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INTERSATELLITE LINK (ISL) APPLICATION TO COMMERCIAL COMMUNICATIONS SATELLITES

VOLUME I
EXECUTIVE SUMMARY

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
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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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EXECUTIVE SUMMARY

1. INTRODUCTION

A study on "Intersatellite Link (ISL) Application to Commercial Communications Satellites" was performed by the Communications Satellite Corporation under the NASA Lewis Research Center Contract (Contract NAS3-24884). The motivation for the study was "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?" This question was addressed from a rather broad systems perspective of ISL systems applications, network architectures, and their associated cost analysis and benefit evaluations, based on the future Fixed-Satellite Services (FSS) demands and traffic forecast for domestic, regional, and international communications.

The specific objectives of the ISL Applications Study were to:

- Define potential applications of intersatellite links to commercial communication satellites and their benefits.
- Define implementation scenarios for commercial communications satellite systems employing intersatellite links.
- Define technology requirements for ISL systems.

The following three technical tasks were performed to achieve the study objectives:

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

The results of the study are described in the Final Reports, consisting of two volumes:

Volume I: Executive Summary,
Volume II: Final Technical Report.

This Executive Summary presents a brief overview of the study results that are described in detail in the Final Technical Report.

2. DETERMINATION OF ISL APPLICATIONS

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

Major systems characteristics of ISLs and their impact on the Fixed-Satellite Services, shown in Table 1, encompass the following aspects of systems capability:

a. Improvement of utilization of orbit and spectrum resources.
b. Improvement and expansion of the existing commercial satellite services.
c. Evolutionary development of completely new satellite networks based on domestic and regional satellites.

Table 1. 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

The fundamental ISL systems characteristics were evaluated for various categories of ISLs ranging from a very short ISL (less than 0.1° between colocated satellites) to a 120° ISL between ITU regional satellites. Based on the fundamental systems characteristics, figure-of-merit factors of ISLs were derived as part of the technical criteria that were used to determine candidate ISL applications.

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

$$M = M_\theta \bullet M_B \bullet M_T \bullet M_E$$

where M_θ = Orbital arc expansion factor.

M_B = Improvement factor in FSS transponder bandwidth utilization.

M_T = Time delay reduction factor.

M_E = Reduction factor of the number of earth station antennas.

These factors were defined and quantified for ISL applications to FSS.

A relative ranking of various ISL applications was derived including the figure-of-merit factors identified above and other sets of criteria consisting of:

- o ISL traffic requirement.
- o New services potential.

The six candidate ISL applications selected for further study are listed below:

Selected ISL Applications

a. CONUS, Four-Zone Coverage Domestic Services

b. (1) CONUS-European Region

   (2) North America-European Region

c. CONUS-International

   (1) CONUS-POR

   (2) CONUS-AOR

d. ITU Region 1-International

   (1) Region 1-AOR

   (2) Region 1-IOR

e. ITU Region 1-2-3

   (1) Region 1-Region 2

   (2) Region 2-Region 3

   (3) Region 3-Region 1

f. Intercluster ISL for CONUS

3. NETWORK ARCHITECTURES AND COST ANALYSIS

For each of the candidate ISL applications, ISL versus corresponding non-ISL satellite systems architectures were derived based on the following:

- Satellite-addressable traffic models for the year 2001.
- ISL capacity for a 100-percent capture of traffic.
- 4,500 half-voice circuits per 36-MHz equivalent transponder technology, employing 32-kbit/s rate encoding of speech with digital speech interpolation and QPSK/TDMA transmission.

- Space hardware technology available at the end of 1990 for ISL implementation.
- ISL and non-ISL systems providing the same services.

Both microwave (60 GHz) and optical (0.85 μm) ISL implementation approaches were evaluated for payload sizing and cost analyses. The overall systems cost analysis was performed for the "add-on" systems cost comparisons between ISL and non-ISL systems for each ISL application. Other qualitative systems benefits of each ISL application were also addressed.

3.1 ISL TRAFFIC MODELS

The space segment and ISL capacity requirements were derived from the FSS traffic models available for this study:

- NASA-Supplied U.S. Domestic Traffic Model for the Year 2000.
- INTELSAT Traffic Data Base.
- FCC's Space WARC 1985 Traffic Forecast and Others.

A generalized traffic grouping program was developed to quantify ISL traffic models for various potential applications. An orbital arc analysis program was also developed to quantify the orbital arc expansion capability of the ISL.

ISL capacity requirements were determined from traffic models for applications to U.S. domestic, regional, international, and ITU regional group ISLs.

3.2 NETWORK ARCHITECTURES AND PAYLOAD CONFIGURATIONS

3.2.1 NETWORK ARCHITECTURES

Table 2 shows a summary of the selected ISL network architectures including the ISL range, ISL payload terminal capacity, and satellite orbital locations.

The CONUS ISL application for the four time zone coverage satellite (Figure 1) provides a significant expansion of the useful orbital arc. The CONUS satellites, under a 30° elevation angle criterion for K_a-band services, can be placed anywhere within the following arc segments:

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

In comparison, the corresponding non-ISL CONUS coverage satellites for K_a-band services must be placed in a slot between 98°W and 103°W, i.e., the useful orbital arc length is only 5°.

The ISL satellite locations were determined with the use of elevation angle contours and orthographic maps of each coverage from each orbital location. Figure 2 shows the ITU regional three-satellite systems network architecture with ISLs.

A simplified representation of ISL vs non-ISL satellite constellations for each application is illustrated in Figure 3. Intercluster ($\leq$ 0.1°) ISL satellites can be

Table 2. 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

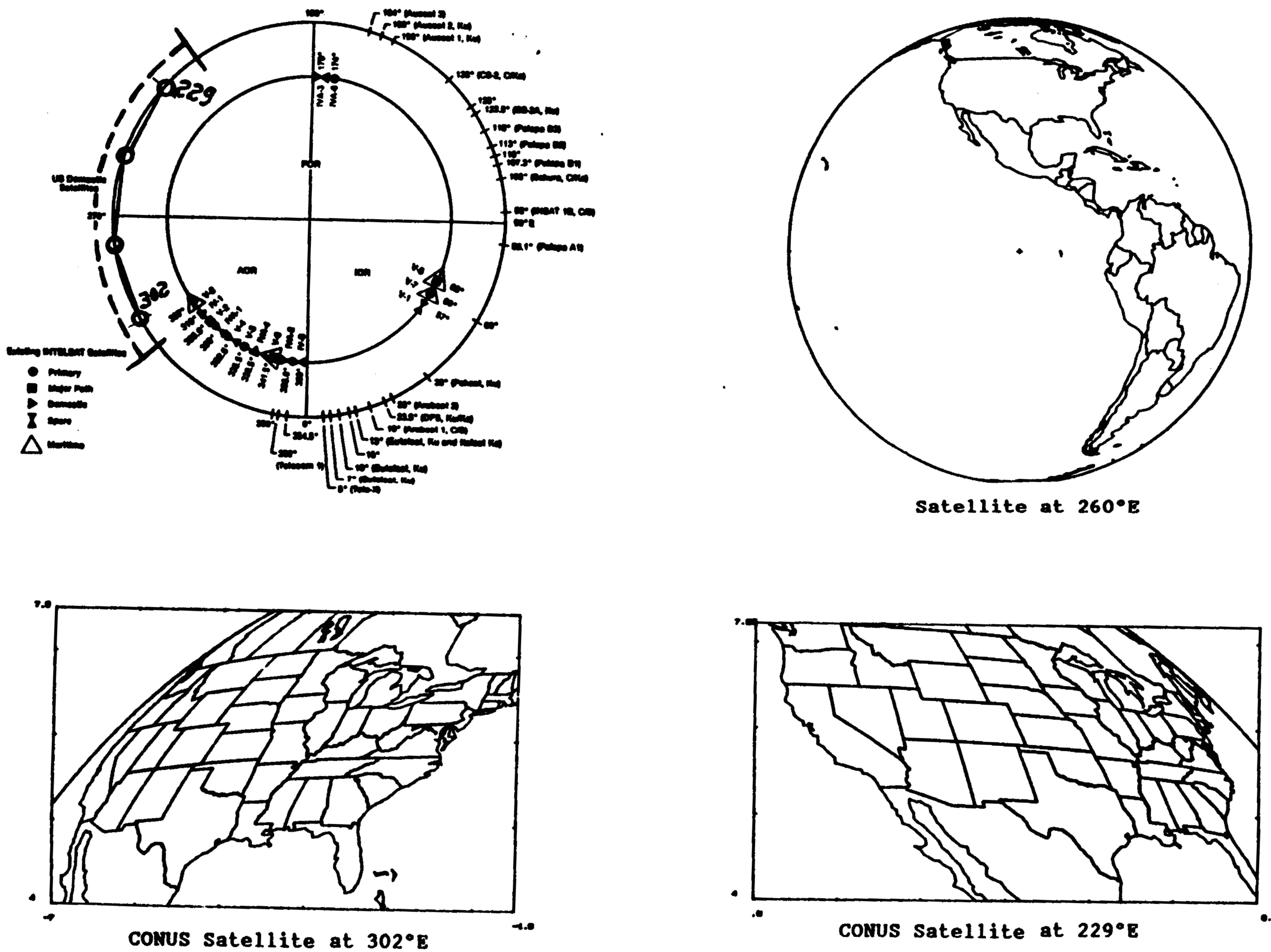


Figure 1. ISL Application (No. 1) for CONUS

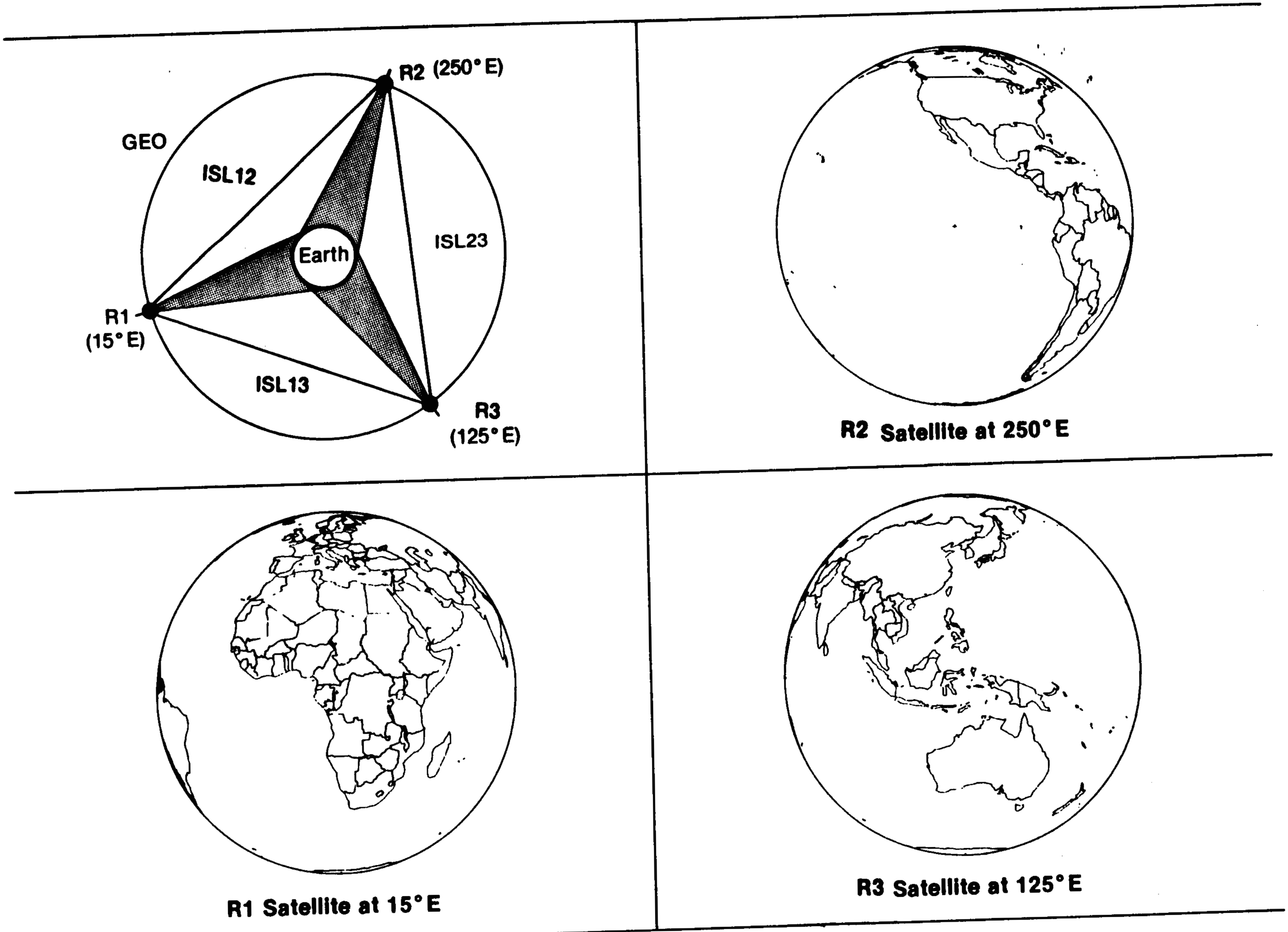


Figure 2. Three ITU Regional ISL Satellite System

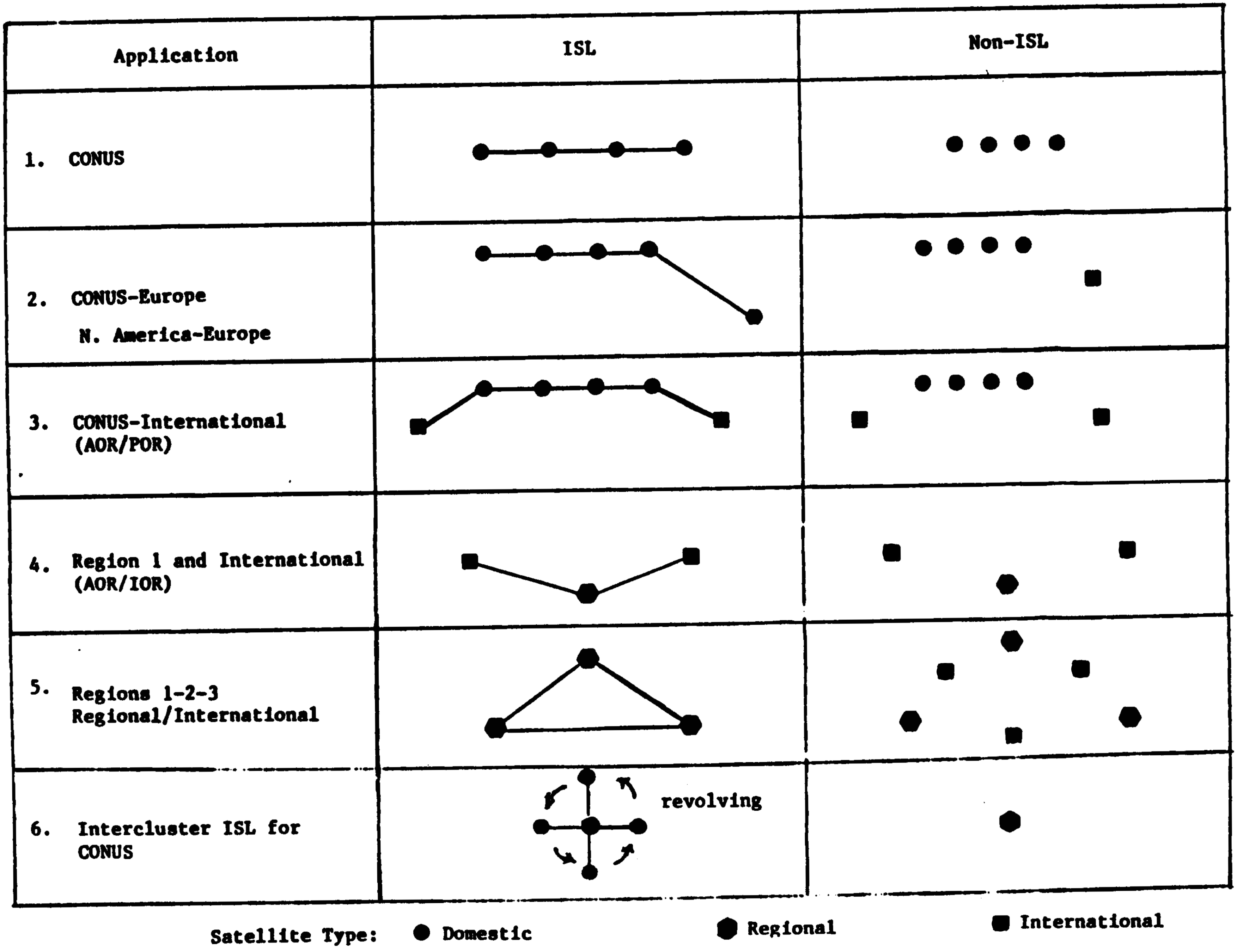


Figure 3. ISL vs Non-ISL Satellite Constellations

interconnected as a revolving star configuration or a string configuration.

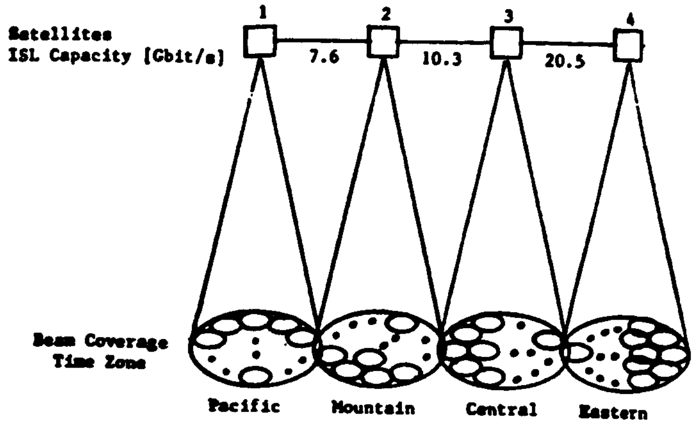
The CONUS ISL vs non-ISL system architecture is shown in Figure 4. Each zone satellite employs extensive frequency reuses with a number of spot beams in the C-, K_u-, and K_a-bands. The up-link and down-link capacity requirement ranges from 125 transponders for the Mountain time zone satellite to 1,145 transponders for the Eastern time zone satellite.

Figure 4 shows two different non-ISL systems architectures:

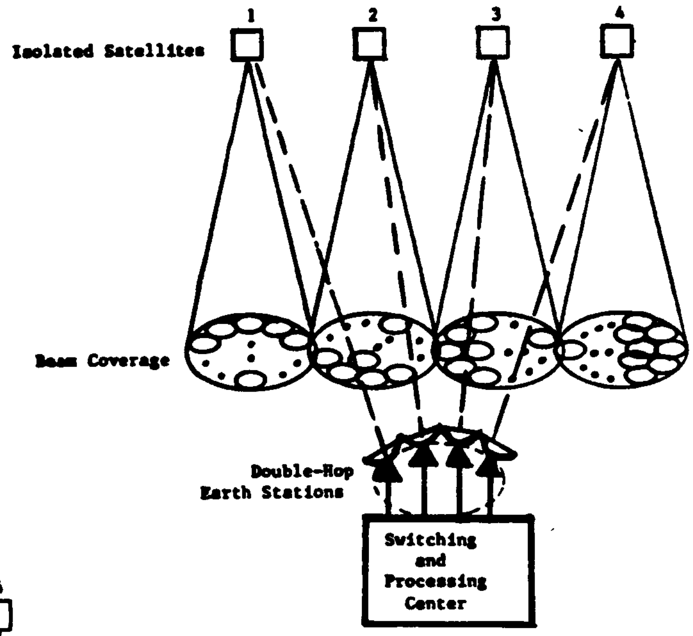
a. Double-Hop Network as Architecture I.
b. Multiple Colocated Earth Station Network as Architecture II.

Traffic interconnectivity in the double-hop network can be provided at a central switching/processing station. Architecture II is a rather conventional non-ISL network.

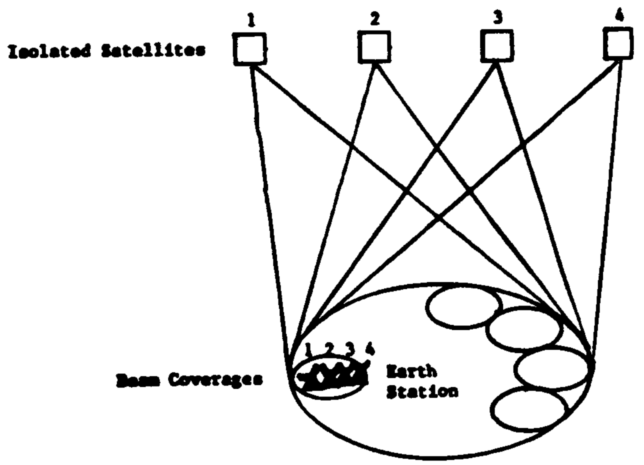
The multiple-hopping network configurations were taken as representative non-ISL system architectures for the other ISL application, except Application No. 6 (Intercluster ISL), identified in Table 2. Multiple colocated partitioned satellites without ISLs or a large "super" satellite were considered as the corresponding non-ISL system of the intercluster ISL.



Application No. 1. CONUS ISL System Architecture



CONUS Non-ISL System Architecture 1



CONUS Non-ISL System Architecture 2

Figure 4. CONUS ISL and Non-ISL System Architectures

3.2.2 PAYLOAD CONFIGURATIONS

For each network architecture, ISL payload configurations and spacecraft sizing were determined. Microwave (60 GHz) and optical (0.85 µm) implementations of the ISL payload were evaluated comparatively for mass, power, and size requirements.

The basic ISL system parameters defined for the payload sizing of microwave and optical ISL terminals are shown below:

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

The ISL link design provides a BER $\leq 10^{-7}$ transmission performance. For a given ISL distance and transmission capacity, ISL payload design involves trades between the antenna aperture size and on-board HPA power. The design parameters were selected based on the state-of-the-art hardware characteristics.

The ISL payload sizing algorithm was developed, using satatistical techniques, to estimate mass and power requirements. The antenna and repeater HPA characteristics were used as input parameters for payload sizing. The state-of-the-art optical ISL payload data were updated through industry contact.

In addition, ISL interface and integration issues to the host spacecraft were addressed.

3.2.3 COST ANALYSIS AND BENEFIT EVALUATION

ISL payload cost models were developed for both optical and microwave technology implementations. The cost drivers are the aperture size and mass and power of repeater HPAs. The model provides nonrecurring and recurring cost estimates for each of the following subsystems:

- Fully gimballed antenna.
- Repeater and electronic power subsystem.
- Bus or support subsystem.
- Management/engineering function.

Table 3 shows the ISL payload terminal cost estimates for each application. The cost is given in 1986 dollars. The averaged total cost ratio between optical ISLs and the corresponding microwave counterpart of each application is 1.075.

The host spacecraft sizing was derived from the statistical figure-of-merit of the space segment, which is

Table 3. ISL Payload Terminal Analysis* [Cost in $M, 1986]

No.	Application	Traffic Requirement [Mbit/s]	Optical ISL			Microwave (60 GHz) ISL		
			Non-Rec.	Rec.	Total	Non-Rec.	Rec.	Total
1a	CONUS	7,600	16.519	6.536	23.055	16.815	5.078	21.893
1b	CONUS	10,300	17.785	7.137	24.922	17.866	5.511	23.377
1c	CONUS	20,500	21.914	9.101	31.015	-	-	-
2a	CONUS - Europe	618	11.713	4.229	15.942	12.885	3.798	16.683
2b	N.A. - Europe	677	11.906	4.324	16.230	12.948	3.814	16.762
3a	CONUS - POR	317	10.473	3.615	14.088	12.651	3.739	16.390
3b	CONUS - AOR	1,220	11.191	3.961	15.152	13.261	3.897	17.158
4a	R1 - AOR	845	13.968	5.349	19.317	13.066	3.845	16.911
4b	R1 - IOR	200	10.723	3.742	14.465	12.552	3.714	16.266
5a	R1 - R2	1,430	19.289	7.993	27.282	13.392	3.933	17.325
5b	R2 - R3	360	13.978	5.361	19.339	12.678	3.746	16.424
5c	R3 - R1	576	14.963	5.848	20.811	12.858	3.791	16.649

*Note: Program management costs are not included.

defined as the on-station cost per 36-MHz equivalent transponder per year. Figure 5 represents the space segment figure-of-merit as a function of the number of transponders per spacecraft. Platform payloads indicated by PL1 and PL2 in Figure 5 correspond to advanced payload design technology [1,2].

The cost comparison between ISL and corresponding non-ISL systems for each application was made for the add-on systems costs: ISL payload and its launch costs constitute the add-on systems cost of an ISL network, while that of a double-hopping network includes a transponder double charge as well as the relay station cost.

The total systems add-on cost of the CONUS ISLs for four zone coverage satellites is about $207 million. The corresponding non-ISL systems add-on costs are shown parametrically in Figures 6a and 6b for Architectures I and II, respectively.

For Architecture I, the 36-MHz equivalent transponder double charge was assumed to be $0.112 million (nominal). A K_a-band relay station cost was $6 million per station plus $3.6 million for operation and maintenance (O&M) for 12 years. The cost break-even point of the ISL is about $0.01 million for the nominal estimate in Figure 6a. It may be increased to $0.02 million in the worst case if the relay station cost is reduced by 50 percent from the nominal and the ISL payload cost is higher than the cost model prediction by 25 percent.

Figure 6b shows a comparison of the total add-on system costs between ISL and the conventional multiple colocated earth station antennas. A single torus antenna earth station at a cost of $10.5 million, including a 12-year O&M cost, was used instead of multiple antennas due to its cost-effectiveness.

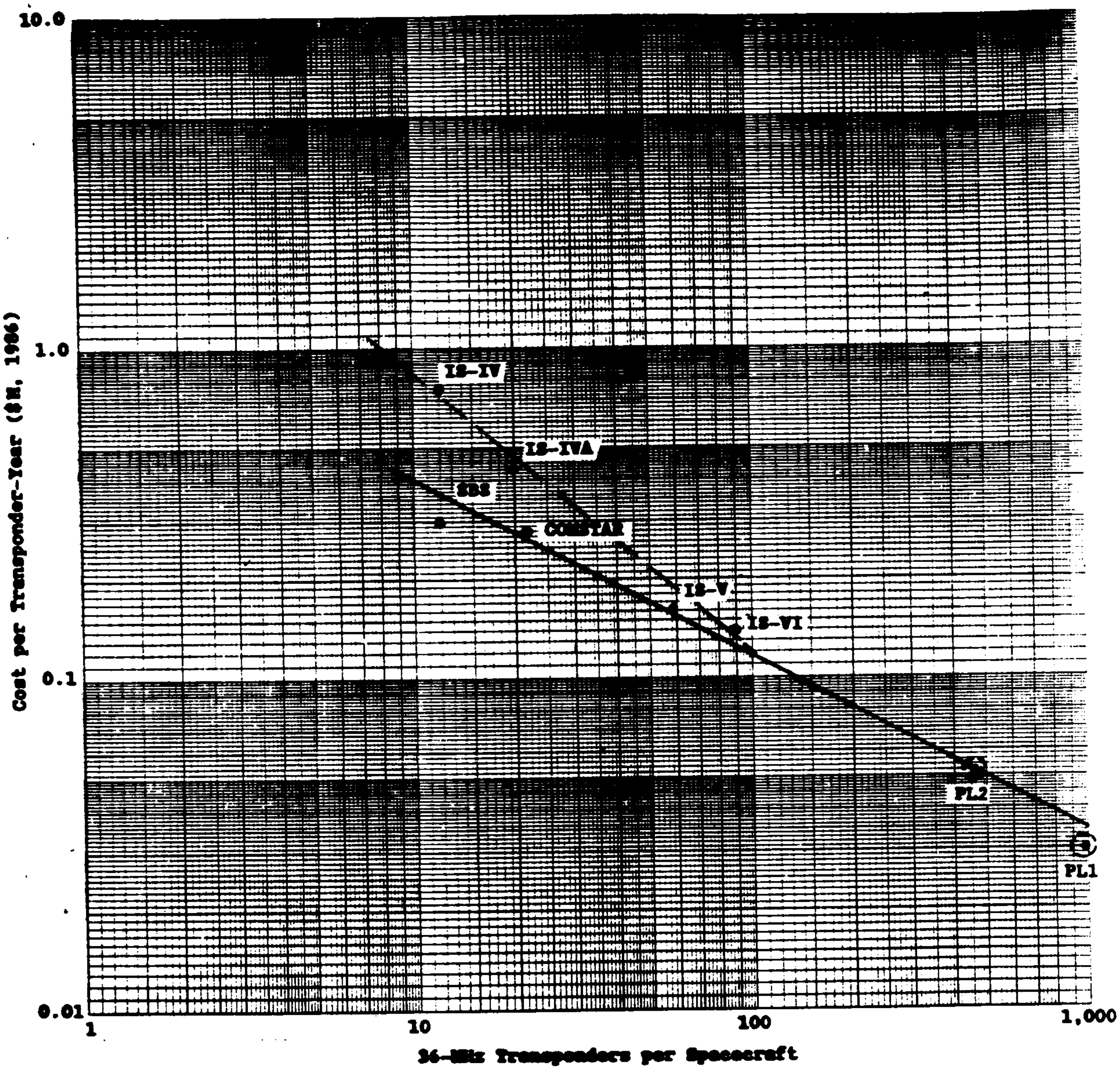


Figure 5. Figure of Merit of Space Segment Cost

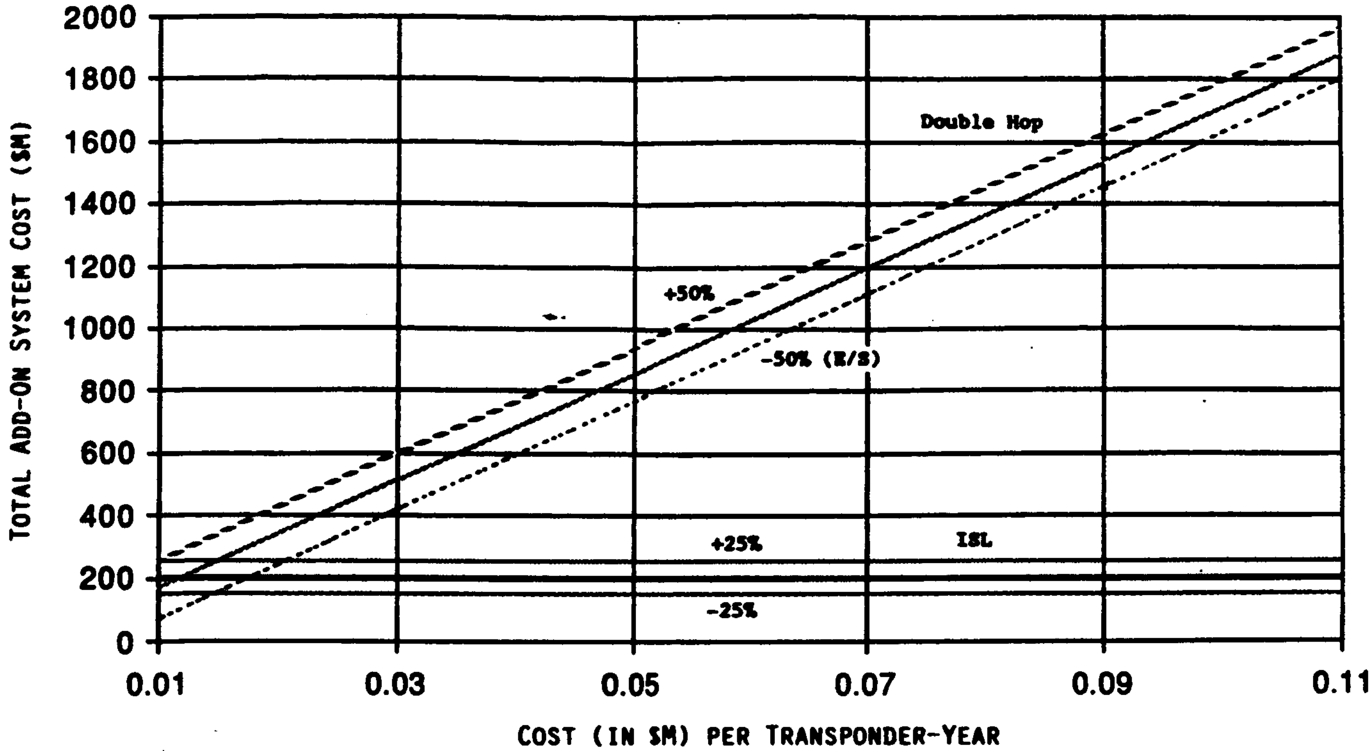


Figure 6a. ISL vs Double-Hop Systems Incremental Cost [$M, 1986]

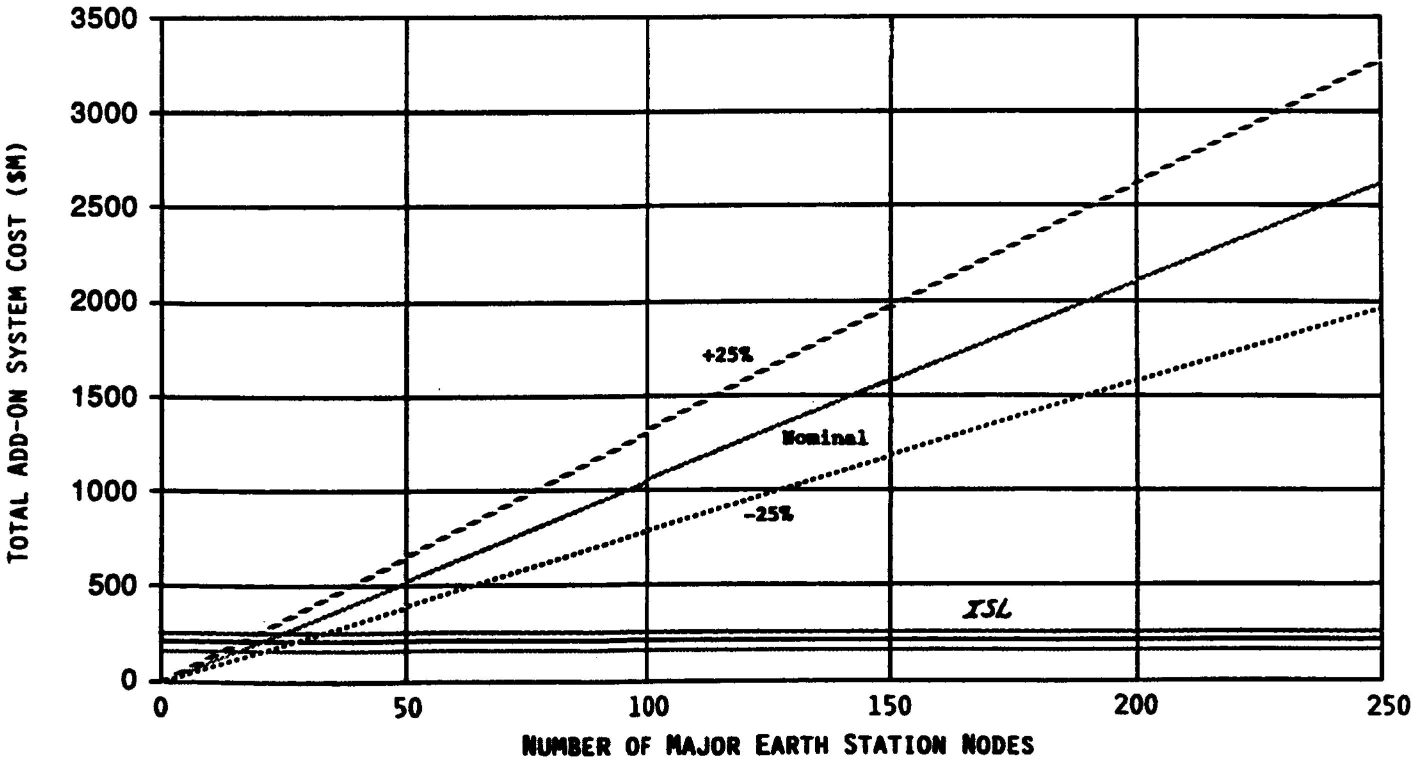


Figure 6b. ISL vs Conventional Multiple Earth Station Antenna Systems Incremental Cost [$M, 1986]

The cost break-even point is 20 (±7) major nodes for a ±25-percent tolerance in the cost estimates.

The total add-on systems costs for each selected application is summarized in Table 4. The ISL systems cost-effectiveness was defined as the add-on systems cost ratio of the corresponding non-ISL system to that of the ISL system. Figure 7 shows the ISL systems cost advantage ratio for each application. Applications No. I and No. II represent the CONUS ISL application (No. 1) with reference to non-ISL Architectures I and II, respectively. The cost-effective ISLs are identified when the ratio exceeds one in Figure 7.

Intercluster ($\leq$ 0.1°) ISLs interconnecting colocated, functionally partitioned satellites are useful to provide an equivalent "super" satellite. However, a comparison of intercluster ISLs, colocated partitioned satellites without ISLs, and a single "super" payload concept shows that the intercluster ISLs do not offer any significant systems advantage over the two alternatives.

In addition to the quantified cost-effectiveness, the ISL provides other benefits in systems planning and operational aspects. Discussions are provided in Volume II of this Final Report.

4. IMPLEMENTATION SCENARIOS AND TECHNOLOGY ISSUES

4.1 DEVELOPMENT OF IMPLEMENTATION SCENARIOS

Implementation scenarios were developed for the following time frame:

Table 4. 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.

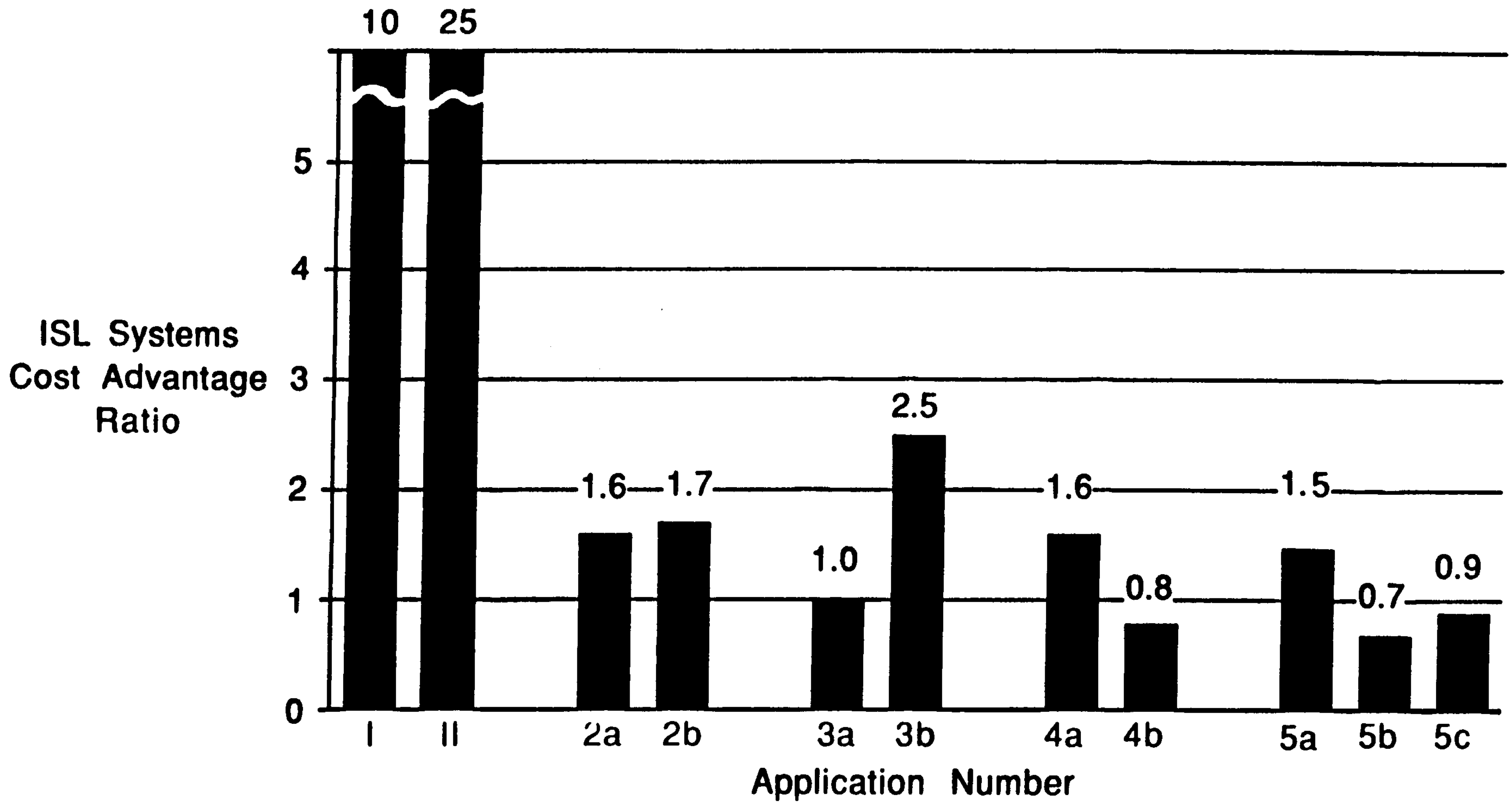


Figure 7. ISL Systems Incremental Cost Advantage Ratio with Respect to Non-ISL Systems

- The first launch in 1993-94.
- Widespread use of ISLs in 2000.

Therefore, the ISL implementation scenarios were developed in two categories:

a. Technology implementation to provide full availability of the space hardware technology.
b. Network implementation of the selected ISL applications.

The ISL technology development scenarios are summarized in Table 5. Critical technology items were identified and the subsystems requirements were defined, along with the development time frame recommended for each item.

The network implementation scenarios were developed under certain assumptions. A key assumption is the successful completion of the current experimental ISL space programs, such as ACTS Lasercom and European DRS intersatellite links, in accordance with their projected schedule.

The evolving ISL network, initiated by U.S. domestic and European applications, can be developed in a number of simplified scenarios. Figure 8 shows these scenarios. Various institutional, economical, and political factors will play a major role in determining the eventual path of ISL network development.

4.2 TECHNOLOGY ASSESSMENT

Critical technology issues were identified for both microwave and optical ISLs. The following major areas were

Table 5. 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.

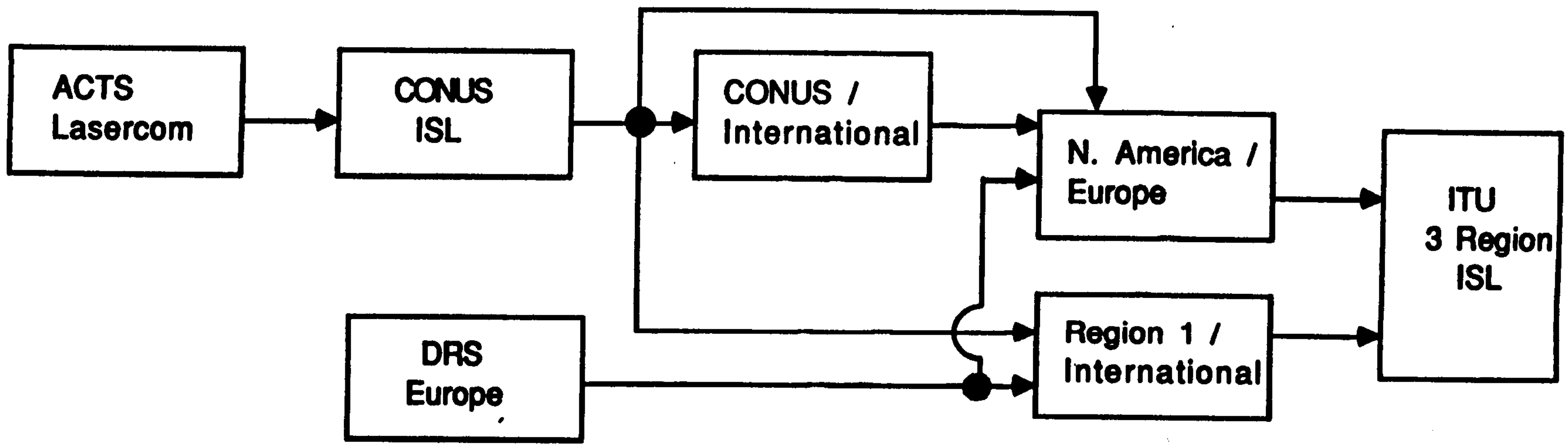


Figure 8. Major ISL Applications Scenario for Commercial FSS Communications

assessed in detail for the SOA capability and further development needed:

- Pointing, acquisition, and tracking (PAT).
- Transmitter and receiver, including issues of designs for solar conjunction and heterodyne systems alternative.
- Prototype payload system design and development.
- In-orbit testing and on-station performance monitoring.

To provide technology readiness for the implementation scenarios for ISLs, technology development programs were formulated, and their program cost and risk estimates were derived, as shown in Table 6.

5. 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

Table 6. 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

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:

- 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 double-hopping 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.

B. <u>Other Systems Benefits</u>

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 Augstroms.
    - 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.

- <u>Issues of Heterodyne System Using Diode Lasers</u>

  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 were derived in the study.

6. 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 [3] 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 listed in Table 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 9):

- 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 approach. Cost analyses and systems benefit

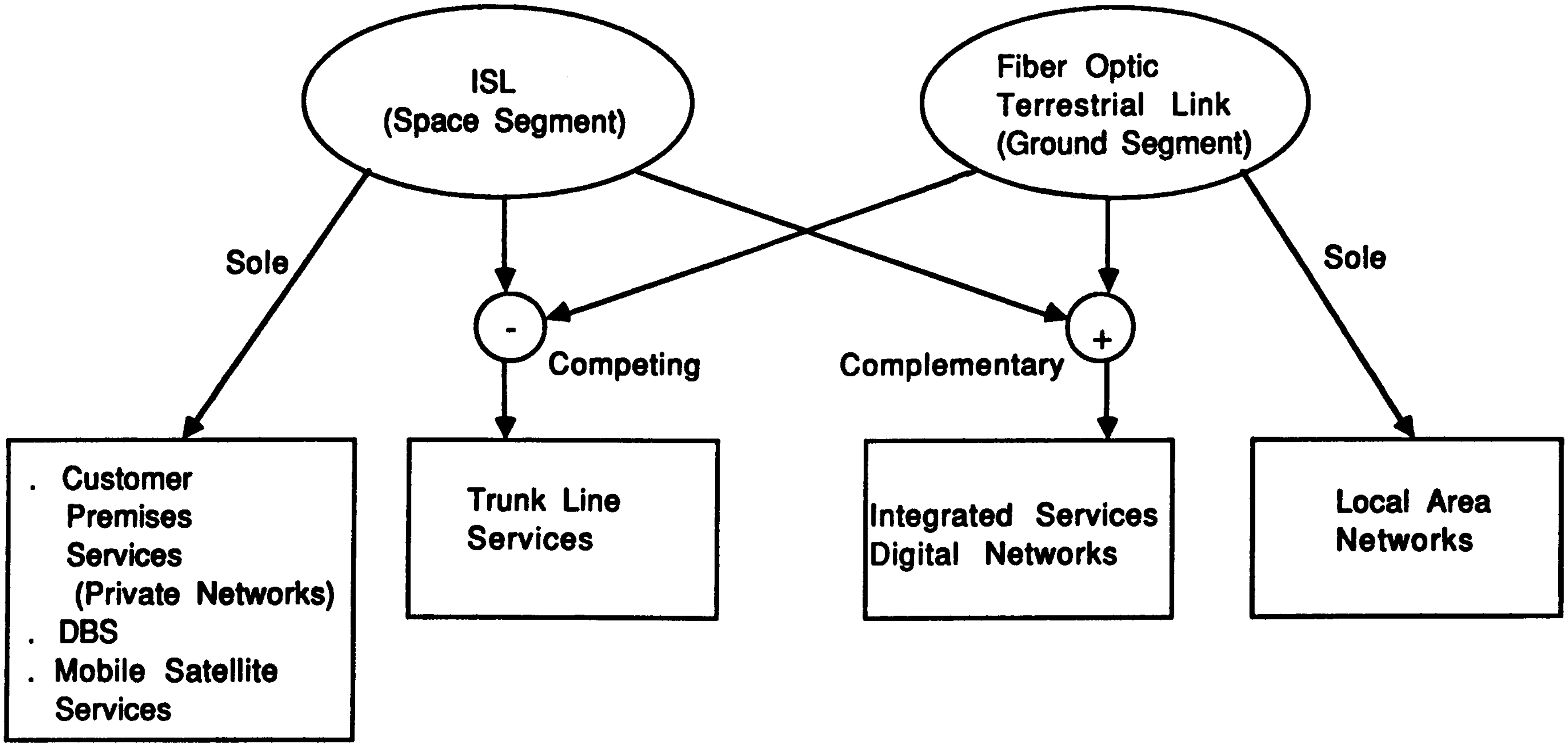


Figure 9. Fiber-Optics Impact to ISL Applications

evaluations 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.

7. REFERENCES

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