.207	5.604	6.489	3.244
• Repeater	5.186	0.749	4.641	0.600
• Thermal Control	0.126	0.184	0.062	0.117
• P/L Total	16.519	6.536	11.191	3.961
• Program Management	7.417	2.902	5.025	1.759
Program Total	23.936	9.438	16.216	5.720
	33.374		21.936	

Table 6-12. ISL Payload Systems
Total Cost Estimate

No.	ISL Applications	Cost[a] ($M, 1986)
1	CONUS-4 Zone Coverage	147.3 (207.1)[b]
2	CONUS-Europe	29.2
	North America-Europe	29.8
3	CONUS-POR	25.6
	CONUS-AOR	27.7
4	ITU Region 1-AOR	35.7
	ITU Region 1-IOR	26.4
5	ITU Regions 1-2	51.1
	ITU Regions 2-3	35.8
	ITU Regions 3-1	38.6

[a]Noncurring and recurring costs plus program management cost (about 45%).
[b]Including launch cost (based on $35K per kg of add-on dry mass.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

Potential applications of intersatellite links to domestic, regional, and global satellite communications services were identified through comprehensive investigations on fundamental systems characteristics of ISLs and satellite-addressable traffic models.

An ISL (30° typical) is cost-effective for applications where the intersatellite traffic requirement is large, exceeding about eight 36-MHz equivalent transponder capacity. The 4,500 half-voice circuits per 36-MHz transponder technology for the year 2000 time frame was assumed in the analysis. Employing a transmission technology of 8 kbit/s per half-voice circuit, the 30°-to-70° ISLs are cost-effective, in a statistical sense, when the ISL capacity exceeds 300 Mbit/s to 360 Mbit/s. The cost-effectiveness of ISLs was determined from detailed cost analyses of the "add-on" systems with reference to the corresponding non-ISL satellite systems which provide the same services.

A. Cost-Effective ISL Applications

ISL applications for U.S. domestic services could provide the largest systems cost benefit. CONUS ISLs interconnecting four time-zone coverage satellites, as an example, are cost advantageous over the non-ISL satellite systems in two architectures when:

- The figure of merit of the on-station host spacecraft is larger than $0.01 to 0.02 million per 36-MHz equivalent transponder per year in the double-hop system (Architecture I), or
- The number of major earth station nodes exceeds 20 ($\pm$7) in a conventional multiple-antenna earth station system (Architecture II).

Currently a domestic transponder cost (launch plus satellite cost) is approximately $0.2 million per year. This indicates that the ISL system is more cost-effective than the corresponding non-ISL system unless the space segment cost per transponder is reduced to about 1/20 of the present cost.

The current population of transmit and receive earth stations is more than 550 within the U.S. Some earth stations may need connectivity to more than one CONUS satellite. The number of major earth station nodes which require full access to the CONUS satellites in the non-ISL system (Architecture II) is estimated to exceed 30 as a minimum. Therefore, the CONUS applications are more cost-effective than the non-ISL system for both cases: (a) Architecture I for the double-hop network, and (b) Architecture II for the multiantenna earth station network.

Other cost-effective applications of ISLs for the year 2001 time frame are:

- CONUS-to-Europe, and North America-to-Europe,
- CONUS-to-AOR international communications,
- ITU Region 1-to-AOR international communications,
- ITU Region 1-to-Region 2.

Marginal cases from cost considerations alone are the ISL applications for

- ITU Region 1-to-IOR international,
- ITU Region 2-to-Region 3,
- ITU Region 1-to-Region 3.

The ISL systems cost-advantage ratio of each application was quantified, as shown in Table 5-8.

B. Other Systems Benefits

In addition to the quantified cost-effectiveness, ISL applications provide a number of systems benefits in operational and planning aspects:

- The expansion capability of useful orbital arc, which alleviates the prime orbital slot allocation problem in existing satellite systems,
- An effective conservation of the FSS bandwidth by avoiding multiple hopping of the existing network,
- A fundamental role of the ISL that could be a key systems driver for evolutionary development of completely new satellite networks based on domestic and regional satellites.

The FSS offered by existing systems can be improved and expanded with ISL applications. The coverage extension with ISLs allows more users direct access to the satellite network, providing reduced transmission time delay and improved quality of transmission. As a result, ISL applications can increase the effectiveness of satellite communications and provide more cost-competitive services.

ISLs cross-linking regional/domestic satellites can lead eventually to a new global satellite network architecture. The existing three ocean region international satellite system for global coverage could be replaced by three ITU regional satellite systems employing ISLs. The coverage of world land masses can, then, be increased by about 15 percent for K_a-band satellite services. The integrated space segment encompassing a "switchboards in the sky" concept will be evolved with the introduction of ISLs.

C. Intercluster ($\leq$ 0.1°) ISL

ISLs interconnecting colocated small satellites can be used to implement a functionally large satellite in a time-phased way. Each satellite is virtually a part of the large spacecraft through a frequency band division or time divisions. Cross strapping between individual satellites is provided by ISLs.

The colocated partitioned satellites without ISLs can function as a virtual large satellite if traffic cross strapping between the satellites is provided on the ground.

A single large platform payload can provide large cost-benefit advantages because of the high ratio of payload-to-spacecraft housekeeping requirements. Traffic interconnectivity is achieved entirely with the on-board switching network. The only technological constraint is the launch vehicle limitation. Space assembly of the payload may be needed if a payload is excessively large beyond the current STS capability.

It was determined that intercluster ISLs do not provide any significant systems advantage over the partitioned small satellites without ISL. In the year 2000 time frame, a large platform payload with or without space assembly is most likely to be implemented as the most cost-effective space segment approach.

D. Optical ISL as the Technology Driver

The averaged total cost ratio between an optical ISL employing diode lasers and the corresponding microwave (60 GHz) ISL is 1.075. The optical payload cost is higher by about 7.5 percent. However, this difference is not considered significant, and it is determined that a 60-GHz ISL and a 0.85-μm optical ISL payload for applications to cross linking isolated satellites (30°-70° ISL) are almost cost-competitive.

The large-sized antenna requirement (2 m in diameter typical) of a 60-GHz ISL payload imposes real-estate problem and constraints for integration to the host spacecraft. There are also possibilities of harmful intersystem as well as intrasystem interference in the microwave band for frequency sharing with other radio services within the ITU allocation.

Optical frequencies are completely free from interference, and no intersystem coordination is needed for optical ISL implementation. There is basically no bandwidth limitation with an optical carrier. The compact sized ISL payload, even if it is somewhat heavier than the microwave counterpart, is advantageous for integration to the host spacecraft. The interface requirement between the host spacecraft and the ISL payload is approximately the same for optical and microwave implementations.

For these reasons, optical ISL implementations were taken as the technology driver for the future FSS communications services in this study.

E. ISL Technology Development Scenarios

The following critical ISL technology areas were identified:

- Laser transmitter lifetime/reliability improvement to support a 10-to-12 year mission in space.
- Pointing, acquisition, and tracking subsystem performance verification in the in-orbit dynamic mode operation.

The following scenarios were developed for critical technologies to meet the first launch taking place in 1993-94:

- NASA should support ongoing Lasercom component R&D programs to ensure their availability by the end of 1989,
- Develop critical subsystems and ISL payload system specifications, including in-orbit testing programs by the end of 1990,
- Develop a prototype flight ISL payload in 1990-1993.

F. ISL Network Systems Implementation

The evolving ISL network initiated by the U.S. domestic and European regional applications can be developed in a number of possible alternative paths. A mature ISL network will lead to three ITU regional ISL systems. For the introduction and widespread use of ISLs, NASA's leadership role toward commercial communications applications is indispensable. An ISL is a long-term, high risk technology to private industry. It would be profitable only when a large transmission capacity (i.e., exceeding 300 Mbit/s rate) cross-link services are required.

NASA should develop the CONUS ISL network system as an integral part of the next generation GEO platform payloads. Widespread use of ISLs may be possible in a long-range time frame, beginning in the early 2000s.

G. Critical Technology Programs

Critical technology areas were identified through the assessment of the state-of-the-art technologies each for microwave and optical ISL implementations.

- Pointing, Acquisition, and Tracking (PAT Subsystem)

  - The SOA microwave technology has been well developed, and there is no critical area that needs further development.
  - The SOA performance of the optical PAT subsystem is capable of providing a fine pointing accuracy of about 0.2-μ radian (at one standard deviation of noise equivalent angle) in a laboratory environment. Limited information is available currently for the assessment of the optical PAT performance in a dynamic GEO spacecraft environment including in-orbit stationkeeping maneuvers. It needs further study through detailed analysis and/or simulation of the host spacecraft dynamics impact on the optical PAT performance and its associated design specifications.

- **Transmitters and Receivers**

  - At 60 GHz, space-qualified performance of NASA-developed TWTAs needs to be demonstrated through further testing. Thermal vacuum temperature cycling performance tests should be adequate. The implementation of 60-GHz ISLs does not require any other new development programs for components.
  - For optical implementation, the critical components to be developed are:

    - Diode laser sources; single-mode high output ($\geq$100 mW), 10-year lifetime, and spectral stability over the life to be better than a few Angstroms.
    - Staircase avalanche photodiodes to reduce the excess noise factor at least by a factor 2 in the direct detection receiver.

- **Design for Solar Conjunction**

  The SOA technology shows that the narrowband optical filter bandwidth that can be used to minimize the solar background noise power is limited to about 40 Å. It causes a degradation of ISL link performance (C/N) by about 2.5 dB. Further improvement is possible with more stable spectral performance of laser diodes.

- **Issues of Heterodyne System Using Diode Lasers**

  The selection between a direct detection and a heterodyne detection system will eventually depend on specific applications and environmental effects. The development of noise-free avalanche photodetectors will provide a direct detection system performance approaching the near quantum-limited heterodyne performance.

- <u>In-Orbit Testing</u>

  New test methodology must be developed for in-orbit testing and on-station performance monitoring of the ISL communications system. Adequate provisions must be made also for TT&C and the ISL payload.

The program schedule, cost, and risk estimates for major subsystems technologies are provided in Table 6-1 and Table 6-10, respectively. The cost estimates of baseline ISL payloads, including nonrecurring and recurring costs, are given in Table 6-11. Table 6-12 shows the ISL payload systems total cost for the selected ISL applications.

7.2 RECOMMENDATIONS

Based on the results of this study, the following recommendations are drawn:

a. NASA should support the ongoing Lasercom components R&D programs to obtain space-qualified devices by the end of 1989 and initiate system-level ISL payload design studies.

   The critical components technology identified in NASA's Lasercom program are consistent with the basic technology requirements identified in this study:

- GaAlAs Diode Laser,
- Laser Beam Combining,
- Solid-State Photomultiplier (Staircase APD),

The system level payload design study is needed for the development of flight ISL specifications for preoperational commercial systems. The critical subsystems technology programs described in Section 6 should be supported for the development of the first ISL payload to be launched in 1993-94.

b. The emerging fiber-optics impact on the cost-effectiveness of the ISL applications should be assessed in a follow-on study. The satellite-addressable traffic models used in this study may need modifications due to the competitive nature of the two technologies (re: Figure 6-6):

- Decreased satellite traffic volume for trunk-line services.
- Increased satellite traffic for customer premises services (CPS) using VSATs, mobile satellite services, and possibly DBS services in the future.

The satellite network architectures for ISL-CPS services could employ a multicarrier FDMA up-link and a single-carrier TDMA down-link scheme, or some other approaches. Cost analyses and systems benefit evaluation for ISL-CPS vs the corresponding fiber cable network are needed to assess the ISL systems advantages further.

In addition, the technology needs of ISLs for future global ISDN approaches should be evaluated as a part of the follow-on study.

c. The extremely high precision performance of the pointing, acquisition, and tracking (PAT) subsystem is prerequisite for an ISL. The state-of-the-art optical technology indicates pointing accuracies of about 0.2-μ radian (1 σ) achievable in the laboratory environment. The implementation of an ISL for commercial communications demands satisfactory performance verification of the PAT subsystem in the on-station dynamic environment, including the effects of frequent stationkeeping maneuvers of geostationary satellites. NASA should support a study on this issue to derive the specifications of the ISL payload for commercial communications.

d. NASA should plan CONUS ISL network systems as an integral part of the GEO platform payloads which do not exceed the STS launch capability. The ISL applications to CONUS will provide more cost-effective services than the corresponding non-ISL CONUS satellite system.

NASA should initiate an effort to develop domestic and international standards and protocols for the ISL interface network. Institutional and operational planning toward mature three regional ISL network systems in a long range time frame (2000s) needs further study.

8. REFERENCES

[1] A. C. Clarke, "Extra-Terrestrial Relays--Can Rocket Stations Give Worldwide Radio Coverage?" Wireless World, October 1945, pp. 305-308.

[2] W. W. Ward, D. M. Snider, and R. F. Bauer, "A Review of Seven Years of Orbital Service by the LES-8/9 EHF Intersatellite Links," IEEE International Conference on Communications, June 20-23, 1983, pp. 1171-1180.

[3] D. K. Sachdev and T. Chidambaram, "Intersatellite Links for International Communications, Conference Record, 1981 IEEE International Conference on Communications, June 14-18, 1981, pp. 70.2.1-70.2.6.

[4] G. R. Welti, "Microwave Intersatellite Links for Communications Satellites," Conference Record, IEEE International Conference on Communications, June 14-17, 1982.

[5] G. R. Welti and Y. S. Lee, "Study of Intersatellite Links," Task 6 Final Report of Planning Assistance for the 30/20 GHz Program. Contract No. NAS3-22905, November 1981.

[6] Y. S. Lee and R. E. Eaves, "Implementation Issues of Intersatellite Links for Future INTELSAT Requirements," IEEE International Conference on Communications, June 20-23, 1983, pp. 1189-1195.

[7] COMSAT ITS, "Intersatellite Link Implementation On-Board INTELSAT VI," Final Report submitted to INTELSAT, February 1982.

[8] Denise S. Ponchak and Rodney L. Spence, "Application of Intersatellite Links to Domestic Satellite Systems," Conference Proceedings, 11th Communications Satellite Systems Conference of AIAA, March 16-20, 1986, pp. 29-38.

[9] ITU, The Radio Regulations, Edition of 1982, Geneva.

[10] R. Lovell and C. L. Cuccia, "Global Interconnectivity in the Next Two Decades--A Scenario," 11th AIAA Communications Satellite Systems Conference, Conference Proceedings, March 17-20, 1986, pp. 39-49.

[11] J. E. Board, "Concept for a Worldwide Satellite Integrated Services Digital Network," 11th AIAA Communications Satellite Systems Conference, Conference Proceedings, March 17-20, 1986, pp. 92-100.

[12] N. Shacham, et al., "Speech Transport in Packet-Radio Networks with Mobile Nodes," IEEE Journal on Selected Areas in Communications, Vol. SAC-1, No. 6, December 1983, pp. 1084-1097.

[13] A. Gatfield, "Error Control on Satellite Channels using ARQ Techniques, COMSAT Technical Review, Vol. 6, Spring 1976, pp. 179-188.

[14] FCC Report and Order, "Licensing of Space Stations in the Domestic Fixed-Satellite Service and Related Revisions of Part 25 of the Rules and Regulations," CC Docket No. 81-704, released on August 16, 1983.

[15] D. Ponchak, Private Communication, May 20, 1986.

[16] S. Stevenson, W. Poley, and J. Salzman, "Demand for Satellite-Provided Domestic Communications Services to the Year 2000," NASA TM-86894, November 1984.

[17] W. Poley et al., "A Comparison of Domestic Satellite Communications Forecasts to the Year 2000," NASA TM-83516, October 1983.

[18] INTELSAT, "The INTELSAT Traffic Data Base Resulting from the 1984 Global Traffic Meeting," August 13, 1984.

[19] FCC WARC-85 Advisory Committee, "First Report on the Advisory Committee for the ITU's World Administrative Radio Conference on the Use of the Geostationary-Satellite Orbit and the Planning of the Space Services Utilizing It," December 1983.

[20] J. E. Hollansworth, J. A. Salzman, and J. R. Ramler, "Telecommunications Forecast for ITU Region 2 to the Year 1995," NASA Technical Memorandum 87077, August 1985.

[21] G. Smith and G. Berretta, "Geostationary Orbit Capacity in Relation to Services Expansion and Technology Development," AIAA 9th Communication Satellite Systems Conference, March 7-11, 1982.

[22] W. R. Schnicke, J. B. Binckes, and D. H. Lewis, "Transponder Supply/Demand Analysis for the Geostationary Orbit," COMSAT Technical Review, Vol. 14, No. 2, Fall 1984, pp. 339-368.

[23] General Electric, "Intersatellite Link Communications Antenna," Final Report submitted to INTELSAT, Contract No. INTEL-054, November 1983.

[24] COMSAT, "Spacecraft Subsystem and Components Data Base; Volume 2, The Source Book," Final Report for Contract INTEL-317, Subtask TSC-317-85-322, submitted to INTELSAT in October 1985.

[25] NASA Goddard Space Flight Center, "The Direct Detection Laser Transceiver, DDLT," in RFP 5-90143/237, June 10, 1986.

[26] J. B. Abshire, "Performance of OOK and Low-Order PPM Modulations in Optical Communications when using APD-Based Receivers," IEEE Transactions on Communications, Vol. COM-32, No. 10, October 1984, pp. 1140-1143.

[27] J. A. Vandenkerckhove, "Economics of Telecommunications Space Segments," 34th Congress of the International Astronautical Federation, IAF-83-234, October 10-15, 1983.

[28] Ford Aerospace and Communications Corporation, "Communication Platform Payload Definition Study Final Report," NASA Lewis Research Center, Contract No. NAS3-24235, March 1986.

[29] RCA Astro-Electronics, "Communications Platform Payload Definition Study," Final Report, NASA Lewis Research Center, Contract No. NAS3-24236, July 1986.

[30] P. W. Young, L. M. Germann, and R. Nelson, "Pointing, Acquisition, and Tracking Subsystem for Space-Based Laser Communications," SPIE Proceedings, Vol. 616, Optical Technologies for Communication Satellite Applications, January 1986, pp. 118-128.

[31] NASA Lewis Research Center, "NASA Communications Industry Briefing--Summer '86," July 22-23, 1986.

[32] Richard L. Moat, " ACTS Baseband Processing," IEEE Global Telecommunications Conference, December 1-4, 1986, Conference Record, pp. 578-583.

[33] R. R. Lowell and C. Louis Cuccia, "NASA's Communication Program Examined for the 1980s and 1990s--Part I and II," Microwave Systems News and Communications Technology, August 1986, pp. 79-90 (Part I) and November 1986, pp. 132-139 (Part II).

[34] M. W. Fitzmaurice, "Advanced Communications Technology Satellite--Laser Communications Package," presented at the NASA Communications Industry Briefing--Summer '86," July 22-23, 1986.

[35] L. Frecon, J. C. Boutemy, and E. Sein, "The Use of Optical Intersatellite Links for European Relay System," SPIE Proceedings, Vol. 616, Optical Technologies for Communication Satellite Applications, 1986, pp. 49-68.

[36] H. Lutz, "Optical Inter-Satellite Links," ESA Bulletin No. 45, February 1986, pp. 74-80.

[37] E. W. Ashford, D. L. Brown, and K. G. Lenhart, "The ESA Data-Relay Satellite Programme," ESA Bulletin No. 47, 1986, pp. 15-20.

[38] J. M. Lopez and K. Yong, "Acquisition, Tracking, and Fine Pointing Control of Space-Based Laser Communication Systems," SPIE Proceedings, Vol. 295, Control and Communication Technology in Laser Systems," 1981, pp. 100-114.

[39] E. Sein et al., "Acquisition and Fine-Pointing Control for a 400-Mbps Link Between a Low-Earth Orbiter and a Geostationary Satellite," SPIE Proceedings, Vol. 616, Optical Technologies for Communication Satellite Applications, 1986, pp. 141-159.

[40] Hughes Aircraft Co., "A Study to Define the Impact of Laser COmmunication Systems on Their Host Spacecraft," Final Report for Contract NAS5-27139, NASA CR-175272, April 1984.

[41] G. Koepf, R. Peters, and R. Marshalek, "Analysis of Burst Error Occurrence on Optical Intersatellite Link (ISL) Design," SPIE Proceedings, Vol. 616, Optical Technologies for Communication Satellite Applications," 1986, pp. 129-136.

[42] J. Dale Barry, "Design and System Requirements Imposed by the Selection of GaAs/GaAlAs Single Mode Laser Diodes for Free Space Optical Communications," IEEE Journal of

Quantum Electronics, Vol. QE-20, No. 5, May 1984, pp. 478-491.

[43] W. L. Casey, "Design of a Wideband Free-Space Lasercom Transmitter," SPIE Proceedings, Vol. 616, Optical Technologies for Communication Satellite Applications, 1986, pp. 92-99.

[44] R. J. Smith, "Wideband Lasercom Transmitter Performance," SPIE Proceedings, Vol. 616, Optical Technologies for Communication Satellite Applications, 1986, pp. 100-104.

[45] M. Sholley and A. Nichols, "60 and 70 GHz (HEMT) Amplifiers," 1986 IEEE MTT-S International Microwave Symposium Digest, June 2-4, 1986, pp. 463-465.

[46] D. Paul, "Estimation of Background Radiation in Optical ISLs," COMSAT Labs Technical Note, December 17, 1985.

[47] R. M. Gagliardi and S. Karp, "Optical Communications," New York, N.Y.: John Wiley & Sons, 1976. Chapter 6.

[48] V. Chan, L. Jeromin, and J. Kaufmann, "Heterodyne LASERCOM Systems using GaAs Lasers for ISL Applications," Conference Record, IEEE International Conference on Communications, June 19-22, 1983.

[49] J. E. Kaufmann and L. L. Jeromin, "Optical Heterodyne Intersatellite Links using Semiconductor Laser," IEEE Global Telecommunications Conference, November 26-29, 1984, pp. 961-968.

[50] Y. Yamamoto, "Heterodyne Versus Direct Detection," Proceedings of the Fifteenth National Science Foundation Grantee-User Meeting on Optical Communication Systems, June 1-3, 1983, pp. 153-170.

[51] J. Potukuchi, F. T. Assal, and R. C. Mott, "A Computer-Controlled Satellite Communications Monitoring System for Time Division Multiple Access," COMSAT Technical Review, Volume 14, No. 2, Fall 1984, pp. 391-430.

[52] I. Dostis et al., "In-Orbit Testing of Communications Satellites," COMSAT Technical Review, Vol. 7, No. 1, Spring 1977, pp. 197-226.

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APPENDIX A. TRAFFIC GROUPING PROGRAM

A.1 INTRODUCTION

For a given traffic matrix of a large number of earth stations, the program reduces the traffic matrix for any specified small number of constituent groups of earth stations. This program is useful in estimating the space segment and ISL capacity requirements.

The derivation of the analysis equations is described below. A sample example of the computer program usage is described in this appendix.

A.2 ANALYSIS

The N x N traffic matrix, T, denotes the amount of traffic (in number of equivalent voice circuits) from one earth station (E/S) to another. For a set of N earth stations, let E denote the set of E/S numbers from 1 to N:

$$E = \{1, 2, 3, \ldots, N\}$$

The objective is to compute the traffic maxtrix for any specified small number of E/S groups, M, where M is usually much less than N. Let GE denote the specified set of E/S groupings (i.e., a partition of set E).

$$GE = \bigcup_{L=1}^{M} G_i$$

$$G_i \cap G_j = 0 \text{ (null set)}, \; 1 \leq i \neq j \leq M$$

$$G_i \subset E$$

$$|G_i| = \text{dimension of set } G_i$$

$$N = \sum_{i=1}^{M} |G_i|$$

The M groups of earth stations, as defined, partition the T matrix into M^2 submatrices. Therefore, each element of the reduced (or group) traffic matrix, TG, is equal to the sum of all the elements of the corresponding submatrix.

$$TG(I1,J1) = \sum_{\ell=L1}^{L2} \sum_{k=K1}^{K2} T(IGE(k),IGE(\ell))$$

$$TG(I1,J1) = (I1,J1) \text{ element of TG}, \; 1 \leq I1, \; J1 \leq M$$

IGE: one dimensional array whose first $|G_1|$ elements are elements of G_1, next $|G_2|$ elements are elements of G_2, etc., and last $|G_M|$ elements are elements of G_M.

$$K2 = \sum_{i=1}^{I1} |G_i|$$

$$K1 = K2 - |G_{I1}| + 1$$

$$L2 = \sum_{J=1}^{J1} |G_j|$$

$$L1 = L2 - |G_{J1}| + 1$$

The computer program computes the elements of the traffic group matrix as derived in the above equations.

A.3 PROGRAM

The flowchart of the program is shown in Figure A-1. A sample run and a listing of input/output data is given below.

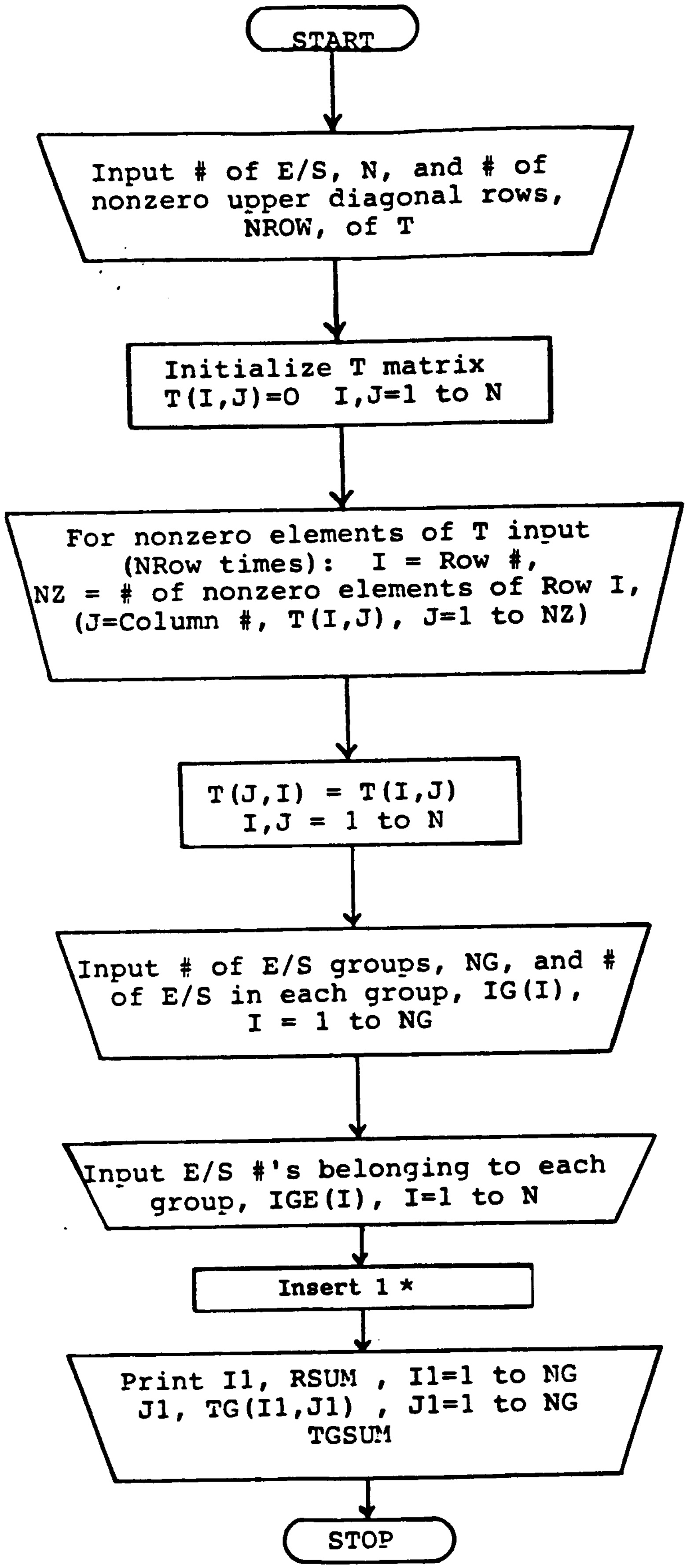
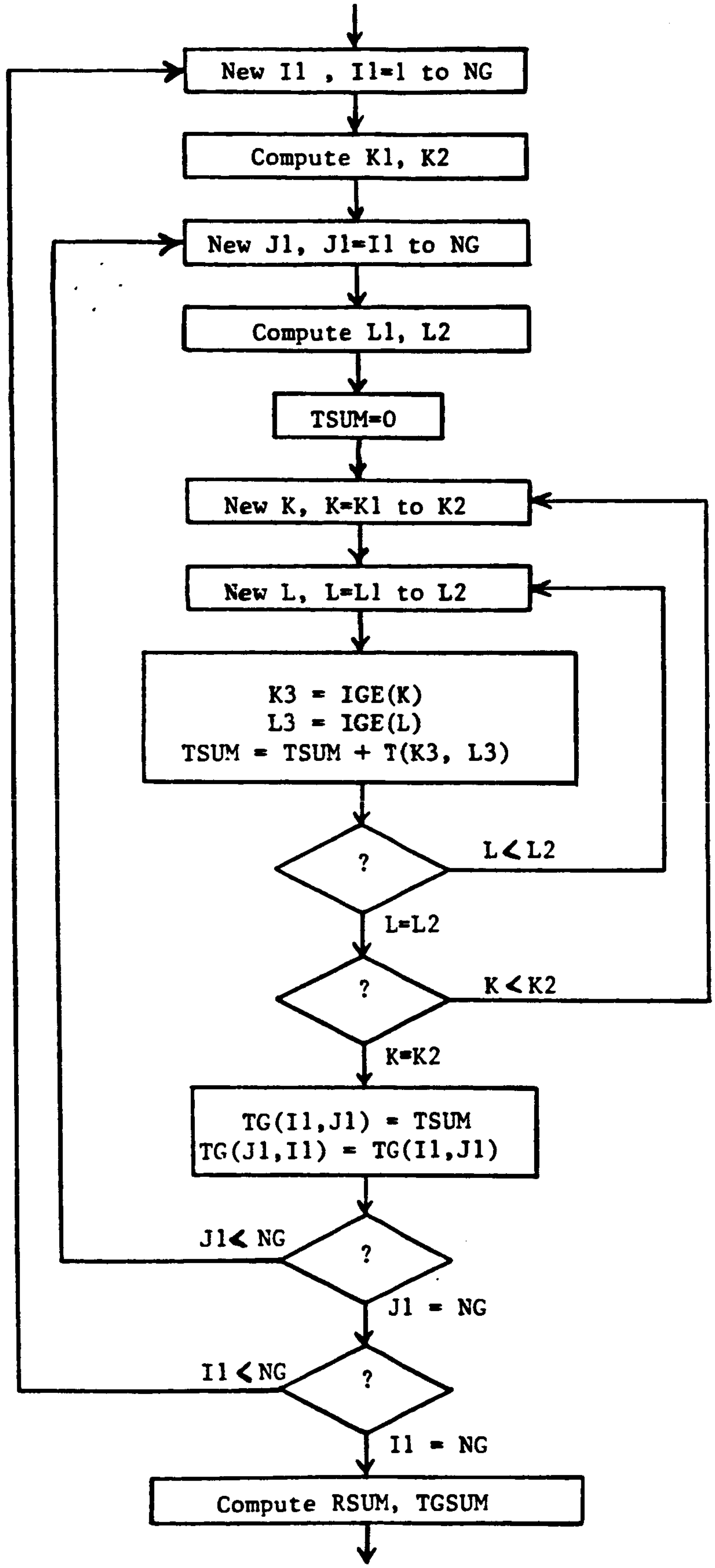


Figure A-1. Program Flowchart



Insert 1* (Cont.)

Figure A-1. Program Flowchart (Cont.)

Table A-1. List of Countries and a Grouping for POR-1995

Country	Number
Australia	1
Canada	2
China (Pek)	3
China (Tai)	4
Fiji	5
France (N.C)	6
Hong Kong	7
Indonesia	8
Japan	9
Korea	10
Malaysia	11
Mexico	12
New Zealand	13
Philippines	14
Singapore	15
Thailand	16
U.S.-Guam	17
U.S.-Haw	18
U.S.	19

Group 1: U.S.-Haw., U.S.

Group 2: Canada

Group 3: Mexico

Group 4: China (Pek), China (Tai), Hong Kong, Japan, Korea, Malaysia, Singapore, Thailand

Group 5: Australia, Fiji, France (N.C) Indonesia, New Zealand, Philippines, U.S.-Guam

TABLE A-1. List of Countries and
a Grouping for POR-1995 (Cont.)

```
.t tp95 data

19 17
1 17 2 292 3 27 4 24 6 47 7 389 8 91 9 274 10 49 11 100 12 22 13 285
 14 16 15 220 16 41 17 10 18 50 19 1240
2 12 3 11 4 45 7 150 8 24 9 87 10 30 11 70 13 12 14 59 15 77 16 11 18 13
3 8 7 142 9 49 11 20 14 11 15 98 16 13 18 4 19 234
4 10 8 48 9 350 10 113 11 117 13 9 15 42 16 79 17 2 18 22 19 908
5 1 10 7
6 6 7 12 9 6 13 14 14 24 15 38 19 19
7 8 8 57 9 303 10 107 13 24 16 23 17 8 18 43 19 875
8 7 9 143 10 35 11 29 13 9 16 5 18 18 19 36
9 9 11 154 12 63 13 32 14 60 15 304 16 95 17 15 18 180 19 2604
10 8 11 73 13 9 14 35 15 83 16 29 17 16 18 34 19 1497
11 3 13 21 18 15 19 560
13 5 14 8 15 15 16 7 18 15 19 185
14 3 17 8 18 40 19 602
15 3 16 86 18 39 19 590
16 2 18 9 19 297
17 2 18 56 19 160
18 1 19 1

R;
.t gp95 data

5 2 1 1 8 7
18 19
2
12
3 4 7 9 10 11 15 16
1 5 6 8 13 14 17
-
```

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Table A-1. List of Countries and a Grouping for POR-1995 (Cont.)

```
trfgrp

ENTER UNIT 7 INPUT DATA SET NAME
.tp95 data

ENTER UNIT 8 INPUT DATA SET NAME
.gp95 data

EXECUTION BEGINS...

 FROM GROUP   TO GROUP  TRAFFIC (# OF EQUIV. VOICE CIRCUITS) SUBTOTAL

 1                                                            10351.0
   1      2.0     2      13.0     3      0.0     4   7908.0
   5   2428.0
 2                                                              889.0
   1     13.0     2       0.0     3      0.0     4    489.0
   5    387.0
 3                                                               85.0
   1      0.0     2       0.0     3      0.0     4     63.0
   5     22.0
 4                                                            15189.0
   1   7908.0     2     489.0     3     63.0     4   4880.0
   5   1849.0
 5                                                             5710.0
   1   2428.0     2     387.0     3     22.0     4   1849.0
   5   1024.0

 TOTAL TRAFFIC :     32224.0
R;
```

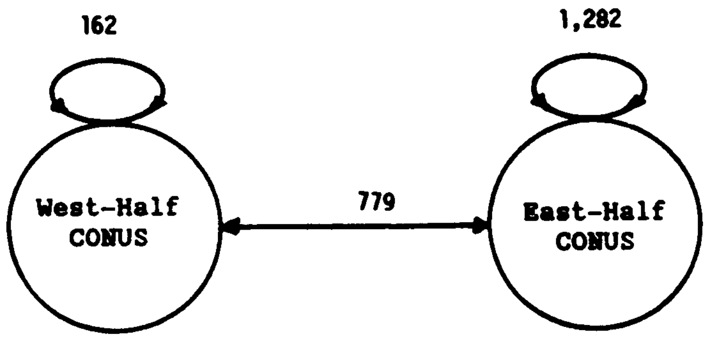
APPENDIX B. TRAFFIC DATA PACKAGE

Some results of traffic analyses are contained in this appendix. The first part includes CONUS traffic models for (a) East- and West-half coverages in Figure B-1 and (b) four time zone coverages in Figure B-2. It is based on the NASA-supplied CONUS Traffic Model for the year 2000.

The second part contains international traffic models for the years 1995 and 1998. The INTELSAT traffic data base resulting from the 1984 Global Traffic Meeting was used for this analysis. For each ocean region a grouping of countries was taken and the traffic matrix was computed for the given grouping as follows:

AOR

For the year 1995, a total of 94 countries was considered in 7 groups, as listed in Table B-1. The results of the traffic model are listed in Table B-2 and shown in Figure B-3. Table B-3 lists a grouping of 102 countries in 7 groups for AOR for the year 1998. The number of countries is increased for 1998 per the available INTELSAT traffic data base. The results of the traffic model are listed in Table B-4. Next, the traffic model was determined for the 7 regions (North America, South America, Asia, South Pacific, Europe, Middle East, and Africa) and is listed in Table B-5 and shown in Figure B-4. With reference to Table B-3, North America includes countries of Groups 1 and 2; South America includes countries of Groups 3 and 4; Europe includes countries of Group 5, the Mideast includes countries of Group 6, and Africa includes countries of Group 7.

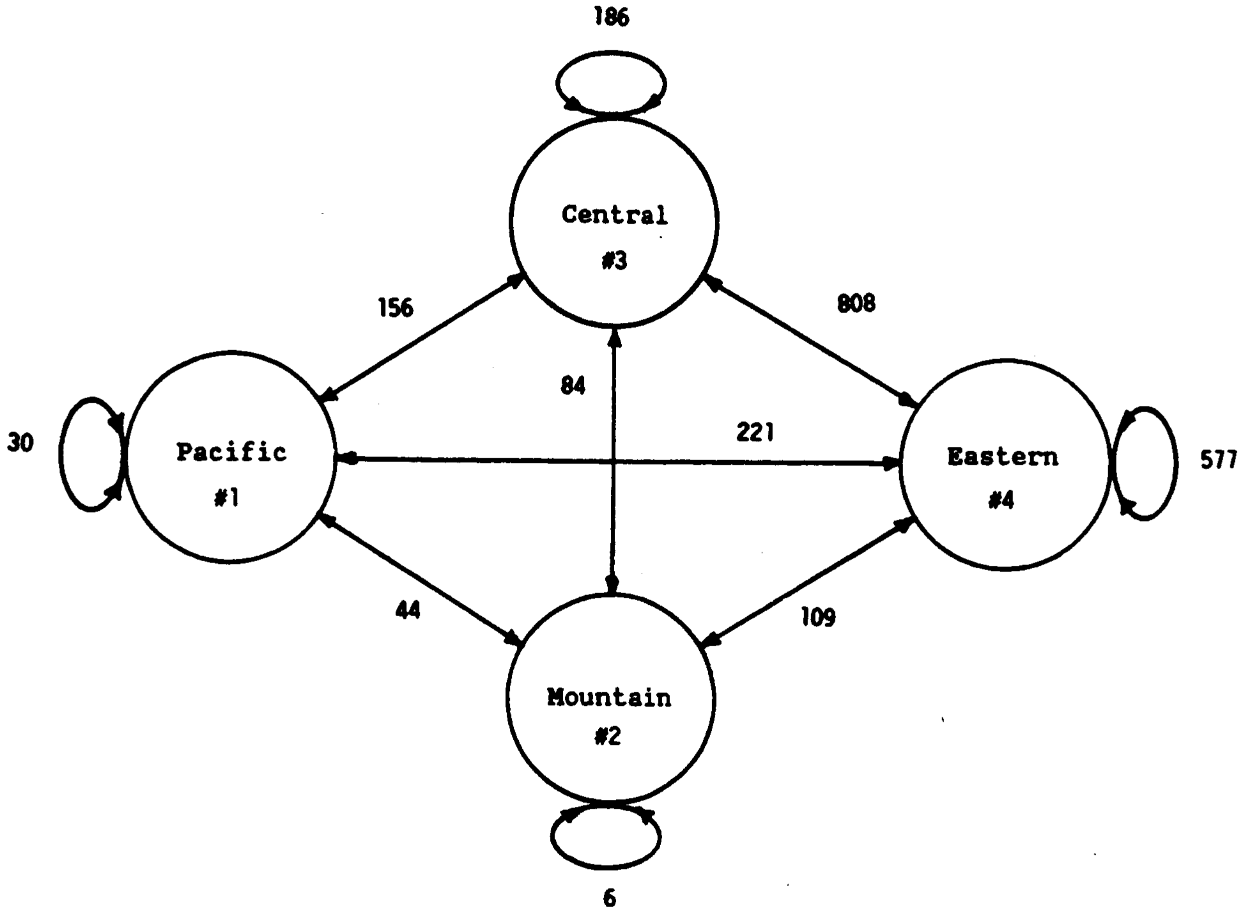


(a) Transponder Requirement

From \ To	WEST CONUS	EAST CONUS
West CONUS	728,410	1,751,460
East CONUS	1,751,460	5,768,914
Total	10,000,252	

(b) Traffic Matrix in Number of Equivalent Half-Voice Circuits

Figure B-1. East- and West-Half CONUS Coverage Traffic Model and Transponder Requirement



(a) Transponder Requirement

To / From	Pacific	Mountain	Central	Eastern
Pacific	134,346	99,335	355,445	497,504
Mountain	99,335	27,214	189,134	244,621
Central	355,445	189,134	836,138	1,818,191
Eastern	497,504	244,621	1,818,191	2,594,094
Total	10,000,252			

(b) Traffic Matrix in Numbers of Equivalent Half-Voice Circuits

Figure B-2. Four Time Zone CONUS Coverage
Traffic Model and Transponder Requirement

Table B-1. A Grouping for AOR-1995
(94 Countries)

Group 1

U.S.			

Group 2

Canada			

Group 3

Bahamas	El Salvador	Honduras	Panama
Barbados	France (MA)	Jamaica	Trinidad and Tobago
Costa Rica	Guatemala	Mexico	U.S. (PR)
Dom. Rep.	Haiti	Nicaragua	

Group 4

Argentina	Chile	France (FG)	Surinam
Bolivia	Colombia	Paraguay	Uruguay
Brazil	Equador	Peru	Venezuela

Group 5

Austria	Greece	Poland	Turkey
Belgium	Ireland	Portugal	U.K.
Cyprus	Italy	Romania	U.S.S.R.
France	Netherlands	Spain	Yugoslavia
Germany, FR	Nordic Grp	Switzerland	

Group 6

Algeria	Iran	Mali	Sudan
Angola	Iraq	Mauritania	Tanzania
Bahrain	Israel	Morocco	Togo
Benin	Ivory Coast	Mozambique	Tunisia
Cameroon	Jordan	Niger	Uganda
Chad	Kenya	Nigeria	U.A.E.
Congo	Kuwait	Qatar	Upper Volta
Egypt	Lebanon	Saudi Arabia	Yemen, A.R.
Ethiopia	Liberia	Senegal	Zaire
Gabon	Libya	Sierra Leone	Zimbabwe
Ghana	Malawi	South Africa	

Group 7

Iceland	U.K. (ASC)	U.K. (BER)	

Table B-2. Traffic Model for AOR-1995 (94 Countries)

From Group \ To Group	1	2	3	4	5	6	7	Subtotal
1	0	0	3,827	5,947	24,137	6,036	274	40,221
2	0	0	461	393	2,128	726	42	3,750
3	3,827	461	442	943	2,349	39	19	8,080
4	5,947	393	943	2,246	4,242	300	0	14,071
5	24,137	2,128	2,349	4,242	396	12,085	336	45,673
6	6,036	726	39	300	12,085	3,420	0	22,560
7	274	42	19	0	336	0	0	671
Total	135,026							

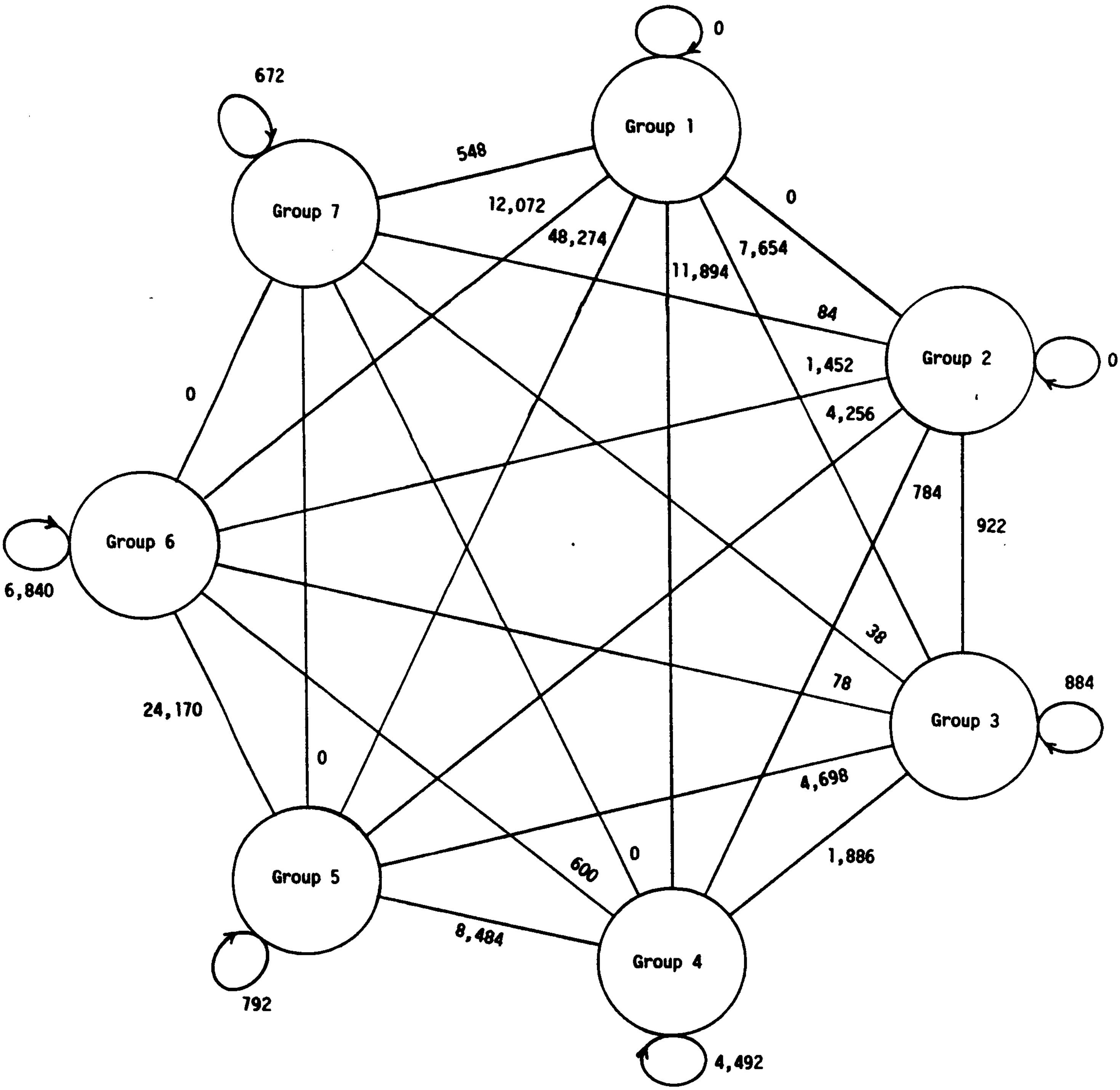


Figure B-3. Traffic Model for AOR-1995
(94 Countries)

Table B-3. A Grouping for AOR-1998
(102 Countries)

Group 1			
U.S.	India (Vikram)	U.K.-Mercury	
Group 2			
Canada			
Group 3			
Bahamas	El Salvador	Honduras	St. Lucia
Barbados	France (Martinique)	Jamaica	St. Vincent
Costa Rica		Mexico	Trin & Tobago
Cuba	Guatemala	Nicaragua	U.K.-Antigua
Dom. Rep.	Haiti	Panama	U.K.-Bermuda
			U.S.-Puerto Rico
Group 4			
Argentina	Chile	Japan	Surinam
Bolivia	Columbia	Paraguay	Uruguay
Brazil	Ecuador	Peru	Venezuela
Group 5			
Austria	Germany, FR	Italy	Spain
Belgium	Greece	Netherlands	Switzerland
Cyprus	Hungary	Nordic Grp	Turkey
Czechoslo- vakia	Iceland	Poland	U.K.
	Ireland	Portugal	U.S.S.R.
France		Romania	Yugoslavia
Group 6			
Algeria	Iraq	Libya	Sudan
Bahrain	Israel	Mauritania	Syria
Egypt	Jordan	Morocco	Tunisia
Iran	Kuwait	Qatar	U.A.E.
	Lebanon	Saudi Arabia	Yemen A.R.
Group 7			
Angola	Ghana	Mozambique	Tanzania
Benin	Ivory Coast	Niger	Togo
Cameroon	Kenya	Nigeria	Uganda
Congo	Liberia	Senegal	Upper Volta
Ethiopia	Malawi	Sierra Leone	Zaire
Gabon	Mali	South Africa	Zambia
			Zimbabwe

Table B-4. Traffic Model for AOR-1998
(102 Countries)

FROM GROUP	TO GROUP	TRAFFIC (# OF EQUIV. VOICE CIRCUITS)							SUBTOTAL
1									54640.0
	1	6912.0	2	0.0	3	4859.0	4	7434.0	
	5	27868.0	6	5184.0	7	2383.0			
2									4624.0
	1	0.0	2	0.0	3	608.0	4	392.0	
	5	2693.0	6	649.0	7	282.0			
3									10414.0
	1	4859.0	2	608.0	3	624.0	4	1206.0	
	5	3032.0	6	47.0	7	38.0			
4									17383.0
	1	7434.0	2	392.0	3	1206.0	4	2872.0	
	5	5093.0	6	274.0	7	112.0			
5									54557.0
	1	27868.0	2	2693.0	3	3032.0	4	5093.0	
	5	950.0	6	6727.0	7	8194.0			
6									15169.0
	1	5184.0	2	649.0	3	47.0	4	274.0	
	5	6727.0	6	1992.0	7	296.0			
7									12921.0
	1	2383.0	2	282.0	3	38.0	4	112.0	
	5	8194.0	6	296.0	7	1616.0			

TOTAL TRAFFIC : 169708.0

Table B-5. Traffic Model for AOR-1998 (102 Countries)

From \ To	N. America	S. America	Asia	S. Pacific	Europe	Mideast	Africa	Subtotal
N. America	6,912	13,293	0	0	30,561	5,833	2,665	59,264
S. America	13,293	5,908	0	0	8,125	321	150	27,797
Asia	0	0	0	0	0	0	0	0
S. Pacific	0	0	0	0	0	0	0	0
Europe	30,561	8,125	0	0	950	6,727	8,194	54,557
Mideast	5,833	321	0	0	6,727	1,992	296	15,169
Africa	2,665	150	0	0	8,194	296	1,616	12,921
Total	169,708							

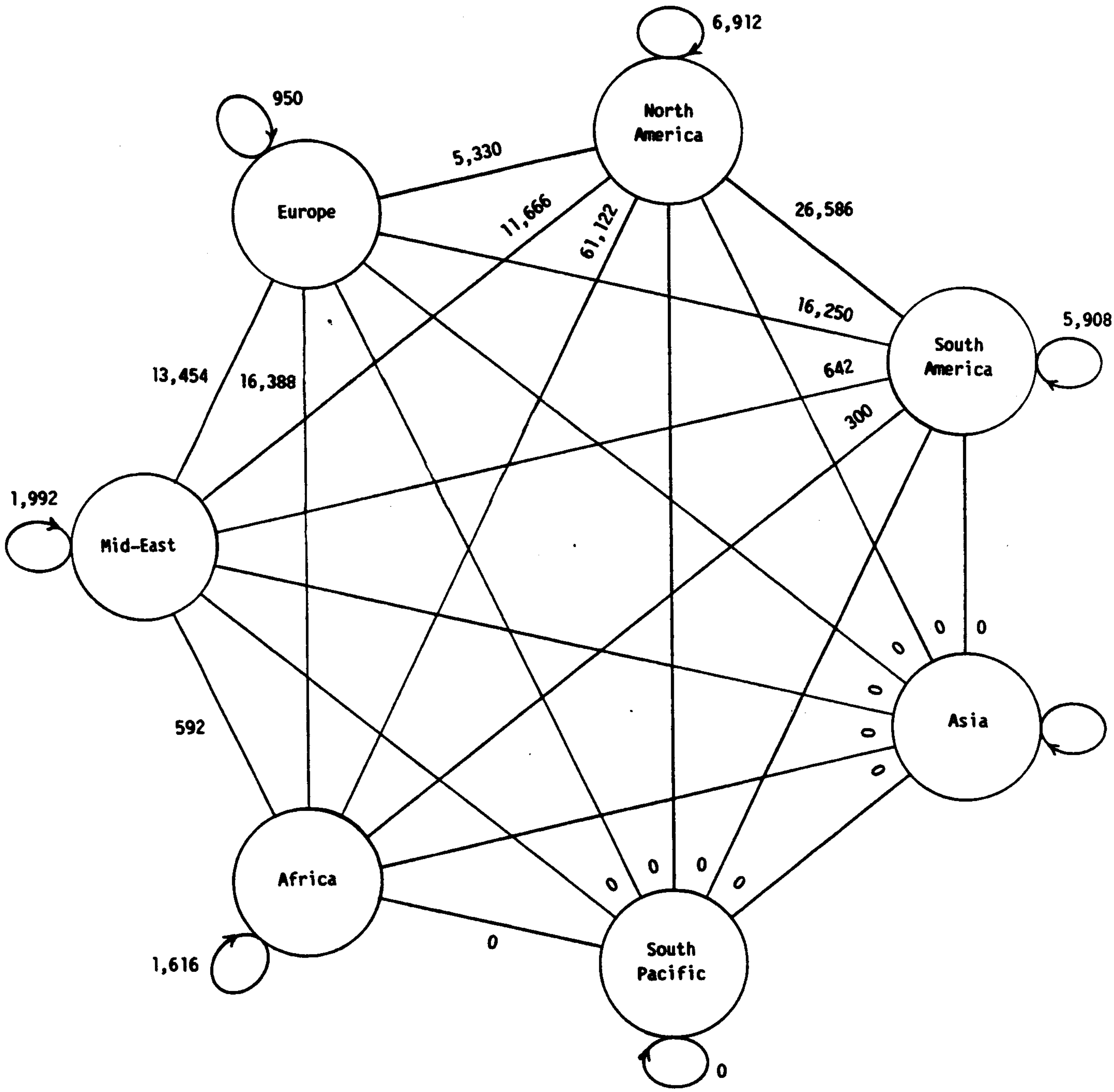


Figure B-4. Traffic Model for AOR-1998
(102 Countries)

IOR

A total of 70 countries in 7 groups was considered for the year 1998, as listed in Table B-6. The results of the traffic model are listed in Table B-7. The traffic model was derived for the same 7 regions, and the results are listed in Table B-8 and shown in Figure B-5. In Table B-8, South America includes countries of Group 7 (Table B-6); Asia includes countries of Groups 1 and 5; the South Pacific includes countries of Group 6; Europe includes countries of Group 4; the Mideast includes countries of Group 2, and Africa includes countries of Group 3.

POR

For the year 1995, a total of 19 countries was considered in 5 groups, as listed in Table B-9. The results of the traffic model are listed in Table B-10. For the year 1998, a total of 22 countries was considered in 7 groups, as listed in Table B-11. The number of countries for 1995 and 1998 was determined from the available INTELSAT traffic data base. The results of the traffic model are listed in Table B-12. The traffic model was then determined for the 7 regional groups as in AOR and IOR, and the results are listed in Table B-13 and shown in Figure B-6. In Table B-13, North America includes countries of Groups 1 and 2 (Table B-11), South America includes countries of Group 3, Asia includes countries of Groups 4 and 7, the South Pacific includes countries of Group 5, and Europe includes countries of Group 6.

Table B-6. A Grouping for IOR-1998
(70 Countries)

Group 1			
Bangladesh	India	Pakistan	Sri Lanka
Group 2			
Algeria	Iran	Lebanon	Qatar
Bahrain	Iraq	Libya	Saudi Arabia
Egypt	Jordan	Morocco	Syria
	Kuwait	Oman	U.A.E.
Group 3			
Kenya	Madagascar	Nigeria	Zambia
		South Africa	Zimbabwe
Group 4			
Austria	Germany F.R.	Nordic Grp	Switzerland
Belgium	Greece	Poland	Turkey
Czechoslovakia	Ireland	Portugal	U.K.
France	Italy	Romania	U.S.S.R.
	Malta	Spain	Yugoslavia
Group 5			
Brunei	Hong Kong	Korea	Philippines
China (Pek)	Indonesia	Korea P.R.	Singapore
China (Tai)	Japan	Malaysia	Thailand
Group 6			
Australia	France (F.P.)	France (N.C.)	New Zealand
Group 7			
Argentina	Canada	Colombia	Paraguay
Brazil	Chile	Panama	U.S.
			Venezuela

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Table B-7. Traffic Model for IOR-1998 (70 Countries)

FROM GROUP	TO GROUP	TRAFFIC (# OF EQUIV. VOICE CIRCUITS)	TO GROUP	TRAFFIC	TO GROUP	TRAFFIC	TO GROUP	TRAFFIC	SUBTOTAL
1									7168.0
	1	246.0	2	2264.0	3	112.0	4	2996.0	
	5	1008.0	6	104.0	7	438.0			
2									14481.0
	1	2264.0	2	3050.0	3	67.0	4	5691.0	
	5	2899.0	6	229.0	7	281.0			
3									3338.0
	1	112.0	2	67.0	3	416.0	4	1962.0	
	5	426.0	6	345.0	7	10.0			
4									27662.0
	1	2996.0	2	5691.0	3	1962.0	4	6.0	
	5	11744.0	6	5263.0	7	0.0			
5									18772.0
	1	1008.0	2	2899.0	3	426.0	4	11744.0	
	5	3866.0	6	0.0	7	437.0			
6									5993.0
	1	104.0	2	229.0	3	345.0	4	5263.0	
	5	0.0	6	0.0	7	52.0			
7									1138.0
	1	438.0	2	281.0	3	10.0	4	0.0	
	5	437.0	6	52.0	7	0.0			

TOTAL TRAFFIC : 78464.0

Table B-8. Traffic Model for IOR-1998 (70 Countries)

From \ To	N. America	S. America	Asia	S. Pacific	Europe	Mideast	Africa	Subtotal
N. America	0	0	0	0	0	0	0	0
S. America	0	0	875	52	0	201	10	1,138
Asia	0	875	5,312	104	14,740	4,363	538	25,932
S. Pacific	0	52	104	0	5,263	229	345	5,993
Europe	0	0	14,740	5,263	6	5,691	1,962	27,662
Mideast	0	201	4,363	229	5,691	3,850	67	14,401
Africa	0	10	538	345	1,962	67	416	3,338
Total	78,464							

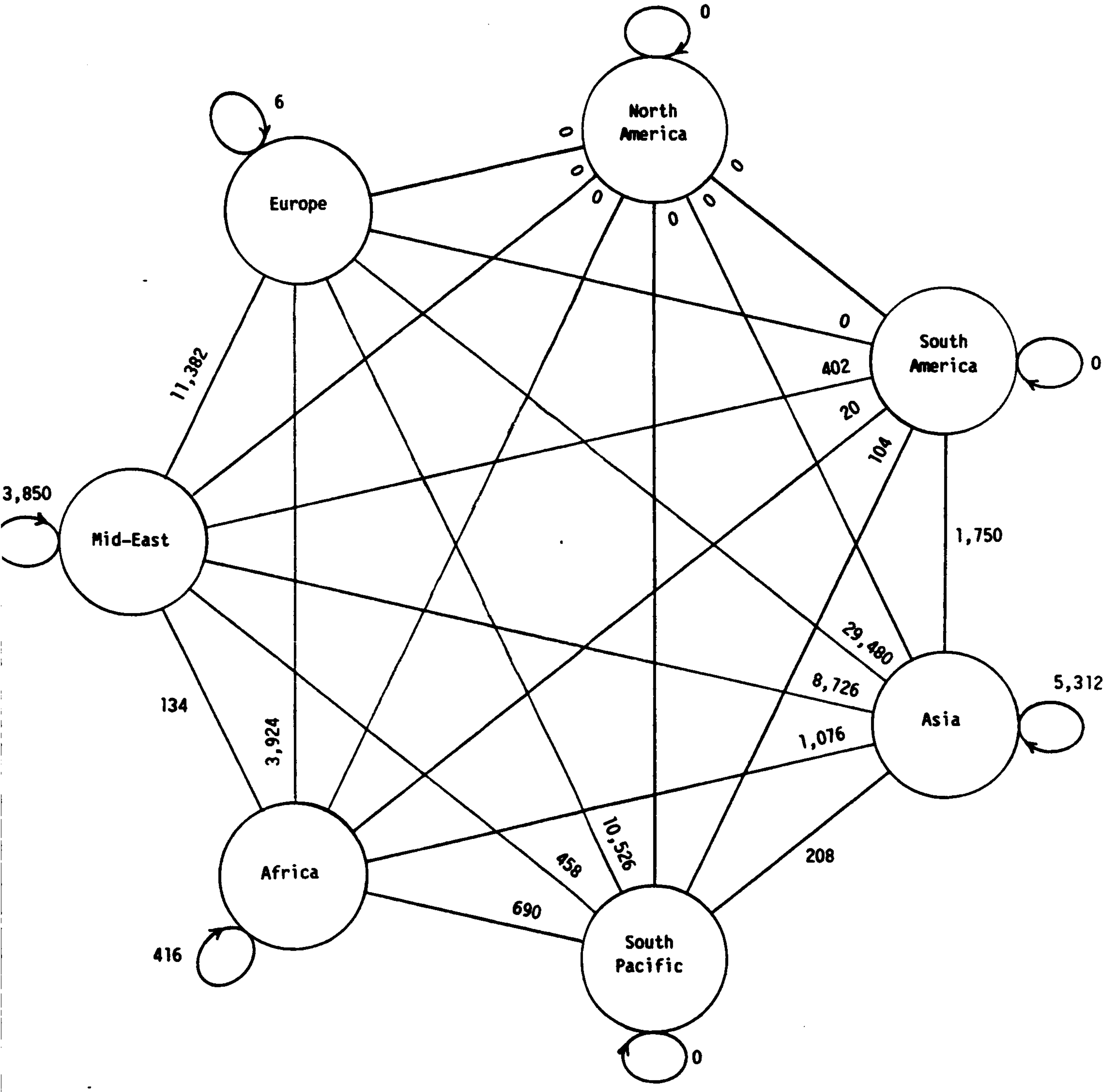

Figure B-5. Traffic Model for IOR-1998 (70 Countries)

Table B-9. A Grouping for POR-1995 (19 Countries)

<u>Group 1</u>			
U.S.-Hawaii	U.S.		
<u>Group 2</u>			
Canada			
<u>Group 3</u>			
Mexico			
<u>Group 4</u>			
China (Pek)	Hong Kong	Korea	Singapore
China (Tai)	Japan	Malaysia	Thailand
<u>Group 5</u>			
Australia	Fiji	Indonesia	Philippines
	France (N.C.)	New Zealand	U.S.-Guam

Table B-10. Traffic Model for POR-1995 (19 Countries)

From Group \ To Group	1	2	3	4	5	Subtotal
1	2	13	0	7,908	2,428	10,351
2	13	0	0	489	387	889
3	0	0	0	63	22	85
4	7,908	489	63	4,880	1,849	15,189
5	2,428	387	22	1,849	1,024	5,710
Total	32,224					

Table B-11. A Grouping for POR-1998 (22 Countries)

<u>Group 1</u>			
U.S.-Hawaii	U.S.		
<u>Group 2</u>			
Canada			
<u>Group 3</u>			
Mexico			
<u>Group 4</u>			
China (Pek)	China (Tai)	Japan	Malaysia
China (Sha)	Hong Kong	Korea	Singapore
			Thailand
<u>Group 5</u>			
Australia	France (NC)	Indonesia	Philippines
		New Zealand	U.S.-Guam
<u>Group 6</u>			
France	Italy		
<u>Group 7</u>			
India			

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Table B-12. Traffic Model for POR-1998 (22 Countries)

FROM GROUP	TO GROUP	TRAFFIC (# OF EQUIV. VOICE CIRCUITS)							SUBTOTAL
1									14164.0
	1	2.0	2	0.0	3	0.0	4	10498.0	
	5	3375.0	6	0.0	7	289.0			
2									845.0
	1	0.0	2	0.0	3	0.0	4	547.0	
	5	246.0	6	0.0	7	52.0			
3									113.0
	1	0.0	2	0.0	3	0.0	4	84.0	
	5	29.0	6	0.0	7	0.0			
4									20247.0
	1	10498.0	2	547.0	3	84.0	4	6546.0	
	5	2572.0	6	0.0	7	0.0			
5									8023.0
	1	3375.0	2	246.0	3	29.0	4	2572.0	
	5	1378.0	6	423.0	7	0.0			
6									423.0
	1	0.0	2	0.0	3	0.0	4	0.0	
	5	423.0	6	0.0	7	0.0			
7									341.0
	1	289.0	2	52.0	3	0.0	4	0.0	
	5	0.0	6	0.0	7	0.0			

TOTAL TRAFFIC : 44156.0

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Table B-13. Traffic Model for POR-1998 (22 Countries)

From \ To	N. America	S. America	Asia	S. Pacific	Europe	Mideast	Africa	Subtotal
N. America	2	0	11,386	3,621	0	0	0	15,009
S. America	0	0	84	29	0	0	0	113
Asia	11,386	84	6,546	2,572	0	0	0	20,588
S. Pacific	3,621	29	2,572	1,378	423	0	0	8,023
Europe	0	0	0	423	0	0	0	423
Mideast	0	0	0	0	0	0	0	0
Africa	0	0	0	0	0	0	0	0
Total	44,156							

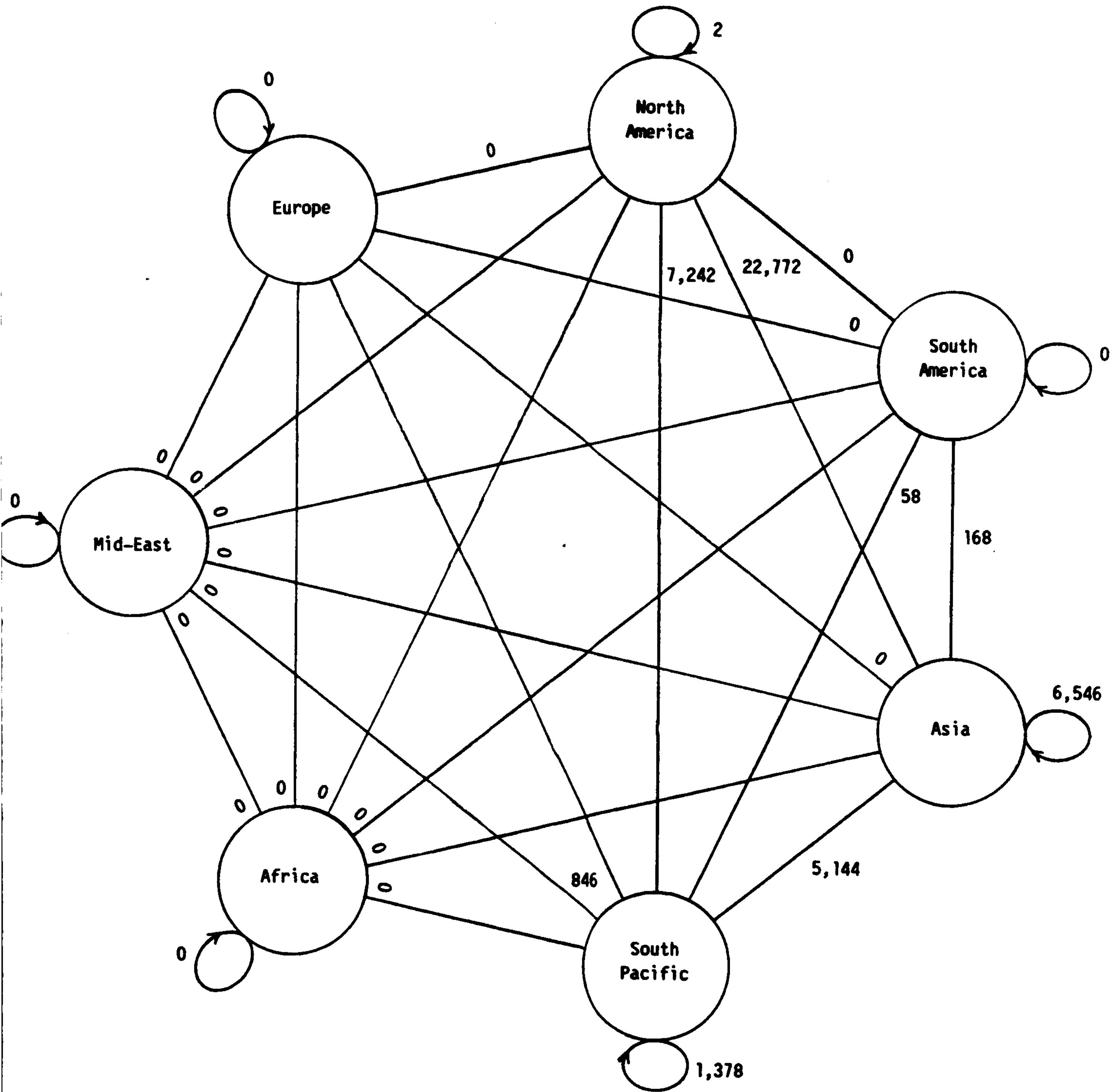


Figure B-6. Traffic Model for POR-1998 (22 Countries)

SEVEN GROUP REGIONAL TRAFFIC MODEL

Table B-14 and Figure B-7 show the results of the traffic model for all 3 Ocean regions combined for the year 1998. The traffic model in TAble B-14 is the combined result of Table B-5 (AOR '98), Table B-8 (IOR '98), and Table B-13 (POR '98).

ITU REGIONAL TRAFFIC MODEL

From Table B-14 the traffic model for the three ITU regions was derived and is shown in Figure B-8.

Table B-14. Traffic Model for 1998 (AOR, IOR, POR)

From \ To	N. America	S. America	Asia	S. Pacific	Europe	Mideast	Africa	Subtotal
N. America	6,914	13,293	11,386	3,621	30,561	5,833	2,665	74,273
S. America	13,293	5,908	959	81	8,125	522	160	29,048
Asia	11,386	959	11,858	2,676	14,740	4,363	538	46,520
S. Pacific	3,621	81	2,676	1,378	5,686	229	345	14,016
Europe	30,561	8,125	14,740	5,686	956	12,418	10,156	82,642
Mideast	5,833	522	4,363	229	12,418	5,842	363	29,570
Africa	2,665	160	538	345	10,156	363	2,032	16,259
Total	292,328							

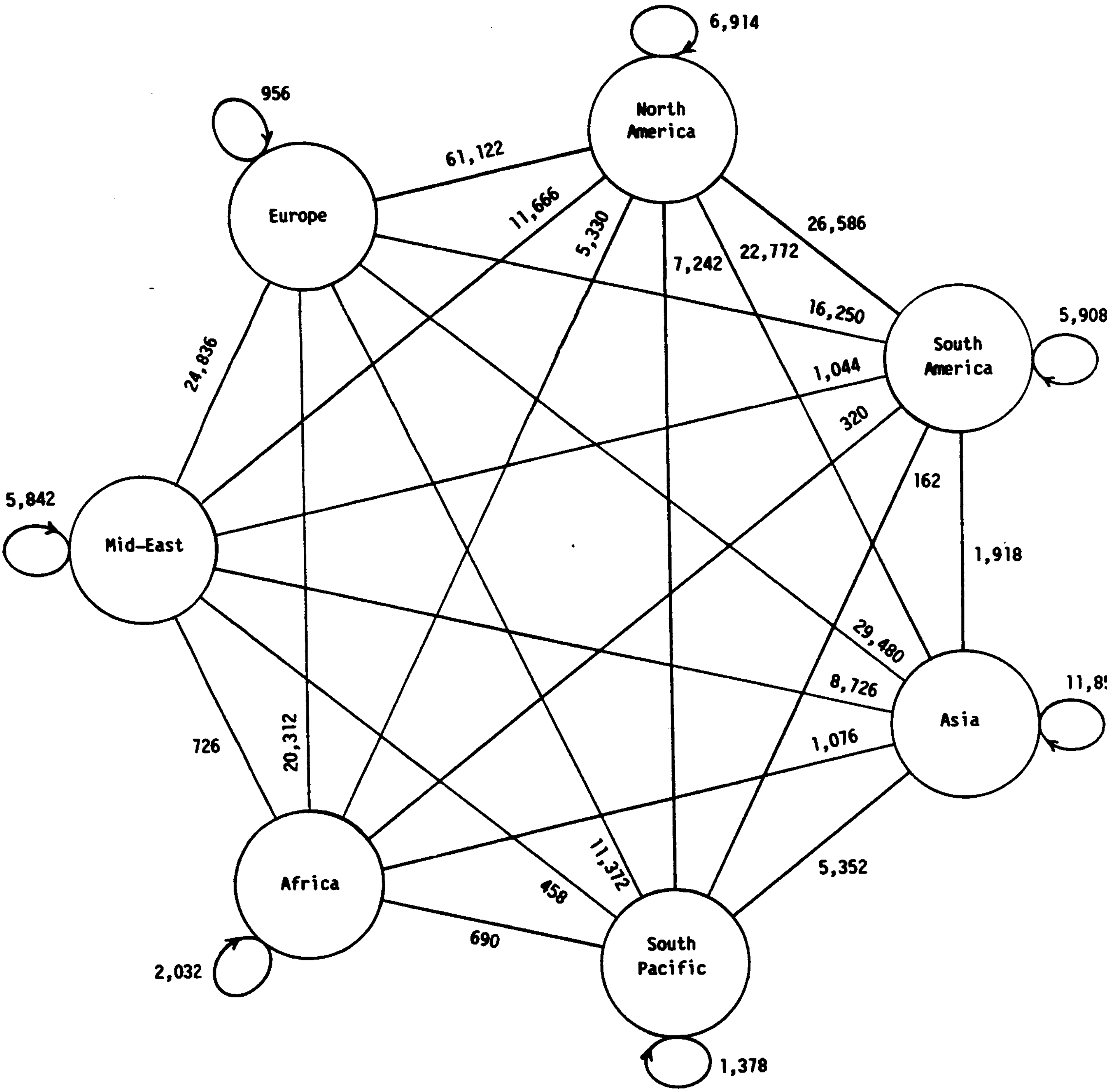
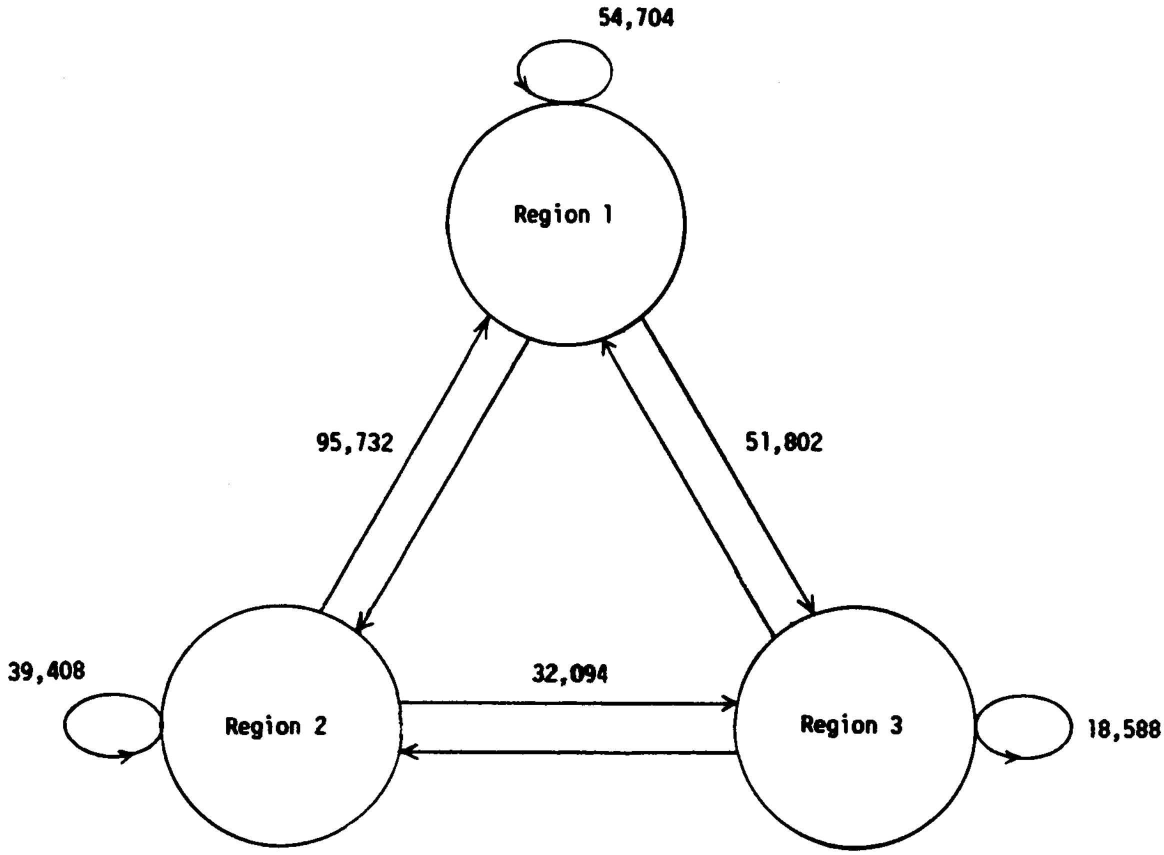


Figure B-7. Traffic Model for 1998 (AOR, IOR, POR)
(Total, Half Circuits)



To / From	Region 1	Region 2	Region 3	Subtotal
Region 1	54,704	47,866	25,901	128,471
Region 2	47,866	39,408	16,047	103,321
Region 3	25,901	16,047	18,588	60,536
Total	292,328			

Region 1: Europe, Middle East, Africa
Region 2: North America, South America
Region 3: Asia, South Pacific Countries

Figure B-8. Traffic Model for ITU Regions for 1998

APPENDIX C. A COMPUTER PROGRAM FOR ISL ORBITAL ARC EXPANSION ANALYSIS

For a given range of geostationary satellite orbit locations, the program computes the amount of the earth station (E/S) traffic (in percent of total traffic) of a given coverage area that is visible for a minimum specified elevation angle. This analysis is useful for the evaluation of ISL orbital arc expansion capabilities.

The derivation of the analysis equations is described below.

C.1 ANALYSIS

For a given coverage area which contains a number of earth station locations and E/S traffic in number of equivalent half-voice circuits, the percentage of total E/S traffic accessible from a given geostationary satellite orbit position is computed for any specified elevation angle. The synchronous satellite geometry is shown in Figure C-1. In this figure, S is the subsatellite point, ε is the elevation angle, ES is the great circle arc from E/S to subsatellite point, L is the E/S latitude, and δl is the longitude difference between the E/S and satellite ($\delta l = l_E - l_s$, l_E and l_s are E/S and satellite longitudes, respectively). The following equations can be written from the geometrical considerations:

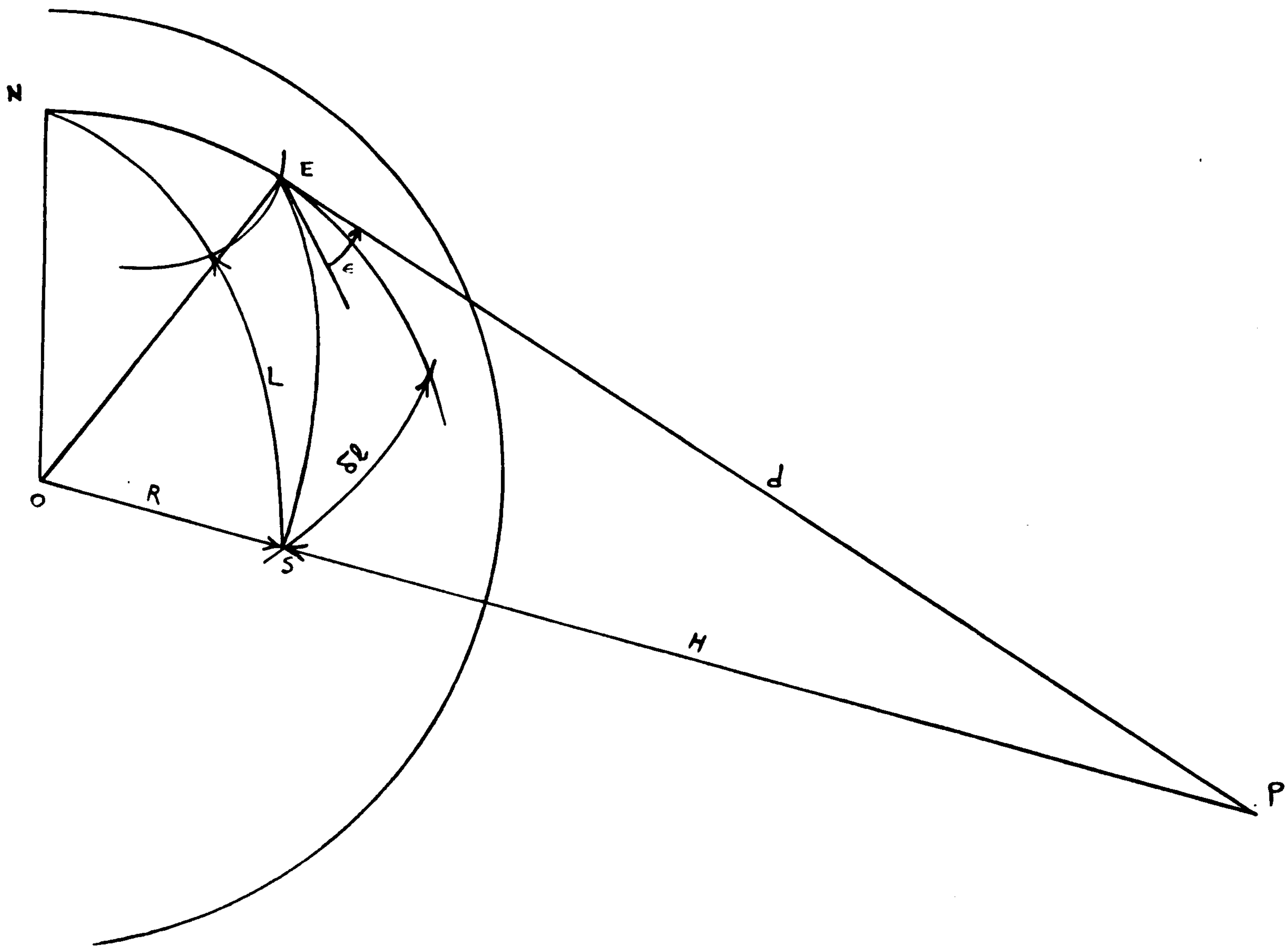


Figure C-1. Synchronous Satellite Geometry

$$\frac{\sin ES}{d} = \frac{\sin (90° + \epsilon)}{R + H} = \frac{\cos \epsilon}{R + H}$$

$$d^2 = R^2 + (R + H)^2 - 2R(R + H) \cos ES$$

$$= H^2 + 2R(R + H)\ (1 - \cos ES) \qquad \text{(C-1)}$$

where d = Slant range,
R = Earth radius,
H = Geostationary altitude.

The elevation angle, ε, is computed by eliminating d in equation (C-1).

$$\cos \varepsilon = \frac{R + H}{d} \sin ES$$

$$= \frac{(R + H) \sin ES}{\sqrt{H^2 + 2R(R + H)\ (1 - \cos ES)}} \qquad \text{(C-2)}$$

The great circle arc, ES, is computed in terms of L and $\delta 1$ using the following equation that holds for spherical triangle NES:

$$\cos ES = \cos NE \cos NS + \sin NE \sin NS \cos N \qquad \text{(C-3)}$$

where $NE = 90° - L$
$NS = 90°$
$N = \delta 1$

Equation (3) is simplified:

$$\cos ES = \cos L \cos \delta 1 \qquad \text{(C-4)}$$

Finally, ε is computed in terms of L and $\delta 1$ by eliminating ES in equations (C-2) and (C-4).

$$\cos E = \frac{(R + H)\sqrt{1 - \cos^2 L \cos^2 \delta 1}}{\sqrt{H^2 + 2R(R + H)\,(1 - \cos L \cos \delta 1)}} \qquad \text{(C-5)}$$

The program was implemented using the following parameters for the satellite and E/S:

n = Number of earth stations.

LNE(I), LTE(I), T(I) = E/S longitude, latitude, and traffic (in number of circuits) for I = 1 to n.

LNS(J) = Satellite longitude for J = 1 to m.

ELVM = Specified elevation angle minimum.

ELV = Elevation angle of I^{th} E/S to J^{th} satellite location (computed by equation (C-5)).

TM(J) = Percentage of total traffic within the main beam of satellite that is seen with elevation angles greater than or equal to ELVM (for J = 1 to m).

TM(J) is computed from the following equation:

$$TM(J) = \frac{100}{TT} \sum_{C} T(I) \qquad J = 1 \text{ to } m \qquad \text{(C-6)}$$

where $$TT = \text{Total traffic} = \sum_{I=1}^{n} T(I)$$

$$C = \{I : |LTE(I)| \leq ALFA \text{ and } |LNE(I) - LNS(J)| \leq ALFA \text{ and } ELV \geq ELVM\}$$

and ALFA = Angle subtended by great circle arc ES for zero elevation angle = $\cos^{-1}$ (R/R + H).

In equation (C-6), C is the set of all E/S indices that are visible from J^{th} satellite location with elevation angles greater than or equal to ELVM.

The computer program computes the percentage of total traffic versus the satellite locations. An example of the program input/output is given below.

C.2 PROGRAM

The flowchart of the program is shown in Figure C-2. A listing of input data (arbitrary) set and a sample run are shown in Tables C-1 and C-2, respectively.

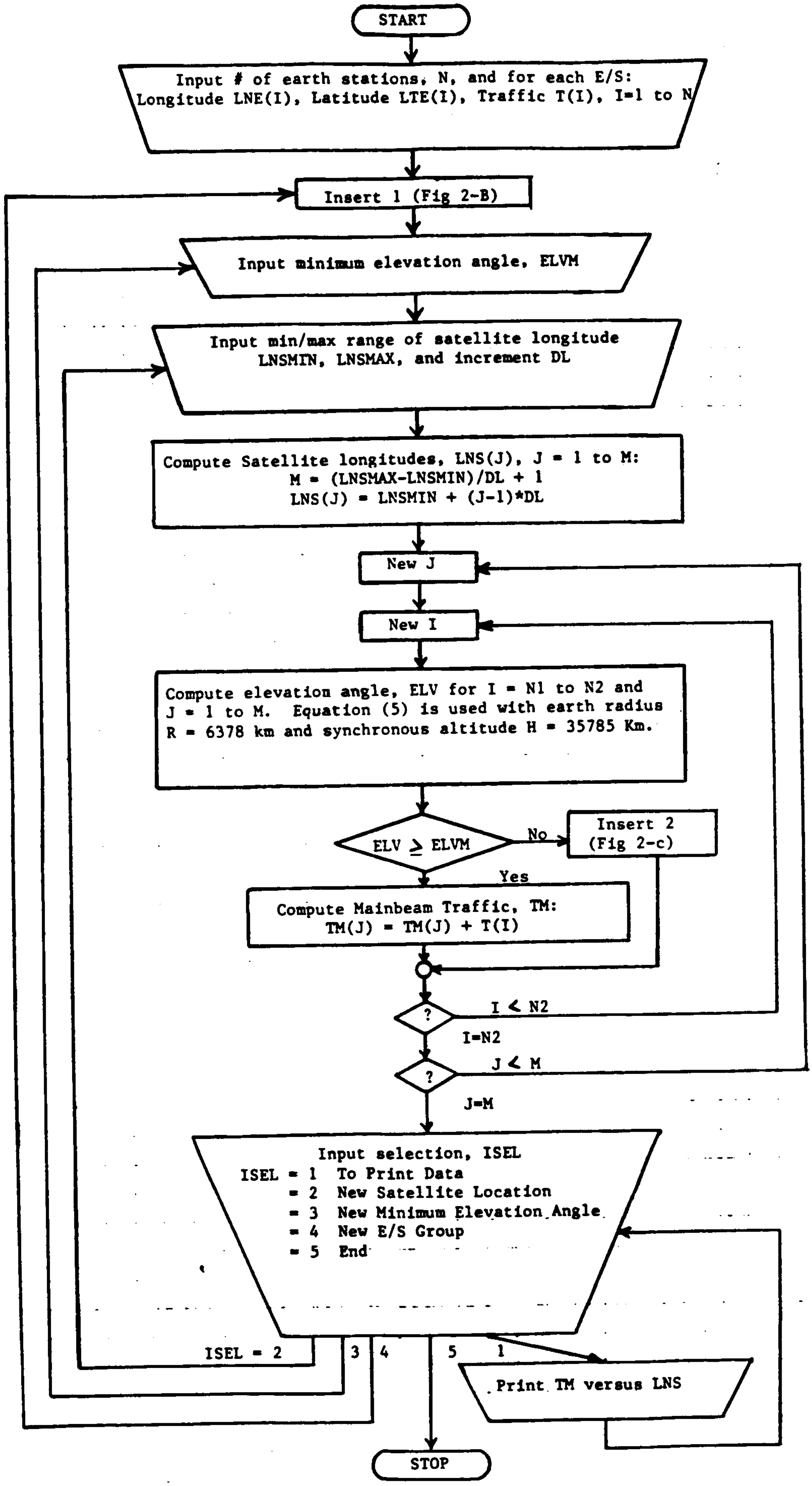
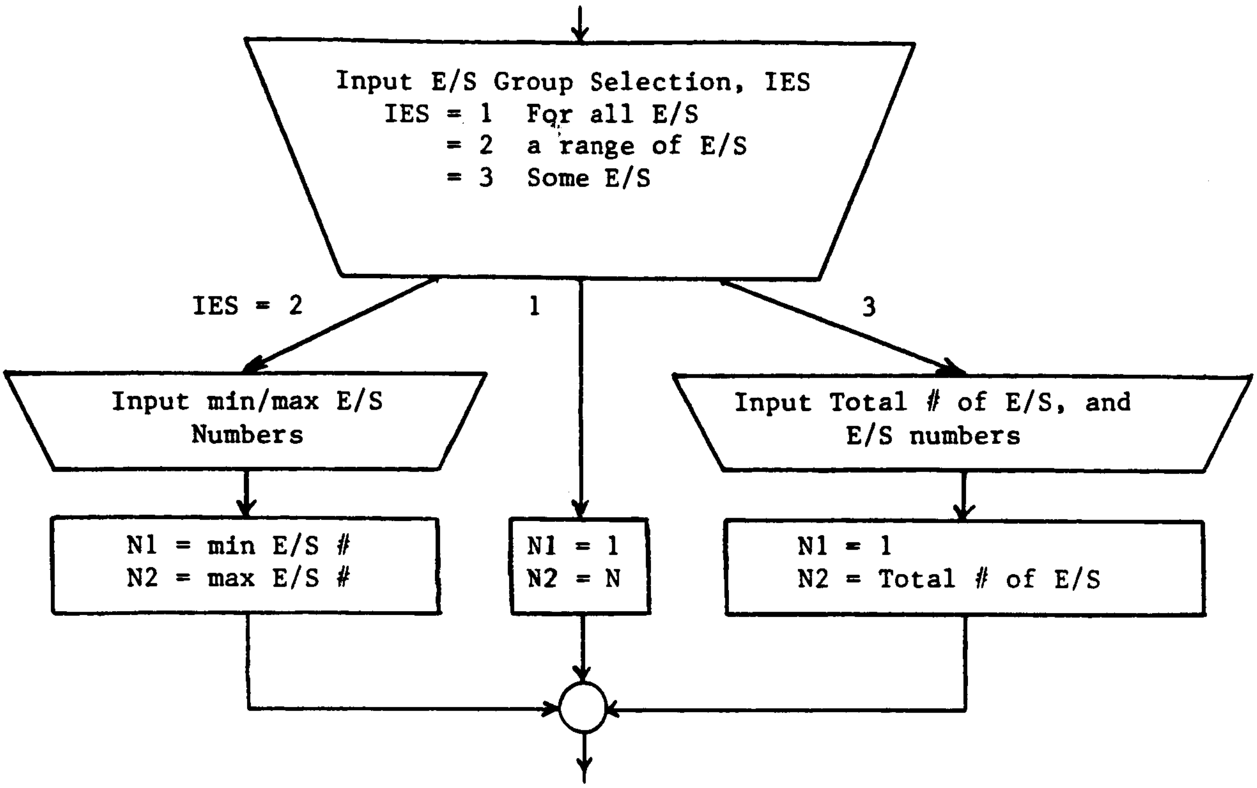
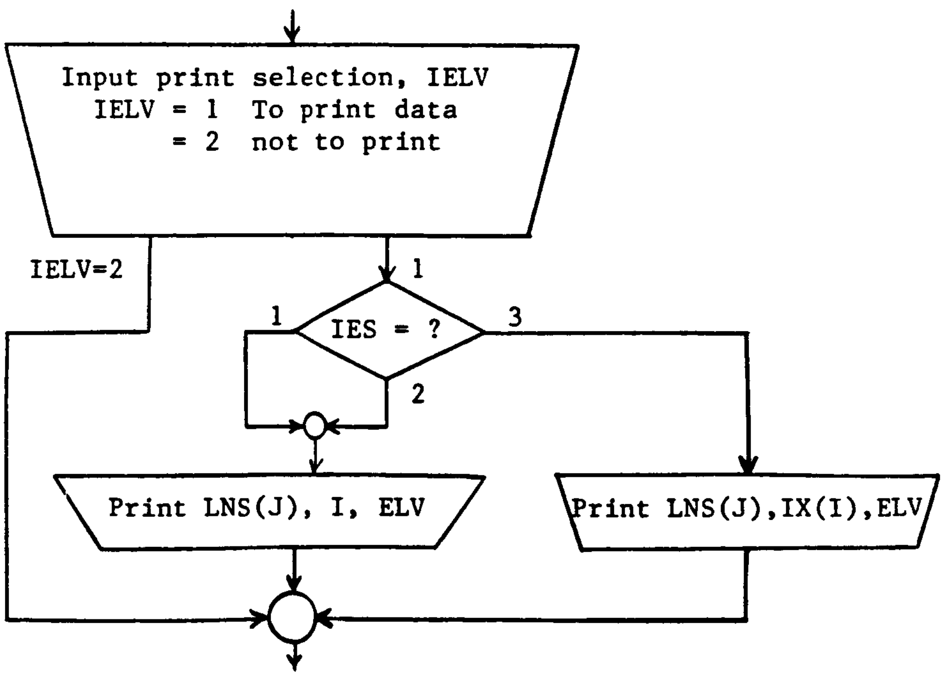


Figure C-2. Program Flowchart



Insert 1 of Figure C-2



Insert 2 of Figure C-2

Figure C-2. Program Flowchart (Cont.)

Table C-1. Listing of Input Data

```
l dt1.data

A61510000 DSNAME='M5IKB.DT1.DATA'
A61510098 INVALID LINE NUMBER, NONUM ASSUMED
18
-122.3 47.2 2
-124.2 43.4 .3
-122.2 37.8 8
-118.3 34 9
-119.3 35.8 .8
-119.1 34.4 .9
-113.6 44 .5
-97.5 35.4 1
-96.8 32.5 4
-95.4 29.8 7
-87.6 41.8 8
-81.7 41.5 2
-90 30 3
-81 29.2 2
-77 38.9 5
-74 40.7 10
-71 42.3 5
-70.3 43.6 3
A61510001 END OF DATA
READY
```

Table C-2. A Sample Run

```
exec trfarc

IKJ56700A ENTER POSITIONAL PARAMETER INPUT -
dt1.data

ENTER 1 FOR ALL E/S , 2 A RANGE OF E/S , 3 SOME E/S
?
1

ENTER MINIMUM ELEVATION ANGLE IN DEGREES
?
10

ENTER MINIMUM/MAXIMUM SATELLITE LONGITUDE DEG E , AND INCREMENT IN DEGREES
?
-180 0 10

ENTER 1 TO PRINT ELEVATION ANGLES BELOW MINIMUM VALUE , 2 OTHERWISE
?
1


   SATELLITE LONGITUDE   E/S #   ELEVATION ANGLE
         DEG E                         DEG

        -180.00            7          8.13
        -170.00            8          5.53
        -170.00            9          5.45
        -170.00           10          4.65
        -170.00           13          0.06
        -160.00           11          4.35
        -160.00           12          0.06
        -160.00           13          0.63
        -160.00           14          0.89
```

Table C-2. A Sample Run (Cont.)

-150.00	12	7.45
-150.00	14	9.65
-150.00	15	4.40
-150.00	16	1.07
-150.00	17	0.59
-150.00	18	1.26
-140.00	16	9.30
-140.00	17	6.73
-140.00	18	5.90
-60.00	1	9.04
-60.00	2	9.06
-50.00	1	3.24
-50.00	2	2.72
-50.00	3	5.32
-50.00	4	9.26
-50.00	5	0.05
-50.00	6	0.51
-40.00	4	0.90
-40.00	5	0.06
-40.00	6	0.20
-40.00	7	3.03
-30.00	8	9.60
-20.00	8	1.46
-20.00	9	2.41
-20.00	10	3.96
-20.00	11	7.09
-20.00	13	0.63
-10.00	11	0.51
-10.00	12	4.93
-10.00	13	0.06
-10.00	14	7.09
-10.00	15	9.11
0.0	14	0.05
0.0	15	1.30

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Table C-2. A Sample Run (Cont.)

```
          0.0          16          3.30
          0.0          17          5.27
          0.0          18          5.47
ENTER 1 TO PRINT DATA , 2 NEW SATELLITE LOCATION , 3 NEW MINIMUM ELEVATION ANGLE
 , 4 NEW E/S GROUP , 5 END
?
1


   SATELLITE LONGITUDE   MAINBEAM TRAFFIC
         DEG E          % OF TOTAL CIRCUITS

        -180.00               29.4
        -170.00               30.1
        -160.00               46.9
        -150.00               62.2
        -140.00               74.0
        -130.00              100.0
        -120.00              100.0
        -110.00              100.0
        -100.00              100.0
         -90.00              100.0
         -80.00              100.0
         -70.00              100.0
         -60.00               96.0
         -50.00               70.6
         -40.00               69.9
         -30.00               60.5
         -20.00               37.0
         -10.00               25.2
           0.0                 0.0
ENTER 1 TO PRINT DATA , 2 NEW SATELLITE LOCATION , 3 NEW MINIMUM ELEVATION ANGLE
 , 4 NEW E/S GROUP , 5 END
?
5

READY
```

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APPENDIX D. SUMMARY DATA OF MASS, POWER, AND COSTS OF TEN COMMERCIAL SPACECRAFT PROGRAMS

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SPACECRAFT MASS, POWER AND COST SUMMARY

Spacecraft Program	A	B	C	D	E	F	G	H	I	J
Payload Mass (Kg)	241	292	269	117	556	694	156	172	181	95
Payload Power (W)	754	875	621	1486	1418	1489	298	423	465	562
S/C BOL (Nominal)										
- Mass (Kg)	950	1108	938	629	2211	2250	702	791	809	559
- Power (W)	1742	1742	1345	2642	2650	2780	569	708	760	1118
Nonrecurring Costs (1986$) in Millions										
Payload	58.82	6.61	47.84	18.04	63.92	97.13	22.81	17.49	9.75	2.62
Support Subsys.	65.49	0.95	56.99	15.55	109.53	83.21	51.29	19.15	4.28	12.38
TOTAL PROGRAM	182.79	10.76	154.36	48.04	243.55	234.40	113.92	53.28	19.07	22.88
Total Recurring Costs (1986$) in Millions										
No. of Flight Spacecraft	7	2	7	2	5	5	4	3	3	3
Payload	106.87	43.48	136.84	28.13	157.51	187.43	28.65	43.15	37.50	10.27
Support Subsys.	90.73	27.61	95.94	24.21	141.53	103.55	63.62	41.30	39.04	21.69
TOTAL PROGRAM	262.62	99.60	292.42	80.14	448.29	381.85	138.97	127.30	108.45	51.48

NOTE: a) Payload includes: Antenna and Repeater Subsystems
b) Support Subsystem includes: Telemetry, Tracking & Command, Electrical Power, Structure, Thermal Control, Attitude Control and Propulsion

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APPENDIX E. EARTH STATION COST MODEL

Earth Station Cost Model

Item	Cost Estimating Relationship: 6/4 GHz	14/11 GHz	20/30 GHz
C_{ANT} - Antenna Cost	$= 0.222 \times 10^6 (D/10)^2;\ D \geq 10$ m $= 0.150 \times 10^6 (D/10)^3 + 3{,}000;\ D < 10$ m	$= 0.0625 \times 10^6 (D/5)^2;\ D \geq 5$ m $= 0.045 \times 10^6 (D/5)^3 + 3{,}500;\ D < 5$ m	$= 0.069 \times 10^6 (D/5)^2;\ D \geq 5$ m $= 0.050 \times 10^6 (D/5)^3 + 3{,}500;\ D < 5$ m
C_{HPA} - HPA Cost	$= 2 \times 10^5 (P/3{,}000)^{0.5};\ P \geq 3{,}000$ $= 1.2 \times 10^5 (P/3{,}000)^{0.5} + 2{,}000;\ P < 3{,}000$	$= 2 \times 10^5 (P/2{,}000)^{0.5};\ P \geq 2{,}000$ $= 1.3 \times 10^5 (P/2{,}000)^{0.5};\ P < 2{,}000$	$= 3 \times 10^5 (P/2{,}000)^{0.5};\ P \geq 2{,}000$ $= 1.95 \times 10^5 (P/2{,}000)^{0.5};\ P < 2{,}000$
C_{LNA} - LNA Cost	$= 4.0 \times 10^3 (80/T_{ES})^2 + 200;\ T \geq 80$ $= 40 \times 10^3 (80/T_{ES})^{0.67};\ T < 80$	$= 3.0 \times 10^3 (350/T_{ES})^2 + 2{,}000$	$= 4.5 \times 10^3 (350/T_{ES})^2 + 3{,}000$
C_1 Subtotal	$= C_{ANT} + C_{HPA} + C_{LNA}$		
	Digital Transmission	FDM/FM/FDMA*	
C_{MOD} - Cost of Modem	$C_{MOD} = 2.0 \times 10^4 (R_b/1.0 \times 10^6)^{0.2}$	$C_{MOD} + C_{INT} = 67 \times 10^3 + C_{UP}$ $+ 1{,}000\ N_{VC}$ $+ N_{DEST}\ (6{,}000 + C_{DN})$	Same
C_{INT} - Multiplex and Interface Equipment	$C_{INT} = R_b/31.25;\ R_b < 1.5 \times 10^6$ $= 48 \times 10^3 (R_b/1.5 \times 10^6)^{0.5};$ $R_b > 1.5 \times 10^6$		Same
C_{POW} - Cost of Power Subsystem	$= 1.0 \times 10^5 (D/30 + P/1.0 \times 10^4 + N_{VC}/200)$		Same
C_{AAC} - Alarm and Control	$= 1.0 \times 10^5 (D/30)$		Same
C_{APC} - Automatic Power Control	$= 75{,}000$ (@ 14/11 GHz only)		Same
C_2 Subtotal	$= C_{MOD} + C_{INT} + C_{POW} + C_{AAC} + C_{APC}$		
C_3 - Cost of Test Equipment and Spares, Station Integration and Test, Equipment Installation and Delivery, Housing and Facilities	$= 0.3\ C_1 + 0.5\ C_2 \quad D < 4$ m $= 0.45\ C_1 + 0.65\ C_2 \quad 4 \leq D < 7$ m $= 0.55\ C_1 + 0.75\ C_2 \quad D \geq 7$ m		Same
C_{ES} (Total)	$= C_1 + C_2 + C_3$		

*C_{UP} = cost of up-converter (25×10^3); N_{VC} number of voice channels; N_{DEST} = number of destinations; and C_{DN} = cost of down-converters (25×10^3).

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