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INMARSAT COMMUNICATIONS SYSTEM:
A SYSTEMS APPROACH

by

Aristides Ioannis Fasoulas

June, 1991

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Inmarsat Communications System:
A Systems Approach

by

Aristides I. Fasoulas
Lieutenant Commander, Hellenic Navy
B.S., Hellenic Naval Academy, 1976

Submitted in partial fulfillment
of the requirements for the degree of

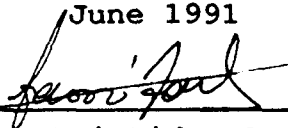
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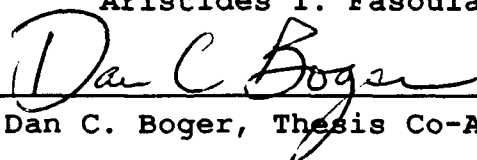
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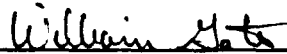


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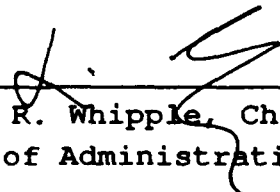
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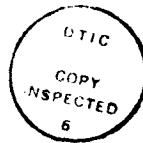
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ABSTRACT

This study describes the history of satellite communications from its beginning to the current date and explains the major components of satellite communications. It describes the satellite communications technology, and identifies some of its problems such as speech echo, data transmission, and digital network synchronization. It deals with U.S military and international satellite communications systems, and especially with Inmarsat. It also presents the possible threats for a satellite communications system and discusses how to deal with them. Finally, it introduces some conditions and technical considerations of the Inmarsat system in the Hellenic environment and provides some basic information for choosing a satellite system from an economic point of view.



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TABLE OF CONTENTS

I. INTRODUCTION	1
A. BACKGROUND	1
B. OBJECTIVES	1
C. ORGANIZATION	2
II. DEVELOPMENT OF SATELLITE COMMUNICATIONS	4
A. HISTORICAL BACKGROUND	4
B. SATELLITE COMMUNICATIONS TECHNOLOGY	6
1. Basic Concepts of Satellite Communications Systems	6
a. Satellite RF-Link	7
b. Communications Subsystem	8
(1) Communications Repeater	9
(2) Communications Antenna	12
c. Communications Satellite (spacecraft)	14
(1) Spin Stabilization	17
(2) Three Axes Stabilization	17
d. Earth Station	18
(1) Earth station antenna	18
(2) Receivers	21
(3) High power amplifier	23

(4) Upconverter	24
(5) Primary power	24
e. Terrestrial link	25
2. Orbits	26
a. General	26
b. Foundation of the theory	27
c. Orbital perturbations	27
d. Geostationary orbit	28
(1) Slant range and Coverage angle	29
(2) Advantages of Geostationary orbit	31
(3) Disadvantages of geostationary orbit	32
3. Multiple Access	32
a. General	32
b. Frequency-division multiple access	33
(1) Advantages of FDMA	34
(2) Disadvantages of FDMA	34
c. Time-division multiple access	35
(1) Advantages of TDMA	36
(2) Disadvantages of TDMA	36
d. Code-division multiple access	37
(1) Advantages of CDMA	38
(2) Disadvantages of CDMA	38
e. Comparison of multiple access techniques	40
C. SPECIAL PROBLEMS IN SATELLITE COMMUNICATIONS	41

1.	Speech echo	41
a.	Echo suppression	41
b.	Echo cancellation	42
2.	Data transmission	42
a.	Protocols	42
3.	Digital network synchronization	44
D.	RELIABILITY OF SATELLITE COMMUNICATIONS SYSTEMS	44
1.	General	44
2.	Classes of failure	45
3.	Mean time between failures (MTBF)	46
4.	Probability of survival or reliability	47
5.	Mission Reliability	48
a.	Without spare satellite in orbit	48
b.	With a back-up satellite (in orbit)	48
E.	ADVANTAGES AND DISADVANTAGES OF SATELLITE COMMUNICATIONS	49
1.	Advantages	50
2.	Disadvantages	50
III.	MILITARY SATELLITE COMMUNICATIONS	51
A.	BACKGROUND	51
B.	DEVELOPMENT OF US MILITARY COMMUNICATION SATELLITE PROGRAMS	51
1.	IDCSP (Initial Defense Communication Satellite Program)	53

2.	DSCS II (Defense Satellite Communication System, Phase II)	54
3.	DSCS III	54
4.	Tactical Satellites (TACSAT)	56
5.	Fleet Satellite Communications (FLTSATCOM)	57
6.	LEASAT Satellite	59
C.	ADVANTAGES/DISADVANTAGES	60
1.	Advantages	60
2.	Disadvantages	60
IV.	INTERNATIONAL SATELLITE COMMUNICATIONS : INMARSAT	61
A.	INTRODUCTION	61
1.	Intelsat (International Telecommunication Satellite Consortium) . .	62
a.	Intelsat-1	62
b.	Intelsat-2	62
c.	Intelsat-3	63
d.	Intelsat-4	63
e.	Intelsat-4A	64
f.	Intelsat-5	64
g.	Intelsat-5A	65
h.	Intelsat-6	65
i.	Intelsat-7	66
2.	Eutelsat (European Telecommunications Satellite Organization) . . .	66
B.	INMARSAT	66
1.	Background	66

a.	The Establishment of INMARSAT	67
b.	Purpose	68
c.	Organization	68
2.	Facts about INMARSAT	68
a.	Maritime applications	69
b.	Aircraft applications	69
c.	Land applications	69
3.	The satellite system	70
4.	User terminals	74
a.	Standard-A terminal	74
(1)	Above and Below Deck Equipment (ADE and BDE) ...	75
(2)	Tracking and Stabilization	75
(3)	SES's antennas	76
b.	Standard-C terminal	76
(1)	Two-way communications	78
(2)	FleetNet & SafetyNet	78
5.	Coast Earth Stations (CES)	78
a.	Antenna	80
b.	L-band functions	80
6.	The Global Maritime Distress and Safety System (GMDSS)	81
a.	Background	82
b.	The new system	82
7.	Aeronautical Satellite Communications	83
C.	FUTURE DEVELOPMENTS OF INMARSAT SYSTEM	84

V. SATELLITE COMMUNICATIONS VULNERABILITY	87
A. INTRODUCTION	87
B. THREATS TO COMMUNICATION LINKS	88
1. Uplink	89
2. Downlink	89
3. Throughlink	90
4. Crosslink	90
C. JAMMING SIGNALS	90
1. Interception and Jamming	91
2. Jammer Description	91
3. Jamming of links using FDMA/PSK	93
4. Antijamming Techniques using spread spectrum	94
5. Uplink-Downlink Jammer	96
a. Uplink Jammer	96
b. Downlink Jammer	97
D. SUMMARY AND CONCLUSIONS	97
a. Frequency hopping vs Jammers	98
VI. CONDITIONS AND TECHNICAL CONSIDERATIONS OF INMARSAT SYSTEM	
IN THE HELLENIC ENVIRONMENT	100
A. INTRODUCTION	100
B. INMARSAT IN HELLENIC ENVIRONMENT	100
1. Background	100
2. Thermopylae's Coast Earth Station	101

3.	Services provided and Dialing procedures	102
a.	Services	102
b.	Dialing procedures	103
(1)	Sending a telex to a ship from Greece	103
(2)	Making automatic calls from a ship	103
(3)	Sending a telex from a ship	104
(4)	Making a call to a ship from Greece	105
C.	ECONOMICS OF SATELLITE BUSINESS SERVICES	106
1.	Background	106
2.	Economically Relevant Technical Properties of Satellites	106
3.	Charges for INMARSAT services in Greece	107
D.	TECHNICAL CONSIDERATIONS FOR INMARSAT IN THE HELLENIC ENVIRONMENT	117
1.	Uplink and Downlink calculations	117
a.	Uplink calculation (Frequency 6.42 GHz)	119
b.	Downlink calculation (Frequency 1.54 GHz)	119
VII.	CHOOSING A SATELLITE COMMUNICATIONS SYSTEM	121
A.	INTRODUCTION	121
B.	ECONOMICS OF A COMMUNICATION SYSTEM	121
1.	Economics of Scale	121
2.	Market Demand and Supply	122
C.	EVALUATING TELECOMMUNICATION SYSTEMS	125
D.	BASIC CONCEPTS OF COST-EFFECTIVENESS ANALYSIS	126

1. Background	126
2. Cost Structure	126
3. Life-cycle cost	127
a. Research and Development cost (R&D)	128
b. Investment cost	128
c. Operation and Support cost (O&S)	128
d. Salvage cost	128
E. COST-EFFECTIVENESS ANALYSIS	130
1. Satellite Cost Model	131
a. Assumptions	131
b. Cost Structure	132
c. Cost Elements	132
(1) Investment Cost	133
(2) Operation and Support cost	135
VIII. CONCLUSIONS AND RECOMMENDATIONS	136
A. CONCLUSIONS	136
B. RECOMMENDATIONS	137
LIST OF REFERENCES	138
BIBLIOGRAPHY	140
INITIAL DISTRBUTION LIST	143

LIST OF TABLES

Table 1. GENERIC COMMUNICATIONS SATELLITE	14
Table 2. SATELLITE SUBSYSTEMS	15
Table 3. CHARACTERISTICS OF MULTIPLE ACCESS TECHNIQUES	40
Table 4. COMPARISON OF TECHNOLOGIES	49
Table 5. TACSAT ACCESSES	57
Table 6. FLTSATCOM CHANNELS	58
Table 7. THE SATELLITE SYSTEM	71
Table 8. INMARSAT's MAIN PARAMETERS	73
Table 9. CHARACTERISTICS OF STANDARD-A SES ANTENNA	76
Table 10. COAST EARTH STATIONS IN OPERATION	79
Table 11. CHARACTERISTICS OF INMARSAT-2	85
Table 12. JAMMING TECHNIQUES	99
Table 13. SHORE-TO-SHIP END USER CHARGES	107
Table 14. SHIP-TO-SHORE TELEPHONE CHARGES	108
Table 15. SHIP-TO-SHORE TELEX CHARGES	109
Table 16. SHIP-TO-SHORE TELEGRAPHY CHARGES	110
Table 17. SHIP-TO-SHIP TELEPHONE CHARGES (IOR TO AOR)	111
Table 18. SHIP-TO-SHIP TELEPHONE CHARGES (IOR TO IOR)	112
Table 19. SHIP-TO-SHIP TELEPHONE CHARGES (IOR TO POR)	113
Table 20. SHIP-TO-SHIP TELEX CHARGES (IOR TO AOR)	114
Table 21. SHIP-TO-SHIP TELEX CHARGES (IOR TO IOR)	115

Table 22. SHIP-TO-SHIP TELEX CHARGES (IOR TO POR)	116
Table 23. SATELLITE COST ELEMENTS	134

LIST OF FIGURES

Figure 1. Basic Satellite Links	7
Figure 2. End-to-end Satellite Communications Link	9
Figure 3. Communications Repeater	10
Figure 4. Wideband communications receiver-downconverter	11
Figure 5. Communications subsystem diagram	13
Figure 6. Spin-stabilized spacecraft	16
Figure 7. Three axes stabilized spacecraft	16
Figure 8. Block diagram of an earth station	19
Figure 9. Paraboloid antenna	21
Figure 10. Cassegrain antenna	21
Figure 11. Receiver chain	22
Figure 12. Upconverter, single conversion	24
Figure 13. Upconverter, dual conversion	24
Figure 14. Placement of a satellite in a geostationary orbit	29
Figure 15. Coverage angle and Slant range	30
Figure 16. FDMA frame structure	34
Figure 17. TDMA network	37
Figure 18. Principle of CDMA, Encoding	39
Figure 19. Principle of CDMA, Decoding	39
Figure 20. Basic classes of protocols	43
Figure 21. Interface between satellite system and terrestrial facilities	44

Figure 22. Bathtub failure rate curve	46
Figure 23. INMARSAT's coverage area	72
Figure 24. A Standard-A SES Antenna	76
Figure 25. Coast Earth Station	81
Figure 26. INMARSAT-2	86
Figure 27. Jammer and Repeater Geometry	92
Figure 28. Sending a telex to a ship from Greece	103
Figure 29. Making automatic calls from a ship	104
Figure 30. Sending a telex from a ship	105
Figure 31. Economies-of-scale diagram	122
Figure 32. Demand and Supply	123
Figure 33. Change in the Quantity Demanded	124
Figure 34. Change in the Quantity Supplied	125
Figure 35. Life-Cycle Cost Structure	129
Figure 36. Satellite Cost Structure	133

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I. INTRODUCTION

A. BACKGROUND

Recent years have witnessed dramatic changes in telecommunications. They are nowhere more apparent than in the communications satellite sector. The rate of development of satellite communications over the last 30 years has been swift and spectacular. International communications volume has increased by a factor of almost one hundred in three decades, mainly as a result of satellites. Nearly 150 satellites are in geostationary orbit today. This number is expected to grow to 300 by the end of this century. Approximately 170 countries use domestic satellite television, radio, telephone, and/or data services. Costs have fallen, satellite lifetimes have expanded, and technological innovations have come quickly.

B. OBJECTIVES

The underlying purpose of this thesis is to analyze the International Maritime Satellite system (INMARSAT). Primary emphasis will be on determining if this communications satellite system is effective, reliable, and survivable in a hostile environment. Also, depending upon the advantages and disadvantages of such a system, would it provide security and survivability in the Hellenic environment? Of particular concern will be the system's ability to maintain an operational communication link in a jamming stressed environment.

Cost considerations are always crucial to the development and success of communications systems. While specific costs for the development and deployment of the INMARSAT system will not be examined, key factors affecting those costs will be reviewed.

C. ORGANIZATION

This thesis is arranged into eight chapters, each having specific objectives as follows:

CHAPTER II provides the historical background to give the reader a quick insight into the development of satellite communications through the last 30 years. Specifically, it gives the general description of a satellite communications system and its subsystems. It also includes information about satellite orbits, multiple access techniques, and focuses on some special problems of satellite communications. Finally, it considers reliability, and examines the advantages and disadvantages of these systems.

CHAPTER III provides the reader with a general overview of the United States military satellite communications systems (unclassified part), and focuses on the requirements such a system has to satisfy.

CHAPTER IV deals with International Satellite Communications systems, and presents a general overview of the INTELSAT program. Primary interest is on the technology applied to the INMARSAT system. This is discussed in more detail. It also includes an economic analysis of the INMARSAT system from a subscriber's point of view.

CHAPTER V presents the possible threats for a satellite communications system and discusses how to deal with them.

CHAPTER VI introduces some conditions and technical considerations of the INMARSAT system in the Hellenic environment.

CHAPTER VII presents the basic information needed for choosing a satellite communications system from an economic point of view.

CHAPTER VIII discusses the conclusions and findings of this study.

II. DEVELOPMENT OF SATELLITE COMMUNICATIONS

A. HISTORICAL BACKGROUND

The first operational communication satellite was the moon which was used as a passive reflector by the U.S Navy in the late 1950s for low-data-rate communication between Washington D.C and Hawaii. The first communication through an artificial satellite occurred in October 1957 when the Soviet satellite Sputnik I transmitted telemetry information for twenty-one days. This success was followed by a large space activity by the United States, starting with Explorer I. This satellite was launched in January 1958 and transmitted telemetry for nearly five months. The first artificial satellite used for voice communications was Score, which was launched in December 1958 and used to transmit President Eisenhower's Christmas message of that year.[Ref. 1:p. 1]

During this first period in the history of satellite communications, some problems and limitations arose, such as cargo size, launch vehicles, and the reliability of the electronics used in space. To try to solve some of these problems, an experimental passive repeater, ECHO I, was launched and placed in medium-altitude orbit in 1960. The approach for this experiment was simple and credible (signals were reflected from the metallic surface of this satellite), but large transmitters were needed on the ground to transmit even very low rate data.[Ref. 2:p. 3]

Bell Systems planned and built Telstar I and II, which were active communication satellites and were launched into a medium-altitude elliptical orbit by NASA in July 1962 and May 1963, respectively. Project Telstar is the best known of active communication satellites, probably because it was the first to transmit television programs across the

Atlantic. The communication capacity of Telstar I and II was one TV channel or 600 voice telephone channels.[Ref. 2:p. 3]

The most important question that arose in the early 1960s concerned the orbit to use for a communication satellite. Medium altitude satellites have the advantage of low launch costs, higher payloads and short propagation times. Their disadvantage is the requirement to track the satellite in orbit with earth stations and to shift operations from one satellite to another. So the synchronous or geosynchronous orbit was introduced. This orbit was first introduced by Arthur C. Clarke in the mid-1940s. It is in the equatorial plane with orbital period synchronized to the rotation of earth.[Ref. 3:p. 2]

The first test at a synchronous orbit was made by NASA's SYNCOM I in February 1963. Although this attempt resulted in a failure SYNCOM II and III, launched in July 1963 and August 1964 respectively, were able to complete successful synchronous orbit placement and to establish communication through this kind of link.[Ref. 1:p. 2]

As the cost of satellites decreased, it was understood that they could replace the suboceanic cables with lower costs and better effectiveness. The Communication Satellite Act, signed by President Kennedy in 1962, was the beginning for the establishment of INTELSAT. An organization that includes about 170 nations, INTELSAT was formed in July 1964, and in April 1965 its first satellite (Early Bird) was launched and placed in geosynchronous orbit. Early Bird, with 240 telephone circuits, doubled the capacity of services that existed at the time. Since it became active, INTELSAT has launched six classes of satellites, INTELSAT I to INTELSAT VI. At about the same time, April 1965, the Soviet Union launched its first communications satellite in high altitude orbit (Molniya), which provides TV and voice communications in the Soviet Union.[Ref. 1:p. 3]

By the mid-1970s, a new kind of satellite communications service, domestic satellites, began to appear. The cost of satellites began decreasing from the early years, so it was sensible to launch domestic and regional satellites to create telecommunication networks over areas much smaller than the visible earth. In the United States alone, there are eight main domestic satellite communications carriers.[Ref. 1:p. 3]

INMARSAT was established in July 1979 and began operations in February 1982. Its mission was to develop a space segment in order to improve maritime communications, and if practicable, to improve aeronautical communications. More than 70 countries and 10,000 ships use the services of INMARSAT today, with all ships being able to use the system whether or not their country is a member.[Ref. 3:p. 29]

Several satellite communications systems have been established for the purpose of offering telecommunications services among areas where there were not such services or they were inadequate. Such a system is the European EUTELSAT, which primarily offers services which are not obtainable through INTELSAT in Europe, that is, main route telephony and TV distribution services. Eutelsat launched its first satellite in October 1983 (EUTELSAT I-F1). EUTELSAT I-F2 was launched in August 1984 and is satisfying its mission as the primary operational satellite.

B. SATELLITE COMMUNICATIONS TECHNOLOGY

1. Basic Concepts of Satellite Communications Systems

A communication satellite system consists of several complicated and interrelated subsystems, the satellite RF link, the communication satellite, the communications subsystem, the earth station and the terrestrial link.

a. **Satellite RF-Link**

A communications satellite normally operates as a faraway line-of-sight microwave repeater offering communication services among multiple earth stations in different geographic places. The functionality of a satellite link is designated by its channel capacity. There are a lot of definitions which are related with the functionality of a link and some (more commonly used) are listed below and illustrated in Figure 1. [Ref. 3:p. 19]

- A *channel* is a one-way link which connects an earth transmitting station with an earth receiving station through a satellite.
- A *circuit* is a full-duplex link which connects two earth stations.
- A *half circuit* is a two-way link which connects an earth station and a satellite.

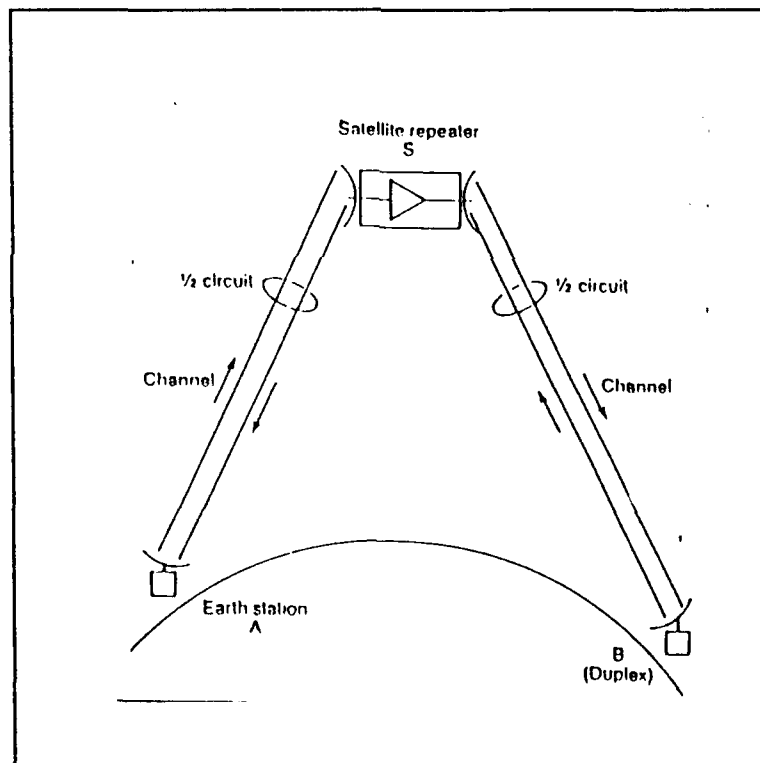


Figure 1. Basic Satellite Links

The capacity of a link is designated by the types and numbers of channels and the functional requirements of each channel. The channel-carrying capability of a Satellite RF link is directly related to the overall available carrier-to-noise ratio. When one RF link is planned, three basic factors are considered:[Ref. 1:p. 16]

- *Uplink* which represents the channel between a transmitting earth station and a satellite. Its quality depends on the power of the transmitting earth station, the gain of the transmitting and receiving antenna and the system's noise temperature.
- *Downlink* which represents the channel between the satellite and the receiving earth station. Its quality depends on the transmitter's power, the transmitting and receiving antenna's gain and the receiving system's noise temperature.
- *Satellite electronics* which produces undesirable noise signals. Their performance depends primarily on intermodulation effects which cause several impairments.

The overall carrier-to-noise ratio present in the link is a combination of three factors: the uplink carrier-to-noise ratio, downlink carrier-to-noise ratio and electronics systems equivalent carrier-to-noise ratio which are related with the uplink, downlink and satellite electronics mentioned above. Figure 2 shows an end-to-end satellite communication link [Ref. 1:p. 15].

b. Communications Subsystem

From a communication point of view, a satellite may be thought of as a faraway microwave repeater which receives uplink signals and after filtering, amplification, processing and frequency translation to the downlink band, retransmits them. So the main parts of the communication subsystem are the communications repeater and the communications antenna.

(1) *Communications Repeater*

The communications repeater is an interconnection of many channelized transponders and generally consists of four modules which are:[Ref.4 p.55]

- A wideband communications receiver/downconverter.
- An input multiplexer.
- Channelized traveling wave tube amplifiers(TWTAs).
- An output multiplexer.

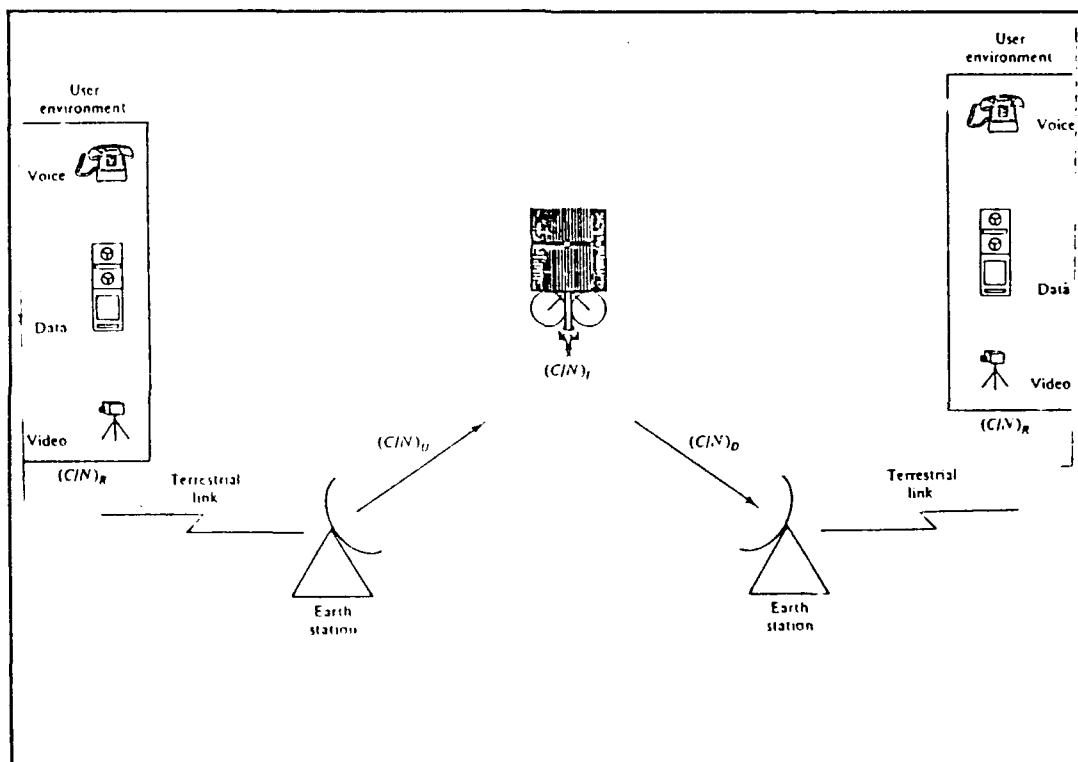


Figure 2. End-to-end Satellite Communications Link

The diagram of the communication repeater is shown schematically in Figure 3 [Ref. 4:p. 57].

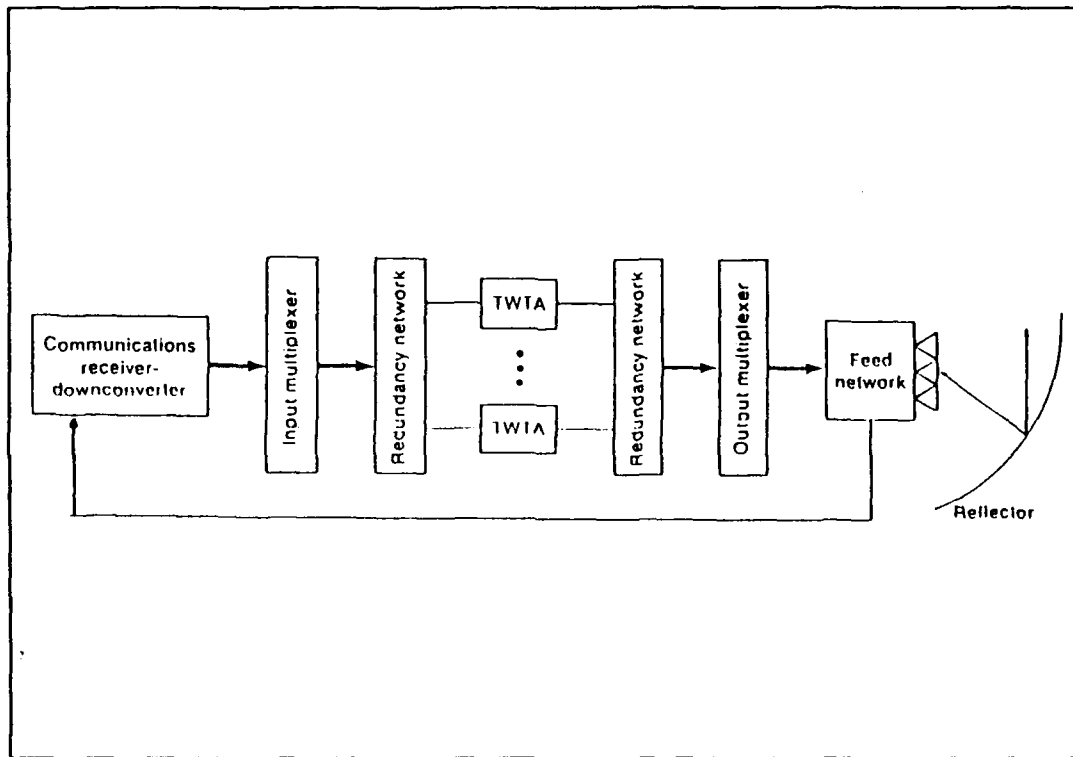


Figure 3. Communications Repeater

There are two types of satellite transponders, the conventional and the regenerative transponder.[Ref. 5:p. 82]

- A conventional transponder is a transponder which simply translates the received signal from uplink frequency to downlink frequency and retransmits it after amplification.
- A regenerative transponder performs on board detection of the received uplink signal prior to baseband processing and remodulation for the downlink.

In communication satellite operations, 6 GHZ and 14 GHZ uplinks are paired with 4 GHZ and 12 GHZ downlinks, respectively. The C-band frequencies (6

(6 and 4 GHz) have the advantages of enough bandwidth, almost zero fading, low rain loss and economic and reliable microwave devices.[Ref. 4:p. 55]

The wideband communications receiver/downconverter operates within the 500 MHz bandwidth designated for Uplink signals (5.9 to 6.4 GHz and 14 to 14.5 GHz for C and Ku-band respectively). After two filterings through a waveguide bandpass filter, and two amplifications from a low noise amplifier, the signal is downconverted to 11.7 to 12.2 GHz or 3.7 to 4.2 GHz downlinks. After downconversion, the signal is amplified again and passes through a ferrite isolator to the input multiplexer. The diagram of the wideband communications receiver/downconverter is shown in Figure 4 [Ref. 4:p. 58].

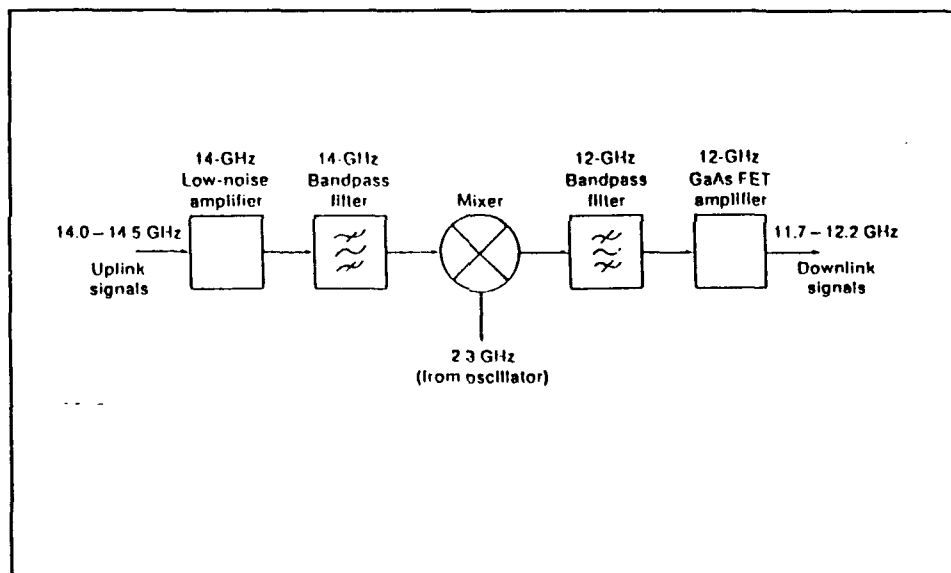


Figure 4. Wideband communications receiver-downconverter

The function of input multiplexer is to distinguish the 500 MHz bandwidth into transponder channels whose bandwidth depends on the satellite's mission.

The channelized TWTAs amplify the low-level downlink signal to a high level for retransmission to earth. The TWTAs are the major nonlinear device in a transponder and is very important because it can influence the link performance.

Its size depends on the mission and is about 15 to 30 W for a 61 MHz Ku-band transponder. Nowadays, solid state power amplifiers based on gallium arsenide field effect transistors have been developed and included in various satellites, such as SATCOM V, TELSTAR 3, and INTELSAT VI. The expectation is that these amplifiers will provide longer life and better reliability than TWTAs because of their superior linearity, which provides greater communications capacity and is critical to modulation techniques.[Ref. 6:p. 118]

After the TWTAs, the downlink signals are combined by the output multiplexer and retransmitted to earth.

(2) *Communications Antenna*

The earth subtends an angle of about 18 degrees to a satellite in geostationary orbit. If a satellite-mounted antenna is radiating energy equally in all directions, a high percentage of this energy is lost to space. In order to increase the amount of transmitter power which is actually transmitted to earth, the radiation must be concentrated to the direction preferred. In microwave radio frequencies, this can be accomplished by employing antennae with dish-shaped reflectors.

The main operation of the antenna is to provide shaped downlink and uplink beams for transmission and reception of telecommunications signals in the operating frequency bands.

To increase the communication capacity of the satellite **frequency reuse** is applied with **polarization** and **beam separation** methods. The polarization method uses the principle that electromagnetic waves generally can be made to vibrate uniformly

in one of several planes or directions of polarization. The technique enables a single range of frequencies to be re-used by arranging to transmit (and receive) with different polarization to that applied to the initial use. The beam separation technique relies on the fact that if two beams illuminate different regions without overlapping, then each beam can employ the same frequencies without mutual interference.

Nowadays most communications satellites are equipped with several antennae. The main categories of antennae are:[Ref. 6:p. 103]

- Omnidirectional.
- Global or earth coverage.
- Hemi/zone.
- Spot beam.

A typical arrangement of the communications subsystems, which originates from the specification of the telecommunications package for the United Kingdom UNISAT Satellite, is shown in Figure 5 [Ref. 6:p. 114]:

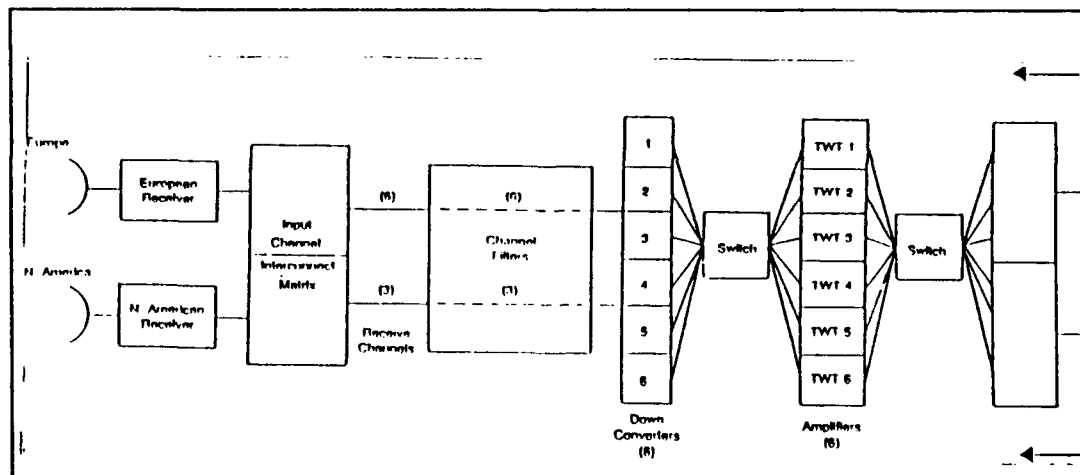


Figure 5. Communications subsystem diagram

c. *Communications Satellite (spacecraft)*

The spacecraft provides a platform on which the communication equipment can operate and maintains this platform in the chosen orbit. The design of such spacecraft is very complicated because it involves several branches of engineering and physics. Satellite design and construction introduce several specific problems. First of all, the very inaccessibility of a spacecraft for repair purposes necessitates strict reliability requirements. Secondly, like any other equipment, satellites have a limited life span, and for obvious economic reasons it is desirable that this is optimized with respect to development and procurement costs. Finally, it has to operate effectively and efficiently in the hostile environment of space, and this suggests quite unique engineering problems which dictate equally unique solutions. For satellite communications system engineers, it is valuable to have an understanding of the above problems and how the design and construction process works.

In recent years, several spacecrafts have been developed for national and regional markets. Basically, three generic communications satellites have been proven in space and are summarized in the Table 1 below [Ref. 3:p. 10]:

Table 1. GENERIC COMMUNICATIONS SATELLITE

	Manufacturer				British Aerospace/ Matra
	RCA		Hughes		
Satellite	Satcom	Series 4000	HIS 376	HIS 393	ECS
Total weight (kg)	600	750	540 to 661	1090	610 to 680
Total power (Watts)	1000 - 1375	2260	900 - 1118	2250	1100
First launch	October 82	November 85	November 80	November 87	June 83
Lifetime (years)	10	10	7 - 10	10 - 12	7

The cost of the communication package itself is only about 20% of the total cost. The remaining cost is due to the platform and launch. If we exclude the communication subsystem, which was described above, then in Table 2 we can see a the subsystems and their main parameters, of a typical communication satellite: [Ref. 1:p. 111]

Table 2. SATELLITE SUBSYSTEMS

System	Function	Principal Quantitative Characteristics
Communications Transponders Antennas	Receive, amplify, process, and retransmit signals; capture and radiate signals	Transmitter power, bandwidth, G/T , beamwidth, orientation, gain, single-carrier saturated flux density
Structure	Support spacecraft under launch and orbital environment	Resonant frequencies, structural strengths
Attitude control	Keeps antennas pointed at correct earth locations and solar cells pointed at the sun	Roll, pitch, and yaw tolerances
Primary power	Supply electrical power to spacecraft	Beginning of Life (BOL) power, End of Life (EOL) power, solstice and equinox powers, eclipse operation
Thermal control	Maintain suitable temperature ranges for all subsystems during life, operating and nonoperating, in and out of eclipse	Spacecraft mean temperature range and temperature ranges for all critical components
Propulsion	Maintain orbital position, major attitude control corrections, orbital changes, and initial orbit deployment	Specific impulse, thrust, propellant mass
Telemetry, tracking, and command (TT&C)	Monitor spacecraft status, orbital parameters, and control spacecraft operation	Position and velocity measuring accuracy, number of telemetered points, number of commands
Complete spacecraft	Provide satisfactory communications operations in desired orbit	Mass, primary power, design lifetime, reliability, communications performance — number of channels and types of signals

A communication satellite is usually stabilized that the communications antenna points toward the earth on one hand, and the solar-energy-collecting system points toward the sun for efficient collection of solar energy on the other. Two different kinds of stabilization have been used in communications satellite design and they are:

- Spin stabilization
- Three axis or body stabilization

The schematic diagram for both stabilization techniques is shown in Figures 6 and 7 [Ref. 7:pp. 46,48]:

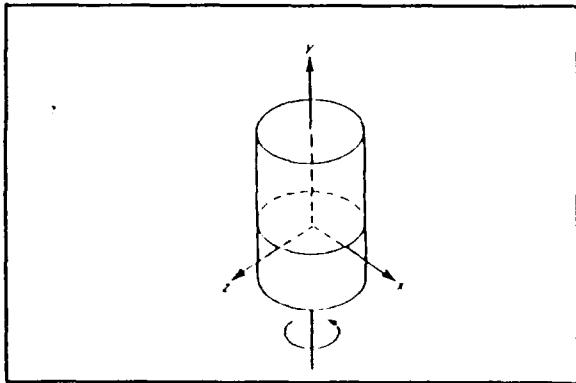


Figure 6. Spin-stabilized spacecraft

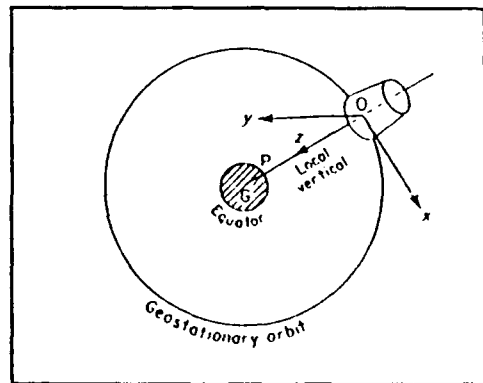


Figure 7. Three axes stabilized spacecraft

(1) *Spin Stabilization*

Usually a cylindrical satellite spins around its main axis of symmetry, and is balanced so that the main axis is also one of the main axes of inertia. Thus, while the satellite is in synchronous equatorial orbit, the main axis is parallel with the earth's geographic polar axis. For a stable spinning condition, the ratio of the moments of inertia of the spacecraft must satisfy the relationships: [Ref. 7:p. 46]

$$I_y/I_x > 1 \quad (1)$$

$$I_y/I_z > 1 \quad (2)$$

Typical inertia ratios range from 1.1 to 1.3, and a typical spin speed is 100r/min. Spin-rate maintenance can be achieved through metered impulses by boosting the secondary propulsion jets. [Ref. 7:p. 46]

Spinning satellites can reach attitude accuracy on the order of a few tenths of a degree. While the spacecraft is spinning, the communications antenna has to be pointed towards the earth. In order to achieve this, it's necessary to detect the local vertical and both decouple the antenna mount from the spinning main body and despin the mount. This process can be done either electronically or mechanically.

(2) *Three Axes Stabilization*

Communications satellites in geostationary orbits are often stabilized in three axes with respect to a geocentric system that rotates with the earth. For a body stabilized spacecraft, these three axes appear to be stationary to an observer located at the earth's surface point, point P in Figure 7. Although it appears to an observer at point P that it is stabilized, it has an angular motion with respect to inertial space in order to maintain

its axis z along the local vertical GO. This angular velocity is called "pitch rate", and for a synchronous orbit it is equal to the earth's angular velocity. [Ref. 7:p. 49]

$$\Omega = 7.27 \times 10^{-5} \frac{\text{rad}}{\text{sec}}$$

Antenna and solar panel pointing requirements are solved using the same techniques as in the spin stabilization case mentioned above.

d. Earth Station

One of the main elements in a satellite link is the earth station. The earth station is the collection of equipment on the surface of the earth which is used for communication with the satellite, regardless of whether the equipment is a fixed, ground mobile, maritime or aeronautical terminal.

The performance of an earth station is specified by its equivalent isotropic radiated power (EIRP) and its gain-to-system noise temperature ratio (G/T). EIRP is the product of the power output of the high power amplifier at the antenna and the gain of the transmitting antenna. The receiving system sensitivity is determined by G/T, which is the ratio of the receive gain of antenna to the system noise temperature. For a 10m earth station this is 33db/k and for a satellite receiver system it is -6db/k.

The block diagram of an earth station is shown in Figure 8.

(1) Earth station antenna

The earth station antenna is an important part of the RF terminal. It serves for both transmission and reception, but not necessarily simultaneously.

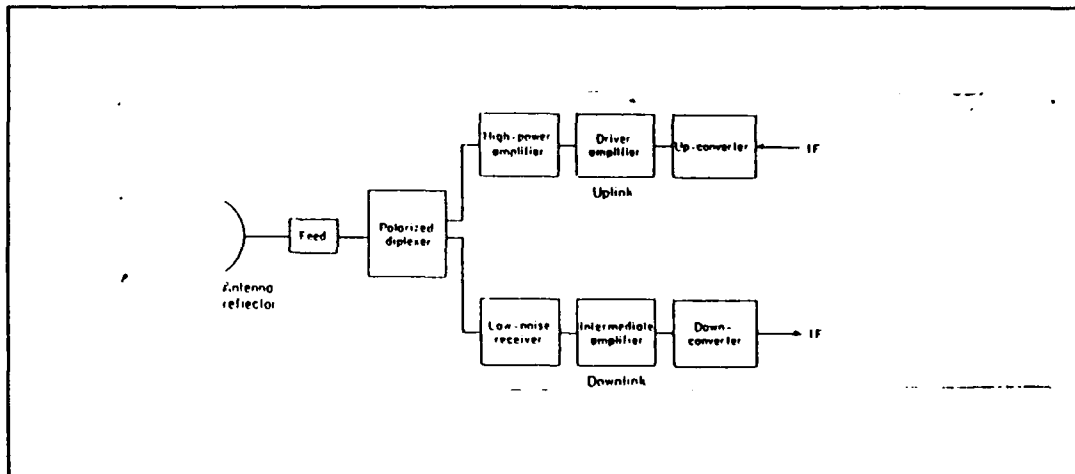


Figure 8. Block diagram of an earth station

The antenna subsystem consists of the antenna proper, typically a reflector and feed; separate feed systems to permit automatic tracking; and a duplex and multiplex arrangement to permit the simultaneous connection of many transmit and receive chains to the same antenna.

The earth station antenna has to satisfy three main requirements which are: [Ref. 4:p. 71]

- Highly directive gain in a given direction that is the ratio of the maximum radiation intensity produced in that direction, to the maximum radiation intensity produced in the same direction from a reference antenna with the same power input.

$$G_{\max} = \frac{4 \times \pi \times \phi_{\max}}{W}$$

- Low noise temperature so that the total noise temperature that limits the sensitivity of the earth station, which is proportional to the antenna temperature, can be kept low.

- Easily steered so that a tracking system can comprise whatever control limits and drives are necessary to keep the antenna pointed at the spacecraft which results the minimum antenna pointing loss.

The two most common types of earth station antennas, which satisfy the above requirements, are the **paraboloid** antenna with a focal point feed and the **cassegrain** antenna [Ref. 4:p. 71].

The paraboloid antenna consists of a reflector and a feed. On the transmission section, the signal energy from the high power amplifier is radiated at the focal point by the feed. This illuminates the reflector, which reflects and focuses the signal energy into a narrow beam. On the receive section, the signal energy captured by the reflector converges on the focal point and is received by the feed, which then directs it to the low noise amplifier. This type of antenna is easily steered and has a gain efficiency of 50-60%. The only disadvantage is that sometimes there is high antenna noise distribution. This is particularly troublesome when the antenna has a high elevation angle, because the feed illuminates the ground which has high noise temperature.

The cassegrain antenna is a dual reflector antenna. It consists of a paraboloid main reflector, whose focal point is coincident with the virtual focal point of a hyperboloid subreflector, and a feed whose phase center is at the real focal point of the subreflector. During transmission, the signal energy from the high power amplifier is radiated at the real focal point by the feed. This illuminates the surface of the subreflector, and reflects the signal energy back to the main reflector, where it is reflected again to form the antenna beam. During reception, the signal energy captured by the main reflector is directed toward its focal point. From this point the subreflector again reflects the signal energy back to its focal point where the feed receives the incoming signal energy and directs it to the low noise amplifier. This type of antenna is more expensive but has

advantages over the paraboloid, such as low noise temperature, better pointing accuracy, and flexibility in feed design. Both types of antennas are shown in Figures 9 and 10 below [Ref. 4:pp. 72,73].

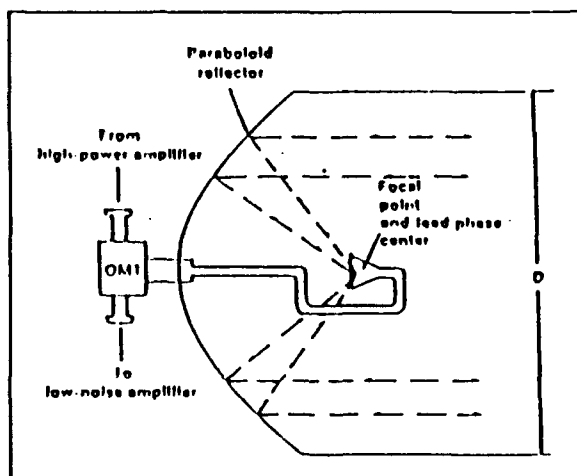


Figure 9. Paraboloid antenna

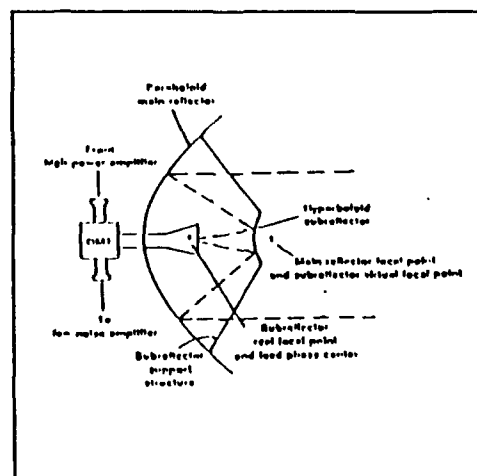


Figure 10. Cassegrain antenna

(2) Receivers

To receive a signal from a satellite, several distinct functions must be performed. The signal must first be amplified, then reduced to a lower frequency so that is convenient for further amplification and demodulation, then demodulated and delivered to baseband processing equipment.

As used in this thesis, the term receiver chain means specifically low-noise amplifiers, down converters and demodulators. Down conversion can be accomplished either in one step, going directly from the satellite downlink carrier frequency to the intermediate demodulator frequency, or in several steps. Usually two stage down conversion is used when the same receiver is to be tuned to a multiplicity of channels.

A prototypical receiver chain for general cases is shown in Figure 11 below

[Ref. 8:p. 321].

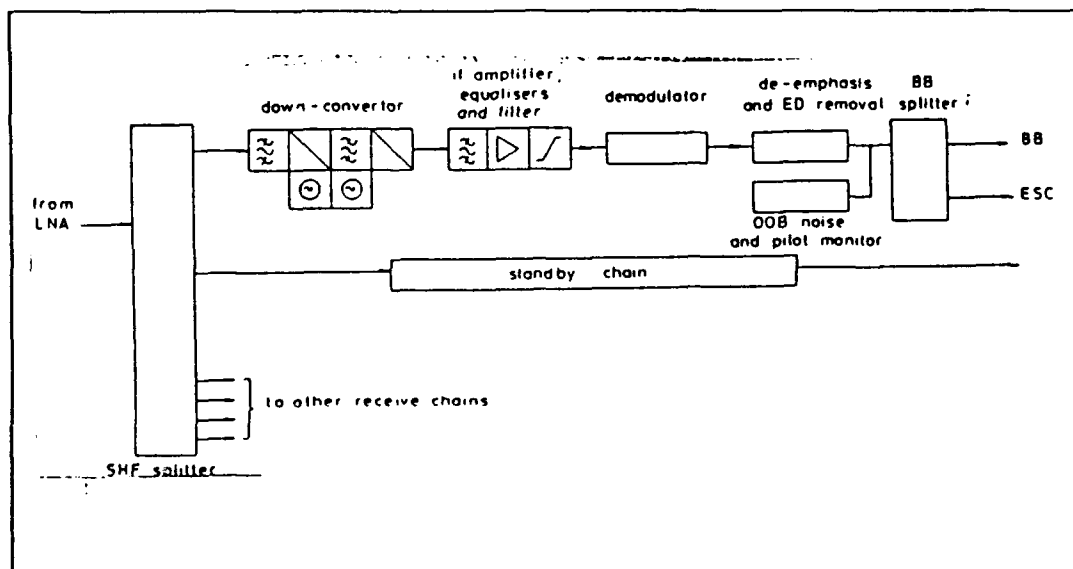


Figure 11. Receiver chain

The low-noise amplifier, first stage of the receiver, is critical in determining the earth station performance. Because of the very low signal power at the receiving antenna, this amplifier must be very sensitive and create as little noise as possible. In order to avoid losses and noise created by waveguides, this amplifier is mounted on the antenna dish, receiving the energy from the focusing element. Usually cryogenically cooled parametric amplifiers and solid-state components such as FETs are used in the amplifier chain, to have high gain with low-noise performance.

The noise introduced by the amplifier is calculated by: [Ref. 7:p. 103]

$$N=k \times B \times T$$

where k =Boltzmann's constant= 1.38×10^{-23} j/k

B =Bandwidth in hertz

T =Effective input noise temperature in kelvins

In addition to the receiver electronic equipment noise, antenna noise, as well as atmospheric and cosmic sources, must be added at the receiver input. Thus, the total noise temperature that limits the sensitivity of the earth station is a combination of the following: [Ref. 7:p. 103]

- Sky noise, atmospheric absorption, and rain.
- Transmission-lines losses including the feed losses.
- Receiver system temperature.
- Antenna noise temperature.

(3) *High power amplifier*

A high power amplifier usually uses a Traveling Wave Tube (TWT) or a Klystron. If multicarrier function is anticipated, the total power of the amplifier must be substantially higher than the power per carrier in order to avoid intermodulation products. This is necessary because of the nonlinear characteristics of these devices when operated close to saturation level. The traveling wave tube can achieve a bandwidth on the

order of 10%;hence, it can cover the entire 500 MHz allocated for satellite communications. The Klystron amplifier can provide higher gain and better efficiency than the TWT but at a much smaller bandwidth, on the order of 2%. For low power applications, Impatt diode amplifiers or GaAs ET amplifiers can be used with better efficiency than the TWT or Klystron amplifiers.[Ref. 4:p. 94]

(4) Upconverter

The upconverter accepts the modulated IF carrier from the carrier modulator and translates its IF frequency to the uplink RF frequency by mixing the IF frequency with a local oscillator frequency. In Figures 12 and 13 below, a single and a dual conversion are shown [Ref. 4:p. 107]:

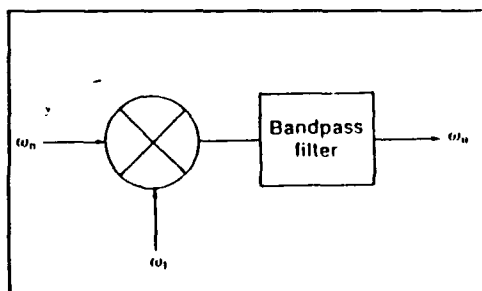


Figure 12. Upconverter, single conversion

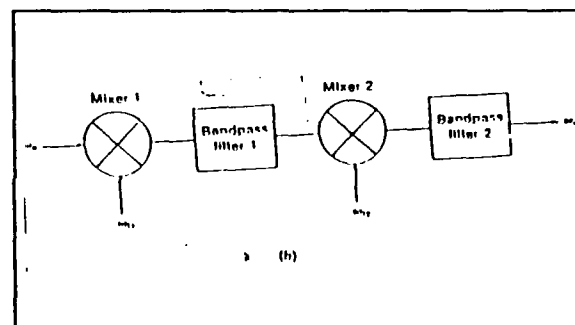


Figure 13. Upconverter, dual conversion

(5) Primary power

Primary power systems vary from plain battery or solar-cell-operated remote transmitters for data gathering to huge combined commercial power and diesel generator systems for large stations. Almost all transmit and receive earth stations require

some kind of uninterruptable power system, that is, emergency power to continue the communications during commercial power outages. Almost all systems today use batteries to effect this transition. Some systems have been devised in which motor generators store enough energy in flywheels to permit a smooth mechanical transition.

e. Terrestrial link

From the earth station, the signal is carried to the customers' premises through a terrestrial transmission medium. For this purpose, coaxial cable, fiber-optic cable, twisted-wire pair, microwave links, etc., can be used. The nature of the signal and the distance to be carried will affect the cost and the method which will be used. Fiber optics are most appropriate for broadband signals over a few kilometers distances, twisted-wire pair for narrow-band signals over short distances and microwave links for multiplexed broadband signals over long distances.

To provide adequate satellite service to a user, the service requirements must be well specified in terms of quality. Quality of service, specified in terms of parameters such as link availability, bit error rate, transmission rate, and signal-to-noise ratio may be translated into a required carrier-to-noise ratio $(C/N)_r$ in the RF link. The required $(C/N)_r$ is then compared with the available carrier-to-noise ratio $(C/N)_a$ to determine the overall link's capacity. In order to achieve the required quality several basic baseband processing stages must be considered, including: [Ref. 3:p. 22]

- Source coding and/or modulation, where a source signal is coded in digital form or processed in analog form to be ready for terrestrial transmission and multiplexing. In analog transmission AM and FM modulation is used, while in digital PCM is used.¹

¹ AM=Amplitude Modulation
FM=Frequency Modulation
PCM=Pulse Code Modulation

- Multiplexing, where in analog transmission FDM is used while in digital transmission TDM is used.²
- Channel coding.
- Multiple access, where FDMA is the most common method in use, because it was a natural extension of the FDM systems that were in use for many years in terrestrial carrier systems. It employs multiple carriers within the same transponder. We can also use TDMA which employs a single carrier which is time shared among many users, and CDMA wherein all uplink signals occupy the same frequency band at the same time.³

2. Orbits

a. General

Generally speaking there are four types of orbits which might be suitably used today for satellite communications. These are:

- Low earth orbit (< 300 miles above earth's surface)
- Medium earth orbit (7000-8000 miles above earth)
- Geosynchronous orbit (exactly 22,238 miles above earth).
- Super synchronous orbit (between geosynchronous and lunar orbits).

Low earth orbits are used most often because they are the easiest and least expensive. The possible applications and uses of this orbit are reconnaissance, vacuum experiments, localized weather, resource imaging, etc.

Medium orbit satellites are normally launched into a polar orbit and are programmed when they pass over the earth to stay in the sun's illumination. This is

² FDM=Frequency Division Multiplexing
TDM=Time Division Multiplexing

³ FDMA=Frequency Division Multiple Access
CDMA=Code Division Multiple Access
TDMA=Time Division Multiple Access

important for remote sensing and weather monitoring. This type of orbit is also suitable for navigational purposes.

Geosynchronous orbit is a single very precise orbit which allows a satellite to complete one revolution around the earth every 24 hours.

b. Foundation of the theory

The most accessible way of developing orbital mechanical theory, at least as applied to earth satellites starts with Newton's law of gravitation, and the second law of motion.

The characteristics of a satellite orbit are ruled by Kepler's laws that is,

- The orbit of each planet (satellite) is an ellipse with the sun (earth's center) at a focus.
- The line joining the planet (satellite) to the sun (earth's center) sweeps out equal areas in equal times.
- The squares of the orbital periods of two satellites have the same ratio as the cubes of their mean distances from the center of the earth.

c. Orbital perturbations

The earth's distorted shape, the atmosphere, the presence of the sun and moon, and other factors give rise to a series of important orbital perturbations. They affect both the launch sequence and the final operational orbit, and influence the design of the spacecraft in many ways. In a typical geostationary communications satellite, provisions for dealing with the gravitational effects of the sun and moon and anomalies of the earth's gravitational field normally add from 20-40% to the total dry mass of the spacecraft in station-keeping propellant. [Ref. 1:p. 46]

Orbital perturbation of artificial satellites can be placed into three categories:

- Those due to the presence of other large masses (i.e., sun and moon).
- Those resulting from not being able to consider either the earth or the satellite as a point mass.
- Those due to nongravitational sources such as the radiation pressure of the sun, the earth's magnetic field, micrometeorites, and atmosphere.

d. Geostationary orbit

Three-fourths of the cost of a communications satellite is related to launching and maintaining it in its operational orbit so that the communications package can function satisfactorily. Although a number of different orbits have been used for special purposes in satellite communication, and will continue to be used, the main interest for this application is in the geostationary orbit. This is a circular orbit whose period of rotation is equal to that of the earth's and whose plane is in the plane of equator. Figure 14 shows a placement of a satellite, launched from Cape Kennedy, in geostationary orbit.

[Ref. 4:p. 49]

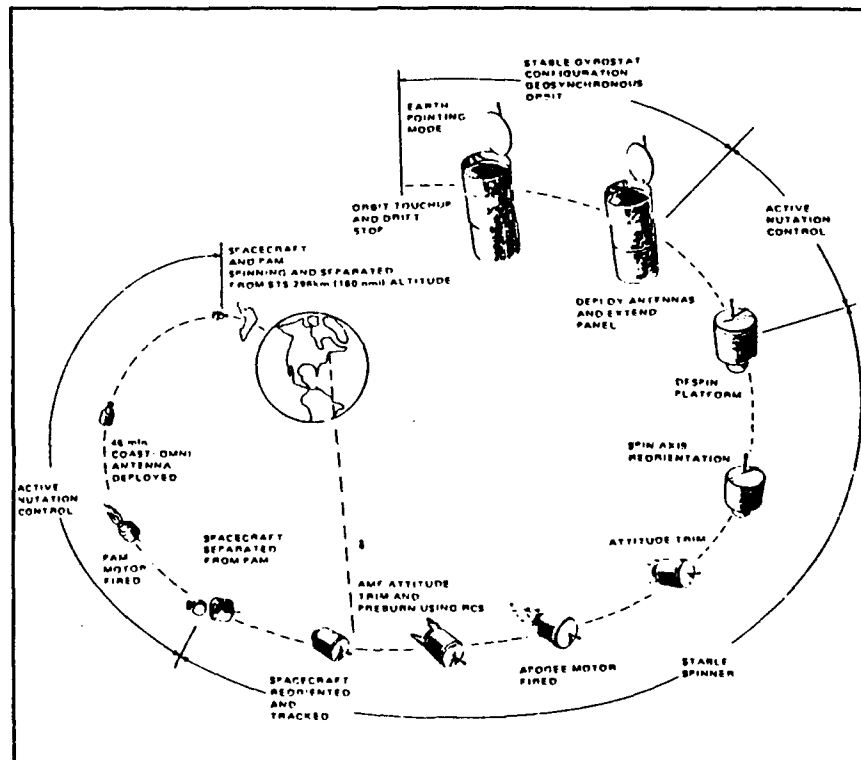


Figure 14. Placement of a satellite in a geostationary orbit

(1) *Slant range and Coverage angle*

The area of the earth seen by a satellite at any moment is bounded by a circle whose radius depends on satellite altitude H and earth antenna elevation angle E . Although a geostationary satellite is visible from about the 42% of the earth's surface, whether or not a station is in line-of-sight depends upon its angle of elevation relative to the fixed satellite position. Actually with only three satellites in geostationary orbit we are able to cover the whole globe, with the exception of the polar regions above latitudes 75N and 75S, assuming a 5 degree minimum elevation angle.

The coverage geometry is shown in the Figure 15 below [Ref.4 p.44],

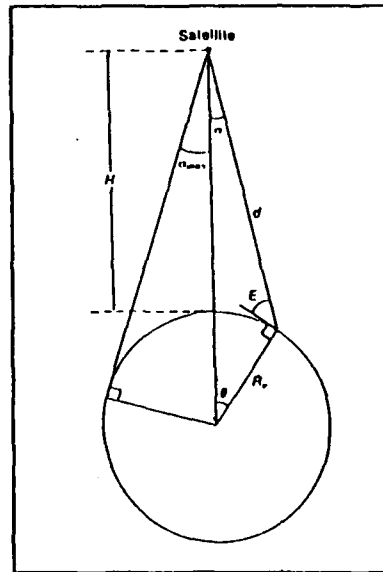


Figure 15. Coverage angle and Slant range

where the earth coverage angle $2a(\max)$ is the total angle inclined by the earth as seen by the satellite.

The communication coverage angle $2a$ is similarly defined by the equation:

$$2a = 2 \times \sin^{-1} \left(\frac{R_e}{R_e + H} \times \cos E \right)$$

where R_e is the assumed's spherical earth radius, H is the altitude of the satellite orbit, and E is the elevation angle of the earth station antenna.

For a geostationary orbit the altitude H of a satellite is 35,786 Km and R_e is assumed to be about 6,378 Km thus if we put $E=0$ degrees then the earth coverage

angle is calculated as $2a(\max)=17.4$ degrees. The angle θ which is the angular radius of the satellite footprint is:

$$\theta = 180^\circ - (90^\circ + E + a) = 90^\circ - E - a$$

The slant range d can be calculated as:

$$d^2 = (R_e + H)^2 + R_e^2 - 2 \times R_e \times (R_e + H) \times \cos \theta$$

(2) *Advantages of Geostationary orbit*

- The cost and complexity of earth stations is at a minimum because the satellite remains stationary relative to earth thus the cost of sophisticated tracking equipment is avoided.
- The break in transmission, which occurs when a non-stationary satellite disappears over the horizon, is avoided because locations within the satellite's area of coverage remain in line-of-sight contact.
- A large number of earth stations are able to intercommunicate because of the large coverage area.
- A relatively small number of satellites are able to provide total global coverage.
- The geostationary satellite, except for minor drifts, experiences no motion relative to the earth station. Thus, there is almost no Doppler shift, which is desirable for many synchronous digital systems.

(3) *Disadvantages of geostationary orbit*

- Latitudes greater than 81.5 degrees North and South are not covered; this is reduced to 77 degrees North and South if antenna's elevation angle is less than 5 degrees.
- The received signal strength is very weak, because of the great distance (signal strength is inversely proportional to the square of the distance). It is on the order of 1 picowatt.
- The signal propagation time is also proportional to distance. At 270 milliseconds (average), this is sufficient to affect the transmission efficiency.
- Compared with lower orbits, more powerful rocketry and fuel supplies are needed to achieve geostationary orbit.
- With increasing altitude, the effects of earth and moon eclipses are increased.
- The free space loss increases with the increase of distance.

3. **Multiple Access**

a. *General*

Communication satellites demonstrate that satellite repeaters can provide a communication capacity equal to or greater than that available by other means, and a single communication satellite can provide many communication channels between widely separated points. Generally, the various earth stations accessing a satellite are not similar to each other, because their size, capacity, and operation frequency depend on the requirements of the network they serve. A single earth station may access one or more transponders and it may use one carrier per transponder or multiple carriers per transponder. In turn, it may receive one or several carriers. Thus, each satellite transponder may be accessed by one or more carriers. As a result, and because each transponder is a nonlinear repeater with limited power and bandwidth, a serious network problem exists. This becomes more complicated if the communication requirements for each node change

from second to second. To satisfy these access requirements some modulation techniques have been developed. The most frequently used are:

- Frequency-division multiple access (FDMA).
- Time-division multiple access (TDMA).
- Code-division multiple access (CDMA), which is subdivided into spread-spectrum multiple access (SSMA) and pulse-address multiple access (PAMA). SSMA utilizes angle-modulation coding and PAMA utilizes amplitude-modulation coding.

b. Frequency-division multiple access

In frequency-division multiple access, the repeater bandwidth is divided into a number of nonoverlapping frequency bands which form access channels. Each link is assigned an access channel. If more than one FDMA carrier accesses the same transponder, the transponder's nonlinearities dictate a back-off and this reduces the total transponder capacity. To improve multicarrier operation, hard-limiting transponders could be used.

Whenever two or more independent signals pass through a hard-limiting repeater, the power ratio of any two component signals at the output will generally differ from the power ratio of the same two components at the input, the change supporting the stronger signal at the expense of the weaker one.

There are two main FDMA techniques in operation today. These are the multichannel-per-carrier transmission, and the single channel-per-carrier transmission. In multichannel-per-carrier transmission or FDM-FM-FDMA the transmitting earth station frequency division multiplexes several signal sideband suppressed carrier telephone channels into one carrier baseband assembly. This frequency modulates a RF carrier and is transmitted to a FDMA satellite transponder. In the single channel per carrier technique (SCPC), each telephone channel independently modulates a separate RF carrier and is

transmitted to a FDMA satellite transponder. The modulation can be analog, such as FM, or digital, such as PSK [Ref. 4:p. 194].

Figure 16 shows a 36 MHz transponder frequency assignment with four FDMA carriers. The receiving earth stations separate the carriers by using the appropriate filters. In deciding on the frequency assignments for each carrier, one must consider three basic factors:

- Total useful bandwidth per transponder.
- Available power and uplink power control capability.
- Interference.

The advantages and disadvantages of FDMA are summarized as follows [Ref. 7:p. 293]:

(1) *Advantages of FDMA*

- Channel availability is fixed.
- No central control is required.
- Users with several capacity needs are easily served.
- Relatively unsophisticated earth stations (simplicity).

(2) *Disadvantages of FDMA*

- Intermodulation requires back-off, reducing transponder throughput.
- The system is vulnerable to jamming.
- Rigid system; reassigning resources to reflect traffic change is difficult.

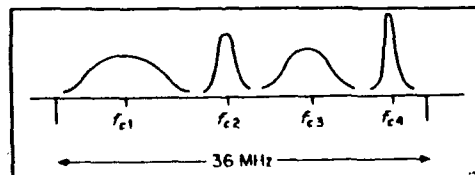


Figure 16. FDMA frame structure

c. Time-division multiple access

All the stations in a TDMA system transmit on the same carrier frequency.

In some relatively lightly-loaded systems, the earth stations transmit at random, but TDMA systems serving fixed stations carrying relatively heavy traffic are mainly ordered systems in which each station waits for its turn to transmit a burst of data in accordance with a prearranged time plan.

Generally, a TDMA system is a true orthogonal system, since only one carrier operates at a given time. As a result, the nonlinear nature of the transponder is minimized, no multicarrier interference is generated, and the full power of the transponder is available as well as the full bandwidth. This technique is an energy-efficient technique, however, TDMA requires network synchronization, coded messages, and buffer storage from burst to burst. The message must be coded in order to provide address, timing, and other pertinent information. Short guard intervals (of the order of 1 microsecond) are left between bursts to allow for small timing errors. In order to accomplish the above functions a certain loss of efficiency occurs. A TDMA system can attain more than 90 percent efficiency of satellite power utilization. In contrast, a FDMA system may lose 3 to 6db of the available power. Since the transponder never has to amplify more than one carrier at a time, there is no intermodulation and no significant back-off is necessary; it is therefore possible to use practically all the power which the output amplifier can deliver.

Each earth station must [Ref. 8:p. 224]:

- Store the information that arrives from the terrestrial network and which will comprise its next burst of transmission and transmit it at the precise time necessary to ensure that, when it arrives at the satellite, it does not overlap the leading or succeeding bursts.

- Store the information which arrives from the satellite and addressed to the station, and read the information out to the terrestrial network at both the appropriate rates and to the correct circuits.

The frame rate, that is the time required to include in sequence all the bursting stations, defines the data rate per burst. Each burst duration is a fraction of the frame duration. The maximum burst rate is also limited by the satellite EIRP and the earth station's G/T. All information, including voice, must be digitized, because TDMA works with digital signals. In Figure 17 the TDMA concept is shown.

The advantages and disadvantages of TDMA are summarized as follows
[Ref. 7:p. 293]:

(1) *Advantages of TDMA*

- Transponder bandwidth and power fully utilized.
- No complicated frequency assignments.
- Users with different capacity requirements are easily served.
- Flexible system: resources are easily reassigned.

(2) *Disadvantages of TDMA*

- Guard times and headers reduce throughput.
- Central timing and synchronization control are required.
- High cost earth terminals.
- Even low traffic users must have full EIRP and G/T terminals.

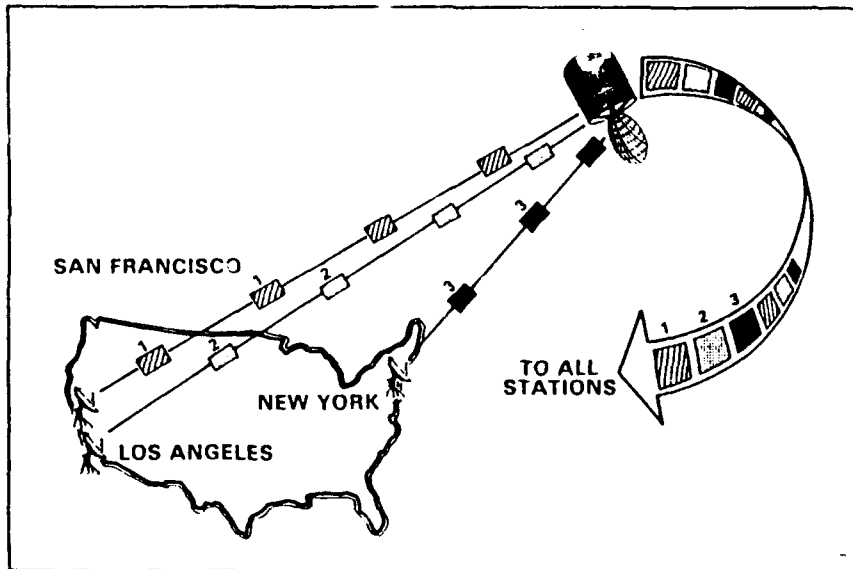


Figure 17. TDMA network

d. Code-division multiple access

In code-division multiple access operation, several stations use the same carrier frequency and associated bandwidth at the same time. This activity uses a technique which lies within the broad area of spread-spectrum communications and application is limited to digital transmissions.

One way of generating a CDMA transmission is to combine a chain of pseudo-random pulses with the message signal. The pulse repetition rate of the pseudo-random signal must be high enough to spread the signal over the whole of the available bandwidth. One message bit is therefore combined with a chain of many pseudo-random bits. For example, the message might have an information rate of 50 Kbits/s and the pseudo-random sequence might have a chip rate of 5 Mbits/s so that every message bit is combined with 100 chips. The receiving station knows the pseudo-random sequence and is able to generate a chip chain which is consistent with the intended transmission. Thus, the receiving station is able to unscramble the message by a process analogous to coherent

detection. All the other transmissions, which are combined with different pseudo-random sequences, look like noise. The signal-to-noise power ratio is proportional to the number of chips per bit and the quantity $10\log(\text{chips per bit})$ is called processing gain.

As a consequence of the processing gain relationship, the number of stations which can be served in the same band by CDMA techniques is largely determined by the number of chips per bit. Another important factor is the degree of equality between the received power levels from the different stations. If considerable differences exist, the ratio of the weaker signal-to-noise-plus-other-signals may be too small, even with the advantage of the processing gain, to allow extraction of the data message with small bit error rate.

The advantages and disadvantages of CDMA are summarized as follows [Ref. 7:p. 293]:

(1) *Advantages of CDMA*

- No central control; fixed channels.
- All earth terminals interchangeable.
- Earth station sophistication is at baseband.
- Relatively immune to external interference.

(2) *Disadvantages of CDMA*

- Transponder must be backed off; reduced throughput.
- Only a limited number of orthogonal codes exists.
- Works efficiently with preselected data rates.

The principle of CDMA is illustrated in Figures 18 and 19.

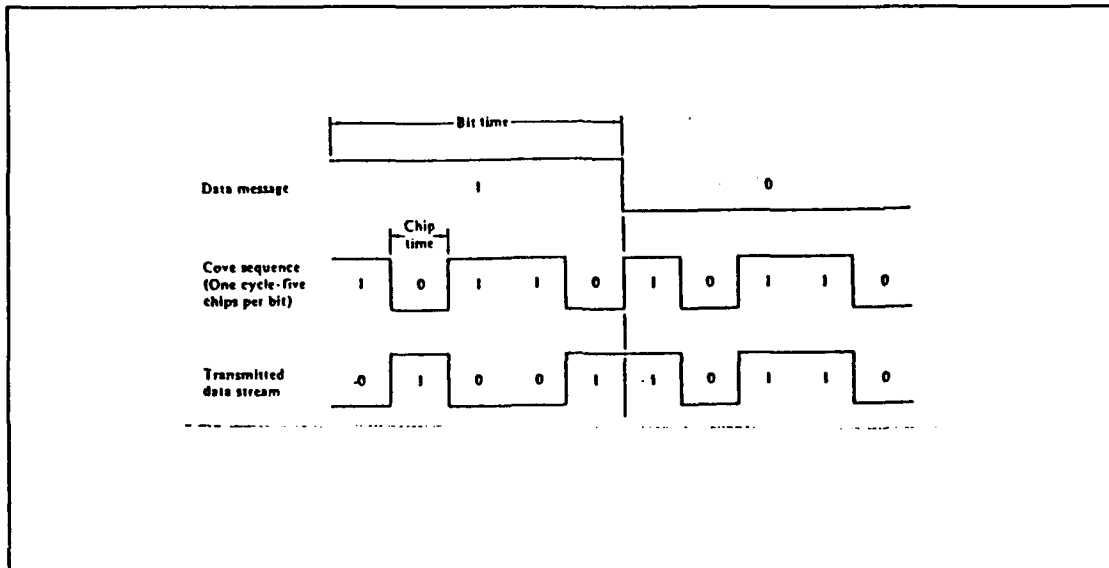


Figure 18. Principle of CDMA, Encoding

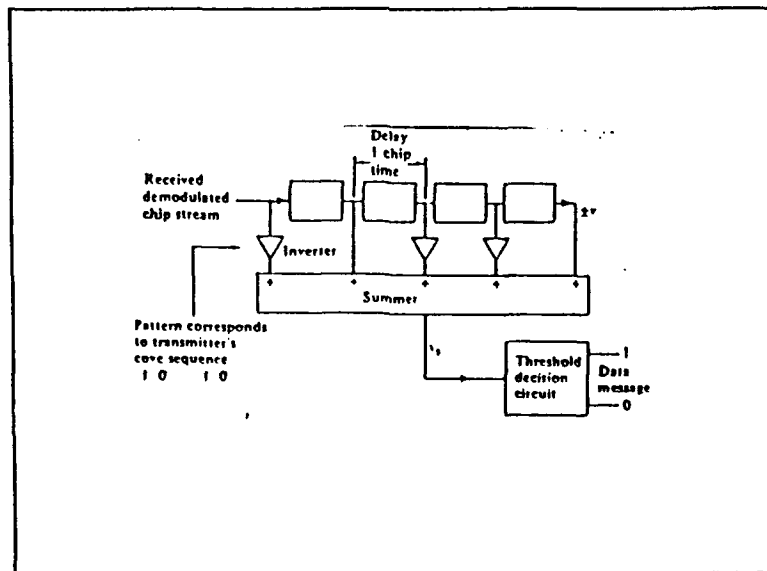


Figure 19. Principle of CDMA, Decoding

e. *Comparison of multiple access techniques*

Table 3 summarizes the characteristics of the three multiple access techniques.

Table 3. CHARACTERISTICS OF MULTIPLE ACCESS TECHNIQUES

Access technique	Advantages	Disadvantages
FDMA	Channel availability is fixed. No central control is required. Users with various capacity needs are easily accommodated. Relatively unsophisticated earth stations.	Intermodulation requires back-off, reducing transponder throughput. Rigid system; reassigning resources to reflect traffic change is difficult.
TDMA	Transponder bandwidth and power fully utilized. No complicated frequency assignments. Users with different capacity requirements are easily accommodated. Flexible system: resources are easily reassigned.	Guard times and headers reduce throughput. Central timing and synchronization control are required. High-cost earth terminals. Even low-traffic users must have full EIRP and C/T terminals.
CDMA	No central control; fixed channels. All earth terminals interchangeable. Earth station sophistication is at baseband. Relatively immune to external interference.	Transponder must be backed off; reduced throughput. Only a limited number of orthogonal codes exist. Works efficiently with preselected data rates.

C. SPECIAL PROBLEMS IN SATELLITE COMMUNICATIONS

The development of modern satellite communications technology using satellites in geostationary orbit has generated many new services and capabilities not practical when using terrestrial systems. The unique geometric advantage of a satellite in stationary orbit allows multiple access by many earth stations on the earth's surface through a single satellite repeater. This high altitude repeater creates long-distance, wideband network facilities at low cost compared to other media. A result of the high altitude of the geostationary orbit is the rather long transmission time delay which can create undesirable subjective effects of echos on voice circuits, reduced throughput efficiency on data circuits, and synchronization problems for digital transmission.

1. Speech echo

At geostationary altitude, it takes about 270 milliseconds for signals to travel from the transmitting earth station through the satellite to the receiving earth station. The extent to which speakers notice and are affected by echo depends, greatly on both its loudness and the time which elapses between the speech and its echo. There are two techniques in use for controlling echo on satellite circuits, echo suppression and echo cancellation.

a. Echo suppression

Echo suppressors used on satellite channels employ digital technology, and apart from having several other advantages, they have a far faster reaction time than analogue suppressors. The available model of a suppressor can be programmed to allow a weaker signal to break in sooner, thereby reducing the amount of speech clipping.

b. Echo cancellation

Echo cancelers overcome the inherent conflict present in echo suppressors by automatically synthesizing a replica of the expected echo on the receive path, and then subtracting it from the echo when it is received, thus canceling the echo component of the received signal.

2. Data transmission

The economics of long-distance telecommunications via satellite has created many new applications, services, and opportunities for data communication users. Unfortunately, the computer communications protocols, data modems, and echo control devices developed originally for terrestrial networks are not suitable for use in the long-time delay environment of satellite communications. The impact of the delay on data circuits can be measured in terms of reduction in data throughput efficiency, plus potential modem and protocol malfunction due to mishandling of delayed echoes.

a. Protocols

A set of rules that govern the exchange of data between information systems is called a protocol. A protocol can be regarded as a specialized and self-contained communications system in miniature. Its rules will initiate and perform specific actions, either on request or in response to some event. The most important functions and properties of a data link control protocol are:

- Link Initiation and Termination.
- Synchronization.
- Link control.
- Error Detection and Correction.
- Flow control.

There are three basic classes of protocols in use nowadays, which are summarized below and illustrated in Figure 20 [Ref. 1:pp 374-376]

- Block-by-block transmission.
- Continuous block transmission with restart after error detection.
- Continuous block transmission with selective block repeat.

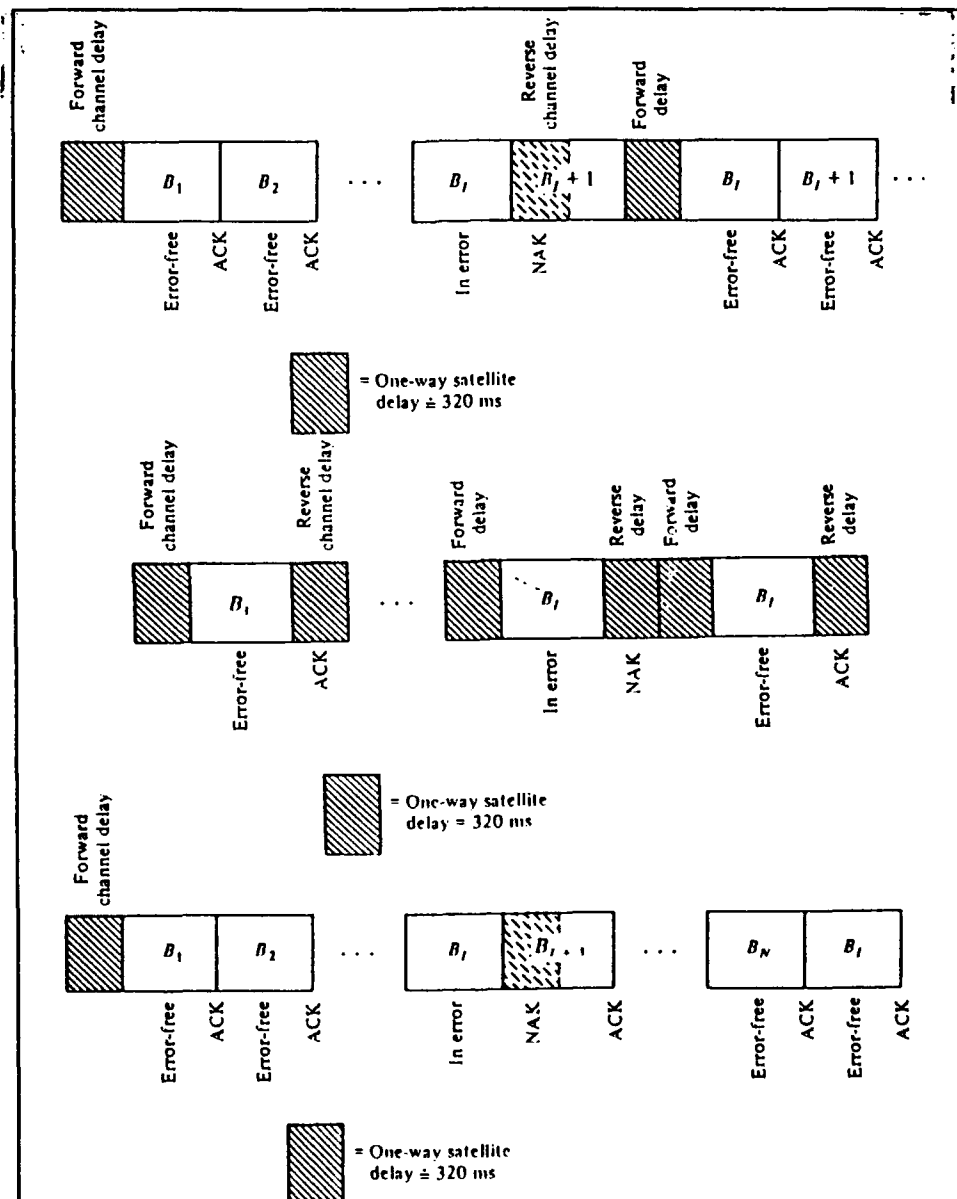


Figure 20. Basic classes of protocols

3. Digital network synchronization

A satellite in geostationary orbit does not remain exactly stationary. Departure from a stationary position is influenced by a number of factors, including the earth's nonsymmetrical gravitational field and perturbations caused by the sun and moon. Inaccuracies in correcting satellite position and adjusting orbital parameters also contribute to the nonstationarity of the orbit. Although the total change in position translates into a change in transmission time of less than 0.5%, the variation is significant enough to require some compensation on satellite links exchanging digital data with synchronous terrestrial networks. In order to solve this problem, an elastic buffer (digital interface) is inserted between the satellite facilities and the terrestrial network, as shown in Figure 21 [Ref. 1: p.384]

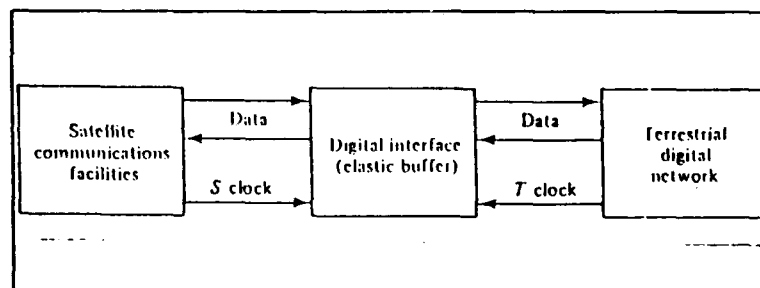


Figure 21. Interface between satellite system and terrestrial facilities

D. RELIABILITY OF SATELLITE COMMUNICATIONS SYSTEMS

1. General

Reliability, as a function of time, is the probability that a component will not fail before time t . For satellite communications systems, reliability depends on two main parts of the system, the satellite and the ground segment. The primary measure of system effectiveness is called operational availability and refers to the total time during the

mission's duration when the system or the equipment is capable of meeting specified performance standards. This may be defined as the ratio of *time available when needed* to *total time needed*.

For satellite communications systems, availability depends on the launch's success, number of operational satellites, replacement time and back-up satellites [Ref.5 p.355]. Operational availability normally depends on reliability, maintainability and supply. Thus, for satellite communications systems, availability depends only on reliability, because maintainability and supply are not possible.

2. Classes of failure

Since reliability deals with performance for a given time, or with the accomplishment of a certain mission of a specified duration, it is logical to study failures from a time-characteristic point of view. Generally failures are classified into three categories, in which the last two are particularly relevant for complex equipment such as a satellite. [Ref. 5:p. 355]

- *Initial failures* which are caused by a defect present at the time the equipment was first put into operation.
- *Chance or random failures* which result from unavoidable, unpredictable or unusually severe stresses that exceed the failure resistance of the part or component during its useful life period. The breakdown of a capacitor as a result of a transient surge of voltage is an example.
- *Wear-out failures* which result from the depletion of some material or property necessary for the proper operation of a component. This depletion may be caused by abrasion, chemical reaction etc. For example, the chemical exhaustion of dry cell batteries and wear-out of bearings. In most cases, this type of failure can be reduced through improvement in design or replacement of components prior to expected wear-out.

If we assume that a failing part is replaced instantaneously, it is possible to determine the instantaneous failure rate for given equipment over the equipment life.

The curve of failure rate against time is called a bathtub curve and is illustrated in Figure 22 below: [Ref. 10:p. 261]

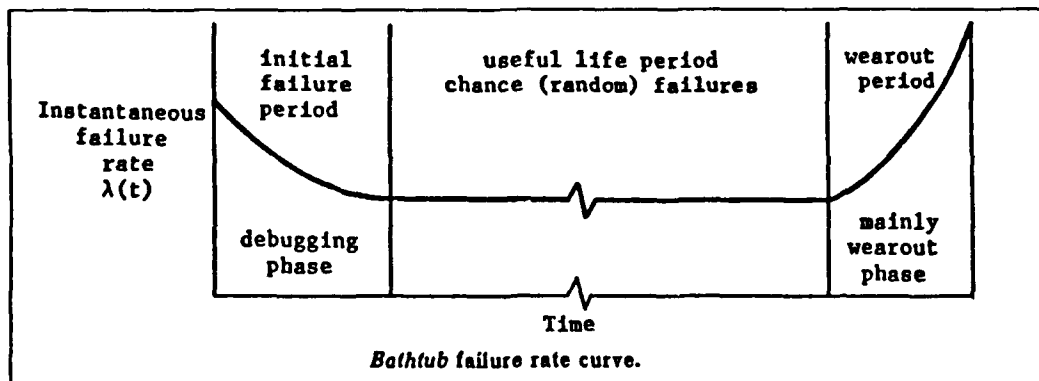


Figure 22. Bathtub failure rate curve

In a satellite, the infant mortalities are eliminated in advance of the launch by various methods such as heat cycling and operating the equipment and components (burn in), and therefore over the duration of the mission, most electronics and mechanical components will exhibit a constant failure rate λ , often expressed in Fit (number of failures per 10^9 hours) [Ref. 5:p. 355].

3. Mean time between failures (MTBF)

The mean (expected) time to failure or mean time between failures (MTBF) can be found from the expression:

$$E(T) = \int_0^{\infty} t \times f(t) dt$$

where T is the time at which failure occurs and $f(t)$ is the probability density function for T . [Ref. 5:p. 357]

For the case where l is constant, that is for chance failures, we have $T=1/l$ and the above expression becomes:

$$E(T) = \int_0^{\infty} t \times l \times e^{-l \times t} dt = \frac{1}{l}$$

For satellite communication systems, when we have a satellite with maximum life V , the average life τ (TAO) is given by [Ref. 5:p. 357]:

$$\tau = T \times (1 - e^{-\frac{V}{T}})$$

where τ (tao) is dependent on the mean time to failure T , as defined for constant failure rate l . t/T is the probability of failure during the mission life V .

4. Probability of survival or reliability

If equipment has a failure rate of l , its probability of no failure, that is its reliability at an instant of time t , is given by

$$R = e^{-\int_0^t l \times dt}$$

When the failure rate is constant the above expression becomes [Ref. 5:p. 356]

$$R=e^{-l \times t}$$

5. Mission Reliability

To ensure service which is defined by a given availability A during a fixed period L , we must plan the number n of satellites to be launched during the system lifetime L . The required number of satellites n and the system's availability A will be evaluated in two typical cases in which the time required to replace a satellite in orbit is T_r and the probability of launch success is p [Ref. 5:p. 358].

a. Without spare satellite in orbit

- *Required number of satellites:* As the average life of a satellite is $t(\text{tao})$, during L years, on average $S=L/t$ satellites have to be placed in orbit and $n=S/p$ launches must be attempted.
- *System availability:* The system unavailability is given by $B=T_r/p \times T$ and the system's availability is given by $A=1-(T_r/p \times T)$

b. With a back-up satellite (in orbit)

If a back-up satellite has a failure rate l and a life V equal to an active satellite, it would be necessary to launch n times and the system availability is A as follows:

$$n = \frac{2L}{p \times T \times (1 - e^{-\frac{V}{T}})}$$

$$A = 1 - \left(\frac{2T_r^2}{p^2 \times T^2} \right)$$

E. ADVANTAGES AND DISADVANTAGES OF SATELLITE COMMUNICATIONS

Many new technologies are emerging during the late 1980s and early 1990s. The five most popular are satellites, digital microwave radio, fiber and coaxial cables, local distribution radio, and wire pairs. Table 4 below lists each technology and illustrates those applications for which it performs best [Ref. 1:p. 25].

Table 4. COMPARISON OF TECHNOLOGIES

Technology	Network Distance	Data Rate	Connectivity	Primary Consideration
Satellite	Long haul	Medium to high speed	Multipoint-to-multipoint Point-to-multipoint Multipoint-to-point	Propagation time delay
Digital microwave radio	Local/regional	High speed	Point-to-point	Transmission-path geometry
Fiber optics/ Coaxial cable	Local/regional	High speed	Point-to-point	Construction cost (cable duct availability)
Local distribution radio	Local/regional	Medium to high speed	Point-to-point Point-to-multipoint	Transmission-path geometry
Twisted pairs	Local	Low to medium speed	Point-to-point	Construction cost (cable duct availability)

In general the advantages and disadvantages of communications satellites are:

[Ref. 9:p. 10]:

1. Advantages

- Wideband capability.
- Wide area coverage readily possible.
- Distance-insensitive costs.
- Counterinflationary cost history.
- All users have the same access possibilities.
- Point to point, point to multipoint (broadcast), and multipoint to point(data collection) are all possible.
- Inherently suited for mobile applications.
- Readily compatible with new technology.
- Capabilities sometimes greater than immediate needs.
- New and fresh concepts and opportunities.
- Services directly to the users' premises.

2. Disadvantages

- High initial investment in space segment normally required.
- New investment may be required in earth stations.
- Short satellite lifetimes (7-10 years).
- Orbit/spectrum crowding, frequency sharing, power flux density limits.
- Access to end user may be difficult for engineering or regulatory reasons.
- Institutional/legal/regulatory aspects.
- Possibly difficult or expensive maintenance.

III. MILITARY SATELLITE COMMUNICATIONS

A. BACKGROUND

When the concept of using satellites for communication purposes became a possibility, the military soon realized that satellites could play an important role in military communications as well. In particular, they could interconnect widely dispersed forces around the world to their strategic headquarters (both during peace time and in tactical battle field situations) and as a means of quickly and reliably transferring information on military intelligence.

While civil communications satellites could also, to some extent, be used for these purposes, it was felt that the military requirements for secure communications, free of interception and/or jamming, radiation hardening of the satellites themselves, etc., guaranteed the development of dedicated satellites for the military. Several countries have therefore developed such systems for this purpose.

B. DEVELOPMENT OF US MILITARY COMMUNICATION SATELLITE PROGRAMS

The US military role in space communications may be considered to have begun on December 18, 1958 when the US Army launched the upper stage of an Atlas B missile into orbit after loading it with an active repeater communications payload. This satellite was called SCORE and operated for twelve days before its batteries failed. Only a few hours of communications experiments took place due to the limited time it was visible from ground stations. [Ref. 11:p. 64]

The second US military experiment in space communications was on October 4, 1960 when US Army successfully launched its first real active repeater satellite, the COURIER 1-B. This was the back up of COURIER 1-A which failed due to an explosion of its Thor-Able Star launcher. COURIER 1-B was used for a number of real-time and store-and-forward communication experiments until, seventeen days after its launch, a failure in its command system put it out of operation permanently. [Ref. 11:p. 64]

Following the COURIER program, a number of experiments were carried out by and for the military using the LES (Lincoln Experimental Satellite) series, developed by the Lincoln Laboratory of MIT. This program started with the launch of LES-1 on February 1965 and ended on March 1975 with the launch of LES-8 and LES-9. LES-8 and LES-9 are the latest in the Lincoln Lab series and are the first of their satellites to employ:

- Three axis stabilization.
- Radioisotope Thermoelectric Generators (RTG's) instead of solar cell arrays.
- Ka-band payloads whose antennas can be oriented for use either for space-to-ground links or for inter-satellite cross links between the two.
- Pulsed-plasma thrusters for station keeping.

After all the experimental programs described above, there was a relatively long time before the US military launched any further communications satellites. In 1960, ARPA⁴ initiated the ADVENT project, to develop an advanced military geosynchronous satellite. However, the program proved to be too advanced for the state of art at that time, so it was finally canceled in 1962. With the cancellation of ADVENT, another less ambitious project

⁴ARPA=Advanced Research Projects Agency

was started by SAMSO⁵, which was called Initial Defense Communication Satellite Program (IDCSP) and was intended to be convertible to a global operational system.

[Ref. 12:p. 150]

1. IDCSP (Initial Defense Communication Satellite Program)

At first the idea was to develop a satellite which could be launched, several at a time, into polar orbits of about 8000 Km altitude using an Atlas-Agena launcher. The progress in the concurrent development of the Titan 3C allowed a redirection of the original program, to a system to be deployed into near-geosynchronous orbits. The IDCSP satellites were designed by Philco-Ford with a spin-stabilized configuration which would need neither active attitude control nor any station keeping. In order to inactivate the on-board transmitters, a timing device was included which would shut down the satellite about 6 years after its launch.

The satellite had a 91 cm diameter, 81 cm high polyhedron with each of its 24 faces covered with solar cells. Protruding from one end was the toroidal beam communications antenna, while a foreshortened telemetry antenna occupied the opposite end. A cold gas nitrogen jet system was used to spin up the satellite initially, after which the altitude of the satellite was maintained only passively due to its gyroscopic stability. The communications payload consisted of a single simple 20 MHz bandwidth repeater, with the only major element of redundancy being provided by two different TWTA's, one being switched on only when on-board logic detected a failure of the other[Ref.12 p.150].

In June 1966, the first seven IDCSP satellites were launched together with a similar experimental gravity gradient stabilization satellite.

⁵SAMSO=Space And Missile Systems Organization

A second set of eight satellites was launched unsuccessfully in August 1966. During 1967 and 1968 nineteen more satellites were launched making a total of twenty-six which exceeded the design goal for their lifetime considerably.

2. DSCS II (Defense Satellite Communication System, Phase II)

The DSCS II satellites followed the IDCSP satellites. The US military decided in June 1968, after two years of experiments with IDCSP, to develop the Phase II system which would consist of much more sophisticated satellites in geostationary orbit.

TRW was selected to develop the new satellites under a project called 777. Their design was a dual spin configuration, with a large rotating drum shaped structure covered with solar cells, surmounted by a platform that could be dispun to maintain its antennas facing earthward. The satellite was more than 2.7m in diameter and nearly 4m high. Full telecommand capability with an automatic attitude control system and capability to perform full station keeping was included in the design. The payload consisted of a broadband four channel repeater incorporating extensive redundancy. Two horn and two repointable reflector antennas provided both global and spot beam coverage. [Ref.12 p.151]

The satellites were planned to be launched two at a time by any of the TITAN launcher configurations. In total, sixteen DSCS II satellites were launched in several successive orders starting in November 1971. Some of the satellites failed because of various problems which led to their destruction or loss of service, but the program was generally successful in providing for the military's long distance strategic communication needs.

3. DSCS III

In 1975, the military issued requests for proposals for their third generation satellite system, DSCS III. Hughes and General Electric started parallel design studies to

define the configuration of a much higher performance satellite than those of DSCS II. Now, the requirements were specifically for a three axis stabilized satellite, using a number of anti-jamming techniques, including the use of antennas with narrow spot beams for transmission, and receive antennas that could electronically avoid the hostile jamming stations. In addition, spread spectrum multiple access techniques were to be incorporated with a frequency hopping capability as another protection against hostile interference. Finally, G.E was awarded the contract for the development of the DSCS III satellites in February 1977. The initial contract for one qualification and two flight demonstration satellites was worth more than \$75 million. [Ref. 12:p. 152]

The communication system on this third generation satellite is the most advanced of its type, particularly with regard to its antennas. For reception, there are two earth coverage horns and one multibeam (61 beams) waveguide lens array antenna operating at X-band and a crossed bowtie antenna operating at UHF. For transmission, there are two earth coverage horns, two 19 beam waveguide lens arrays and one deployable gimbaled parabolic antenna at X-band, and a crossed dipole UHF antenna. The satellite measures some 2.4m in diameter and 2m high, has two deployable panel solar array wings, and uses four inertial wheels for stabilization on station. [Ref.11 p.152]

The program was delayed until October 1982 when the first demonstration satellite was launched together with the FM16 (Flight Model #16) of DSCS II satellites. Although the plan was for 12 production satellites to be ordered after the successful in orbit testing of the demonstration models, only 7 have so far been reported to have been contracted for. The first two of these were launched in October 1985, using the Space Shuttle. [Ref. 11:p. 152]

4. Tactical Satellites (TACSAT)

The satellites of the IDCSP and DSCS series were intended primarily for strategic, high data rate military communications, using a small number of earth terminals, each having large diameter antennas. However, there is a need for tactical communications amongst field units and between field units and their tactical headquarters, where the use of such large antennas is not generally feasible. In order to develop the capability and ground equipment for multiple access satellite communications between mobile terminals numbering in hundreds and in order to determine the best frequencies for future operational tactical communications services, TACSAT was conceived. The contract to develop TACSAT was awarded to Hughes Aircraft Company (HAC) in late 1960's.

[Ref. 13:p. 236]

TACSAT's design requirements dictated a number of features not present in previous communication satellites. Since there was virtually no interest in tactical communications in the commercial field, engineers who worked on TACSAT were frequently treading on new ground. Its beginning-of-life mass in geostationary orbit of 1600 lbs made it the heaviest communication satellite of its time, and its overall dimensions (2.8m in diameter and 7.6m high) made it the largest. [Ref. 13:p. 236]

It was spin stabilized but because of its large antenna structure and launch vehicle fairing constraints, it did not spin about the axis having the maximum amount of inertia. In order to overcome this unstable condition, special stabilizing elements were employed.

With a total radiated RF power of 260w, TACSAT was also the most powerful communication satellite of its time. It had a total of sixteen solid-state UHF power amplifiers, any thirteen of which were generally operated at a time, to provide a total of

230w RF output and three 20w X-band TWTA's, any two of which would provide 30w total RF at the output. The UHF repeater on TACSAT was designed to cope simultaneously with 666 accesses, while the X-band repeater could accommodate an additional 207. The breakdown of these is shown in Table 5. [Ref. 13:p. 236]

Table 5. TACSAT ACCESSES

Repeater	Mobile Antenna Type	Modulation	No. of Accesses
UHF	1.2 m diameter (truck mounted) Aircraft blade type	FM voice	8
		Encrypted voice	8
		Vocoded voice	20
		Teletype	630
X-Band	1.2 m diameter (truck mounted)	FM voice	52
		Encrypted voice	23
		Vocoded voice	132

5. Fleet Satellite Communications (FLTSATCOM)

The US Navy was a heavy user of the capacity of both the LES series of satellites and TACSAT, for both experimental and pre-operational communications with its units. In late 1972 the Navy, together with the Air Force, contracted with TRW to develop the satellites for an operational satellite system called FLTSATCOM. The TRW design was for a large (2.3m diameter body, 6.6m high with antennas deployed) three axis stabilized satellite.

FLTSATCOM was designed to provide one way shore-to-fleet communications and two way communications between ships and aircraft. It had both UHF and X-band transponders, and the channel allocations are shown in Table 6. [Ref. 13:p. 237]

Table 6. FLTSATCOM CHANNELS

Number of Channels	Function	Primary User	Bandwidth (KHz)	EIRP (dBW)
1	Fleet broadcast	USN	25	26
9	Fleet relay	USN	25	26-28
12	AfSatCom	USAF	5	16.5
1	Wideband comms.	USAF	500	27

The first satellite was launched on February 9, 1978 and placed into operation in geostationary orbit at 100 degrees west longitude. Three more successful launches took place in the following two and one half years, but during the launch of FM-5 on August 1981 some problems were encountered which finally were traced to the collapsing of the shroud of the Atlas Centaur launcher, resulting damage to the antennas.

The subsystems that comprise the FLTSATCOM system are: [Ref. 14:p. 84]

- Fleet Satellite Broadcast Subsystem (FSB) which provides the capability to transmit Fleet Broadcast message traffic in a high level jamming environment.
- Common User Digital Information Exchange Subsystem (CUDIXS)/Naval Modular Automated Communication System (NAVMACS).
- Submarine Satellite Information Exchange Subsystem (SSIXS).
- Anti-submarine Warfare Information exchange Subsystem (ASWIXS).
- Secure Voice Subsystem.
- Tactical Intelligence Subsystem (TACINTEL).

6. LEASAT Satellite

The last generation of communication satellites for Navy use has been obtained on a leased basis, hence the program name, LEASAT. When the Navy initiated a procurement action for its next generation of satellites to replace FLTSATCOM, its request for proposals called for the lease of communications services, rather than for the development and purchase of satellites. The contract was awarded to HAC which proposed to build five LEASAT satellites to provide communications from four orbital locations (the fifth was a spare on ground). The LEASAT design was unique in that it was the first communication satellite designed specifically to be launched only by the Space Shuttle. LEASAT is 4.22m in diameter and 4.30m long when mounted in the Shuttle. It has an integral solid motor perigee stage, and two liquid bi-propellant apogee engines.

The payload includes two large deployable helical antennas, and 12 fully solid-state UHF repeaters. It has seven 25 KHz UHF downlink channels, one 500 KHz wideband channel and five 5 KHz channels. One of the seven 25 KHz UHF downlink channels is the downlink for Fleet Satellite Broadcast (FSB) message traffic. The broadcast uplink is SHF with translation to UHF occurring in the satellite. [Ref. 14:p. 89]

The first LEASAT was launched in August, 1984 and the second in November of the same year. In April, 1985 LEASAT-3 was launched but it was inoperable due to a failure of one on-board timer until the end of 1985, when it was fixed during the launch of the LEASAT-4 in August 1985.

C. ADVANTAGES/DISADVANTAGES

The satellite communication systems have already and will continue to provide effective solutions to many of the problems inherent in Military operations. Some of the advantages and disadvantages of the current communication satellite systems are:

1. Advantages

- Satellites are able to provide connectivity to and from geographically remote areas with few support facilities which may be subject to enemy hostile actions.
- In a case of political instability, satellite communications allow independence on overseas communication sites.
- Satellite communications connect widely separated members in the chain of command, rapidly and reliably passing information.
- Satellite communication systems can reduce the probability of position intercept and increase resistance to jamming.

2. Disadvantages

- Cost constraints led to decisions based on space segment cost only and produced integrated, multi-function spacecraft which could become single-point targets for attempts at destruction or jamming by the enemy.
- Limitations on operation in the UHF band are due to frequency congestion, lack of bandwidth, and inadequate jamming resistance.
- Heavy rainfall can cause high propagation losses at EHF.

IV. INTERNATIONAL SATELLITE COMMUNICATIONS : INMARSAT

A. INTRODUCTION

In 1956, the first intercontinental telephone cable came into service. It substituted for the few HF radio circuits on which international telephony was dependent. This Transatlantic Telephone cable (TAT 1) had an initial capacity of thirty-six circuits, which was thought to be enough to carry all the transatlantic traffic for some years ahead. But the demand for calls increased very rapidly when users discovered the importance of telephone service. TAT 1 was followed by a succession of transoceanic cables of ever-increasing capacity. However, shortages in intercontinental circuits were frequent during the 1960's and 1970's.

When trials with INTELSAT-1 concluded that the delay via a satellite was not a large disadvantage for the majority of the users, the satellite was quickly pressed into commercial use.

Although communication satellites were first to provide a complementary service to long-distance cables, there are important differences between the two means of transmission. These include: [Ref. 8:p. 7]

- Cables are best suited to the provision of point-to-point circuits whereas the multiple-access property of satellite systems means that they can provide point-to-multipoint service or multipoint-to multipoint service.
- The cost of cable circuits increases with their length whereas the cost of satellite circuits is independent of the distance between earth stations.
- Satellite transmission can leap over physical and political barriers that are impassable to cables.
- Satellites can provide service to mobile stations.

1. Intelsat (International Telecommunication Satellite Consortium)

On August 20, 1964, after some two years of discussions and negotiations, eleven countries signed an agreement bringing into existence an Interim "International Telecommunications Satellite Consortium". The consortium would own and operate, on behalf of its signatories, satellites to provide international communications services. A brief description of the Intelsat series satellites is provided below: [Ref. 15:pp. 269-277]

a. Intelsat-1

Less than a year after the agreement was signed (1965), the first satellite, Intelsat-1, manufactured by Hughes Aircraft Company, was launched and began to provide trans-Atlantic service. Its capacity was 240 simultaneous telephone channels or one television channel. Despite having an intended design life of only 18 months, Intelsat-1 continued to provide service continuously for almost four years. It was placed in a reserve mode in January, 1969.

b. Intelsat-2

Intelsat-2, also built by Hughes, was similar in design and channel capacity to Intelsat-1. Its first launch was unsuccessful (October 1966) due to a failure of its apogee kick motor. The second flight model was successfully launched and placed into orbit in January 1967. It provided communications capacity in the Pacific Ocean region until February 1969. The third flight model was launched in March 1967 and placed into service in the Atlantic Ocean region, where it operated continuously until January 1970. It was then operated as a spare until its transponder failed in December 1970. In September 1967, flight model four was launched and provided service in the Pacific Ocean region, with some interruptions, until it was terminated September 1971.

c. *Intelsat-3*

The contract to provide the third generation of Intelsat satellites, Intelsat-3, was won by TRW Corporation. It carried dual repeaters with a combined capacity of 1200 telephone circuits. A total of eight Intelsat-3 flight models were procured. Three of these failed to reach geostationary orbit (#1,5,8). Flight model #2 was launched in December 1968 and placed into service in the Atlantic Ocean region. It soon experienced problems, which were corrected for a time, but it finally failed completely in April 1970. Flight model #3 was launched in February 1969. However shortly after its launch it experienced problems that reduced its capacity. It was moved from its Pacific Ocean position to the Indian Ocean and it was operated with only occasional outages until it was put in a reserve status in July 1972. In May 1969 flight model #4 was launched and positioned over the Pacific. When it began operation in July 1969, Intelsat was, able to provide global service to its users for the first time. Flight models #6 and #7, which were launched in 1970, each experienced problems. Thus, they were retired as soon as the satellites of the Intelsat-4 generation became available to take over their functions.

d. *Intelsat-4*

Even before the first Intelsat-3 satellite was launched, it became apparent that the growth in traffic demand would soon make even larger satellites necessary. Hughes Aircraft Corporation (HAC) won the competition to supply these, with a design based upon the successful TACSAT military satellite. With capacity improvement from using twelve separate channelized repeaters, a theoretical capacity of up to 9000 simultaneous telephone circuits was possible, depending upon the traffic pattern and modulation schemes used. A total of eight Intelsat-4 satellites were procured. All the flight

models except Flight model #6 were launched and placed in orbit successfully, between 1971 and 1976 making this series of satellites highly successful on the whole.

e. Intelsat-4A

Although Intelsat-4 had more than five times the capacity of Intelsat-3, it soon proved to be insufficient to cope with the demand for international satellite communications. Because of the success of the Intelsat-4 series, Intelsat elected to procure a growth version of its design from Hughes, designated 4A, rather than to open a new competition for a next generation satellite. Intelsat-4A obtained the necessary increase in capacity by expanding the payload from 12 to 20 repeaters, and by increasing from 2 to 3 spot beam antennas. The corresponding maximum capacity of this configuration was some 15000 telephone circuits. A total of six Intelsat-4A satellites were procured, the first of which was launched in September 1975. All remaining flight units were launched over the next 2.5 years, with the exception of Flight model #5. This satellite had a launch failure in September 1977. This series formed a new global network in the three ocean regions served by Intelsat.

f. Intelsat-5

Intelsat-5 was a major departure from its predecessors. It was three axis stabilized, while all previous satellites in the Intelsat series were spin or dual spin stabilized. It was also the first dual band Intelsat satellite, using an allocated 500 MHz in 21 transponders operating at C-band, and another 500 MHz in 6 transponders at Ku-band. Its capacity was 12,000 voice circuits and two television channels. The first of nine Intelsat-5 satellites to be launched experienced several anomalies shortly after its launch. Three of these were considered significant enough to require design changes in later models. However, the problems didn't stop when these changes were made. Further anomalies

were encountered in later flight models. Nevertheless, while these problems sometimes reduce the quality of the transmissions through these satellites, they are still usable.

g. Intelsat-5A

In 1980, Intelsat satellites were carrying some two-thirds of the world's international overseas telephone traffic, and the amount of this traffic was growing at a rate of nearly 25% per year. Thus, even before the first Intelsat-5 was launched, it was realized that satellites with even greater capacity would soon be required to keep up with the growth. The overall telephone traffic capacity was increased to 16000 two way circuits by Intelsat-5A satellites.

h. Intelsat-6

Planning for international communications is a long-term business, and the planning for the post-Intelsat-5 era commenced in 1975 with long-range forecasts of traffic and service requirements in the three ocean regions. A large number of different system configurations were analyzed, and work on specification of the Intelsat-6 satellite commenced in 1979. The 1982 price for the initial five satellites was about \$525 million. It was intended that the first Intelsat-6 should be brought into operation in the Atlantic Ocean Region in 1987, but shortages of launch vehicles resulting from problems with the Shuttle and Ariane programs postponed this until late 1989. Each Intelsat-6 satellite is able to carry over 30000 telephone circuits and four television transmissions. To date, flight models #1 and #3 were launched successfully on November 2, 1989 and June 23, 1990, respectively. Flight model #2 failed to reach geostationary orbit on March 14, 1990.

According to design specifications, Intelsat-6 promises to be a successful series of telecommunication satellites, but we have to wait for results in the very near future. [Ref. 8:p. 22]

i. Intelsat-7

Intelsat's present plans are to specify a satellite which is primarily geared to the requirements of the Pacific Ocean region, but can easily be adapted to the Atlantic Ocean region, where the traffic is growing very fast. The communication package will probably be similar to Intelsat-5 and Intelsat-6, but with a smaller bandwidth. The first Intelsat-7 series satellite will be launched in 1993 at the earliest. [Ref. 8:p. 22]

2. Eutelsat (European Telecommunications Satellite Organization)

Eutelsat is a regional system which provides communications between a group of countries with common interests. It offers a way of spreading the very large investment required to establish a satellite system in the area of Europe. The services which are offered by Eutelsat are: [Ref. 3:p. 31]

- It channels a significant portion of intra-European public telephone traffic.
- It leases portions of the space segment for the distribution of television programs.
- It provides multi-service transmissions tailored to the specific needs of the business community.
- It provides for the transmission of Eurovision television programs.

The great success of the Eutelsat I satellites, in 1983-1984, led the way for the second generation of Eutelsat satellites. The first flight unit of this generation was launched in mid-1989. Eutelsat has an option for two additional units. [Ref. 3:p. 31]

B. INMARSAT

1. Background

By resolution A.305 (VIII) of 23 November 1973, the Assembly of the Inter-Governmental Maritime Consultative Organization (IMCO) decided to convene an

international conference to set up an international maritime satellite system and to conclude agreements to implement this decision. [Ref. 16:p. 215]

The commercial maritime satellite communications service was first provided by the MARISAT system, which was established in 1976 by four major communications entities of the U.S. This system was originally intended for U.S. domestic communications, but the service is open to vessels of other countries, too. Today MARISAT satellites are positioned one each over the Atlantic, the Pacific and the Indian Oceans. [Ref. 18:p. 334]

The European Space Agency's MARECS program covers the development, launch and in-orbit operation of communication satellites to be integrated in global maritime communication system. The MARECS satellite is part of a global communications system configured to provide high quality full-duplex, reliable real-time voice, data, and teleprinter services between SES and CES with automatic connections to the terrestrial network. [Ref. 18:p. 336]

a. The Establishment of INMARSAT

Pursuant to this decision, the International Conference on the Establishment of an International Maritime Satellite System was convened in London on 23 April, 1975 for its first session. The conference concluded its work at its third session on 3 September 1976. The following were adopted by the conference:

- Convention on the International Maritime Satellite Organization (INMARSAT).
- Operating agreement on the International Maritime Satellite Organization (INMARSAT).

Both agreements entered into force on 16 July 1979, 60 days after the date on which states representing 95% of the initial investment shares had become parties to them. The Organization's headquarters are in London.

b. Purpose

The main purpose of INMARSAT is to make provisions for the space segment to improve maritime communications, thereby improving communications concerning distress and safety of life at sea, efficiency and management of ships, maritime public correspondence services, and radio determination capabilities. The organization seeks to serve all areas where there is need for maritime communication and acts exclusively for peaceful purposes. [Ref. 8:p. 238]

c. Organization

INMARSAT has three main organs:

- The Assembly, where all member states are represented and have one vote each.
- The Council, which has 22 signatories and voting power in relation to investment shares.
- The Directorate, headed by a director-general.

Substantive decisions are taken with a two-thirds majority, both in the Assembly and in the Council. The functions of the Assembly are to consider and review the general policy and lay term objectives of the Organization, express views, and make recommendations thereon to the Council. All other decisions are taken by the Council. So the Council decides on all financial, operational, technical, and administrative questions.

2. Facts about INMARSAT

INMARSAT is an internationally-owned cooperative which provides mobile communications worldwide. From its establishment, it has evolved to become the only provider of global mobile satellite communications for commercial and distress and safety applications at sea, in the air, and on land.

Thirty-two states had become parties to the INMARSAT convention by 1980, and by June 1990 INMARSAT had 59 member countries. The services that the INMARSAT can now support include: [Ref. 17:pp. 1-4]

a. Maritime applications

- Direct dial telephone.
- Telex.
- Facsimile.
- Electronic mail and data connections for maritime applications.

b. Aircraft applications

- Flight-deck voice and data.
- Automatic position and status reporting.
- Direct-dial passenger telephone.

c. Land applications

- Two way data communications.
- Position reporting.
- Electronic mail.
- Fleet management.

Current maritime users of the system include oil tankers, liquid natural gas carriers, offshore drilling rigs, seismic survey ships, fishing boats, cargo and container vessels, passenger liners, ice breakers, tugs, cable-laying ships and luxury yachts, among others. The system is also used on land and in the air for several applications, including the provision of commercial, emergency transportable communications at times of human disaster and natural catastrophe. [Ref. 17:pp. 1-4]

In 1990, INMARSAT introduced aeronautical services that will provide worldwide aeronautical passenger telephone, facsimile and data services, as well as improve airline operations and air traffic control. Many airlines and corporate aircraft are now being equipped to use these services.

INMARSAT is also introducing a new range of two-way data messaging services which will use low-cost mobile terminals called INMARSAT-C. These terminals are small enough to fit on any boat or vehicle or to be hand carried. These services are being adapted for both maritime and land mobile users. They will be used for a wide variety of applications, including general telex and electronic mail communications, information distribution from one ship or vehicle to a group of specified users, remote monitoring and control, position reporting, and fleet management. [Ref. 17:pp. 1-4]

As of June 1990, more than 11000 user terminals have been commissioned on land, sea, and in the air for use with the INMARSAT system.

INMARSAT is also exploring the possibility of using satellites for position determination and navigation applications. In 1992, INMARSAT plans to introduce a briefcase-sized worldwide mobile telephone service. [Ref. 17:p. 1]

3. The satellite system

In January 1980 a request for proposals for the procurement of the space segment was issued, with commendable speed. In May 1980 INMARSAT received offers to lease satellites from MARISAT and the European Space Agency (ESA), and an offer from INTELSAT to lease maritime communications subsystems (MCSs), which would be added to Intelsat-5 satellites. [Ref.8:p. 239]

It did not make sense to have two competing maritime communications satellite systems, so the INMARSAT started by taking over the MARISAT satellites. However,

additional satellites were required, both as spares and to replace MARISAT due to its limited capacity and life. So INMARSAT leased three MARISAT satellites and provided for the future by ordering two MARECS satellites (from ESA) and taking an option for up to four MCSs. The current configuration of the system is shown in Table 7. [Ref. 17:p. 4]

Table 7. THE SATELLITE SYSTEM

Ocean Region	Spacecraft	Launch Date	Status
Atlantic (AOR)	Marecs-B2	9 November 1984	Operational
	Intelsat V-MCS B	19 May 1983	Operational*
	Marisat-F1	19 February 1976	Spare
Indian (IOR)	Intelsat V-MCS A	28 September 1982	Operational
	Marisat-F2	14 October 1976	Spare
Pacific (POR)	Intelsat V-MCS D	4 March 1984	Operational
	Marecs-A	20 December 1981	Operational*
	Marisat-F3	9 June 1976	Spare

* Inmarsat operates two satellites in its Atlantic and Pacific Ocean Regions (as from September 1989)

As we can see INMARSAT now has satellites in its three ocean regions capable of providing two-way communications services to its users.

Figure 23 shows INMARSAT's coverage area. [Ref. 8:p. 253]

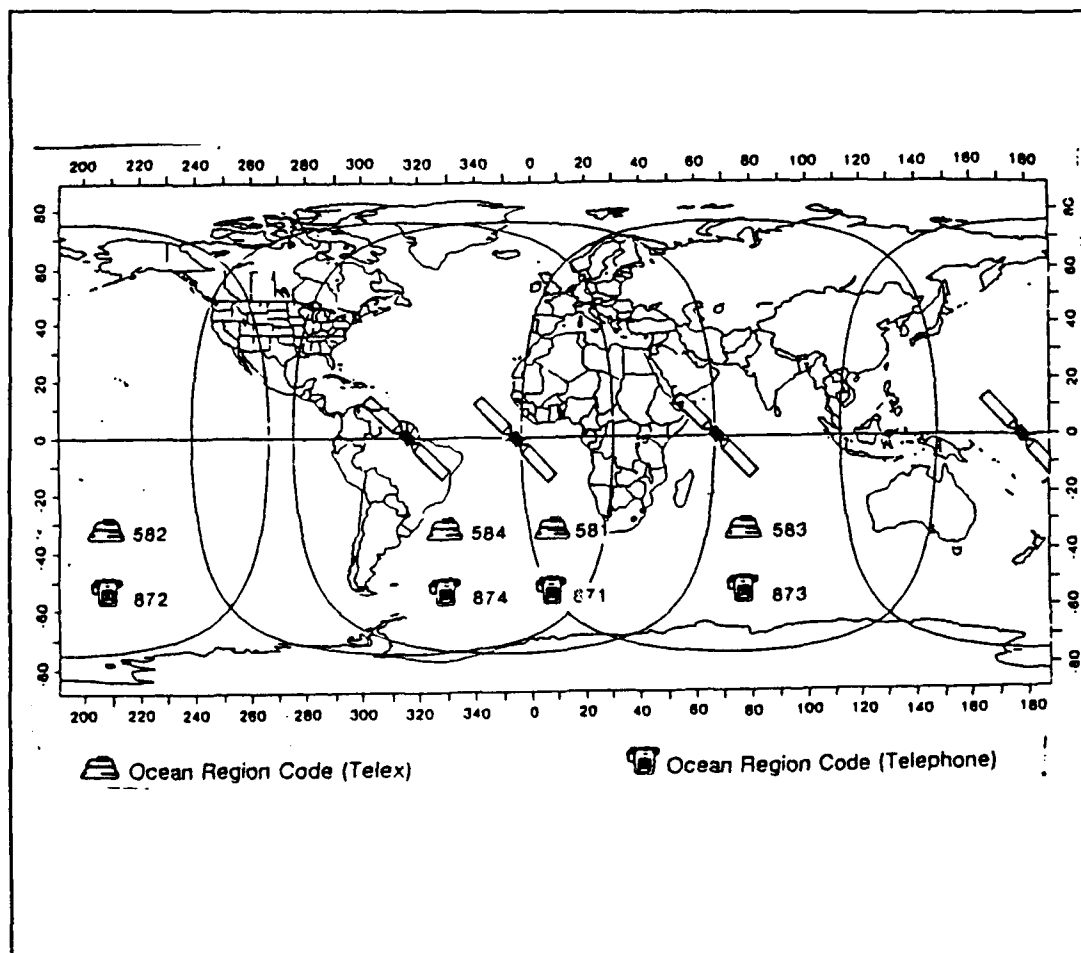


Figure 23. INMARSAT's coverage area

Table 8 shows the main parameters of the INMARSAT system. [Ref. 5:p. 12]

Table 8. INMARSAT's MAIN PARAMETERS

S/C name(s)	MARISAT	MARECS	INTELSAT-5-MCS*
Prime contractor	Hughes Aircraft	British Aerospace	Ford Aerospace
Launch dates	19 February 1976; 9 June 1976; 14 October 1976	A: 20 December 1981 B: 9 November 1984	F5: 28 September 1982 F6: 19 May 1983 F7: 18 October 1983 F8: 4 March 1984
Launcher(s)	Delta 2914	Ariane	Atlas Centaur and Ariane
Launch site	ETR, Florida	CSO, Kourou, French Guiana	ETR and CSO
Design life (yrs)	5	7	7
Orbital positions	15°W; 176.5°E; 73°E	26°W; 177.5°E	63°E; 18.5°W; 60°E; 33°W
Transfer orbit			
Mass (kg)	635	1006 (A); 1014 (B)	1870
Primary power (W)	330	1000	1800 (EOL)
Frequencies	250-400 MHz 1537-1541 MHz 1638.5-1642.5 MHz 4195-4199 MHz 6420-6424 MHz	1538.8-1542.5 MHz 1638.6-1644.5 MHz 4198.5-4200.5 MHz 6416.9-6425 MHz	1535-1542.5 MHz 1636.5-1644 MHz 4192.5-4200 MHz 6417.5-6420 MHz
No. of active transponders	3 (3 UHF; 1 L-band; 1 C-band)	1 C 10L 1 L 10C	2 (1 C-L; 1 L-C) of 7.5 MHz bandwidth each
EIRP (dBW)	UHF (28 dBW—wide band; 23 dBW—narrow band); C (18.8 dBW); L (26 dBW) (Medium Power Band)	C (15.7 dBW) L (24.1 dBW)	C-band (20 dBW) ^a L-band (32 dBW) ^a
'Ground' stations	3 const earth stations: 12.8 mW ~200 ship terminals: 1.2 mW	~15 const earth stations ~2500 ship terminals	Same stations as for MARECS
Capacity	Three UHF channels (one wide band and two narrow band), plus one two way voice circuit and 44 telex channels while US was using UHF (due to power limitations) This rose to nine voice and 110 telex channels when Navy closed use of its UHF channels	46 voice channels. Each channel can carry 25 to 30 telex messages instead of voice	35 voice channels

INMARSAT is now in the process of procuring a second generation of satellites. The INMARSAT-2 spacecraft, the first of which was launched in October 1990, will have three to four times the capacity of the most powerful satellite in the present INMARSAT system. INMARSAT has ordered four INMARSAT-2 satellites from British Aerospace, with options for an additional five. [Ref. 17:p. 2]

4. User terminals

Most current users of the present system use Inmarsat-A terminals or their transportable derivatives. The new Inmarsat-C micro terminal supports the new two-way data-only communications services.

a. *Standard-A terminal*

Mainly for larger vessels or those with sophisticated communications requirements, a standard-A ship earth station (SES) uses INMARSAT satellites to provide high quality connections into the world's international and national telecommunications networks. About 30% of the Standard-A SESs in service are on oil tankers and about 70% are on ships over 10000 tons. [Ref. 8:p. 240]

Standard-A SESs are produced by about a dozen different manufacturers and marketed through thousands of agents worldwide. The most obvious feature of a Standard-A SES is its radome, which encloses a parabolic dish antenna, usually of less than one meter in diameter. The antenna is motorized so that it tracks the satellite precisely, regardless of ship movement. Each comes equipped with an automatic pushbutton telephone and a telex machine. Optional equipment is available for many other services such as facsimile, data transfer, and even television.

Standard-A SES can provide the following services: [Ref. 8:p. 241]

- Telephone.
- Telex (50 Baud).
- Facsimile.
- Data transmission (Up to 9600 B/s).
- 'Broadcast' telex or voice messages to groups of ships.

There are three types of Standard-A system SES:

- Class 1 stations, which carry telephone and telex traffic.
- Class 2 stations, which carry telephone traffic only.
- Class 3 stations, which carry telex traffic only.

(1) Above and Below Deck Equipment (ADE and BDE)

The components of a ship's terminal are categorized as above and below deck equipment. The ADE consists of the antenna and its mounting, the radome, the high power amplifier and the low noise amplifier. The BDE consists of up and down converter units, frequency synthesizers, equipment for processing the signals, a display and control unit, and one or more terminal equipments. [Ref. 8:p. 247]

(2) Tracking and Stabilization

It is not always easy to keep the antenna of a Standard-A SES pointing at the satellite because of: [Ref. 8:p. 248]

- Roll, pitch, and yaw.
- Changes in ship's course.
- Changes in the bearing and elevation of the satellite relative to the ship's movement.

Some common methods of counteracting the above effects are:

- Mount the antenna on a platform which is gyroscopically stabilized by two flywheels spinning on orthogonal axes (counteracts roll and pitch).
- Connecting the drive of the above platform to the ship's compass (counteracts the change in ship's course).
- Providing a step-track system (counteracts the effects of satellite's and ship's motion).

(3) SES's antennas

The use of antennas with diameters as small as 0.9 m has been made possible by the availability, at reasonable cost, of gallium arsenide Low Noise Amplifiers (LNA) with good performance. The characteristics of a Standard-A SES antenna are shown in Table 9 and Figure 24: [Ref. 8:p. 249]

Table 9. CHARACTERISTICS OF STANDARD-A SES ANTENNA

<i>Antenna</i>	
Diameter	0.9-1.2 m
Gain	21-23 dB
Half-power beamwidth ($\pm$)	6-7°
<i>EIRP</i>	
<i>G/T</i> (at 5° elevation with a clear sky)	36 dBW - 4 dB/K

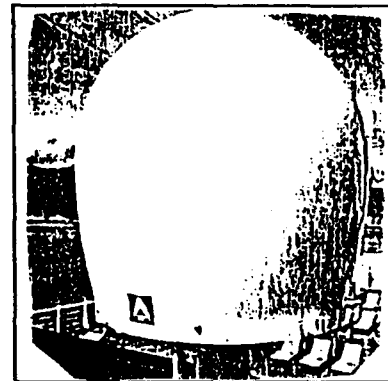


Figure 24. A Standard-A SES Antenna

b. Standard-C terminal

The Inmarsat-C communication system gives two-way store and forward telex or data messaging communications via satellite to and from virtually anywhere on the globe. The terminal is small, simple and robust. The largest versions, with fixed omni

directional antennas, weigh only 6 Kg and measure 30 x 22 x 11 cm (excluding the antenna). Some manufacturers are planning versions that will fit in one hand, a pocket, or a handbag. [Ref. 19:p. 1]

Communications via the Inmarsat-C system are data or message based. This means that anything that can be coded into data bits - any data words, text, language or alphabet - can be transmitted via Inmarsat-C. It can also handle some forms of graphics.

Communications originated from a mobile terminal are transmitted in data packets, via satellite, to a coast earth station. At the coast earth station, the packets are reassembled before being retransmitted to their destination - in the form that has been nominated by the sender, that is, telex, data, etc. - via the national or international telecommunications networks. [Ref. 19:p. 1]

There are three main types of Standard-C SES: [Ref.8 p.260]

- Class 1: which provides the basic functions of ship-to-shore and shore-to-ship message transfer.
- Class 2: this type of SES has two alternative mode of operation which can be selected by the operator. In the first mode it behaves as a Class 1 terminal but can also receive group-call messages when it is not being used for ordinary traffic. In the second mode it can be set to continuous reception of group-call messages.
- Class 3: which is a class 1 terminal with the addition of a second receiver allowing the continuous reception of group-call messages.

With two manufacturers already listing Inmarsat-C terminals for sale, and several others in an advanced stage of development, users will soon have a wide range of equipment from which to choose. The first production model to be type approved by INMARSAT is being manufactured by the Danish firm Thrane & Thrane, it is already available. The T & T terminal has a small, fixed, conical antenna which, because of its light weight and simplicity, can be mounted almost anywhere on a vessel or vehicle. The main

electronics unit is about the size of a large book and weighs only a few kilos. The unit interfaces via an RS232 port to a personal computer for message generation and display.

[Ref. 19:p. 2]

(1) *Two-way communications*

The Inmarsat-C system is capable of providing communications of virtually unlimited length, in both directions, between a mobile and a fixed communication center such as a home or office. These communications take place on a store-and-forward basis, with the store-and-forward message switch being located at the ground station. The store-and-forward procedure provides several advantages for Inmarsat-C such as:

[Ref. 19:p. 2]

- Service at the lowest cost.
- Flexibility in the type of messages (telex, electronic mail, switched data).
- Automatic reprocessing of the messages into the correct delivery mode.

(2) *FleetNet & SafetyNet*

These are two new services which take advantage of the Enhanced Group Call (EGC) which enables messages to be sent to a number of Inmarsat-C mobiles simultaneously. SafetyNet provides a reliable method for the distribution of maritime safety information to specified groups of vessels or to all vessels operating in, or about to enter, specified areas. FleetNet allows commercial messages such as news bulletins, market reports, and commercial weather services to be distributed simultaneously to groups of vessels or vehicles. [Ref. 19:p. 3]

5. **Coast Earth Stations (CES)**

Another component of the INMARSAT system is the Coast Earth Station (CES), which provides the link between the satellites and national and international

telecommunications networks. Coast Earth Stations are generally owned and operated by the signatories of the countries in which they are located. The Signatories are organizations nominated by their countries to invest in, and work with, INMARSAT. As of June 1990, there were 21 CESs in operation, which are shown in Table 10: [Ref. 17:p. 3]

Table 10. COAST EARTH STATIONS IN OPERATION

Country	Location	Coverage Region	Operational Status
Brazil	Tangua	Atlantic Ocean	In operation
Egypt	Mandi	Atlantic Ocean	In operation
France	Pleumeur Bodou	Atlantic Ocean	In operation
Italy	Fucino	Atlantic Ocean	In operation
Kuwait	Umm-al-Alah	Atlantic Ocean	In operation
Poland	Panry	Atlantic Ocean	In operation
Turkey	Ata	Atlantic Ocean	In operation
UK	Unonhilly	Atlantic Ocean	In operation
USSR	Odessa	Atlantic Ocean	In operation
USA	Southbury	Atlantic Ocean	In operation
Denmark, Finland			
Norway, Sweden	Eik	Indian Ocean	In operation
Greece	Thermopylae	Indian Ocean	In operation
Japan	Yamaguchi	Indian Ocean	In operation
Poland	Panry	Indian Ocean	In operation
Saudi Arabia	Jeddah	Indian Ocean	In operation
Turkey	Ata	Indian Ocean	In operation
USSR	Odessa	Indian Ocean	In operation
Japan	Ibaraki	Pacific Ocean	In operation
Singapore	Singapore	Pacific Ocean	In operation
USSR	Nakhodka	Pacific Ocean	In operation
USA	Santa Paula	Pacific Ocean	In operation

a. Antenna

The Figure of Merit (G/T) required at the C-band frequencies is specified as not less than 32 db/K. This requires an antenna with a diameter of at least 10 m. It may, however, be necessary to use a larger antenna in order to achieve the required EIRP (Effective Isotropic Radiated Power), taking into account the maximum number of carriers to be transmitted, the output power of available transmitters, the required back-off, the losses introduced by any transmitter combining networks, which may be necessary, and the diameter of existing antenna designs. For example, the antenna of the British Telecom International CES at Goonhilly Earth Station (which works both L and C bands) has a diameter of 14.2 m; this enables the simultaneous transmission of up to about 40 C-band carriers through a single 3 kW High Power Amplifier. But the precise size of the antenna was determined by the fact that it is an adaptation of an existing design. [Ref. 8:p. 249]

b. L-band functions

The CES needs to be able to receive and transmit L-band signals for three reasons: [Ref. 8:p. 251]

- The satellite transponders convert C-band signals to L-band (and vice versa), so communication between the network co-ordinating station (NCS) and other CESs requires the ability to transmit and receive L-band signals.
- The CES provides automatic frequency control (AFC) for both ship-to-shore and shore-to-ship transmissions, which helps keep the SES as simple and as cheap as is practicable.
- So that a complete test of the CES equipment can be carried out without the co-operation of a SES (a test terminal is provided at each CES for this purpose).

The block diagram of a CES is shown in Figure 25. [Ref. 8:p. 250]

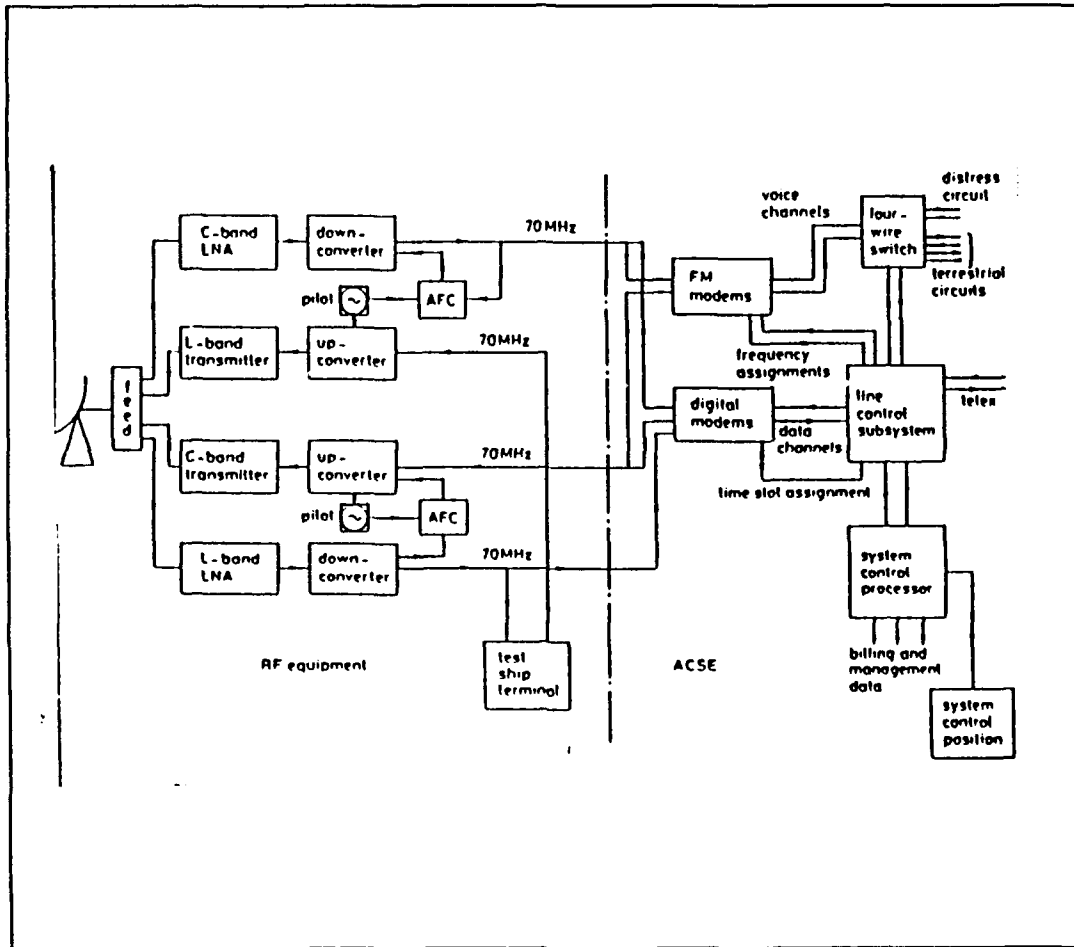


Figure 25. Coast Earth Station

6. The Global Maritime Distress and Safety System (GMDSS)

The International Maritime Organization (IMO) has developed a "Global Maritime Distress and Safety System" (GMDSS) to replace the present maritime distress and safety system. The GMDSS will rely on automation and will use INMARSAT's satellites for rapid and reliable communications. It has been included in new amendments to the SOLAS (Safety of life at Sea) Convention by a conference of Contracting

Governments in November 1988. The amendments will come into force on first of February 1992. [Ref. 20:p. 1]

a. Background

Maritime distress and safety communications have relied primarily on the capability of a ship in distress to alert another ship in the vicinity. Present regulations in the 1974 SOLAS Convention require morse radiotelegraphy on 500 KHz for ships of 1600 gross tonnage and above, and voice radiotelephony on 2182 KHz and 156.8 MHz for all ships of 300 gross tonnage and above. [Ref. 20:p. 1]

b. The new system

The GMDSS has been designed to ensure a combination of safety and efficiency. Consequently, it is a largely automated system and will require ships to carry a range of equipment capable of simple operation. IMO approached this task by defining communications functions which needed to be performed by all ships and then specifying what equipment would meet these functional requirements in defined ocean areas of the world. All ships shall be capable of performing communications functions for the following: [Ref. 20:p. 1]

- Distress alerting, ship-to-shore, shore-to-ship, and ship-to-ship.
- Search and rescue coordination.
- On-scene communications.
- Signals for locating.
- Maritime safety information.
- General radiocommunications.
- Bridge-to-bridge communications.

All SOLAS Convention ships of 300 gross tonnage and above are required to carry a minimum set of equipment, which must include: [Ref. 20:p. 2]

- Facility for reception of maritime safety information by the INMARSAT enhanced group call system (SafetyNet service) if travelling in areas of INMARSAT coverage.
- Satellite emergency position-indicating radiobeacon (EPIRB) capable of being manually activated and of floating-free and activating automatically.
- Depending upon the area in which they operate, an INMARSAT SES

7. Aeronautical Satellite Communications

INMARSAT is intending to offer a wide range of satellite communications services to the world's aviation community. Some of these services were available on a pre-operational basis during 1990, with global operations beginning in 1991 once INMARSAT's second generation satellites become operational. [Ref. 21:p. 1]

Two types of services are under development. The first will provide low speed data links for airline operational, meteorological, air traffic control, position and performance monitoring and safety communications. The equipment required onboard an aircraft in order to access this service will be compact and simple, probably using low-gain conformal patch or blade antennas. [Ref. 21:p. 2]

The second service will require more sophisticated electronically or mechanically steerable, higher-gain antennas. This service will be capable of providing higher-speed data and voice communications, including telephone and facsimile facilities for airline passengers and flight crews.

Several trials and demonstrations using INMARSAT's facilities have already taken place or are planned. These include: [Ref. 21:p. 3]

- An air-ground data transmission link (two way) via INMARSAT that was demonstrated in mid 1985.
- Air-ground satellite communications (voice and data) using a phased-array antenna that was tested in 1986 by German Aerospace Research Establishment.
- An air-ground data link for air traffic services communications demonstrated by the European Space Agency in 1987 in a program called PRODAT.
- A pre-operational telephone service from aircraft, offered by British Airways, British Telecom International and Racal Decca beginning in February 1989.

C. FUTURE DEVELOPMENTS OF INMARSAT SYSTEM

The satellites comprising INMARSAT's first-generation satellite system are almost near the end of their design lives and the available satellite capacity in the Atlantic Ocean region is saturated.

In August 1983, INMARSAT issued calls for tenders on a new series of satellites which could cost several million dollars. The main requirements for the second-generation satellites were summarised as: [Ref. 8:p. 255]

- A considerable increase in capacity relative to MARECS and MCS.
- The ability to operate satisfactorily with a range of mobile terminals and with EPIRBs (emergency position-indicating radio beacons).
- Compatibility with at least two launch vehicles.
- Long life and the utmost reliability.
- Availability by the end of 1988.

INMARSAT's second-generation system is expected to have many more times the capacity of the existing system. A minimum global coverage capacity of 125 channels has been specified for the shore-to-ship transponder (equivalent to around 250 channels with

some measure of carrier voice-activation). This should be sufficient for the busiest ocean region, the Atlantic, at least into the mid-1990s. This capacity should also accomodate Indian and Pacific Ocean region traffic requirements until the mid-to-late 1990s.

[Ref. 16:p. 227]

The characteristics of the second-generation INMARSAT satellite are shown in Table 11. [Ref. 8:p. 257]

Table 11. CHARACTERISTICS OF INMARSAT-2

<i>C-band to L-band repeater</i>		
Receive band	(MHz)	6435.0-6441.0
Transmit band	(MHz)	1530.5-1546.0
G/T	(dB(1/K))	-14
EIRP	(dBW)	39
Capacity (Standard-A voice channels)		125 (250)
<i>L-band to C-band repeater</i>		
Receiv band	(MHz)	1626.5-1647.5
Transmit band	(MHz)	3600.0-3621.0
G/T	(dB(1/K))	-12.5
EIRP	(dBW)	24
Capacity (Standard-A voice channels)		250

In Figure 26 we can see a picture of the INMARSAT's second generation satellite. It can be seen from these characteristics that, although the INMARSAT system does not yet provide full global coverage, the Organization is working to fulfill its mandate to serve all areas where there is a need for maritime and aeronautical communications.

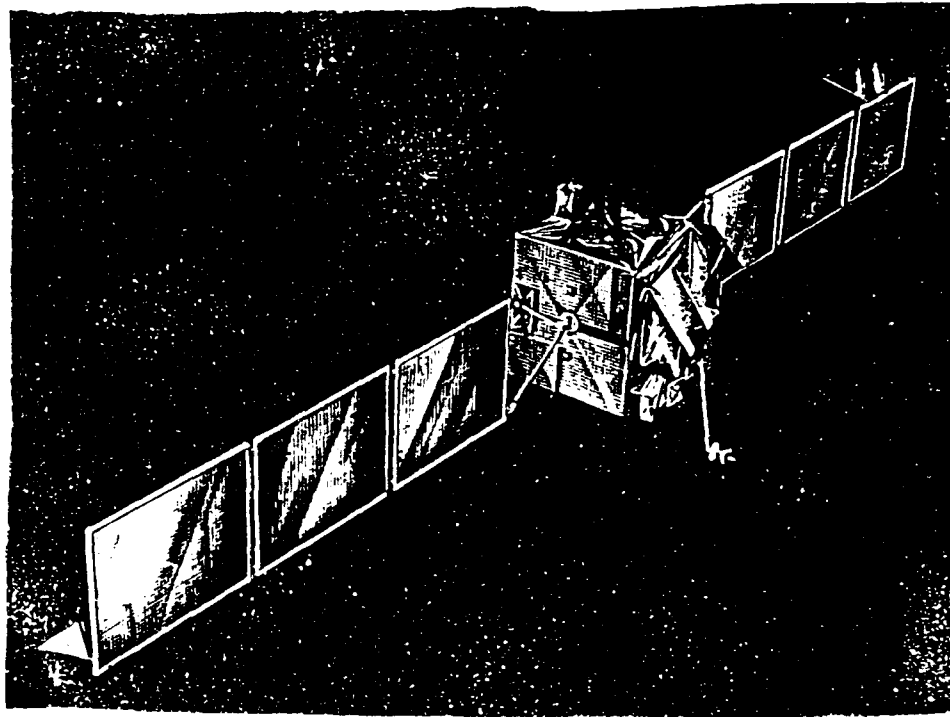


Figure 26. INMARSAT-2

V. SATELLITE COMMUNICATIONS VULNERABILITY

A. INTRODUCTION

Although the frontier of space offers many unique and attractive advantages, it is not without some countervailing disadvantages and limitations.

A given satellite is but one part of a complex space system whose proper functioning requires a launch system, command and control network, and communication links to connect the system's user, usually on the ground, with the orbiting satellite. To disturb the proper functioning of a typical space system, it is necessary only that anyone of these four subsystems fail or be made to be fail. [Ref. 24:p. 89]

Secondly, many of the space systems depend upon more than one satellite in order to function. As increasing numbers of the system's satellites fail, the system is successively degraded.

Another important point to keep in mind is that space systems tend to be inherently fragile. Because they are very expensive to build and to launch, space systems are usually designed to the limit and possess little in the way of performance margin. This makes them inherently vulnerable either to unintentional accident such as an occasionally uncooperative environment, internal failure, or human neglect, or to the direct malevolent action of an opponent. [Ref. 24:p. 89]

Space is not a completely benign environment. Satellites must withstand extreme temperature changes, and the near-vacuum of space offers little protection from external sources of radiation, particularly the sun. And even if the environment of space is less hostile than that of earth, the satellite still has to get there. The shock and vibration stresses

encountered during launch are severe, and special care must be given to a satellite's mechanical engineering to enable it to survive these conditions. Also, satellites have to be able to endure generally without maintenance. Subsystem redundancy in which virtually all black boxes are duplicated and cross-connected, is standard practice throughout the space industry. [Ref. 24:p. 90]

B. THREATS TO COMMUNICATION LINKS

There are several things that can disrupt communications without any help from an opponent, such as interference, atmospheric fades, and, of course, failures of communications equipment.

In a general sense, there are three basic strategies that an enemy might seek against each of the four communications links:⁶ [Ref. 24:p. 100]

- Attempt to make use of the link himself to his own advantage.
- Attempt to deny the use of the link to the legal user.
- Attempt to inject his own signal into the link with the intention of deceiving either the system itself or a user of the system.

The means by which an opponent might attempt to carry out the above strategies include: [Ref. 24:p. 101]

- Collection, which consists of passive interception and perhaps recording of the target signal.
- Jamming, which involves the deliberate transmission of a competing signal at the same frequency as the target signal with the intent of interfering with its reception.
- Spoofing, which consists of the deliberate transmission of a signal that looks very much like the true target signal with the intent, not of interfering, but deceiving the legitimate user.

⁶Ground to satellite (uplink), satellite to ground (downlink), ground to ground through a satellite (throughlink), and satellite to satellite (crosslink).

1. Uplink

Command links or uplinks probably present the widest range of choices for the opponent. He could temporarily deny or limit the use of the satellite by jamming the link. If this happens at a critical time, such as during the launch phase, the effect may even be catastrophic and permanent. Also, he could intercept the signal in order to gain important information about the satellite's purpose and the way it is controlled. But the greatest threat to an uplink, in terms of potential mischief, is spoofing. If an opponent is able to generate his own set of commands and make the satellite act on them, there is no limit, within the bounds of satellite's capability, to what he can do. Also, if done carefully, spoofing is virtually undetectable and almost impossible to prove. [Ref. 24:p. 101]

Fortunately, for each of the above actions, there are countermeasures, such as employment of frequency agility or band spreading against the threat of jamming, encryption against the threat of interception, and some means of validating the authenticity of a transmission against the threat of spoofing. [Ref. 24:p. 101]

2. Downlink

Geometry makes downlinks much harder to attack than uplinks, this is in spite of the fact that the size of the downlink transmitting antenna as well as output power have to be limited. More than compensating for the latter limitation is the fact that the receiving antenna on the ground can be quite large and, as a result, can be highly directional, focused at the satellite itself.

Collection of the downlink signal is a relatively easy matter, but to spoof it or to actively jam it almost requires that the opponent situate himself within the beam of the receiving antenna, that is, between the antenna and the satellite, which is very difficult to accomplish without detection. [Ref. 14:pp. 93-102]

3. Throughlink

Throughlinks can be targeted either on the way up or on the way down. To an opponent, the upward path of a throughlink is very much like an uplink and the downward path much like a downlink. The earth to satellite path is easier to jam or spoof and can be collected by a receiving station very close to the transmitter or from a mobile receiving station such as an airplane or satellite that is within the beam of the upward path. The satellite to earth path is easier to collect but harder to jam or spoof. However, since on a throughlink the information on the upward and downward path is the same, if the opponent has decided to collect he will target the downward path, and if his choice is to jam or spoof he will concentrate on the upward path. [Ref. 24:p. 102]

4. Crosslink

Crosslinks present the most formidable task to the opponent, and therein lies much of their value. A successful attack against a crosslink would almost have to be conducted from an orbiting position somewhere between the two communicating satellites. In order to accomplish all three hostile actions of collection, jamming, and spoofing would require a position between the two satellites. Collection could also be carried out from behind the receiving satellite but not from behind the transmitting satellite. Jamming or spoofing could be accomplished only from behind the transmitting satellite. [Ref. 24:p. 102]

C. JAMMING SIGNALS

In the previous decade most electronic warfare efforts concentrated in the area of radar systems. Communication EW played a secondary role. In this decade, the importance of communication countermeasures and countercountermeasures has gained ever increasing recognition and implementation.

Communication jamming is more difficult than radar jamming since communication involves a one-way-path signal attenuation, rather than a two-way-path attenuation as radar; also encryption is used in communication to generate message security.

In applying jamming to a communication link it would be desirable to know the answers of two fundamental questions. [Ref. 23:p. 18]

- What is the best jamming waveform and strategy?
- How effective will jamming be against the system?

1. Interception and Jamming

The possibility of jamming is not taken into account in the design of commercial satellite systems. The very successes of UHF satellite communications systems in minimizing detection due to emitter interception has made jamming a more promising alternative to a possible enemy.

2. Jammer Description

Communications links can be jammed by the following two types of jammers:
[Ref. 14:p. 93]

- Noise Jammers
- Repeaters

Noise jammers include all systems that generate and transmit their own signal for the purpose of degrading the effectiveness of the victim electronic system such as:

[Ref. 22:p. 117]

- Spot- Noise Jamming
- Barrage Noise
- Multiple Swept Jammers

Repeaters are those systems using transponders and in which the communication signal is received, suitably modulated with amplitude, phase, frequency, and/or time variations, and amplified and retransmitted after processing. Either of the above systems may be used to jam communication satellites via the uplink or downlink paths. Jamming the downlink would require the positioning of a hostile satellite in the region of the satellite to be jammed. This would take time, and countries with advanced space monitoring facilities would detect what was happening in time to plan corrective action, such as switching to an alternate satellite. More practicable and less expensive would be the jamming of the uplink with large earth antennas. Here the element of surprise could be achieved. The jammer and repeater geometry is shown in Figure 27. [Ref. 14:p. 94]

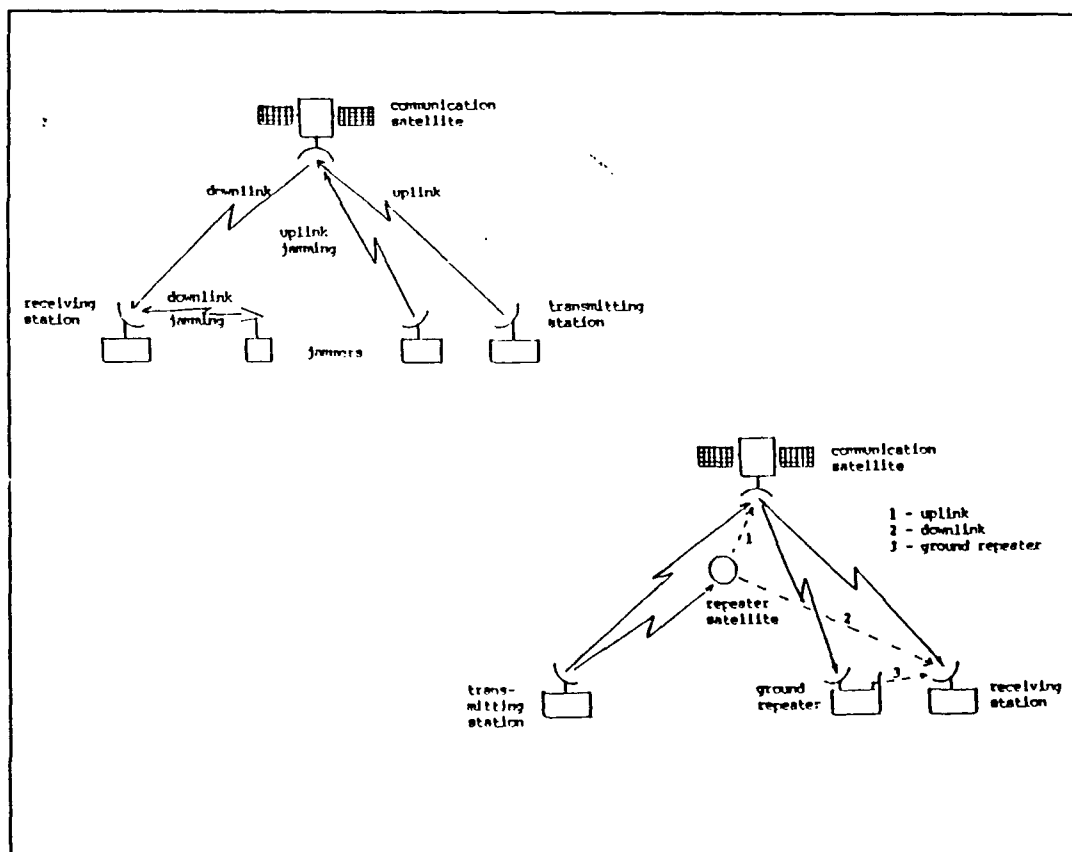


Figure 27. Jammer and Repeater Geometry

The objective of a jammer is to obscure or deny information by masking or increasing the error probability of the detected data. Jammers can be evaluated by the ratio of the jamming signal bandwidth to the communication receiver bandwidth. This ratio is very small for the CW jammer. This appears effective since all jam power will be focused in the receiver bandwidth but notch filters may easily overcome CW jammers.

[Ref. 23:p. 18]

With repeaters, the idea is to receive the signals, process them and retransmit. This is difficult because it is hard to obtain the geometry which is required to effectively use of repeaters. In cases where we manage to achieve the geometry we must carefully use the modulation or delay techniques because a straight repeater is worse than no jamming at all if there is no modulation since it increases the signal power. One advantage of repeaters is that with this technique we are able to operate at the same time against many links.

[Ref. 23 p. 21]

3. Jamming of links using FDMA/PSK

The basic characteristics of jamming with FDMA/PSK are: [Ref. 18:p. 24]

- Since there is no spreading there is no processing gain and the jammer requires no more Effective Isotropic Radiated Power (EIRP) than the signal. This results in less power than in the spread spectrum case.
- The psychological effect which sometimes appears on the jammed channels because of the use of narrowband jammers against some of the users without interfering with the others.
- The carrier local oscillator of PSK receivers is generated by processing of the received signal through squaring loops. In the case of FDMA/PSK since there is no spreading process these circuits can be denied by breaking the loop lock.
- Pulse jamming is better than continuous jamming.

4. Antijamming Techniques using spread spectrum

Protection from the jamming is generally obtained by using spread spectrum techniques, that is frequency hopping or pseudo-noise. [Ref. 14:p. 96]

In recent years, jammers have been smarter and faster at locating, identifying, and jamming a particular communication link. Frequency hopping offers a solution to the problem, working by rapidly switching the transmitter carrier over many channels within a very wide frequency band. Typically, more than 1000 channels may be used and the switching rate may exceed 100 hops per second. Because an enemy cannot be certain when or where transmissions will take place, his jammers must constantly search the spectrum for the signal he expects to jam; thus frequency hopping, which results in short duration transmissions would be effective.

Jamming effectiveness depends upon relative signal strength, dwell time (DT), and the jammer's processing time (PT). If we suppose that we have the maximum signal strength and PT is defined as the time from the target signal's first appearance to the time a jammer can direct energy against a target receiver operating in that net, then the formula for jammer effectiveness as a function of PT , DT, and range is: [Ref. 14:p. 99]

$$\%_{\text{jammed}} = \frac{100 * [DT - 2 * (6.18 * \text{range}) - PT]}{DT}$$

Shortening the DT is a good method for overcoming a jammer, because a shorter DT makes propagation delay significant and jammer-target ranges more critical. Even with an instantaneous PT, a jammer must be within 61 nautical miles to be 25% effective against systems with one millisecond DT. A more realistic 400 microsecond PT requires the jammer

to be within 29 nautical miles, or well within the strike distance of a naval task force. In effect, shorter DT decreases a jammer's effective range. [Ref. 14:p. 99]

Pseudo-noise (PN) spread spectrum is acquired by multiplying the digital data signal by a much faster pseudorandom binary string. The resulting signal is transmitted over a wide band around a fixed-center frequency. Use of this technique decreases the probability of detection as the power density of the transmitted signal is divided by the spreading factor. If the spread is wide, it is possible that the transmission will have less power density than that of ambient noise at the site of an intercepting receiver. Maximum admissible jamming to signal ratio (J/S) at the input of an anti-jam (AJ) demodulator using PN direct sequence is given by: [Ref. 14:p. 99]

$$(J/S)_m = \frac{\frac{W}{2}}{R * (\frac{E_b}{N_0})}$$

where, W=Spreading Bandwidth (Hz)

R=Data Rate (bits/sec)

E_b/N_0 =Energy per bit to noise density ratio (Db).

To increase the jamming resistance we have to spread the signal in a wide band, W, and reduce the information rate. SHF/EHF bands give more bandwidth, W, but as the carrier frequency increases, demodulation becomes more difficult (information is transmitted at very low data rates) due to phase noise of the local oscillators.

5. Uplink-Downlink Jammer

a. Uplink Jammer

For a transparent repeater the protection ratio can be expressed by:

[Ref. 14:p. 101]

$$\left(\frac{J}{S}\right)_u = \frac{G_s}{G_j} * \left(\frac{J}{S}\right)_m * \frac{1}{L} * \left[1 + \frac{L_p * k * \left(\frac{W}{2}\right)}{EIRP_s * \left(\frac{G}{T}\right)_R}\right]^{-1}$$

where $(J/S)_u$ = Jamming to signal ratio.

G_s =Satellite antenna gain in the signal direction

G_j =Satellite antenna gain in the jammer direction.

L_p =Down link free space propagation losses.

$EIRP_s$ =Saturated satellite EIRP at beam edge.

$(G/T)_R$ =Receiving terminal G/T .

L =Limiter suppression factor.

k =Boltzmann's constant.

To improve the uplink $(J/S)_u$, it is necessary: [Ref. 14:p. 101]

- To use a satellite reception antenna with very high directivity.
- To concentrate the power radiated by the satellite in the direction of the small terminals to have $EIRP_s (G/T)_R \gg L_p k w/2$.

For on-board AJ processing the protection ratio is only defined by:

[Ref. 14:p. 102]

$$\left(\frac{J}{S}\right)_u = \frac{G_s}{G_j} * \frac{\frac{W}{2}}{R * \left(\frac{Eb}{No}\right)}$$

b. Downlink Jammer

The acceptable jammer EIRP on the downlink is given by: [Ref. 14:p. 102]

$$J = EIRP_s * \frac{G_s}{G_j} * \frac{d_j}{d_s} * \left(\frac{J}{S}\right)_m$$

where, G_s =Antenna gain of the terminal user in the satellite direction.

G_j =Antenna gain of the terminal user in the jammer direction.

d_s =Distance to satellite.

d_j =Distance to jammer.

Generally, a jammer has an important distance advantage compared with a geostationary satellite, but it can see only a very limited area. To protect the downlink under high RF satellite power, it is required to reduce the coverage area and use a terminal with high directivity antenna.

D. SUMMARY AND CONCLUSIONS

- Satellite communication links using digital PN spread spectrum and FDMA techniques are vulnerable to jamming and denying signals. Two types of interfering signals were discussed, noise jammers and repeaters; each requires a specific geometry to be used effectively. In the jamming of FDMA by noise jammers it is necessary to overcome the signal power to increase the Bit Error Rate (BER). In this case there is a potential advantage of a selective jamming, as the jammed user may feel he is having system problems.

- For spread spectrum jamming the disadvantage in overcoming the processing gain by brute force techniques is apparent. CW jamming is an efficient utilization of power but can be easily filtered.
- A repeater technique can be used to break the delay lock loop if the repeated signal is within one chip; however, this may be difficult to achieve in practice as a result of propagation delay.
- The various jamming techniques against satellite communications are shown in Table 12 [Ref. 18:p. 23].
- Jammers can be located on ground or sea platforms and on satellite or airborne installations, while the jamming can be done through the uplink or downlink paths. The uplink has the advantage of potentially stealing the satellite transponder power and generating intermodulation products. In downlink jamming the jammer's distance from the receiving station is usually shorter than the communication path length, allowing a power advantage over uplink jamming. In contrast to the uplink case the downlink jammer has limited access to users.

a. Frequency hopping vs Jammers

Frequency hopping signals are of the LPI type, thus providing increased capability for covert communication and strong resistance to interference and jamming.

Frequency hopping offers an antidote to smart jammers. Because an enemy never is certain when or where transmissions will take place, his jammers must search the spectrum for the signal he hopes to jam.

The effectiveness of the jammer depends upon the friendly on the air dwell time (DT), the jammer's processing time (PT), and relative signal strength.

Concluding, we can say that:

The higher the hoping rate, the less time a jammer has to disrupt communication.

Table 12. JAMMING TECHNIQUES

JAMMER TYPE	EFFECT AGAINST			REMARKS
	FDMA DIGITAL USING FSK	PM SPREAD SPECTRUM TRIM DIGITAL COMM. USING FSK	ANALOG FM	
1. CW or very narrow band signal	Effective against single link. JSR depends on the allowable BER.	High efficiency due to minimum BW after despreading. Notch filter may be used without damaging the communication spectrum.	Effective with JSR > 1 causing the "capture effect"	May be filtered out by notch filter if the signal BW is narrow, though causes loss of some information in FM.
2. Spot Noise (narrowband noise)	Same as above	Has less power than CW in the post despreading BPF, due to despreading. Hard to filter out.	Effective with JSR > 1 if noise BW is less than the FM BW.	The Spot jammer may be sophisticated, e.g., power management can be used to set the jammer frequency at the appropriate frequency.
3. Swept Spot a) SAW TOOTH b) TRIANGLE c) SINUSOIDAL d) RANDOM e) HOPPING	Can be used against many links. Has the advantage of pulsing. If some jammers are synchronized, this mode causes higher average BER.	Can be used against many links, if swept over more than the transponder bandwidth, thus having an off effect against each of them. Sweeping mode and parameters are determined for each target.	Due to recovering time of the RCVR, jamming at the appropriate rate is more efficient than continuous jamming.	Sweeping in patterns which are not random may be filtered out by tracking filter.
4. WIDE BAND BARRAGE (uniform distributed noise over the bandwidth).	Can be used against many links. JSR depends on the required BER.	Jamming power must be greater than signal by the processing gain due to spreading effect.	Increases the noise level. JSR must be greater than the threshold.	
5. PULSED BARRAGE	With the same average power, higher peak power can be used thus causing higher average BER.	After achieving the JSR to overcome the spreading, causes higher average BER than continuous jamming.	Same as SWEPT SPOT.	
6. PULSED SPOT	Can be used simultaneously against single or few links. High peaks cause high BER.	If JSR to overcome the spreading is achieved has same effect as in FDMA.	Same as SWEPT SPOT but can be used against single link.	
7. REPEATER a) STRAIGHT b) DELAYED c) MODULATION ADDED	Special Techniques like frequency shifting may cause error to the Costas loop.	In special geometry may break the sequence sync. Using a delayed version of the signal.	Adding modulation and/or frequency shifting within the bandwidth may be used.	
8. PULSED CW	Same as PULSED SPOT.	In despreading PULSED CW has highest power in correlator BPF. Due to high peak power, cause high average BER.	Same as SWEPT SPOT.	The pulse width has to be wide in order not to spread the jamming. (BW = 1/τ)
9. SWEPT CW	Very effective since it can steal the local carrier if the sweep is slow enough.	Same effect as BARRAGE.	Same as CW	Special technique against P.L.L.

DEFINITIONS: JSR = Jammer-to-signal ratio
BER = Bit error rate
BW = Bandwidth

VI. CONDITIONS AND TECHNICAL CONSIDERATIONS OF INMARSAT SYSTEM IN THE HELLENIC ENVIRONMENT

A. INTRODUCTION

The world's oldest civilizations were born on the banks of a great river but European civilizations grew up thanks to the sea, the Hellenic Sea, which the Romans so jealously named Mare Nostum. Having the sea on three sides of their country, the Hellenes established contact at a very early stage with the peoples of Asia, Africa and Europe, in the course of which they learned, taught, gave, received and attempted distant journeys not merely to trade but also to expand their horizons.

The Hellenic peninsula, covering an area of 131,944 square kilometers consists of mainland Hellas and the islands. This area contains a population of about 10 million. Geographically it belongs to Europe since it forms the most southerly extremity of the Balcan peninsula. It also has a special link with Europe through the small area of the Ionian Islands. The distance from North to South is 418 miles, that from the most easterly point, the islet of Ypsili, near Castellorizo, to the western point of Corfu is 535 miles.

B. INMARSAT IN HELLENIC ENVIRONMENT

1. Background

Thermopylae is a point 10 kilometers further up the coast, from past volcanic vents earned the area it's the name, which means "hot gates". It was there that 300 Spartans and their King, Leonidas, gave their lives to delay the Persian land army, while the main Hellenic force withdrew to better ground.

The heroic battle brought the name into history and adds a special significance to the unique coast earth station located there.

2. Thermopylae's Coast Earth Station

Thermopylae's coast earth station which covers the Indian Ocean region operates in cooperation with the new Italian CES at Fucino, which covers the Atlantic. This arrangement enables the two stations to operate as though they were a single, two ocean station, with economic benefits to the users in both countries.

At present, Thermopylae has three telephone and four telex lines to Italian exchanges, although there is one less of each in the opposite direction on the premise that ship-to-shore traffic is greater than shore-to-ship. The same reasoning explains the choice of six telephone and seven telex lines from the station to Athens, compared with four telephone and five telex lines back from the Hellenic exchange. There are also dedicated lines to the Athenian maritime rescue coordination center. Apart from telephone and telex, a number of services attainable by a two digit dialing codes are being provided, notably medical service, technical assistance, general information, operator assistance and ship-earth station commissioning. [Ref. 25:p. 2]

The Thermopylae station is the first outside of Norway to be supplied by the Norwegian firm, Elektrisk Bureau (EB). The EB content is 60% of total cost. The antenna and C-band RF equipment were bought from United Antennas Inc. of the USA.

Technically, the CES demonstrates an innovative philosophy. The aim, according to the manufacturers, was to keep costs down on the standard equipment, the antenna and RF equipment, and to concentrate on the complicated part, which is the access control and switching equipment. The antenna itself is a minimum structure carrying no equipment on it other than the low-noise receiving amplifiers. It is also designed for only limited

motion, capable of a maximum azimuthal range of 180 degrees. Even that is constrained to two segments of 90 degrees, selected by manually reattaching the drive screw to one end or the other of a cross beam behind the dish. However, this is sufficient to provide coverage of either the Indian or Atlantic Oceans.

3. Services provided and Dialing procedures

a. Services

The two-digit service codes and the corresponding services provided by Thermopylae CES are:

- Automatic telephony and telex.....00
- Operator assisted calls (Intern./National).....11/13
- International/National Inquiries.....12/24
- Radiotelegrams (telex).....15
- Technical assistance.....33
- Person to Person calls (telephone).....34
- Medical advice (telephone).....32
- Automatic call duration advice (telephone).....37
- Automatic telex test messages.....91
- SES commissioning test.....92
- Collect calls (National telephone calls).....35
- Credit Card calls.....36

b. Dialing procedures

(1) Sending a telex to a ship from Greece

Key international access code (00) followed by the ocean region, ship ID and "end of selection" sign. Figure 28 shows how to send a telex to a ship (ID 1130501) in the Indian Ocean Region.

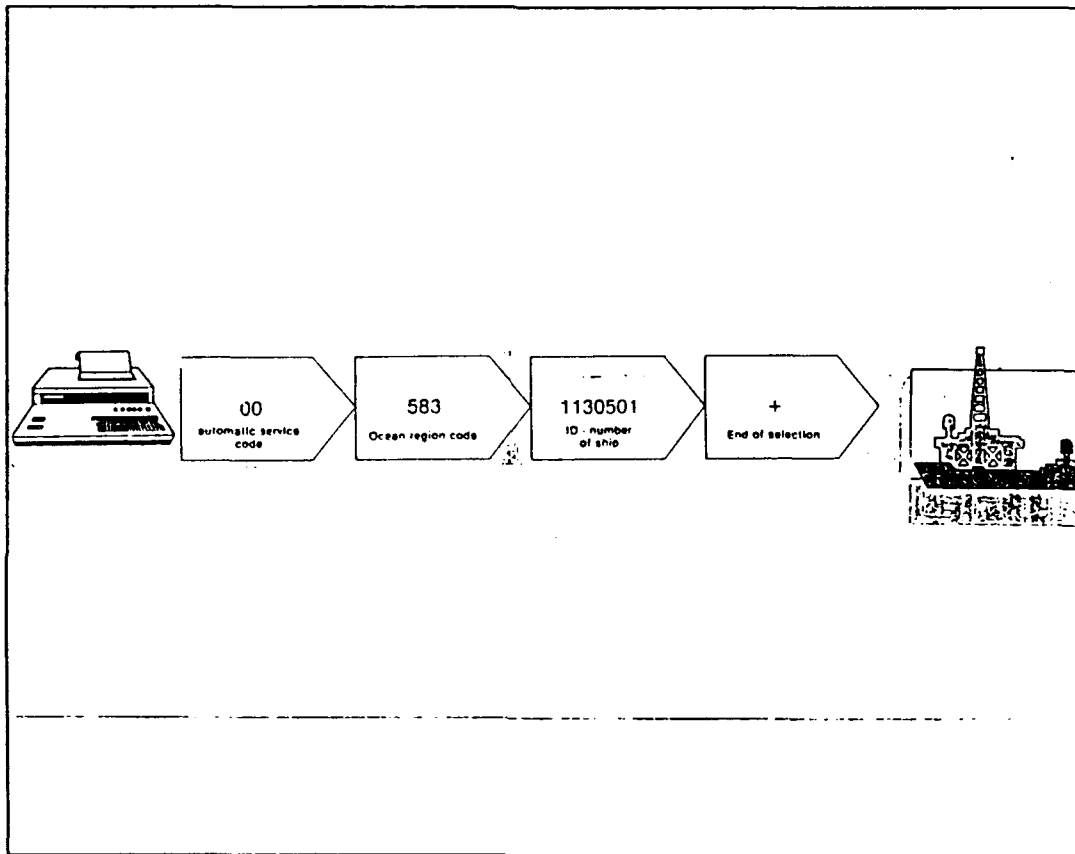


Figure 28. Sending a telex to a ship from Greece

(2) Making automatic calls from a ship

After selecting the identification code for Thermopylae (05 in octal and decimal notation), priority, and channel type (voice channel), you receive a short dial tone (about 1.5 sec). At the tone dial the automatic service code (00) followed by the country code, the subscriber's number and the "end of selection" sign.

Figure 29 shows how to make a call to a Hellenic land subscriber and to another ship in the Indian Ocean Region.

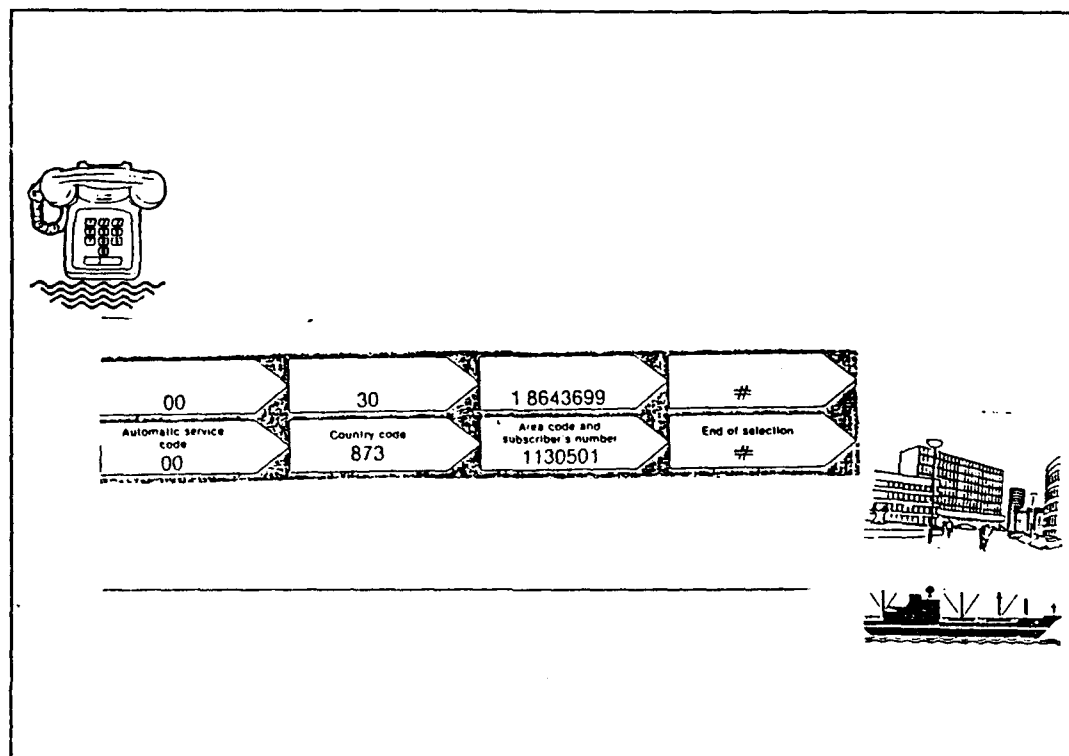


Figure 29. Making automatic calls from a ship

(3) Sending a telex from a ship

After selecting the identification code for Thermopylae CES (05 in octal and decimal notation), priority, and channel type (telex channel), your telex will print out the following:

- Date and UTC time.
- Your ship number and answerback a few seconds later with GA+.

When you receive GA+, you are free to start keying code: automatic service code (00), telex country code, subscriber number and "end of selection" sign. Message duration is provided at the end of the message by keying five dots <<.....>>.

Figure 30 illustrates calls, to a land subscriber, and to another ship in the Indian Ocean Region.

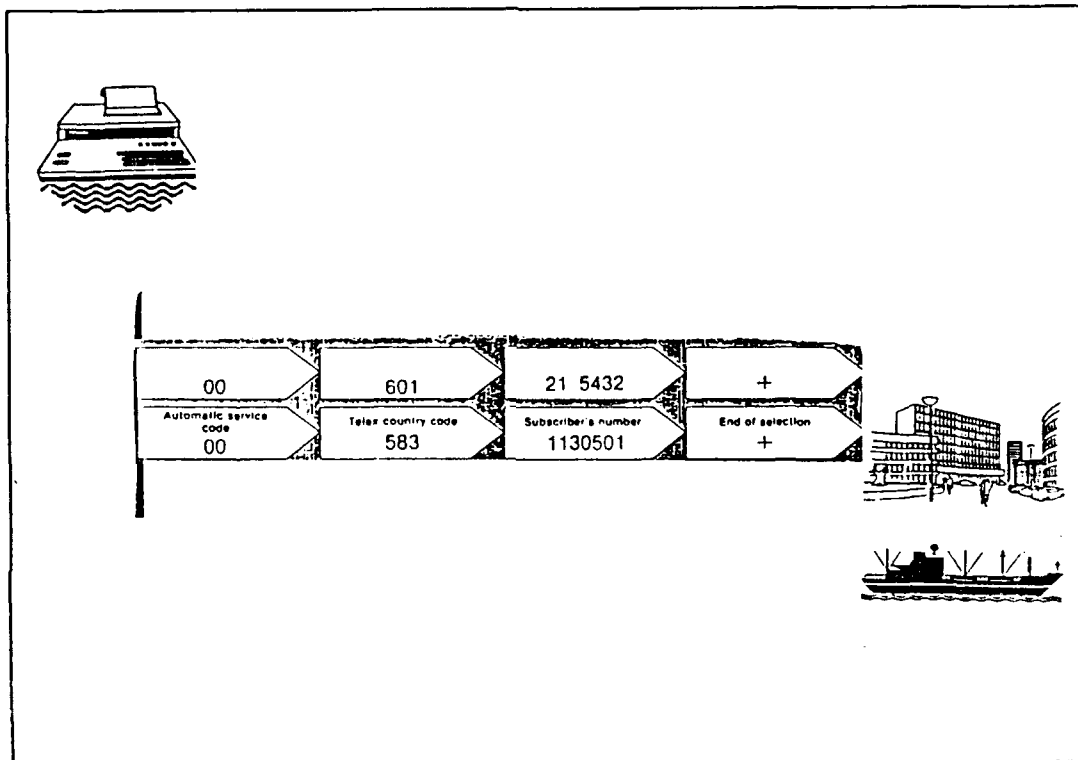


Figure 30. Sending a telex from a ship

(4) Making a call to a ship from Greece

The call is operator assisted. In Athens, Piraeus and their suburbs dial 158. All other regions dial 161. Ask the operator for INMARSAT service and give the ship ID and details for the ship's area.

C. ECONOMICS OF SATELLITE BUSINESS SERVICES

1. Background

The economics of satellite communications have many unusual aspects. It costs no more to transmit a television signal via satellite to one, one hundred, one thousand or even one million receivers. Satellites are also able to interconnect locations thousands of kilometers apart on a distance-insensitive basis. In other words, satellite telecommunications links, in general, cost the same over short and very long-range distances. As a result, they are better suited for certain applications than terrestrial telecommunications, like microwave relay, coaxial and optical fiber cable. [Ref. 3:p. 49]

2. Economically Relevant Technical Properties of Satellites

The most important difference between space-based and terrestrial communication systems concerns the relationship between cost and transmission distance. For all terrestrial systems, total cost varies directly with distance although various fixed costs make this relationship proportional. For example an important cost component of cable technologies is the expensive hierarchical switching required to achieve interconnectivity. Besides distance, the cost of terrestrial modes of communication also increases with difficulties imposed by terrain and climate between the sending and receiving points. [Ref. 3:p. 49]

Satellite technology, by contrast, is inherently insensitive to the distance of transmission, at least within the satellite's coverage zone.

These cost properties imply that the economic advantage of satellites over terrestrial transmission modes is most pronounced when long distances, difficult terrain, severe climate and sparse population are involved.

3. Charges for INMARSAT services in Greece

The charges for the various services provided by the INMARSAT system through Thermopylae CES are shown in the following tables: [Ref. 26:pp. 1-33]

Table 13. SHORE-TO-SHIP END USER CHARGES

<u>End User Charges</u>			
<u>T e l e p h o n e</u>			
	<u>Atlantic</u>	<u>Indian</u>	<u>Pacific</u>
Minimum time	3 mins	3 mins	mins
Unit charge	60 G.F.	60 G.F.	84 G.F.
Overtime	1 min	1 min	1 min
Unit charge	20 G.F.	20 G.F.	28 G.F.
<u>T e l e x</u>			
	<u>Atlantic</u>	<u>Indian</u>	<u>Pacific</u>
Minimum time and overtime	10 secs	10 secs	10 secs
Charge per minute	10 G.F.	10 G.F.	15 G.F.
<u>T e l e g r a m</u>			
Minimum length	7 words		
Charge per word	1.50 G.F.		
Minimum charge	10.50 G.F.		
<u>N O T E</u>			

Telephone and telex calls from foreign countries to ships in the IOR via Thermopylae CES are charged with the CES charge of 18 G.F. per min. for telephone and 9 G.F. per min for telex, plus the existing land line charge between Greece and the country of origin.

⁷G.F stands for Golden Franc which as of January 1991 equals to 0.65 of the dollar.

Table 14. SHIP-TO-SHORE TELEPHONE CHARGES

a) Busy hours (04.01 - 22.00 VIC)

	<u>Automatic</u>	<u>Operator Assisted</u>
Minimum time	10 secs	3 mins
Unit charge	3.17 G.F.	57 G.F.
Overtime	10 secs	1 min
Unit charge	3.17 G.F.	19 G.F.

b) Off-peak hours (22.01 - 04.00 VIC)

	<u>Automatic</u>	<u>Operator Assisted</u>
Minimum time	10 secs	3 mins
Unit charge	2.17 G.F.	39 G.F.
Overtime	10 secs	1 min
Unit charge	2.17 G.F.	13 G.F.

NOTES

1. The above end-user charges for automatic calls to Greece are also applicable for automatic calls to Greece from the AOR via Fucina.
2. Automatic Call Duration Advice (Code 37): 3 G.F. per call.
3. Advice of Duration and Charge for operator assisted calls: 14 G.F. per call.
4. Additional charge for personal, collect and credit card calls: 14 G.F. per call.

Table 15. SHIP-TO-SHORE TELEX CHARGES

END-USER CHARGES FOR MESSAGES TO GREECE

	<u>Automatic</u>	<u>Operator Assisted</u>
Minimum time	10 secs	3 mins
Unit charge	1.50 G.F.	27 G.F.
Overtime	10 secs	1 min
Unit charge	1.50 G.F.	9 G.F.

NOTES

1. The above end-user charges for automatic telex calls to Greece are also applicable for automatic telex calls to Greece from the AOR via Fucino.
2. In automatic telex mode, if Call Duration Advice is required, key 5 dots at the end of the message.

Table 16. SHIP-TO-SHORE TELEGRAPHY CHARGES

END-USER CHARGES FOR TELEGRAMS TO GREECE

Minimum length	7 words
Charge per word	1.50 G.F.
Minimum charge	10.50 G.F.

N O T E

Ships sailing in the AOR may send telegrams to Greece through Fucino by dialing automatically telex No. 210184. The end-user charges are the same as above and billing is made by OTE.

Table 17. SHIP-TO-SHIP TELEPHONE CHARGES (IOR TO AOR)

End-user charges for ship-to-ship calls from a ship in the IOR to a ship AOR.

a) Busy hours (04.01 - 22.00 UTC)

	<u>Automatic</u>	<u>Operator Assisted</u>
Minimum time		3 mins
Unit charge	see notes	123.00 G.F.
Overtime		1 min
Unit charge		41.00 G.F.

b) Off-peak hours (22.01 - 04.00 UTC)

	<u>Automatic</u>	<u>Operator Assisted</u>
Minimum time		3 mins
Unit charge	see notes	84.60 G.F.
Overtime		1 min
Unit charge		28.20 G.F.

NOTES

1. Automatic telephone calls originated from a ship in the IOR and terminating in a ship in the AOR are billed according to the charges and unit charge (minimum time) applied by the two CESs (Thermopylae and Fucino) which operate a special cooperative agreement for this service.

Example:

Billing of an automatic telephone call of 35 secs duration

	<u>Busy hours</u>	<u>Off-peak hours</u>
Thermopylae charge (min.time 10 secs, overtime 10 secs)	4 x 3 GF = 12 GF	4 x 2 GF = 8 GF
Fucino charges (min.time 6 secs, overtime 6 secs)	6 x 2.08 GF = 12.48 GF	6 x 1.4 = 8.46 GF
Total cost of communication:	24.48 GF	16.4 GF

2. The same charges and methodology apply also for automatic telephone calls in the AOR (via Fucino) to IOR direction.

Table 18. SHIP-TO-SHIP TELEPHONE CHARGES (IOR TO IOR)

End-user charges for ship-to-ship calls from a ship in the IOR to a ship in the IOR.

a) Busy hours (04.01 - 22.00 UTC)

	<u>Automatic</u>	<u>Operator Assisted</u>
Minimum time	10 secs	3 mins
Unit charge	6 G.F.	108 G.F.
Overtime	10 secs	1 min
Unit charge	6 G.F.	36 G.F.

b) Off-peak hours (22.01 - 04.00 UTC)

	<u>Automatic</u>	<u>Operator Assisted</u>
Minimum time	10 secs	3 mins
Unit charge	4 G.F.	72 G.F.
Overtime	10 secs	1 min
Unit charge	4 G.F.	24 G.F.

Table 19. SHIP-TO-SHIP TELEPHONE CHARGES (IOR TO POR)

End-user charges for ship-to-ship calls from a ship in the IOR to a ship in the POR.

a) Busy hours (04.01 - 22.00 UTC)

	<u>Automatic</u>	<u>Operator Assisted</u>
Minimum time	10 secs	3 mins
Unit charge	7.17 G.F.	129.00 G.F.
Overtime	10 secs	1 min
Unit charge	7.17 G.F.	43.00 G.F.

b) Off-peak hours (22.01 - 04.00 UTC)

	<u>Automatic</u>	<u>Operator Assisted</u>
Minimum time	10 secs	3 mins
Unit charge	6.17 G.F.	111.00 G.F.
Overtime	10 secs	1 min
Unit charge	6.17 G.F.	37.00 G.F.

Table 20. SHIP-TO-SHIP TELEX CHARGES (IOR TO AOR)

From I O R to A O R

End-user charges for ship-to-ship messages from a ship in the IOR to a ship in the AOR.

	<u>Automatic</u>	<u>Operator Assisted</u>
Minimum time		3 mins
Unit charge	see notes	60 G.F.
Overtime		1 min
Unit charge		20 G.F.

N O T E S

1. Automatic telex calls originated from a ship in the IOR and terminating in a ship in the AOR are billed according to the charges and unit charges (minimum time) applied by the two CESS (Thermopylae and Fucino) which operate a special cooperative agreement for this service.

Example:

Billing of an automatic telex call of 35 secs duration

Thermopylae charges 4 x 1.5 GF = 6 GF
(min.time 10 secs, overtime 10 secs)

Fucino charges 6 x 1 GF = 6 GF
(min.time 6 secs, overtime 6 secs)

Total cost of communication: 12 GF

2. The same charges and methodology apply also for automatic telex calls in the AOR (via Fucino) to IOR direction.

Table 21. SHIP-TO-SHIP TELEX CHARGES (IOR TO IOR)

End-user charges for ship-to-ship messages from a ship in the IOR to a ship in the IOR.

	<u>Automatic</u>	<u>Operator Assisted</u>
Minimum time	10 secs	3 mins
Unit charge	3 G.F.	54 G.F.
Overtime	10 secs	1 min
Unit charge	3 G.F.	18 G.F.

Table 22. SHIP-TO-SHIP TELEX CHARGES (IOR TO POR)

End-user charges for ship-to-ship messages from a ship in the IOR to a ship in the POR.

	<u>Automatic</u>	<u>Operator Assisted</u>
Minimum time	10 secs	3 mins
Unit charge	3.77 G.F.	67.92 G.F.
Overtime	10 secs	1 min
Unit charge	3.77 G.F.	22.64 G.F.

D. TECHNICAL CONSIDERATIONS FOR INMARSAT IN THE HELLENIC ENVIRONMENT

As in any other communications system, the ultimate goal of a satellite system is to provide a satisfactory transmission quality for signals relayed between earth stations. We know from previous chapters, that a satellite link consists basically of an uplink and a downlink. Signal quality over the uplink depends on how strong the signal is when it leaves the originating earth station and how the satellite receives it. On the downlink, the signal quality depends on how strongly the satellite can retransmit the signal and how the destination earth station receives it. Because of the great distances between a geostationary satellite and the earth stations and because the power of the radiated signal diminishes as the square of the distance it travels, the uplink signal received by the satellite and the downlink signal received by the earth station are very weak and can be easily disturbed. In addition, the uplink signal may be contaminated by signals transmitted by other earth stations to adjacent satellites, and the downlink signal may be contaminated by signals coming from adjacent satellites. Furthermore, rain can severely attenuate satellite signals above 10 GHz. All these factors must be taken into consideration in link budget calculations. [Ref. 4:p. 130]

1. Uplink and Downlink calculations

The area of the earth seen by a satellite at any moment is bounded by a circle whose radius depends on satellite altitude H and earth antenna elevation angle E . Although a geostationary satellite is visible from about the 42% of the earth's surface, whether or not a station is in line-of-sight depends upon its angle of elevation relative to

the fixed satellite position. The geometry of coverage angle and slant range is shown in Figure 15 (page 31). For the Hellas case we have: [Ref. 4:p. 45]

$$\sin(a)=[R_e \cos(E)]/(R_e+H) \quad (1)$$

$$R_e = 535/2 = 495 \text{ Km} \quad (2)$$

$$R_e+H = 36279 \text{ Km} \quad (3)$$

where a =coverage angle.

H =Altitude of satellite's orbit (geostationary satellite).

R_e =Hellas area radius.

Equations (1),(2),and (3) imply

$$\sin(a)=495/36279=0.01368 \text{ and } a=0.78 \text{ degrees}$$

The slant range d , which is the distance between satellite and Hellas, is:

$$d = \sqrt{[(R_e+H)^2 + (R_e)^2 - (2 \cdot R_e \cdot (R_e+H) \cdot \cos(w))]} \quad (4).$$

$$w = 90 - E - a = 90 - 23 - 0.78 = 66.22 \text{ degrees} \quad (5).$$

$$H = 35784 \text{ Km} \quad (6).$$

where w =angular radius of the satellite footprint,

E = elevation angle which is 23 degrees for CES Thermopylae.

Equations (4),(5),and (6) imply $d = 36082 \text{ Km}$.

In a digital satellite system the performance of the satellite signal received at an earth station is measured in terms of the average probability of bit error, which is a function of the link carrier-to-noise ratio (C/N). In order to calculate the the carrier-to-noise ratio of the overall satellite link (uplink and downlink) we have to calculate first the carrier-to-noise ratio of the uplink and downlink. The following is an example of the Uplink and Downlink calculations for a CES-Satellite-Ship communication link from the

Thermopylae CES. For the downlink calculations the same elements are used as in the Uplink. [Ref. 9:p. 356]

a. Uplink calculation (Frequency 6.42 GHz)

Carrier EIRP	65 dbw
Free space loss	-200 db
Antenna tracking loss	-2.8 db
Satellite G/T	-19.6 db/K
Boltzmann's constant	228.6 dbw/K-Hz
Noise bandwidth	-46.5 db-Hz
Atmospheric attenuation	-1.0 db
(C/N) _u	23.3 db

b. Downlink calculation (Frequency 1.54 GHz)

Satellite EIRP	27 dbw
Free space loss	-188.5 db
Antenna tracking loss	- 0.9 db
Ship G/T	- 4.0 db/K
Boltzmann's constant	228.6 dbw/K-Hz
Noise bandwidth	-46.5 db-Hz
Atmospheric attenuation	-1.0 db
(C/N) _d	14.7 db ⁸

⁸ The above uplink and downlink calculations are in accordance with the formulas found in References 4 and 9. The values assumed for CES Thermopylae are approximate.

The overall link carrier-to-noise ratio is: [Ref. 9:p. 134]

$$\frac{C}{N} = \left[\left(\frac{C}{N} \right)_u^{-1} + \left(\frac{C}{N} \right)_d^{-1} \right]^{-1}$$

which for our case implies $(C/N) = 13.87$ db

VII. CHOOSING A SATELLITE COMMUNICATIONS SYSTEM

A. INTRODUCTION

Previous chapters discussed satellite communication systems technologies and provided user costs for the INMARSAT system through CES Thermopylae. This chapter provides a brief overview of communication systems economics which would help us in the process of evaluating and choosing a satellite communications system.

B. ECONOMICS OF A COMMUNICATION SYSTEM

Basic economics of the communication system are discussed below for background information.

1. Economies of Scale

Figure 31 shows how system costs, communication volume, and user charges for equipment and service are related. Because of improvements in technology, the costs of the communication system as well as the user terminal costs (A) per unit of capacity tend to drop over time. However, inflation influences the costs and tends to increase the price of a product over time. The cost of equipment tends to drop as production volume increases and time advances because cost reductions related to electronics and computer technology are generally greater than the inflation rate. This results in a reduction of the communication charges necessary to retrieve the costs of a system, and the price of user terminal equipment drops (B) making the service more attractive. This increases the traffic base (C) and the amount of price-sensitive traffic (D), creating a diversion (E) from other alternatives. The lower prices (B) also stimulate the growth of traffic (G) and new types of

traffic (F). Thus, the total communications traffic carried by the systems increases (H). All these factors above create economies of scale (I). The above process feeds back to generate more orders for system and user equipment and further reduces communication charges (A and B). [Ref. 9:pp 83-84]

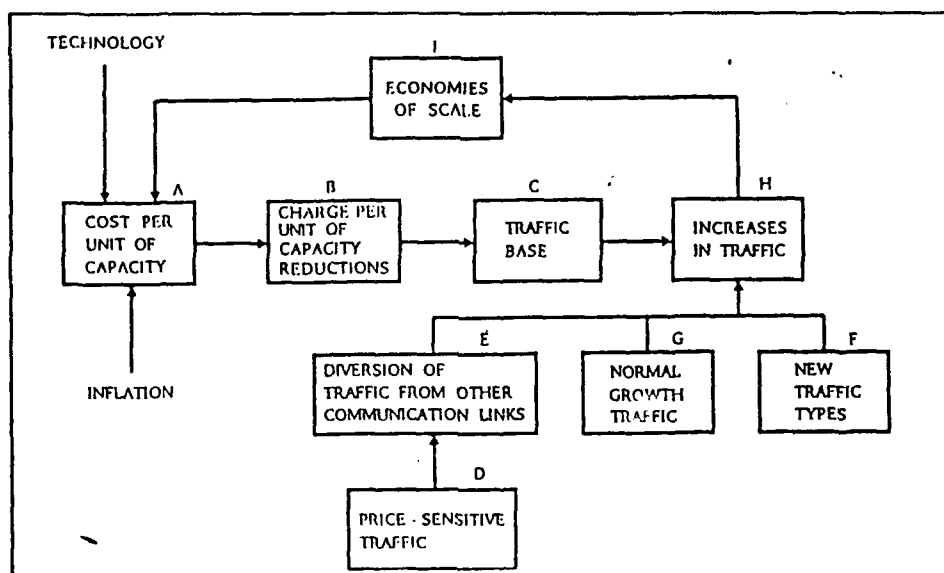


Figure 31. Economies-of-scale diagram

2. Market Demand and Supply

A basic understanding of demand and supply helps to explain and predict the behavior of the market in response to changing conditions. A definition of a market is a group of firms and individuals in contact each other in order to buy or sell some good or service [Ref.27 p:20]. The market demand for a service or good during any period of time will usually rise as its price is dropped. Conversely, the quantity supplied to the market during a period of time will usually rise as the price is increased. In Figure 32 we can see the relationship between quantity and price.

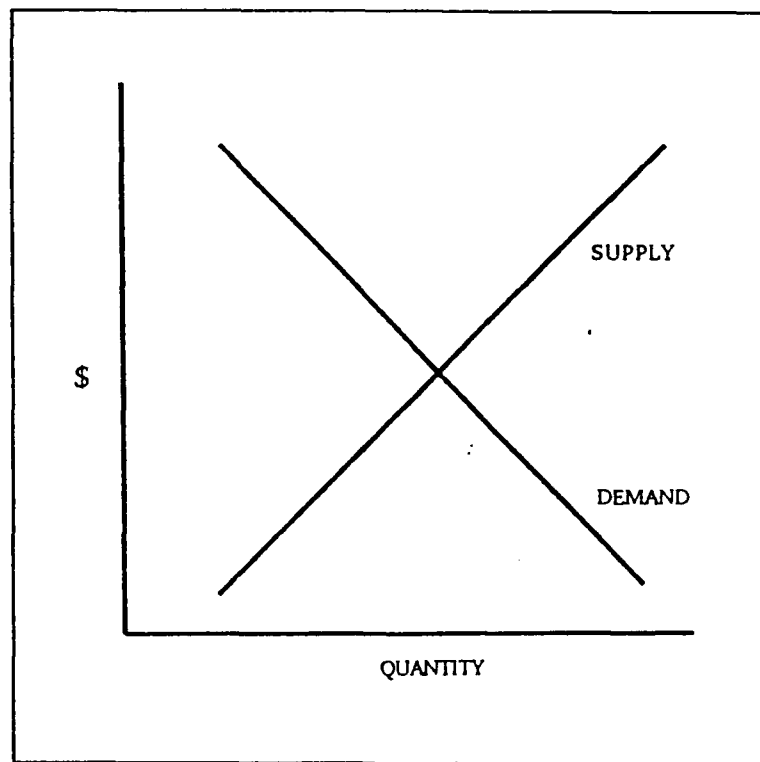


Figure 32. Demand and Supply

The sale of goods and services takes place when the sellers and buyers in the marketplace agree on a price. The total quantity bought and sold in the market will be equal to the amount the buyers are willing to purchase and the sellers are willing to furnish. This is indicated where the demand and supply lines cross.

Actually, market demand and supply curves are usually not linear. Their position and shape are determined by many factors other than price. In Figure 33 we can see an example where an increase in the awareness of a mobile communication system benefits shifts the demand curve to the right. Thus, purchasers require a greater quantity of mobile communication services and both price and quantity increase. [Ref. 28:p 241]

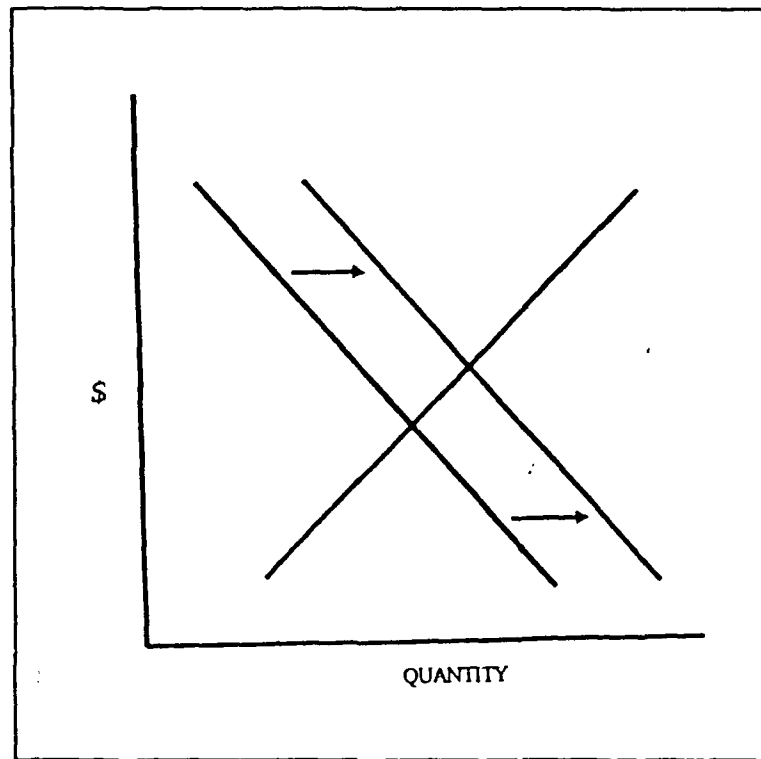


Figure 33. Change in the Quantity Demanded

Supply curves are affected by the level of technology, production economies of scale and the basic costs of raw materials and components. In Figure 34 we can see the change in quantity supplied as the result of a change in communication technology. The supply curve has moved downward because it is now possible to provide communications services at a lower cost and thus, the market price drops and the quantity demanded increases.

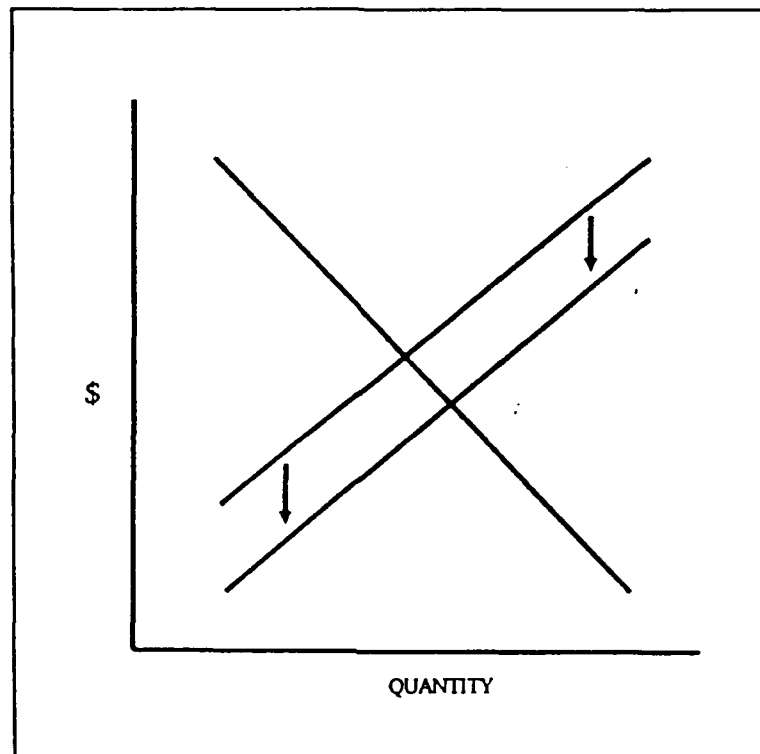


Figure 34. Change in the Quantity Supplied

C. EVALUATING TELECOMMUNICATION SYSTEMS

The evaluation of a telecommunication system, where a number of alternatives exist that provide services of equal value, may be accomplished by comparing them directly against each other. Under such a condition, the objective is to select the alternative that provides the desired service (*technical performance*) at the least cost (*economic performance*).

As soon as alternatives are identified, evaluation criteria have to be established, analytical methods have to be identified, input data have to be collected, and finally the various alternatives have to be evaluated on an equivalent basis. The selection of the best system among several alternatives from different vendors involves the review of all systems' significant performance parameters from the standpoint of maximum or minimum requirement (degree of importance) and a number of evaluation criteria.

The evaluation criteria are dependent on the stated problem and the complexity of analysis. The most important criteria, related to the selection of a telecommunication system among several alternatives, is *cost-effectiveness*, which is based on the technical *effectiveness* and the *life-cycle cost* of the system.

D. BASIC CONCEPTS OF COST-EFFECTIVENESS ANALYSIS

1. Background

Cost-effectiveness is a measure of a system in terms of the system's effectiveness relative to its total life-cycle cost. There are so many factors influencing the effectiveness and costs of a system that it is impossible to measure true cost-effectiveness. For this reason, specific cost-effectiveness Figures of Merit (FOM) are employed. These figures allow the comparison of alternative systems based on the relative merits of each one. The FOM examines specific parameters of a system such as: performance effectiveness, benefits, availability, supply effectiveness, etc., and compares them to a standard base: the life-cycle cost.

System effectiveness is the ability of a system to perform its intended functions. System effectiveness involves a number of parameters, such as performance, operational availability, maintainability, size, weight, etc., that can be used to express system effectiveness in figures of merit.

2. Cost Structure

The cost structure is used as a basis for assessing the life-cycle cost of each alternative being considered. The cost structure (or cost breakdown structure) links

objectives and activities with resources, and constitutes a logical subdivision of cost by functional activity area, major element of system, and/or one or more discrete classes of common or like items. The cost structure, which is usually adapted or tailored to meet the needs of each individual program, should exhibit the following characteristics:

[Ref. 29:p. 14]

- All life-cycle costs should be considered and identified in the cost structure. This includes Research and Development (R&D) cost, Production cost, and Operation and Support (O&S) cost.
- Cost categories are generally identified with a significant level of activity or with a major item of material. Cost categories in the cost structure must be well defined, so everybody involved must have the same understanding of what is included in each category and what is not included.
- Cost must be broken down to the level necessary to enable management to identify high-cost areas and cause-and-effect relationships.
- The cost structure and the categories defined should be coded in a manner to facilitate the analysis of specific areas of interest while virtually ignoring other areas.

3. Life-cycle cost

Life-cycle costing is a systematic, analytical process of determining and listing the total cost of developing, producing, owning, operating, supporting and disposing of equipments or complete systems. The Life Cycle Cost (LCC) is one of the most significant factors for the evaluation of alternative systems, providing decision makers with significant economic information to determine the most cost-effective configuration of a system within budget limitations.

The life-cycle cost includes the following four aggregate areas: [Ref. 30:p. 93]

- Research and Development costs.
- Production and Investment costs.
- Operation and Support costs.
- Salvage costs.

a. Research and Development cost (R&D)

This includes expenditures associated with the initial period of a project such as costs for engineering design, market analysis, initial planning, software, and design documentation.

b. Investment cost

This includes expenditures involved in the purchase phase of a system and is concerned with recurring and non recurring costs, such as process development, facility construction, etc.

c. Operation and Support cost (O&S)

This includes expenditures occurring during the operational period of the system, such as system service, maintainance activities, test and support equipment, system modifications, etc.

d. Salvage cost

This includes expenditures for system retirement, material recycling, non repairable items and spare parts, etc. Usually, it makes a positive cash flow at the end of a LCC analysis reflecting the system's salvage value.

The above four aggregate cost areas can be further broken down into distinct cost elements (CE) such as: [Ref. 30:p. 94]

- Hardware Acquisition.
- Maintenance Sets.
- Replacement Spares.
- Support Equipment.
- Training.
- Technical orders.
- Full Scale Development.
- System Integration.
- System Installation.
- Software Maintenance.

The life-cycle cost structure is illustrated in Figure 35.

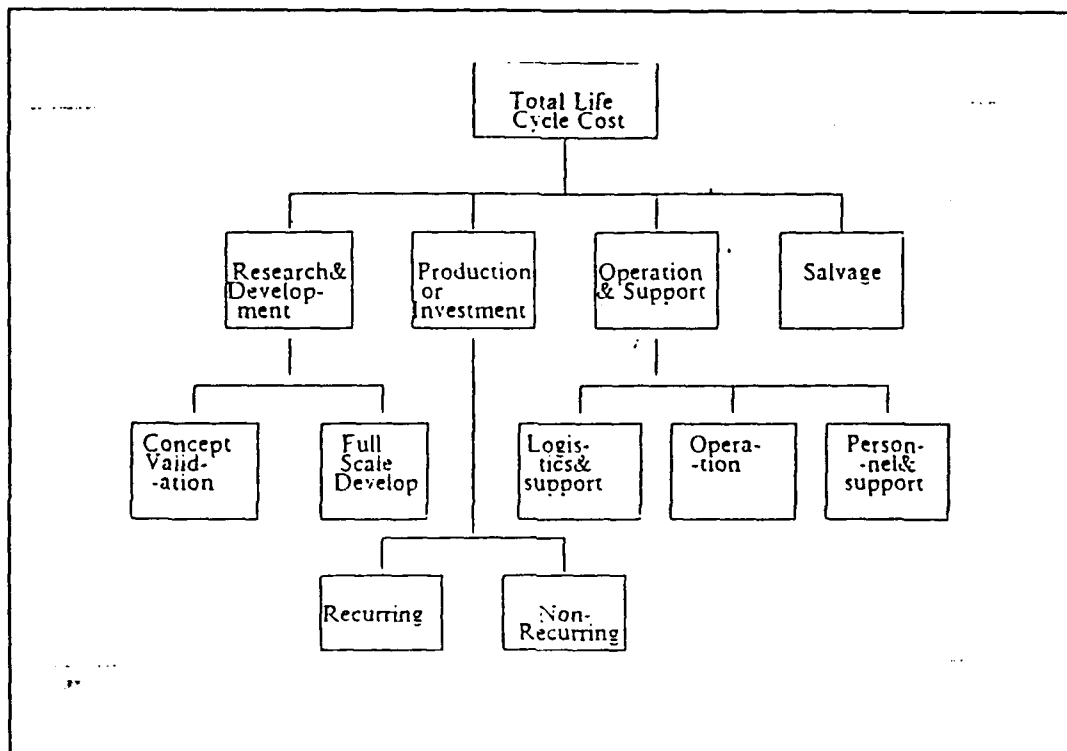


Figure 35. Life-Cycle Cost Structure

E. COST-EFFECTIVENESS ANALYSIS

The basic idea of cost-effectiveness (CE) analysis is to assist the decision maker in identifying a preferred choice among possible alternatives. CE requires that only programs with similar or identical goals be compared and that a common measure of effectiveness be used to assess them. Under cost-effectiveness analysis, the costs and effectiveness of each alternative are determined and compared so that an objective selection can be made based on maximum effectiveness per level cost or least cost per level of effectiveness.

The cost effectiveness evaluation consists of the following steps: [Ref. 30:p. 95]

- Define the desired goals, objectives, missions, or purpose that the system is to meet or fulfill.

- Identify mission requirements essential for the attainment of the desired goals.
- Develop alternative system concepts for accomplishing the mission.
- Establish system evaluation criteria that relate system capabilities of the alternative approaches.
- Select a fixed cost or fixed effectiveness approach.
- Determine capabilities of the alternative approaches.
- Generate a systems versus criteria array.
- Analyze merits of alternative systems.
- Perform sensitivity tests.
- Choose the most attractive alternative based on the concept of minimum cost per unit effectiveness among different alternatives.

Cost-Effectiveness analysis is advantageous because it requires the combining of available cost and effectiveness data to create a CE comparison. It also lends itself to an evaluation of alternatives that are being considered for accomplishing a particular goal.

1. Satellite Cost Model

a. Assumptions

To develop the cost model for a communication satellite system the following general assumptions should be made to avoid complexity of modeling and to make a comparison possible between alternatives:

- R&D and Salvage costs will be assumed zero. Those costs incurred during the development phase are considered sunk costs and not included in the analysis.
- Time period will be considered from the present to 2000.
- This analysis will concentrate only on investment cost.

b. Cost Structure

To develop the cost model using the concept of LCC, the satellite cost break down structure is illustrated on Figure 36. Since R&D and Salvage costs are zero, no break down of costs is included.

c. Cost Elements

The total system life-cycle cost structure is subdivided into lower level cost elements and illustrated in Table 23 [Ref. 29:p. 29]. The eight steps for the cost-effectiveness analysis mentioned above was the main source for cost elements.

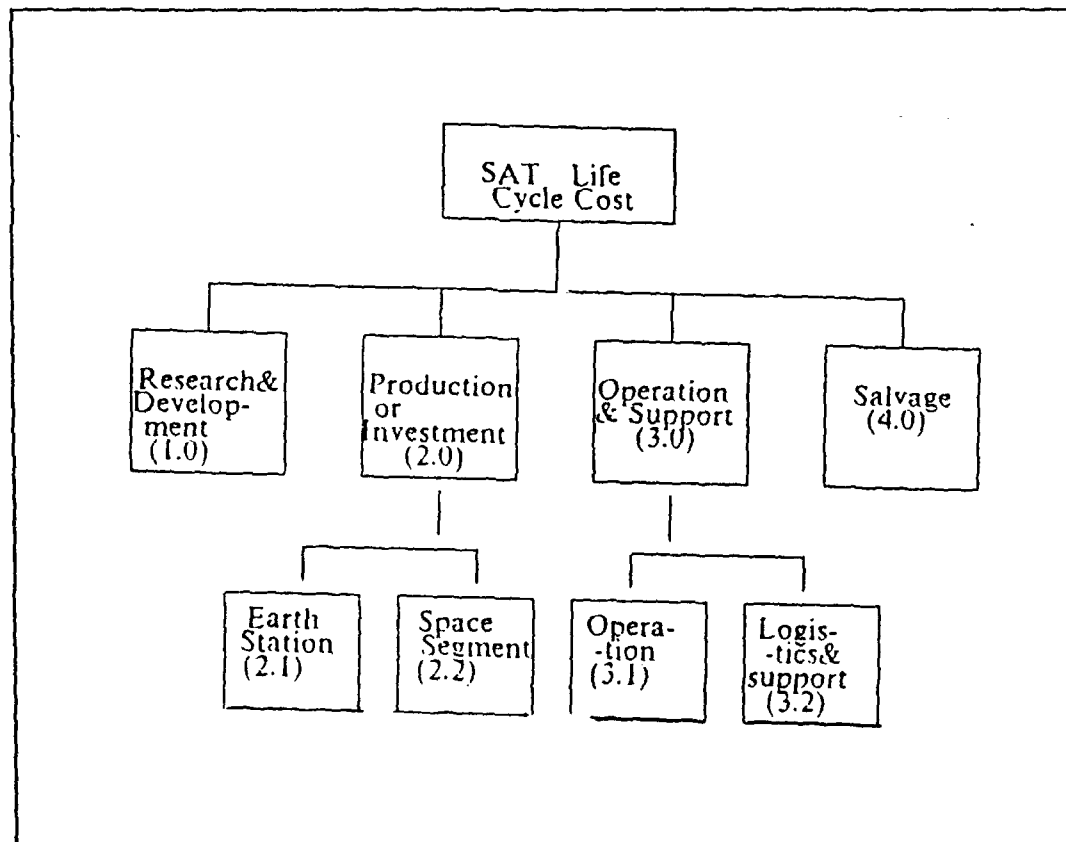


Figure 36. Satellite Cost Structure

Table 23. SATELLITE COST ELEMENTS

-
- 1.0 Research and Development
 - 2.0 Investment
 - 2.1 Earth station equipment
 - 2.1.1 Antenna
 - 2.1.2 LNA
 - 2.1.3 HPA
 - 2.1.4 Converter
 - 2.1.5 Installation
 - 2.2 Space segment
 - 2.2.1 Structure
 - 2.2.2 Thermal control
 - 2.2.3 Propulsion
 - 2.2.4 Electrical power supply
 - 2.2.5 Launch vehicle & orbit operations support
 - 2.2.6 Ground equipment
 - 2.2.7 Communications(mission)
 - 2.2.8 Attitude control
 - 2.2.9 Program mgmt
 - 2.2.10 T1&C
 - 3.0 Operation and Support
 - 3.1 Operation
 - 3.1.1 Operational personnels
 - 3.2 Logistics and support
 - 3.2.1 Maintenance facilities and personnel
 - 3.2.2 Supply support
 - 3.2.3 Test and support equipment
 - 3.2.4 Spare parts
 - 4.0 Salvage
-

(1) Investment Cost

Investment cost for major systems represents approximately 45-47% of the life-cycle cost (LCC) after 10 years of operations. According to Figure 36 the satellite investment cost consists of two parts, earth station and space segment. The earth station cost elements are as follows: [Ref. 29:p. 28]

- Antenna (1a): The cost depends on the antenna diameter. The large antenna includes cost of tracking and frequency reuse.

- Low noise amplifier (LNA): C-band LNA costs are divided into nonredundant and redundant units.
- High power amplifier (HPA): The costs of C-band traveling wave tube (TWT) power amplifier varies the output power between 5W-3KW.
- Converter: Consists of up and down converter.
- Installation: Installation costs are usually considered as 40% of total earth station equipment costs.

The initial investment for the space segment consists of the following elements [Ref. 29:p. 30]:

- Structure: It provides the support and mounting surfaces for all equipment and carries the majority of spacecraft dynamic stress loads.
- Thermal control: It maintains the temperature of the spacecraft platform and mission equipment within allowable limits in certain orbital conditions.
- Propulsion: It provides reaction force for a final maneuver into orbit and orbit changes.
- The electrical power supply: It generates, converts, regulates, stores, and distributes all electrical energy to and between spacecraft components.
- Launch vehicle and orbital operations support: It includes any effort associated with planning for and execution of the launch and orbital operations effort.
- Ground equipment: It includes ground support equipment, in-plant equipment, special tools and test equipment, and any nonhardware efforts associated with ground equipment.
- Communications: This subsystem performs a transmission repeater and signal conditioning function. Its costs include receiving antennas, receiving traveling wave tube amplifiers, transmitters and transmitting antennas etc.,
- Attitude control: It maintains the spacecraft in the required orbit.
- Program level: It includes program management, reliability, planning, quality assurance, system analysis and other costs.

- Telemetry, tracking and command: It includes analog/digital converters, coders, digital electronics/computers, decoders, tape recorders etc.,

(2) Operation and Support cost

Operating costs include those costs for personnel pay and allowances, equipment maintenance, logistics support and consumables. [Ref.29 p.31]

- Operations: This category includes cost associated with the use of the equipment. The cost incurred as a result of direct operation of the equipment and items actually consumed in operation of the equipment are included in this category.
- Operating personnel: It covers the total cost of operating the system for the various applications.
- Maintenance facilities and personnel: The cost is based on the occupancy, utilities, and facility maintenance costs as prorated to the system.
- Supply support: It includes the cost of personnel, material, facilities and other direct and indirect costs required to maintain and support the equipment and for system during the operational phase of its life-cycle.

The next and final step, which is not the underlying purpose of this chapter, is to develop the satellite cost model based on the previously discussed cost structure and cost elements. So someone else, who wants to be involved with satellite communications systems cost evaluation and effectiveness, can use these basic concepts and the data collected, and proceed to further analysis.

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

In this study, the attempt was made to show how telecommunications grew in the last 30 years from its original state into a progressive and more self-reliant telecommunication utility, including the satellites. This study is also intended to be a basic study of satellite communications systems with emphasis on INMARSAT system.

A historical background and the technology of satellite communications have been traced, through the basic concepts of military and international satellite communications, leading up to the conceptualization of the INMARSAT system.

A brief background of satellite vulnerability and some basic concepts of the cost evaluation and cost effectiveness analysis have been described in order to help someone in the process of facing a jamming threat or choosing a satellite system, respectively.

We can summarize our most important conclusions as follows:

- Many new technologies in telecommunications have emerged during the late 1980s and early 1990s. The five most popular are satellites, digital microwave radio, fiber and coaxial cables, local distribution radio, and wire pairs. Some of the advantages of satellite communications are wideband capability, distance-insensitive costs, and suitability for mobile applications.
- INMARSAT is an internationally-owned cooperative which provides mobile communications worldwide. Some of its services are direct dial telephone, telex, facsimile, and electronic mail for maritime applications, flight deck voice and data, automatic position and status reporting, and direct-dial passenger telephone for aircraft applications, position reporting, and two way data communications for land applications.

- Satellite communication links using digital PN spread spectrum and FDMA techniques are vulnerable to jamming and denying signals. Two types of interfering signals were discussed, noise jammers and repeaters; each requires a specific geometry to be used effectively. In the jamming of FDMA by noise jammers it is necessary to overcome the signal power to increase the Bit Error Rate (BER). In this case there is a potential advantage of selective jamming, as the jammed user may feel he is having system problems.
- For spread spectrum jamming, the disadvantage in overcoming the processing gain by brute force techniques is apparent.
- From the earliest years of satellite communications (moon and other passive satellite relays) the effort was concentrated to improve the efficiency, reliability, and capacity of the command and control channels. With each generation of satellites the communication capabilities have been increased, resulting in the development of military satellite systems for secure data transmission.

B. RECOMMENDATIONS

Based on the overall analysis attempted in this study, the following are recommended as areas for further research:

- Cost-effectiveness methodology for evaluating and choosing a satellite communication system for the Hellenic Navy.
- Lease versus buy decision making for a satellite communications system based on INMARSAT.

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