SYSTEM DEVELOPMENT OF A 21ST CENTURY COMMUNICATIONS SYSTEM FOR MOBILE USERS

by

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Abstract

Communications in the 21st century is expected to include a large demand for broadband multimedia services. This demand will be driven by the continued and increasing proliferation of broadband services to fixed users, the growing need for information exchange, and market forces and competition on a global scale. A future need is projected to extend these broadband multimedia services to users aboard mobile platforms. The objective of this report is to utilize the systems engineering process to define requirements for this future system and propose a conceptual design. Communications deficiencies are projected based upon an analysis of communications service needs, projection of the fixed communications architecture of the future, and an assessment of currently planned communications systems. Future mobile communications needs are defined and developed into system operational requirements. Preliminary systems analysis and tradeoffs are performed to propose potential system solutions. Several system planning and management considerations are also addressed towards the realization of this future system. This report proposes that the future need identified would best be satisfied by a Low Earth Orbiting (LEO) satellite communications system utilizing digital B-ISDN technology, high data rate satellite crosslinks, and distributed management through intelligent network concepts. A Life Cycle Cost (LCC) model is also developed to evaluate complete life cycle costs of the LEO SATCOM system at various orbital heights and satellite and launch parameters.

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Introduction

Advances in communications and computing are continuing to shape the global information age of the 1990's and the future communications environment of the 21st century. Demand for enhanced communications services and multi-disciplinary improvements in communications capabilities will realize a proliferation of broadband communications capability to commercial and home users while providing global low data rate access to mobile users and Personal Communications Systems (PCSs). A future need is projected to extend the availability of digital multimedia communication services to mobile (aeronautical, maritime, and land mobile) and remote fixed users at data rates $\geq$ 1.55 Mbps.

This report identifies future needs, develops system requirements, and proposes a conceptual design for a 21st century communications system to fulfill the broadband communications needs of mobile and remote fixed users. Operational needs and market demands for this future system are projected and resulting system requirements defined. Preliminary system analyses and design are presented at a level which highlights major system design tradeoffs and considerations and recommends potential solutions. Several system planning and management considerations are also addressed and areas for future investigation towards a complete development effort are provided. This proposed system will be designed through a systems approach considering all aspects of the system life cycle.

Methodology

To adequately assess needs for a future generation communications system and translate these needs into system requirements, an iterative process of user demand and communications capability assessment will be performed. A projection and analysis of future service demands and capabilities is required because of the cyclical nature of high technology driving forces (discussed in the next section).

The process utilized for the development of this report is a direct application of the system engineering process [1] tailored to this problem and is depicted in Figure 1. The problem, or future communications deficiency, is first identified and defined through an projection of future communications needs, an assessment of existing or planned communications systems to fulfill these needs in the future, and the identification of future deficiencies. After the problem or deficiency is identified and generally described, a needs analysis is performed as part of the conceptual design phase to fully detail the deficiency and assess the demand for fulfilling this deficiency. Feasibility studies are then performed prior to fully defining operational requirements to identify feasible approaches and potential technology solutions in fulfilling user needs. From the definition of the system need, operational requirements are then defined and system maintenance concept developed. Preliminary systems analysis includes the identification of system alternatives, definition of relevant evaluation criteria, development and discussion of system models, and a qualitative evaluation of alternatives leading to a conceptual design. Preliminary design includes functional analysis and requirements allocation at level which demonstrates the application of the system engineering process to this problem and defines a high-level preliminary design. Several design tradeoffs are analyzed and discussed for some of the major design decisions. Finally, planning issues are addressed and areas for further investigation towards a complete system design are detailed.

The intent of this report is to demonstrate the application of the systems engineering process to a future large-scale communications system. The scope of the system design contained herein is limited to several major tradeoffs, analyses, and considerations required through conceptual and preliminary designs. Analyses considered out of scope for this project are identified throughout this report as areas requiring further consideration during actual system design.

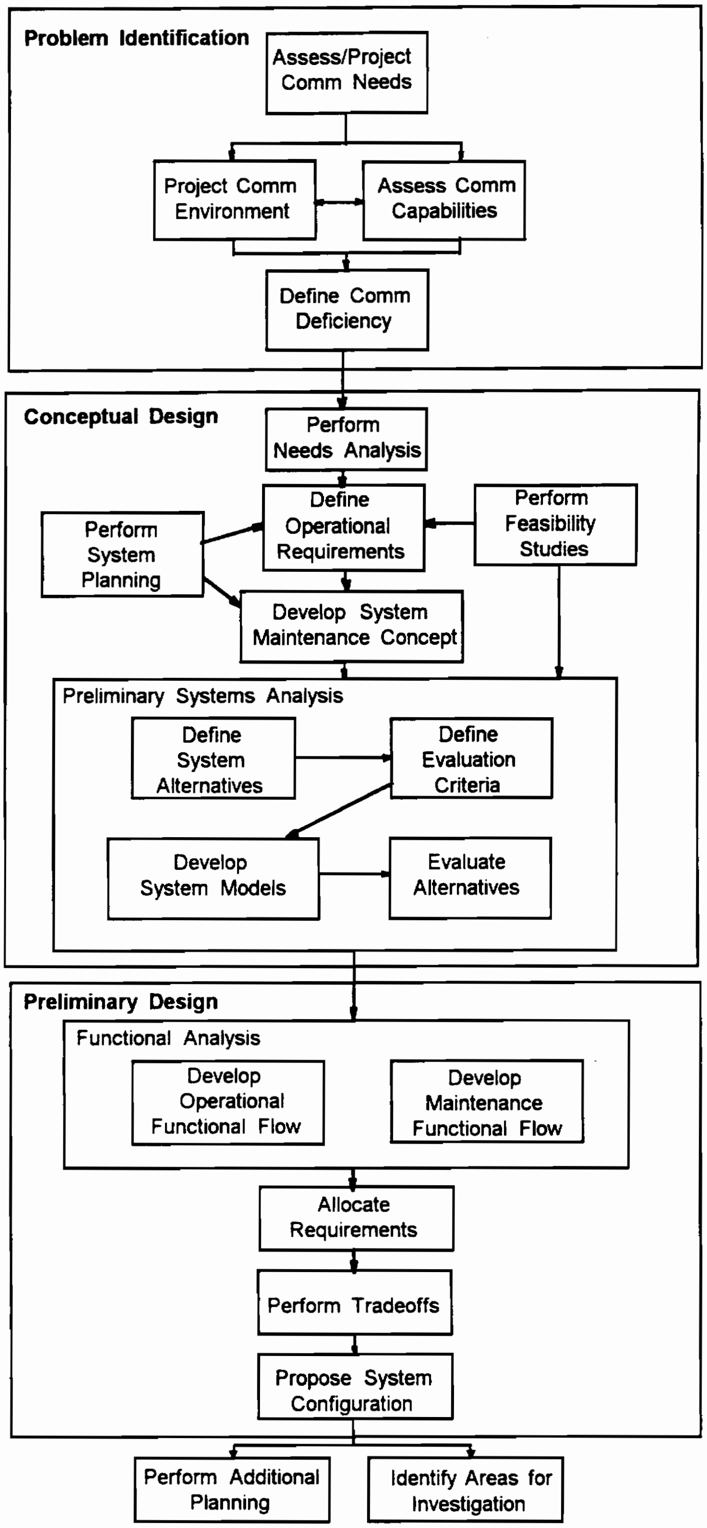


Figure 1 - System Development Methodology

Problem Identification

Communications services have undergone significant changes in the past decade. Advancements made in all areas of communications, computing, and electronics are leading towards a society of global access to distributed multimedia services. These advancements are being driven by, as well as driving, the growing need for communications. In order to assess potential future communications deficiencies, we must project future communications needs and evaluate the projected communications environment in fulfilling these needs.

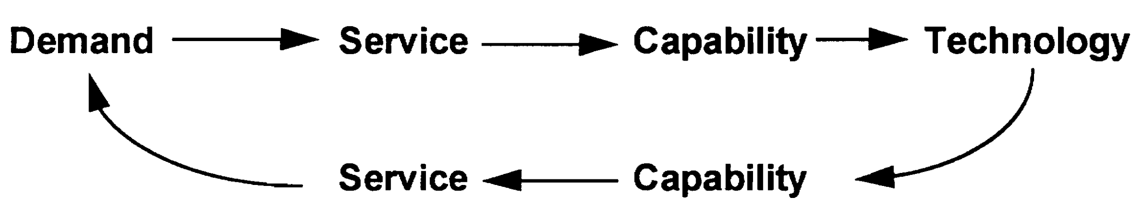
Communications Needs

Communications has become a critical element of our society, affecting all sectors of our culture and daily lives. Businesses worldwide, as well as the entire global economy, rely on the dependable and timely exchange of information every day. Global competition has placed demands on businesses and organizations to provide higher quality products and services more efficiently than ever. This demand for increased productivity has spurred the need for increased communications services and capabilities. Also, as modern countries become more sophisticated and knowledgeable, there is increasing demand to provide this information to developing and third world countries in order to improve the quality of life worldwide. The ability to access, exchange, and provide more and higher quality information (data or audio-visual) has led to improvements in all sectors of society and has provided a means of bringing the world's cultures closer together. In summary, continued improvements in the accuracy, capacity, speed, coverage, and mobility of communications are needed to:

- Improve global access to/dissemination of news
- Improve business efficiency through global data exchange and collaboration
- Improve global communications capability between two or more parties at any location (fixed or mobile)

- Improve all sectors of life in third world/developing countries through enhancement of infrastructure
- Improve system/product realization (development time, costs, quality) through concurrent engineering
- Improve crisis management/response
- Improve education and training

Communications Drivers - The need for communications and computing has driven the continued advancement in integrated circuits, electronics, and other related technology. At the same time, as new basic technology becomes available which allows for increased or enhanced communications, the industry has utilized this technology to enhance existing services or to provide new services. Although part of this process may appear technology driven, there is in fact a cyclical nature of driving forces which can be depicted as follows:



The demand for communications services may drive the need for a required capability and subsequent technology. Conversely, cutting-edge technology may also provide the capability for a new service that will in turn spur demand for that service. In general, high technology has spawned into an age where the general market may not know what they want or need (i.e. demand) until they know what is possible. This condition requires an iterative projection of communications capabilities in the future, what demands these capabilities will be driven by, as well as what demands they may stimulate. Based on this cycle, it is assumed that global market and development forces will consistently demand more and better technology which will eventually stretch communications capabilities to their physical limits.

Broadband Services - Communications services in demand in the future are projected to be largely broadband and multimedia in nature. Multimedia is now a widely known "buzz" word which refers to any device or service which utilizes or provides more than one media simultaneously. Media in this context refers to a form of communication (e.g. text, graphics, audio, video, etc.) versus reference to a communications path (e.g. RF, cable, etc.). The largest multimedia demand is currently in the Personal Computer (PC) market. The typical (mid to high-end) multimedia PC (MMPC) currently consists of a 50 MHz 486 based PC using object-oriented applications (hypermedia) and providing VCR quality still images and video. Typical multimedia networking applications currently in use operate over 10-16 Mbps LANs [2].

There is now a large momentum in the multimedia arena as demonstrated by the formation of the First Cities Consortium [3]. This consortium consists of dozens of US-based technology companies established to create common interfaces, synchronize hardware and software development, and develop interactive multimedia network services aimed at creating market demand. The International Telecommunications Union (ITU) has actively been involved in developing engineering standards in the multimedia area such as the ITU-TS Framework recommendation I.374, "Network capabilities to support multimedia services". Making the move to multimedia networking easier is the fact that over 86% of all homes are expected to have access to coaxial cable by 1995 [4]. Recently proposed alliances between Telephone companies (TELCOs) and CATV companies such as US West/Time Warner, Bell Atlantic/TCI, and BCE/Jones, reflect the foreseen market in the multimedia area.

Based upon the current demand for multimedia discussed above, services required within the future communications structure will be dominated largely by broadband multimedia services. Table 1 lists future broadband service requirements based upon current market direction and projections [2,4,5]. It can be seen that broadband communication needs will span all sectors of society and include both fixed and mobile users. Applications can be seen within the general areas of commercial transportation (including remote business

Table 1 - Future Broadband Service Requirements

SERVICE INDUSTRY	AREA	BROADBAND SERVICES	FIXED USER REQ	MOBILE USER REQ
Civilian Transportation	Traffic Mgmt/Safety	Routing/Control; weather; location; IVHS/ATC	X	X
	Passenger Comms	See Personal/Business/Consumer	X	X
	Passenger Entertainment	See Entertainment	X	X
Transport (Shipping)	Control/Dispatch	Routing instructions/directions	X	X
	Inventory Mgmt	Database Exchange; fascmile	X	X
Government	Law Enforcement	ID Systems; Data searches	X	X
	Defense	Imagery/intel transfer	X	X
	Crisis Management	Fire & Rescue; EBS; Diaster relief support	X	X
Business	Group Collaboration	VideoTeleconferencing; Group Decisioning	X	X
	Documentation	Collaborative Processing	X	X
	Communications	MM E:mail file transfer; videophone	X	X
	Journalism	Reporting/editing	X	X
	Engineering	Concurrent Engineering	X	
Consumer Services	Information Services	Info on Demand: Traffic, Weather, Market, etc.	X	X
	Shopping Services	Electronic Shopping	X	X
Entertainment	Televsion	CATV, HDTV; IATV	X	X
	Movies	Video On Demand	X	X
	Games	Interactive Games on Demand	X	X
Education	Training	Interactive OJT; remote troubleshooting support	X	X
	School	Remote Interactive College (Distance Learning)	X	
Health/Medical	Diagnostics	File/Test Result transfer	X	
	Emergency Services	Vital Statistics/diagnosis exchange	X	X
Private/Personal	Communications	Video Telephony, Telecommuting	X	X

applications), transport (shipping), government (law enforcement, DoD, etc.), health services (e.g., medical emergency), remote education, and personal use.

Multimedia Capacity Requirements - Compression techniques in the areas of voice/audio compression, video compression, and data compression continue to lower the bit rates and processing times required to provide viable multimedia services. Very Large Scale Integration (VLSI) advances have increased the capacity and speed of digital signal processing ten-fold in the last five years from 25 Million Instructions Per second (MIPs) to 250 MIPs [6]. These advances have realized compression techniques which can handle the real-time audio, video, and data compression required for multimedia applications. Table 2 lists current multimedia data rate requirements and compression techniques in use or planned for future use [2,6,7,8]. This data will be used to project multimedia service data rate requirements below.

Broadband Multimedia Requirements - Based on Table 1, multimedia services will be comprised of a particular combination of one or more voice, data, and video channels, where channel refers to an individual media versus a dedicated "circuit-switched" path. Integrating the service requirements of Table 1 with the data rate requirements of Table 2, we can estimate the range of capacity requirements for typical multimedia services by assuming the service consists of:

	Data Rate Range
• One or more video channels (assumes at least MPEG1)	550 kbps - 20 Mbps
• One or more voice/audio channels	2.4 kbps - 512 kbps
• One or more data channels	2.4 kbps - 1.544 Mbps (or higher)

Some of the services listed in Table 1 are asymmetric in nature while others are essentially symmetric "full-duplex" networks. Based upon this data and considering compatibility with existing and planned communications architectures, the extremes for future individual broadband services are projected as:

Table 2 - Multimedia Data Rate Requirements and Compression Techniques

MEDIA	QUALITY	ANALOG BW	UNCOMP. DATA RATE	COMP. STANDARD/ TECNIQUE	COMP. QUALITY	COMP. RATIO	COMP. DATA RATE
Voice	Toll	4 kHz	64 kbps	LPC	Low	4-25:1	2.4 - 16 kbps
				ADPCM	Low/Med	5-10:1	6 - 13 kbps
					G.721	2-4:1	32 kbps
	High	7 KHz	112 kbps		High	2.5 - 1	48 kbps
				Hybrid LPC	Low/Med	25:1	2.4 kbps
					High	6:1	9.6 kbps
Audio	Mono	4 kHz	32 kbps	4 bit ADPCM	G.721	8:1	4 kbps
				8 bit Linear	MPC	4:1	45 kbps
	HiFi	10 kHz	176 kbps	MPEG1	HiFi-CD	5-10:1	64 kbps
				16 bit Linear	CD-DA	4:1	175 kbps
	CD	20 kHz	705 kbps	Dolby AC-1	Recording	3:1	512 kbps
Picture/ Graphics	Various	N/A	N/A	JPEG (DCT)	Low-Good	10-50:1	N/A
				JPEG (DPCM)	Lossless	2:1	N/A
Video	VCR (SIF)	N/A	60 Mbps	DVI (INTEL)	VCR	50:1	1.2 Mbps
				H.261	low-VCR	30-100:1	64 kbps - 2 Mbps
				MPEG1	Low		550 kbps
	NTSC	6 MHz	248 Mbps		VCR	40:1	1.5 Mbps
				MPEG2	NCTS/PAL	40-60:1	4-6 Mbps
	HDTV (digital)	N/A	1 Gbps		CCIR 601	40-60:1	7-10 Mbps
					HDTV	50-65:1	15-20 Mbps
				Wavelets	HDTV	?	?
Data	At Req'd BER	As Req'd	> Nyquist Data Rate	MNP Class 7	Error Free	2:1	As Req'd
				V42bis	Error Free	2:1	As Req'd

MPEG1 video (low)	550.0 kbps
Low quality voice	9.6 kbps
Low quality audio	+ 4.0 kbps
	563.6 kbps
Full Duplex	x 2
	1127.2 kbps
Graphics/Data	+ ? (as req'd)

Low-end broadband service - 1.55 Mbps (DS-1 equivalent)

HDTV Video	20 Mbps
High ADPCM Voice	48 kbps
Dolby Audio	+ 512 kbps
	20.56 Mbps
Full Duplex	x 2
	41.12 Mbps
Data/Graphics	+ ? (as req'd)

High-end broadband service - 45-52 Mbps (DS3/STS-1 equivalent)

The DS-1 rate of 1.55 Mbps should be a practical estimate of a common broadband rate for minimum multimedia services in the future. The STS-1 rate of 52 Mbps would consist of a two-way multimedia service with HDTV quality video in both directions and supporting data and voice channels. This future service is considered unrealistic within the next 15-20 years because of broadband infrastructure implementation, marketability, and bandwidth conservation.

If we assume that any future HDTV quality service is asymmetric and that symmetric services will utilize NTSC or lower quality compression schemes, we can further project effective data rates for three different classes of future broadband services as the following (dependent upon video quality):

- 1.55 Mbps - Low quality two-way MM service
- 6 Mbps - VCR quality two-way MM service
- 18 Mbps - NTSC/CCIR 601 quality two-way MM service
  or
  HDTV quality broadcast service

These broadband service needs are primarily for two-way MM services and video broadcast services. A demand is also expected for STS-1 rates and STS-3 rates (52 and 155 Mbps, respectively) for rapid distribution and exchange of bulk computer data.

Besides supporting the data rate requirements for broadband multimedia services, the communications structure must also meet several other specific criteria for support of multimedia services. The complete list of future needs for support of broadband multimedia services based on current documentation [2] and subjective projections is listed below:

Characteristic	Requirement
• Serviced Data Rates supported	1.55 - 18 Mbps minimum
• System Interactiveness (max time delay)	< 100 ms
• Media Synchronization (time delay variance)	< 10 ms
• Coverage (distance/mobility)	Global; all users
• Complete system compatibility/interoperability	B-ISDN Standard (w/ATM)
• Affordability for equipment and usage	Comparable to current telephone/cable/mobile systems

Communications Environment

Current systems and services which have been newly developed or nearing implementation are discussed below to provide a basis for characterizing and projecting the communications environment of the future to assess the fulfillment of the projected communications needs discussed above.

Spurred by growing demands and advancements in digital signal processing, microwave component and Integrated Circuit (IC) design and fabrication techniques, and intelligent network architecture and algorithm development, communications service capability has flourished over the last two decades. This growth is foreseen to continue over the next two decades with market forces and implementation issues as the largest determining factors.

As discussed previously, future communications will be dominated largely by multimedia services. Multimedia PCs in the late 1990's and early 2000's can be expected to be at least 100 MHz power Reduced Instruction Set Computer (RISC) PCs with > 64 bit architectures [2]. These devices are projected to some day be capable of full motion video (up to HDTV quality) and have network communications capability using wavelet compression and Asynchronous Transfer Mode (ATM) protocols (to be discussed later). These devices, as well as other MM devices, are expected to be located at fixed sites as well as aboard mobile platforms.

Fixed Communications - The future fixed communications architecture can be characterized and projected by assessing service capabilities and demands spurred by advancements in the areas of wire and cable technology, data communications/switching, and satellite communications.

Wire & Cable Technology. Digital transmission techniques such as Asymmetric Digital Subscriber Logic (ADSL) and High Bit Rate DSL (HDSL) now make it possible for small businesses, and in some cases the normal homeowner, to participate in communication services at 1.544 Mbps over normal 2-wire telephone lines [9]. ADSL provides 1.544 Mbps to the user and low speed data/control in the reverse direction (hence asymmetric) but can be used in conjunction with a digital loop carrier to deliver 2-4 Mbps up to 12,000 ft. HDSL provides 1.544 Mbps in both directions over normal analog loops and eliminates the requirement for the typical T1 repeater every mile. The main use of this technology is currently for broadcast or on-line downloading of video and movies, but other applications can be seen. Similar advances in coaxial cable transmission technology have allowed cable subscribers access to other wider band services such as interactive services (home-shopping, home polling, etc.), as well as integrated voice and video services.

Fiber Optic technology has also soared over the past decade and now stands strong as the hard wired media of the future. Recent advances in long-haul fiber optic transmissions include the introduction of "dark fiber" (fiber with no active amplifier elements) and operational demonstration of solitons [10]. These advances may make it possible for optical data at rates of > 10 Gbps to be transmitted around the world several times without any active amplification. The recent operation of the first Fiber-In-The-Loop (FITL) systems have demonstrated the capabilities and benefits of optical fiber wired directly to the home. FITL may be deployed initially as Fiber-to-the-Curb (FTTC) which will allow POTS and N-ISDN, or CATV services depending on the media chosen for the last drop (i.e. copper or cable) [11]. This configuration is referred to a hybrid local loop. Because of the small additional cost required to realize FTTB/FTTH (Fiber-to-the-Building/Fiber-To-the-Home), it can be assumed that there will be a point in the future when this will be the normal configuration. Proliferation of FTTB/FTTH will result in the availability of broadband services at rates as high as 155 or 622 Mbps to the home.

Data Communications/Switching Systems. Efficient high-speed multiplexing, switching, and routing technologies are integral to providing effective high data rate communications in a distributed environment. Progress in this area has been characterized by the development of new switching fabrics, advances in IC fabrication technology, and inception of new network management and routing paradigms. Current standards and highlights in data communications are discussed below.

FDDI. The Fiber Distributed Data Interface (FDDI) set of standards were initially developed to support 100 Mbps high-speed networking over fiber optic cables [12]. FDDI is currently used in LAN applications and provides a synchronous capability which allows transfer a time-sensitive packets such as voice and video packets. The FDDI-II standard adds an isosynchronous capability which ensures timely delivery of sensitive packets even under heavy load conditions. To speed FDDI implementation and provide more options, the FDDI physical interface can now support various multimode fibers, coaxial cable, or twisted shield pair interfaces. The FDDI Follow-on (FFOL) standard is currently in development to define a FDDI backbone network operating at data rates of 155 Mbps - 2.48 Gbps.

Synchronous Digital Hierarchy (SDH). SDH is the CCITT standard which provides a universal digital transport network based upon synchronous transmission methods. SDH supports Synchronous Transport Module (STM) data rates starting at 155 Mbps. SDH is being implemented in a way to facilitate a smooth evolution from existing networks to future broadband networks based on asynchronous transmission methods.

Synchronous Optical Network (SONET). SONET is a standard developed by ANSI and the Exchange Carriers Standards Association (ECSA) for digital optical transmission. SONET uses synchronous techniques to multiplex the overhead and communications payload but allows ATM techniques for multiplexing user channels. SONET also supports an interface to FDDI LANs. SONET is the ANSI/ECSA counterpart to the CCITT SDH standard with some minor differences. Like SDH, SONET supports data rates of 155 - 2,400 Mbps but also supports the STS-1 rate of 52 Mbps and may support other user interfaces such as DS1 (1.544 Mbps) electrical and DS3 (44.736 Mbps) optical interfaces.

Asynchronous Transfer Mode (ATM). ATM is the target transfer mode for the Broadband Integrated Services Digital Network (B-ISDN). ATM provides dynamic high bandwidth, low-delay packet switching and multiplexing for multiple services [13]. ATM provides for efficient communication of high speed data bursts by providing scalability and dynamic bandwidth (53 byte cell is only defined structure). ATM cells are equally suited to carrying digital voice, video or data and can be passed over separate Virtual Channels (VCs) with separately defined Quality of Service (QOS) parameters [14]. Related packets are inherently linked together via a common Virtual Path (VP) to provide synchronized real-time multimedia service. A five byte header within each ATM cell provides VC Identifier (VCI) and VP Identifier (VPI) label information. The service mix and data rates are decoupled from characteristics of the switching fabric and mapping of time slots to channels at call establishment is not performed. With ATM service, users only pay for the cells which they send versus a flat rate for a dedicated service rate which they may not use continuously.

B-ISDN. The Broadband Integrated Services Digital Network (B-ISDN) is the communications standard architecture of the future which will provide broadband multimedia networks. ATM is the target data link platform for B-ISDN which will also make use of intelligent network protocols and techniques discussed below. The CCITT and various other standards bodies are currently developing a family of standards to define all aspects of the B-ISDN and provide for a smooth transition from the current architecture and Narrowband ISDN (N-ISDN) to that of the future.

Intelligent Networks. Advanced Intelligent Networks (AINs) are currently being developed and implemented within the existing telecommunications structure. The aim of AIN is to separate specific service functions from the switching fabrics and transport layers and allocate intelligence to the service providing devices [15]. The goal is to provide for optimally efficient and flexible communications services without reliance on the interconnection system intelligence. The switching functions performed by today's network nodes and systems will be embodied within the interconnection layer of the AIN model. The main roles of the interconnection layer will be for mobility management control (i.e., tracking mobile users), multiple transport control, and to ensure the maintenance of all interconnections between service users. AIN development is currently focusing on the application layer protocol to support intelligent service creation, service interaction, network management, service processing, and network interworking. AINs are considered to be essential in the future telecommunications infrastructure to perform network and systems management within a distributed environment consisting of different network protocols and operating systems. Applications of AINs include global directory services and distributed file systems (to name of few).

Fixed Satellite Communications (SATCOM). The use of more powerful satellite transmitters and continued decrease in size of earth terminals (which can be placed closer to customer premises) has driven the widespread growth of satellite communications over the last decade [16]. Satellite communications for fixed users has sky rocketed over the past 15 years due to the introduction of Very Small Aperture Terminals (VSATs), made possible through the addition of the Ku-band and a steady increase in quantity and competitiveness of satellite providers. Modifications in US regulations on ownership of earth stations and access to the space segment have also driven this change. The development and implementation of the first digital processing and switching satellite communications systems and pending introduction of Low Earth Orbiting (LEO) satellite systems now create new possibilities for SATCOM capabilities and integration within the global communications infrastructure of the future. All existing fixed SATCOM services are now provided by "bent pipe" geosynchronous satellites.

NASA's Advanced Communications Technology Satellite (ACTS) was launched in late 1993 to test high risk SATCOM technology that would otherwise be avoided by the commercial industry due to the investment involved. These technologies include on-board baseband processing, IF microwave matrix switching, hopping spot beams, and adaptive fade compensation [17]. The ACTS operates at the 30/20 GHz K_a frequency band which also required use of advanced microwave and power components. ACTS is providing a variety of capabilities for over 70 experiments sponsored by DoD, Universities, and industry.

A future commercial SATCOM system for fixed applications which was recently proposed is the Teledesic system. Teledesic would be comprised of 840 satellites orbiting at 700 km above the earth to provide integrated digital voice, video, and data on a global scale [18]. The Teledesic system would have an unprecedented impact on global communications by providing 1.55 Mbps access to any location in the world (fixed sites only).

Future Fixed Communications Architecture. Based upon the discussions above, the fixed communications environment of future will be one of ready access to interactive multimedia services for many people. Communications over distributed high data rate networks, servicing businesses and home users alike, may be the norm. As a global example to this vision, China has initiated a project called the Broadband Intelligent Personalized and Integrated Services Digital Network (BIP-ISDN) [10]. This network will be constructed of super high speed fiber optic systems, high speed wideband ATM switching systems, advanced intelligent networks, personal communications systems, and multimedia terminal systems.

In general, the increasing demand to improve the information superhighway at the national and at the global level should drive the implementation, upgrade, and continual improvement of the communications infrastructure. The proliferation of current high data rate standards such as FDDI, SONET, and SDH, as well as broadband capability access via ADSL/HDSL and FTTC, will provide for an eventual transition from the communications environment of today, to an environment similar to the Chinese BIP-ISDN, based on B-ISDN standards and using ATM protocols, AIN methods, and FTTH/FTTB access [19].

Figure 2 provides a projected view of the future communications architecture for fixed users based upon the discussion above. The capabilities provided by this future architecture will allow access to, and should spur demand for, new services for government, business, and home users alike. Of particular interest is the increase in capability that will be provided to the standard homeowner, allowing multi-channel access to the broadband, interactive multimedia services listed in Table 1 at all of the effective data rates previously defined.

It is projected that market demand and technological advances will realize this scenario in the early 21st century, where the standard home compliment of electronic equipment will include a power MMPC, video phone (could be one in the same as PC), and a digital HDTV set [2]. These home electronic devices will

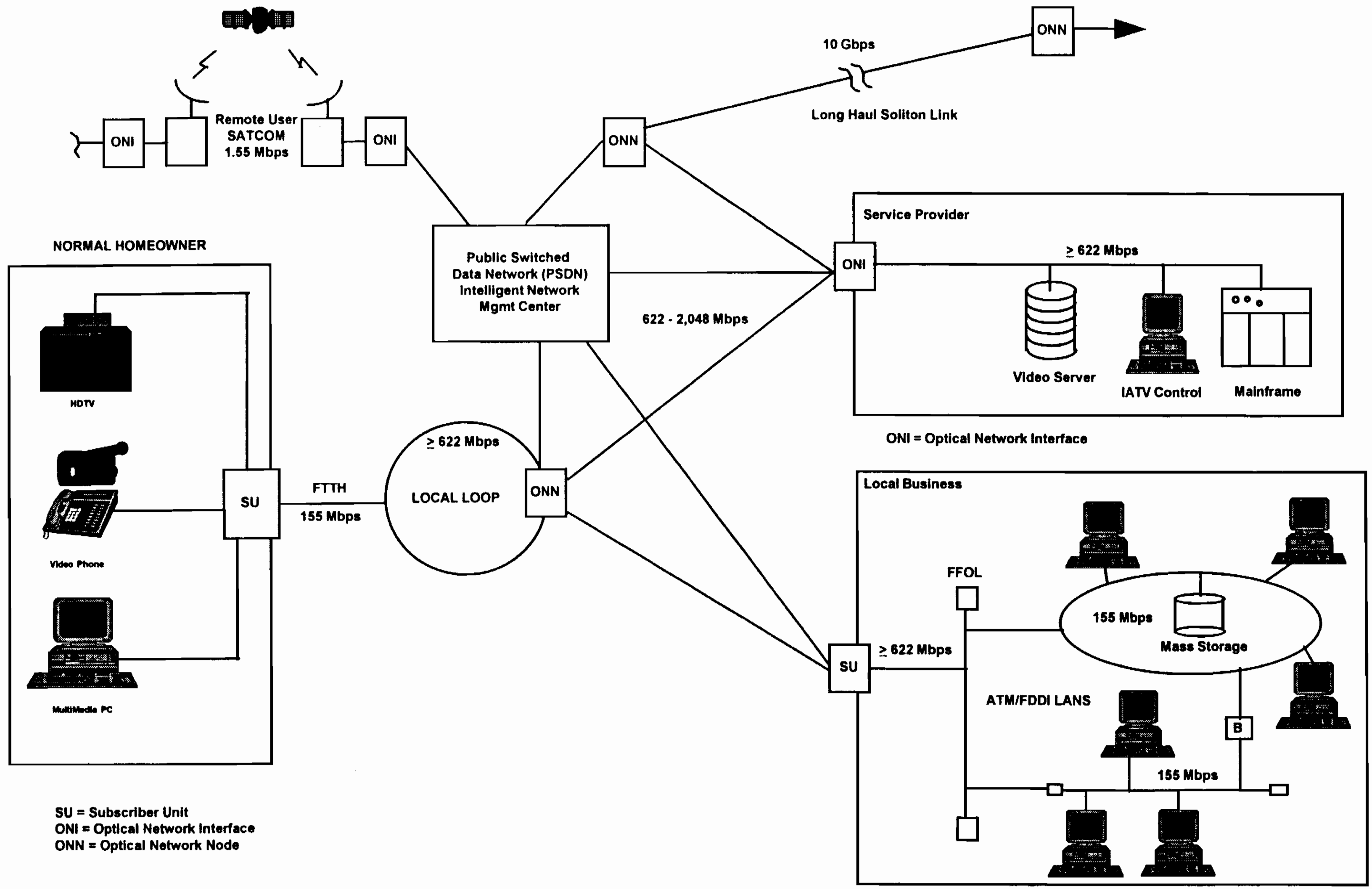


Figure 2 - Future Fixed Communications Architecture

operate somewhere between the data rates of 1.55 Mbps - 155 Mbps and will utilize packet communications protocols (i.e., ATM). Homes and small businesses in remote areas may still gain access to their multimedia services through hybrid FTTC/coax drop configurations, but further advances in coaxial transmission technology should still provide the capability for transfer of at least 100 Mbps.

Standard to large businesses will communicate internally via high speed ATM LANs which are integrated with each other and interface to the outside world at FFOL rates of 622 Mbps or higher. The Public Switched Telephone Network (PSTN) will migrate to the Public Switched Data Network (PSDN) as the benefits of integrated digital services drive the implementation of the information superhighway over an all-fiber backbone. Long distance links will be provided by optical links using soliton transmission techniques to eliminate the need for repeaters and operating at rates as high as 10 Gbps. These systems, plus intelligent networking control and management techniques, will provide the capability of interactive multimedia networks meeting the above stated requirements between fixed users.

Mobile Communications - Mobile communications is currently provided through cellular and cordless microwave technology and geostationary satellites. Mobile wireless applications currently include telephony, paging and message services, low data rate data exchange, locationing, and wireless computing. The growing demand for wireless and mobile communications over the last decade is also driving the introduction of a new class of communications devices known as Personal Communications Systems (PCS) [20]. PCS will become the generic term for communications equipment which can provide personal voice and data service on a global perspective, utilizing equipment small enough to be hand carried. The FCC is in the process of licensing 200 MHz of additional spectrum at 2.5 MHz to create new opportunities in PCS, mobile satellite communications, and wireless technologies. As mobile communications systems and capabilities continue to proliferate the globe, demands for enhanced and additional mobile services can be expected based upon the projected fixed architecture discussed previously. Mobile communications systems are discussed below to project mobile demands and assess mobile capabilities in the future.

Cellular Microwave. Cellular microwave has prospered through the use of analog standards such as the Advanced Mobile Phone Service (AMPS) standard in the U.S.. Cellular microwave technology is currently focused on ways to improve channel coding and medium access methods to maximize system capacity. One such example is the implementation of more efficient and reliable digital services utilizing Code Division Multiple Access (CDMA) and Time Division Multiple Access (TDMA). These and other digital cellular standards, such as the pan-European Global System for Mobile communications (GSM), were implemented in 1991 through different standards bodies and are now in widespread operation. Microcellular and picocellular technology have also become important in metropolitan areas where the demand for system access and mobility has driven requirements for smaller cells, smaller antenna systems, and indoor coverage. Current microwave systems and standards provide for digital voice and data communications services at $\leq$ 32 kbps.

The Digital European Cordless Telephone (DECT) standard will provide the next generation of cordless/telepoint technology operating at 1900 MHz and providing a common air interface capable of up to 384 kbps and ISDN compatibility (DECT is wireless but not for mobile users). For the convergence of this cordless technology with user mobility (vehicular) there are two major efforts underway: the Universal Mobile Telecommunications System (UMTS), being developed under a European collaborative program called RACE, and the related Future Land Mobile Public Telecommunications System (FLMPTS), being studied by the CCIR. Both of these systems plan on providing digital data services up to 2 Mbps to mobile platforms for on/over land and off-shore applications [23].

Mobile SATCOM. Mobile satellite communications initially started through the International Maritime Satellite Organization (INMARSAT) to provide low data rate messaging and emergency communication channels to sea vessels [16]. These services have grown to provide data rates up to 56 kbps for sea vessels and now support voice services to land mobile and aeronautical users. The INMARSAT satellites currently operate at the C and Ku bands which restrict mobile applicability and data capacity due to antenna size requirements.

Where as ACTS has demonstrated advanced SATCOM technology for fixed applications, the Milstar system is doing the same for mobile applications. The Milstar/EHF SATCOM system is a DoD communications system initially designed to provide minimum essential communications through global nuclear war. Milstar is a digitally processed, spread spectrum system which provides service to maritime mobile (ship and submarine), aeronautical mobile, and fixed shore platforms. The Milstar satellite provides baseband switching, utilizes satellite crosslinks for complete global connectivity, and operates at a 44 GHz uplink requiring advanced microwave components and circuitry. The initial implementation of Milstar supports data rates up to 2.4 kbps but an upgrade to the system will provide data rates up to 1.544 Mbps by 1999.

A new class of mobile satellites are now in development which will operate at L and S-band frequencies in Low and Medium Earth Orbits (LEO/MEO) to provide voice and low data rate services globally. These and other existing mobile SATCOM systems and services are listed in Table 3 [16,18]. This list does not include many of the little LEO systems (e.g., Vitasat, Starsys, Gonets) as well as some of the foreign developed big LEO systems (e.g., Signal, COSCAN, Solidaridat) because of space limitations. Most of the systems listed in Table 3 are tailored towards land mobile voice applications and include a position determination/locationing capability. The data rates provided by most of these new mobile SATCOM systems are also tailored to voice and low data rate data applications between 2.4 and 9.6 kbps depending upon the coding, modulation, and access method employed.

If the operational capability dates reflected in Table 3 are realized by the respective SATCOM system developers and corresponding market demands, voice and low data rate communication access will be prolific on a global scale by the end of the century. The addition of these mobile communications providers will also help to spur competition and drive the cost of these services and associated equipment down.

Table 2 - Mobile Satellite Communications Systems & Services

System	Devel Country	Application	Platforms	Coverage	Constellation				Satellites		Data Rates	Ops Cap.	Estimated Costs		
					Orbit	He (km)	Planes	# Sats	Digital	ISLs			Devel	Term	Usage
DoD															
FLTSATCOM	US	T/D (DoD)	F, MM, AM	Global	Geo	35.8k	1	4	No	No	.075-4.8 kbps	<90	*	*	*
DSCS	US	T/D (DoD)	F, MM, AM	Global	Geo	35.8k	1	4	No	No	.075-1,544 kbps	<90	*	*	*
Milstar	US	T/D (DoD)	F, LM, MM, AM	Global	Geo	35.8k	1	4	Yes	Yes	75-2400 bps	93	$ 10 B	$1.2M	*
Milstar II	US	T/D/V (DoD)	F, LM, MM, AM	Global	Geo	35.8k	1	4	Yes	Yes	9.6-1,554 kbps	99	$ 4 B	$1.2M	*
Services															
INMARSAT A	Internat.	T/D	F, MM	Global	Geo	35.8k	1	4	No	No	.03-2.4, 56 kbps	<90	*	$30-400K	$5-20/min
INMARSAT B	Internat.	T/D	F, MM	Global	Geo	35.8k	1	4	No	No	.03-2.4, 56 kbps	94	*	$30-400K	$5-20/min
INMARSAT C	Internat.	D (S&F)	F, MM, AM	Global	Geo	35.8k	1	3	No	No	600, 1200 bps	94	*	$4-10,100K	
INMARSAT M	Internat.	T/D	F, LM, MM, AM	Global	Geo	35.8k	1	4	No	No	2400 bps	94	*	$20-400K	$5.50/min
OmniTracs	US	D/P	F, LM	N/S Am	Geo	35.8k	1	4	No	No	9.6	94	*	*	*
INMARSAT P	Internat.	T/D/P	LM, MM, AM	Global	MEO	10K	3	15	No	No	2.4-9.6 kbps	2000	*	*	*
Systems															
MobileSAT	Australia	T/D	F, LM, MM, AM	Australia	Geo	35.8k	1	1	No	No	2.4,4.8 kbps	94	*	*	$1/min
AMSC	US	T/D/DAB	F, LM, MM, AM	No. Am.	Geo	35.8k	1	1	No	No	2.4,4.8 kbps	95	$150M	$500-$3,500	$1.80/min
Telesat Mobile	Canada	.T/D/DAB	F, LM, MM, AM	No. Am.	Geo	35.8k	1	1	No	No	2.4,4.8 kbps	95	$150M	$500-$3,500	$1.80/min
OrbComm	US	D (S&F)/P	F, LM, MM	Global	LEO	800	3	26	No	No	2.4,4.8 kbps	95	< $150M	$100-$400	$40/mnth
IRIDIUM	US	T/D/P	F, LM, MM	Global	LEO	780	6	66	Yes	Yes	2.4,4.8 kbps	98	$3.3B	$3,500	$2.10/min
Global Star	US	T/D/P	F, LM, MM	Global	LEO	1400	8	48	No	No	4.8-9.6	98	$1.8B	$750	$.66/min
Ellipso	US	T/D/P	F, LM	N/S Hemi	HEO	425-2900	2	24	No	No	4.8-9.6	98	$300M	*	*
Odyssey	US	T/D/P	F, LM	Global	MEO	10.3K	3	12	No	No	4.8-9.6	98	$1.2B	*	*
Aries	US	T/D/P	F, LM	Global	LEO	1000	4	18	No	No	4.8-9.6	98	$400M	*	*
CELSAT	US	T/D/P	F, LM, MM	US	Geo	35.8k	1	3	No	No	4.8-144 kbps	98	*	*	*
Teledesic **	US	T/D/V	FIXED	Global	LEO	700	21	840	Yes	Yes	1.55 Mbps	2001	$9B	?	?

Legend:

D = Data (includes telex/fax)
DAB = Digital Audio Broadcast
P = Position
V = Video
S&F = Store & Forward
T = Telephony

F = Fixed
AM = Aeronautical Mobile
LM = Land Mobile
MM = Maritime Mobile

ISL = Intersatellite Link

Geo = Geosynchronous
LEO = Low Earth Orbit
MEO = Medium Earth Orbit
HEO = Highly Elliptical Orbit

* Information not available or applicable

Communications Deficiency

As broadband services (Table 1) become available to fixed users in the future, there will also be a widespread increase in low data rate ($\leq$ 144 kbps) availability to mobile users through cellular microwave and mobile satellite communications systems. It is projected that sometime during the early 21st Century, land, aeronautical, and maritime mobile users, as well as remote fixed users, will demand access to the broadband communications services that fixed users will access via coaxial or fiber optic cable. In short, rapid growth in the proliferation of broadband services to fixed users will result in large gap in service capability between fixed and mobile or remote users. Figure 3 depicts the chronology of data rate capability for three different classes of communication users including a forecast for the future (for wide area communications versus local LANs and exclusive of DoD systems/applications). This figure clearly highlights the gap between fixed and mobile communications users. This gap in service capability considers all planned mobile communications systems and is quantified as:

Fixed Users:	$\geq$ 155 Mbps
Mobile Users:	$\leq$ 2 Mbps (144 kbps oceanic)

where the implementation of B-ISDN services through FTTH/FTTB access will realize the fixed user communications capability. The mobile user capability considers access to a FLMPTS/UMTS comparable system for land mobile applications and access to a CELSAT comparable system for transoceanic coverage (i.e., > 40 km offshore). This difference in data rate capability can be equated to the following multimedia service capabilities:

Fixed Users: 100 low-end broadband multimedia services
or
12-25 high quality broadband multimedia services
or
8-10 HDTV quality broadcast services

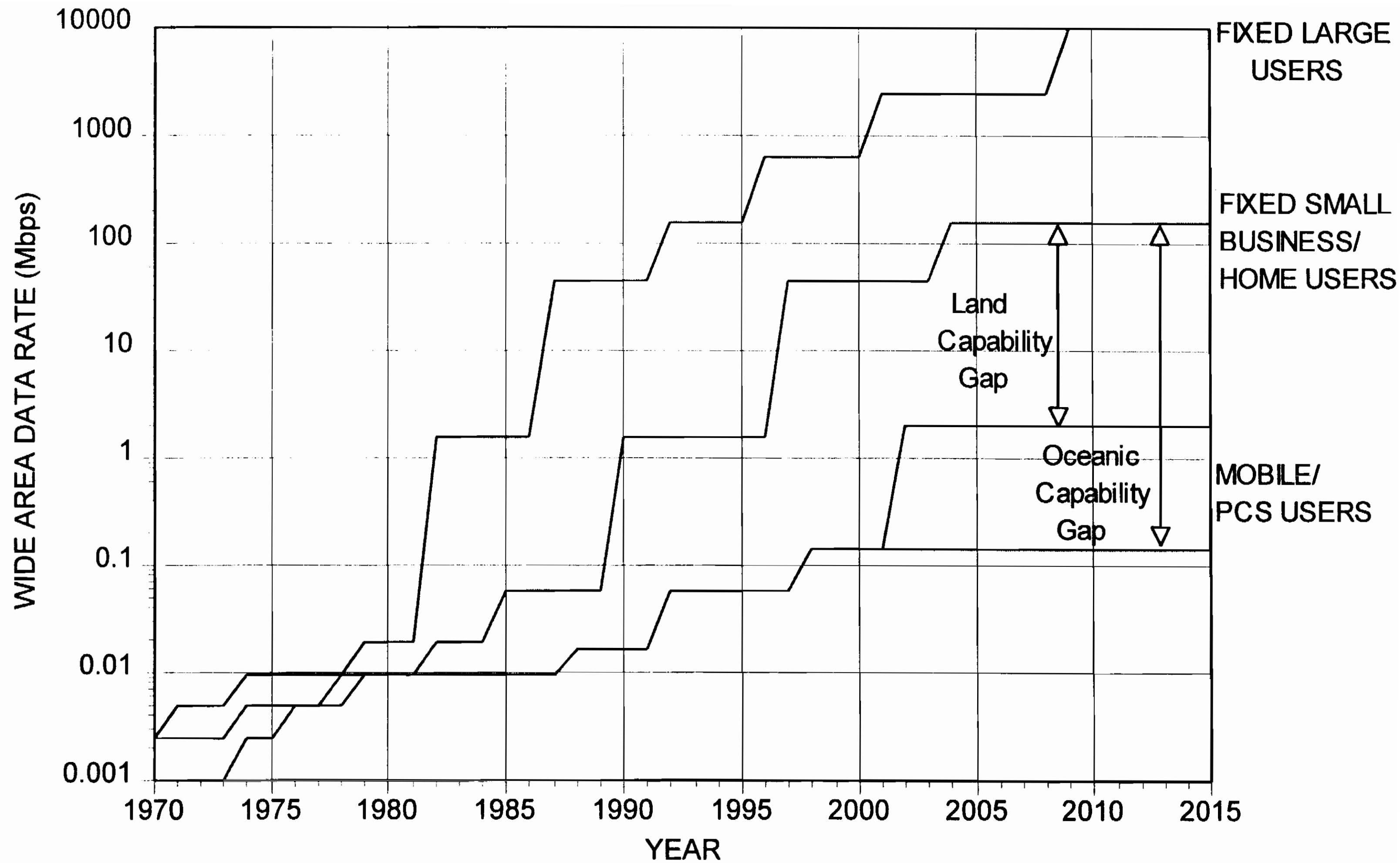


Figure 3 - Communications Capability Timeline

Mobile Users: 1 low-end broadband multimedia service
1 low quality narrowband service (oceanic)

Based upon this situation, it is assumed that sometime in the future, there will be a need for a communications system to provide broadband services to these "disadvantaged" (mobile) users to support the extension of broadband multimedia network services. Current terrestrial systems being deployed or in development will address broadband service needs for the fixed user but not for the mobile user. This problem and resulting need will exist for many different classes and applications of mobile users who will demand comparable Quality Of Service (QOS). A future mobile broadband system must integrate with the fixed communications architecture which will be in place at the time of system implementation and throughout the system life cycle. Based upon these perceived needs and assumptions, the deficiency can be summarized as follows:

Mobile communications system capable of:

- Quality multimedia services (comparable QOS)
- Services provided at 1.55 Mbps, 6 Mbps, and 18 Mbps (minimum)
- Global connectivity capability (at all data rates)
- Service to aeronautical, maritime, and land mobile platforms
- Compatibility with fixed infrastructure (B-ISDN)
- > 95 % availability including transoceanic platforms (minimum estimate for user marketability)
- Cost comparable to fixed services (at least as close as fixed and mobile service costs are proportional today)

To effectively realize this future communications system profitably, we must look far enough into the future to apply current and projected technology to consider the full range of system solutions. To cost effectively develop such a large scale system, a complete systems approach to this problem must be performed.

Conceptual Design

Needs Analysis

To identify and validate the need for a mobile broadband system, user needs of the future, as well as other market influences, must be examined and assessed. Based upon national and international interests in building and enhancing an information superhighway, it can be seen that communications is viewed as a key component of world progress and leadership. Emerging technologies and communications standards will define the future communications architecture portrayed in Figure 2 for fixed users. Also, during the next decade, the proliferation of low data rate mobile & personal wireless communications systems should prime the market and provide a demand for higher data rate communications to these users to support broadband applications.

User Needs - To account for market influences on system design and employment, we must first investigate who will need mobile broadband services. There are five user groups which are assumed to have this need, based upon the user "platform" with further subgroups based on user size & application:

Platform	Example
1) Aeronautical Mobile	
a) large platform	Commercial Airliner
b) small platform	Lear Jet
2) Maritime Mobile	
a) large platform	Cruiseliner
b) small platform	Yacht
3) Land Mobile	
a) large platform	Bus/Train
b) small platform	Truck/RV
4) Land Fixed	
a) hub	Airline Hub
b) remote site	India

5) Personal Mobile
(i.e., no platform) Emergency Services

Needs for mobile and remote broadband services identified in Table 1 will differ depending upon user group/application which will be developed into unique operational requirements. A thorough market analysis and projection of market needs would be an essential step in realizing the actual system requirements. This market analysis is considered out of scope for this project and, therefore, the demands and needs described herein are assumed to be accurate for this system design.

Requirements for the fixed remote sites are to augment remote areas which do not yet have the optical fiber infrastructure of the future but that require connectivity to the same services. Low density areas such as China and India could particularly benefit from this technology as the implementation of the fiber optic infrastructure will take longer. The need for fixed remote sites may depend largely on the fate of the Teledesic system, which proposes to partially satisfy this need (by providing 1.55 Mbps access). Fixed terminals will also be required to support shore bases utilizing the system for communications with mobile assets (Hub arrangement). The portable terminal would not be required to be of the handheld/shirt pocket variety currently envisioned for PCS.

Based upon service needs and market forces, user evaluation criteria for the mobile broadband system can be summarized as the following:

- Provides Global Coverage
- Provides Full service to all mobile users
- Comparable/Interoperable with fixed services
  (embodies many of the technical requirements)
- System conducive to mobile platform constraints
- Demonstrated Reliability (Proven)

These user criteria will be used later in evaluating feasible approaches to satisfying the needs of the mobile broadband system.

Demand Influences - It is currently estimated that anywhere from 30 -100 million subscribers can be expected for spaced-based wireless telecommunications services in the next 10 years [8]. A majority of this demand will be from densely populated land-based users locations (i.e., cities). Due to the global coverage plan for this system, only a few percentage points of the global market should be needed to generate ample returns.

Market influences will determine when and where this capability will be required and how that demand will grow. Demand will not only depend upon market need, but also upon the utilization cost that the market can initially bear and how that demand will change over time. This critical market information will largely determine the system development schedule, funding, and implementation scope and rate. Based upon the future fixed architecture, data rate capabilities (Figure 3), and the projected market needs discussed above, the earliest profitable market demand for the mobile broadband system is estimated to be 2008 [2]. Similarly, the latest market demand for a mobile broadband communications system is estimated to be not later than 2015. Demand for mobile broadband services would be expected in the following order:

1) Commercial Transportation
2) Government
3) Transport
4) Health
5) Private Business
6) Personal

Commercial transportation companies would most likely be the first sector to offer broadband capability for entertainment, information, and business services to passengers, whereby they could pass some of the costs directly to the user. Government and health sector users would also have need for broadband services early-on for law enforcement and emergency services. Demand for broadband service from fixed remote business users may be so large as to monopolize system resources depending upon the state of the optical/coaxial infrastructure in 2008. This demand may have to impose additional requirements on the system to limit fixed use as opposed to mobile use (which may be driven by frequency allocation/licensing). Private users of the mobile broadband system would be the last group from which a market demand would be expected due to potential initial terminal and utilization costs. Although the portable/personal system will probably require less capability from a user perspective, an enormous market can be expected for this variant based upon current demand and directions in wireless/PCS systems for land applications.

Required Resources - Based on initial market and technology assessments, the scope of this system development will require significant financial and human resources. Using development costs for the global mobile SATCOM systems listed in Table 3, the scope of a global mobile broadband system can be expected to cost on the order of $1 to $10 Billion depending upon the system solution chosen. Life Cycle Cost (LCC) elements and a high-level LCC analysis are provided later within this design as initial estimates of the resources required.

Planning for the development of this effort should be geared toward separately defined stages of development and associated financing to ensure that the system is realizable. Final planning of the system will not be fully possible until earlier tradeoffs are performed and preliminary design finalized. This point must be reached before final production and implementation plans can be developed and costed. The Return-On-Investment (ROI) for the system should be estimated and refined at each stage of development to ensure system design-for-profitability and to assist in obtaining financial backing.

Feasibility Studies

Technology-oriented feasibility studies are required during the early stages of system design to consider and evaluate all possible system solutions, and to accurately define bounds on operational requirements without limiting system design solutions. The technologies discussed earlier, as well as cutting edge technology in other electronic and communication areas, should be fully evaluated for applicability to the mobile broadband system development. This feasibility study consists of an overall approach analysis as well as a technology assessment.

The first step in this study will be to determine overall system approaches to providing mobile broadband communications and determine the feasibility of these approaches. The feasible approaches will then be further analyzed during preliminary systems analysis to determine the optimal solution. In order to evaluate potential approaches which satisfy the system needs previously defined, key issues must be addressed to assure that the system itself is feasible. Some of the feasibility analyses are presented in enough detail (i.e., more than just worst case) that they can be utilized for tradeoff analyses during the preliminary design phase.

Approaches - There are several approaches for providing a broadband communications channel through free space [25]. These alternatives, which are applicable to providing higher frequency (GHz range) communications, are compared below against system requirements to identify feasible approaches. An summary analysis of these potential approaches for meeting user needs is summarized in Table 4.

LOS Microwave. Microwave links in the 1 - 13 GHz frequency ranges currently provide point-to-point LOS links for terrestrial communications. This alternative would not satisfy system requirements, particularly maritime requirements, due to the clear LOS requirement and maximum distance of approximately 30 km. There is also insufficient bandwidth and potential interference in the current LOS microwave frequency ranges. Although higher frequency bands are potentially available for this approach, directivity and distance still limit its application. Land LOS communications would also impose undue constraints on the antenna platform (height) or result in significant loss in availability.

Cellular Microwave. Mobile cellular communications and PCS (based on this technology) are also possible alternatives to satisfy mobile

Table 4 - Feasible Approach Analysis

Alternative	Global Cover.	Users Serviced				Fixed Serv. Compar.	Platform Compatible	Proven Reliab	Potential Application
		A	M	L	F				
LOS Microwave	No	P	P	P	C	Yes	No	High	None
Cell. Microwave	No	P	P	C	C	Yes	Yes	High	MDR high density L
Geo Satellite	Yes	C	C	C	C	No	No	High	None
Laser Satellite	Yes	P	P	P	P	Yes	Yes	Low	Satellite X-links
LEO Satellite	Yes	C	C	C	C	Yes	Yes	Med	Full
MEO Satellite	Yes	C	C	C	C	Yes	Yes	Med	Full

A - Aeronautical
M - Maritime
L - Land Mobile
F - Fixed (Land)

P - Partial
C - Complete
MDR - Medium Data Rate ($\leq$ 2 Mbps)

broadband requirements. However, maximum cell size (i.e. range) would not be able to support maritime users or transoceanic aeronautical users. Mobile cellular communications may be feasible to satisfy low-end broadband land mobile needs (particularly densely populated areas) if BW and power requirements can be fulfilled.

Geosynchronous Satellites. Communications satellites operating at geosynchronous orbits could provide the coverage and connectivity requirements of mobile broadband. However, the round trip signal delay of ~240 ms (not including signal processing for digital applications) is assumed to be unacceptable for providing real-time integrated voice and video for broadband services (which can be competitive with terrestrially-offered services). The free space loss may also require prohibitively large terminal antennas and/or amplifiers to mitigate the atmospheric and rain losses induced at potential mobile broadband frequency ranges.

Laser Communications. Laser communications are currently in the laboratory development and initial testing phases. Most likely applications seen for laser communications are for space-based links (such as satellite crosslinks) and high data rate (~10 Gbps) satellite downlinks to diversity ground sites. Key issues with laser communications are mechanical and thermal stresses induced in the payload optoelectronics, pointing and spatial acquisition requirements, platform jitter effects, and adverse impacts of cloud cover [26]. Laser communications are not a feasible alternative for full mobile broadband link connectivity but may be a viable alternative for satellite crosslinks.

LEO Satellites. Satellites orbiting at altitudes of 300 to 2000 km are currently being used or planned to fulfill global fixed and/or mobile low data rate communications needs. LEO satellites offer shorter delay times and can take advantage of smaller ground terminals because of the reduction in free space loss. These benefits come at the expense of a larger number of satellites for the same coverage and an increase in system complexity due to increased doppler shift, spatial acquisition and tracking, and communications hand-off between satellites.

MEO Satellites. Satellites orbiting at altitudes of 2000 to 10000 km are also planned to fulfill global fixed and/or mobile low data rate communications needs in the future. MEO satellites offer shorter delay times than current geosynchronous satellites while reducing the number of satellites required for global coverage as compared to LEO satellites. There is still an increase in system complexity due to increased doppler shift, spatial acquisition and tracking, and communications hand-off between MEO satellites as compared to geosynchronous satellites. More power is required for MEO satellites and corresponding ground terminals versus the LEO approach.

As shown from the above feasibility analysis, LEO/MEO satellite communications and microwave cellular communications are the only means currently available or projected for mobile user broadband services (with the exception of possible laser communications for satellite crosslinks). Also, to provide for complete system capability (service to all users), the system must contain some element of SATCOM. The various design options based upon these alternatives are further analyzed during preliminary design.

Issues - Key issues which must be addressed to determine the feasibility of these mobile broadband approaches include the following:

- Spectrum availability
- Bandwidth capacity
- RF attenuation
- Economic feasibility

Technology issues, such as feasibility of required RF and digital processing component performance, are addressed later as requirements and areas for further investigation. For the purposes of this analysis, it is assumed that the technology will be available at the time of system design to satisfy required performance parameters.

Spectrum Availability. Allocation of the RF spectrum for specific uses is tightly controlled by the International Telecommunications Union (ITU) under the auspices of the United Nations. The ITU is comprised of representatives from over 200 member countries and meets every two years to discuss matters associated with RF spectrum allocation and communications standards. The latest known frequency bands which may be available to support mobile broadband communications are listed in Table 5 [27]. The mobile non-SATCOM frequency bands listed in Table 5 are only those which meet the following conditions to meet system requirements [25,27] :

Condition	Reason
• BW > 100 MHz	Channel capacity
• f < 20 GHz	Cellular vs. LOS
• Does not include SATCOM downlink use	Interference

Based upon known or planned uses of some of these bands, the need for large bandwidth (as discussed below), and the SATCOM transceiver preference of higher U/L frequencies (as compared to D/L), possible frequency assignments to support a SATCOM approach to mobile broadband support are listed in Table 6. Based upon the availability of frequency bands listed in Tables 5 and 6 and the current and projected state of RF microelectronics, allocation and utilization of RF spectrum to support mobile broadband communications appears feasible. The issues of frequency approval and licensing for potential frequency bands are addressed later.

BW Capacity. Throughput data rates defined as system requirements raise the issue of BW capacity to support these requirements. The feasibility of providing communications to support enough users per satellite or cellular base station must be assessed for the identified frequency bands. Design factors which must be considered for this assessment include data encoding scheme, overhead required for system access control and network management, and frequency re-use schemes to increase channel capacity. For feasibility purposes, we will analyze the BW capacity for a SATCOM approach using the potential frequency bands identified and assuming a simple frequency multiple access system.

Table 5 - Potential Mobile Frequency Bands

FREQUENCY BAND	DIRECTION	APPLICATION
4.4 - 4.5 4.8 - 4.99	Non-Sat Non-Sat	F/M F/M
5.85 - 7.07	Non-Sat/Uplink	F/FS/M
7.9 - 8.02	Non-Sat/Uplink	F/FS/M
14.5 - 14.8	Non-Sat/Uplink	F/FS/M
14.8 - 15.35	Non-Sat	F/M
20.2 - 21.2	Downlink	FS/MS
30 - 31	Uplink	FS/MS
39.5 - 40.5	Downlink	F/FS/M/MS
47.2 - 50.2	Uplink	F/FS/M
50.4 - 51.4	Uplink	F/FS/M
66 - 71	Uplink	M/MS/RN/RNS
71 - 74	Uplink	F/FS/M/MS
74 - 75.5	Uplink	F/FS/M
81 - 84	Not Specified	F/FS/M/MS
95 - 100	Not Specified	M/MS/RN/RNS
134 - 142	Not Specified	M/MS/RN/RNS
190 - 200	Not Specified	M/MS/RN/RNS
252 - 265	Not Specified	M/MS/RN/RNS

Legend:
- F - Fixed
- FS - Fixed Satellite
- M - Mobile
- MS - Mobile Satellite
- RN - Radio Navigation
- RNS - Radio Navigation Satellite

Table 6 - Possible Broadband Mobile SATCOM Bands

U/L Frequency (GHz)	U/L Bandwidth	D/L Frequency (GHz)	D/L Bandwidth
71 - 74	3 GHz	39.5 - 40.5	1 GHz
95 - 100	5 GHz	81 - 84	3 GHz
134 - 142	8 GHz	95 - 100	5 GHz

Channel capacity can be analyzed for feasibility by using the relationship [41]:

$$R_m = \frac{B_s B}{B_c}$$

where R_m = max info rate

B = signal bandwidth

B_s = # of bits/symbol

B_c = Coding factor

If we assume the use of BPSK modulation (spectrally inefficient) in which $B_s = 1$ and $B_c = 1.1$ and consider utilization of the entire 3 Ghz uplink bandwidth at the 71-74 Ghz band we get:

$$R_m = 3 \text{ Ghz}/1.1 = 2.72 \text{ Gbps}$$

assuming 20% overhead for acquisition, timing, and network control,

$$R_{m(\text{total data})} = 2.18 \text{ Gbps}$$

Data encoding will also reduce the actual data throughput rate and can be assumed to be necessary to achieve the required BER within the RF path. Assuming rate 2/3 encoding,

$$R_{m(\text{actual data})} = 1.45 \text{ Gbps}$$

The total number of channels possible (without frequency reuse) for 52 Mbps and 6 Mbps channels, respectively would be,

$$N_{CH\ (52\ \text{Mbps})} = 27$$

$$N_{CH\ (6\ \text{Mbps})} = 241$$

Assuming feasibility of 4X frequency reuse through multiple beams,

$$N_{CH\,(52Mbps)} = 108$$

$$N_{CH\,(6\,Mbps)} = 964$$

For the more BW efficient QPSK (with 3 dB additional power) we would get:

$$N_{CH\,(52Mbps)} = 216$$

$$N_{CH\,(6\,Mbps)} = 1928$$

Convolution or block encoding schemes would modify this capacity by k/n where k is the number of symbols represented by n bits. Different modulation and frequency reuse schemes would also modify these results. Table 7 displays the results of this bandwidth feasibility analysis for each of the three uplink RF bands with different modulation, encoding, and reuse schemes for multiple channel data rates. It should be noted that this analysis is best case and does not account for any frequency guard bands, restrictions on the amount of bandwidth available within the band, and other implementation factors.

It can be seen from this short analysis that the mobile broadband system may be BW constrained depending on the number of accessible channels required by each satellite for a profitable system (especially at 52 Mbps and 155 Mbps). Channel capacity could be increased by utilizing a more BW efficient modulation scheme or by improving the frequency re-use factor without causing interference or rendering the system too complex. The design of system overhead and coding necessary to achieve system BER requirements, terminal power output possible, and coverage area of each satellite and specific beams will be critical to realizing this system profitably.

Attenuation. Attenuation due to rain and atmospheric effects are significant issues of concern for any potential RF system operating above 10 Ghz [25]. For feasibility purposes, we will analyze the SATCOM attenuation issue which is the worst case required approach. The total RF path loss is given

Table 7 - Broadband Channel Feasibility Analysis

Uplink Band (GHz)	Best Case Number of Channels/Sat [1] at Channel Rate (Mbps)					Worst Case Number of Channels/Sat [2] at Channel Rate				
	155	52	18	6	1.55	155	52	18	6	1.55
71- 74	126	377	1,090	3,272	12,668	14	41	121	363	1,454
95 - 100	211	629	1,818	5,454	21,818	23	69	202	606	2,424
134 - 142	337	1006	2,909	8,727	34,909	37	111	323	969	3,878

Notes: 1. Best case per satellite assuming QPSK modulation, Rate 3/4 encoding, and 6 times frequency reuse factor
2. Worst case per satellite assuming BPSK modulation, Rate 1/2 encoding, and 2 times frequency reuse factor

by

$$L_{Path} = 92.45 + 20\log F_{(GHz)} + 20\log D_{(km)} + a + b + c + d + e$$

where

a = water vapor attenuation
b = mist/fog attenuation
c = O_2 attenuation (absorption)
d = Other gaseous attenuation
e = rainfall attenuation

The parameters a through d are highly variable dependent on frequency, geographic location, time of year, and weather conditions. There are significant water vapor absorption bands at 22 Ghz and 183 Ghz. There are also two oxygen absorption bands at 60 Ghz and 119 Ghz which must be considered. Total atmospheric attenuation is also a function of path length through the portion of the atmosphere that must be considered. We will assume 6 km of atmosphere for O_2 attenuation and 2 km of atmosphere for water vapor attenuation [28]. Attenuation due to mist and fog and other gases (parameters b and d, respectively) will be assumed to be negligible by comparison.

The specific attenuation due to rain can be computed through use of the Crane Model [25,28] using the power-law relationship

$$A = aR_p^{\,b}$$

where

A = specific attenuation (dB/km)
R_p = point rain rate

The parameters a and b are both functions of operating frequency. The rain point rate is chosen based upon operational area and percentage of year that a specific rain rate is exceeded. Because rain attenuation is expected to be a major contributor to the lower availability of a mobile broadband SATCOM system, we will analyze attenuation for a rain rate of 2.9 mm/hr, which is exceeded 2% of the year or 175 hours/year (i.e. plan 2% loss in availability due to rain alone). The total attenuation exhibited at this mean rain rate also depends upon the 0° isotherm height (which denotes the height at which water particles become ice and are no longer a major attenuation concern) and the height of the ground terminal. Although the 0° isotherm height can reach above 5 km at the equatorial regions, we will analyze an average isotherm height of 3.5 km and a worst case elevation angle of 15°.

Table 8 depicts the total loss due to rain and atmospheric attenuation (for 98% availability) over the mobile broadband frequency ranges of interest at ground level. Rain and atmospheric losses for the aeronautical terminal at cruising altitude are considered negligible in comparison (approximately 2 dB for budget calculation purposes). Figure 4 depicts the total path loss (including free space loss) for the mobile broadband frequencies of interest over various orbital heights. This demonstrates that some of the additional loss due to the rain and atmospheric loss at these EHF frequencies may be gained back by utilizing Low Earth Orbiting (LEO) satellites (in comparison to current geosynchronous satellites at C and Ku Bands). It may be feasible to mitigate the additional 30 dB of loss through power management techniques, additional coding gains, and/or by properly specifying other design parameters. This issue will be further addressed. Market demands for the mobile broadband system are estimated to outweigh the potential availability restrictions imposed by rain and atmospheric attenuation at these frequencies.

Economic Feasibility. In order to adequately assess mobile broadband economic feasibility, a complete Life Cycle Cost (LCC) analysis must be performed based upon estimates for all program cost elements. Major cost drivers will be projected launch costs at the time of system implementation and system development costs, including prototype development and test. Market demand will be driven by the final terminal costs and system utilization costs to the user. These costs should be set forth during preliminary design, used as Design-to-Cost (DTC) parameters, and continually assessed at key program reviews to evaluate the system ROI. A LCC breakdown structure and analysis are provided later, as well as target DTC terminal and satellite costs.

Table 8 - Rain and Atmospheric Losses at Mobile SATCOM Frequency Bands

	Rain Loss @ 98% Availability					H_2O Vapor Loss		O_2 Absorption Loss		Total
F (GHz)	a(f)	b(f)	R (mm/hr)	A (dB/km)	L@15° (dB)	Coeff. (dB/km)	L@15° (dB)	Coeff. (dB/km)	L@15° (dB)	Loss (dB)
39.50	0.325	0.99	2.90	0.93	12.59	0.052	0.4004	0.03	0.70	13.69
40.50	0.325	0.99	2.90	0.93	12.59	0.055	0.4235	0.035	0.81	13.82
71.00	0.79	0.79	2.90	1.83	24.73	0.15	1.155	0.18	4.18	30.06
74.00	0.82	0.78	2.90	1.88	25.40	0.17	1.309	0.09	2.09	28.80
81.00	0.88	0.751	2.90	1.96	26.43	0.21	1.617	0.058	1.35	29.39
84.00	0.905	0.74	2.90	1.99	26.86	0.23	1.771	0.051	1.18	29.82
95.00	0.94	0.722	2.90	2.03	27.37	0.28	2.156	0.046	1.07	30.60
100.00	0.965	0.715	2.90	2.07	27.89	0.3	2.31	0.047	1.09	31.29
134.00	1.15	0.71	2.90	2.45	33.06	0.47	3.619	0.043	1.00	37.68
142.00	1.2	0.71	2.90	2.56	34.50	0.5	3.85	0.035	0.81	39.16

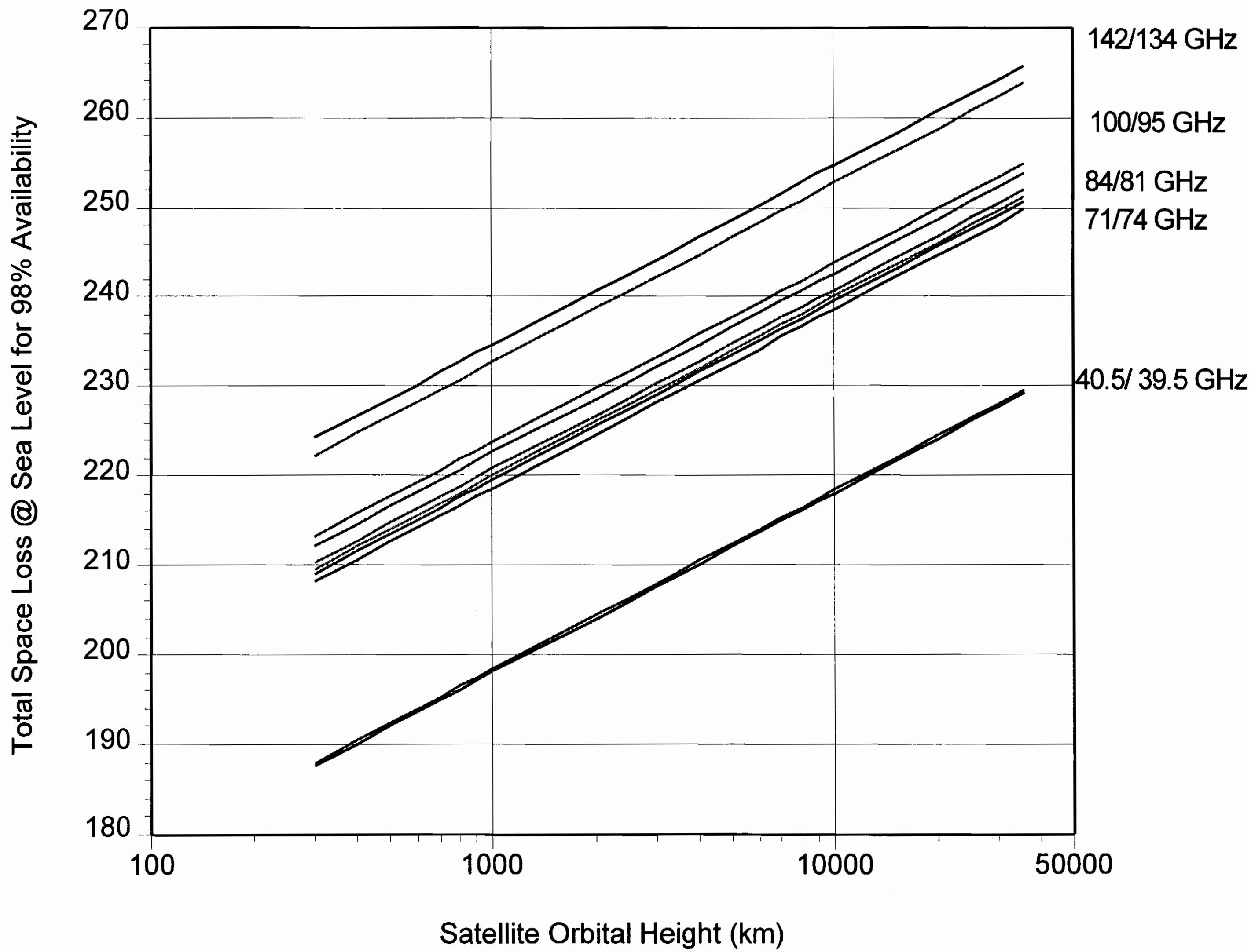


Figure 5 - Mobile SATCOM Space Attenuation

Several external factors can be used as gauges for the potential profitability and ultimate economic feasibility of the mobile broadband system, including:

- IRIDIUM system profitability
- FTTH proliferation/usage costs
- Teledesic system realization/costs

The IRIDIUM mobile SATCOM system should be analyzed and used as a model in assessing economic feasibility and ROI for the mobile broadband system. Total IRIDIUM investment will approach $3 billion dollars by system deployment, which should occur prior to committing finances for full mobile broadband system design. The success or failure of IRIDIUM coupled with the implementation rate of high data rate services to the home (via FTTH) can be used as market gauges for the assessment of mobile broadband marketability and ROI. Additionally, the Teledesic system recently proposed is another large scale, global communications system which can be used not only as an ROI gauge, but will also greatly enhance the global broadband infrastructure for fixed users and potentially accelerate the demand for a mobile broadband system. Both IRIDIUM and Teledesic will also establish improved processes for the "mass" production of communications satellites and associated electronic and digital components.

Based upon the current and projected demand for low data rate mobile and high data rate fixed communications, continued reduction in microelectronics costs, and projected technology improvements, the mobile broadband system is projected to be economically viable if properly developed through a system approach. This conclusion will be reassessed after development of a LCC analysis.

Technology Assessment - Technology areas should be assessed for applicability to the mobile broadband system early in system design to consider the full range of system solutions. Areas identified for feasibility analysis include the following:

1. Artificial Intelligence/Neural Network technology
2. Broadband Packet Switching technology
3. Advanced Antenna technology
4. Advanced Microwave technology

Each of these areas is discussed below for applicability to the mobile broadband communications system including a projection into the future at the required time in the system development cycle. Potential applications of these technologies are summarized in Table 9. These and other technology areas will be discussed throughout this report with technology requirements identified where possible. Areas for investigation will be summarized at the end of this high-level design.

Artificial Intelligence/Neural Network Technology. Artificial intelligence refers to systems which utilize learning processes to adapt their behavior much like human intelligence. Neural networks are based upon algorithms which model the brain whereby a processor "learns" from data inputs [30]. Neural networks can provide (after learning/training) a degree of fault tolerance to data processing functions which have incomplete or imperfect data. Expert networks incorporate the knowledge base of human experts with neural network technology to solve problems which neither could solve on their own.

Pattern recognition is currently the most widespread application of neural networks in use (for Optical Character Readers (OCRs)) with potential applications for data compression. Another branch of neural network applications is function estimation, whereby the network is used as a model for the system and utilizes its adaptive, nonlinear, and statistical properties to predict future system states. Applications of this neural network area include system control and optimization for noise cancellation, weather prediction, and adaptive power control [31]. One of the factors affecting the implementation of neural networks has been the amount of processing time required to run the algorithms, particularly during the training cycle. The introduction of parallel

Table 9 - Technology Assessment Summary

Technology	Primary Applications	Related Applications/Benefits	Risks/Issues
Artificial Intelligence/ Neural Networks	• Distributed AIN Control • Packet Routing/Scheduling • Phased Array Beam Forming • Adaptive Power Control • Continuos Phase Modulators	• Data Compression • Error Control Selection	• Parallel computing reqs • Learning capability • Cost vs. Complexity
Broadband Packet Switching	• Network Management Systems • Satellite Processor Switching • Terminal Processing	• Reduced cost; increased reliability due to demand	• Widespread implementation
Advanced Antennas	• Active Phased Array Antennas for aeronautical platforms • Beam Forming Network Antennas for Satellites	• Reflector/Beam shaping for surface tolerance correction • Electronic Beam Squint pointing and tracking	• Pointing accuracy at higher frequencies • Physical limits on element size and spacing • Cost effective production
Microwave Components	• Phased Array elements/ modules • Transmitter, receiver MMICs • Solid State Power Amps (SSPAs)	• High data rate computing	• Gain/NF reqs at higher freqs • Physical limits on element size and spacing • Cost effective production

computing hardware has recently reduced this problem and has sped the use of neural networks for specific applications. Also, the incorporation of fuzzy logic principles in neural networks provides more user flexibility and adds robustness to the system by defining the system boundaries more loosely.

Potential neural network applications identified for a mobile broadband communications system are listed in Table 9 and cover a wide spectrum of the system design from network control to antenna and receiver design. The application of neural network technology to system design may be essential in these areas to realize the required system (e.g., to efficiently route data packets within required time limits) and to profitably implement it. Neural network technology is projected to be in widespread use by the time of the mobile broadband system design.

<u>Broadband Packet Switching Technology</u>. Broadband packet switching technology has matured greatly over the last five years through the standardization and growing demand for ATM systems. ATM products are now becoming available on the market which provide ATM switching capability at STS-3 rates of 155 Mbps up to rates of 2 Gbps. This technology is currently being extended to handle rates as high as 10 Gbps for the broadband switching of fiber optic trunks. It is estimated that by the turn of the century, ATM systems at 155 Mbps will be in wide spread use and that 10 Gbps systems will be in the initial operation phases [32]. Further advances in IC manufacturing will continue to lower the cost and raise the reliability of these products prior to the need for a mobile broadband system.

<u>Advanced Antenna Technology</u>. Multibeam antennas have dominated the area of advanced satellite communication antenna technology for several years. Multibeam antenna technology continues to increase the capacity of communications satellites and increase the flexibility in coverage areas through the use of Beam Forming Networks (BFNs) [33]. Multi-beam antennas enable frequency reuse through spatial and polarization isolation as well as provide scanning, hopping, or reconfigurable shaped beams for added adaptability.

The demand for light weight antenna systems has also driven the need for printed circuit patch radiators made possible by continued advances in GaAs Monolithic Microwave Integrated Circuitry (MMIC). MMIC technology has also increased the feasibility of using active phased arrays as multi-beam antennas or feeds to reflectors for communications satellites [34]. This technology has been demonstrated and is currently in use at frequencies of 30 Ghz and higher on the NASA ACTS satellite and the DoD Milstar satellite.

Advanced Microwave Technology. Microwave technology has improved greatly over the past ten years driven by the demand for small lightweight cellular communications systems and the continued use of higher frequencies for cellular, satellite communications, and radar technologies. MMIC technology is currently being utilized for advanced antenna systems discussed above as well as in other subsystems of communications and radar equipment. Significant work has already been accomplished in the IC area for w-band frequencies. Low loss millimeter wave circuits from CW IMPATT diodes for 80-96 Ghz have been developed which demonstrated CW power of 500 mW. High efficiency power amps using 0.15 um InP-based HEMT MMIC technology have demonstrated 33% efficiency. A balanced amplifier covering the entire 75-110 GHz band has been tested at 23 dB gain with a Noise Figure (NF) of 6 dB. Also, from a power perspective, SSPA devices incorporating power combining are expected by the end of the decade that would provide 20 W at Ku band.

Operational Requirements

Operational requirements for the mobile broadband system will be fully defined before examining design alternatives to ensure that system objectives are met and that market needs are addressed. The operational requirements must embody the multimedia service requirements previously defined and satisfy the identified deficiency. In defining operational requirements, the following areas must be addressed: system mission, performance requirements, physical requirements, utilization, deployment, life cycle, effectiveness, and environment.

Mission Definition - The mobile broadband system must support the commercial, government, and private broadband communications missions of the following platforms:

1) Aeronautical Mobile (large & small)
2) Maritime Mobile (large & small)
3) Land Mobile (large & small)
4) Fixed (remote user or hub)
5) Portable

Aeronautical Mobile. The large aeronautical mobile platforms mission will primarily support commercial airline flights. The platform mission includes several different stages including taxi, takeoff, ascent, cruise, descent, and landing. Total mission time will range from 45 minutes to 10 hours and a specific platform will accomplish between one and five missions a day. The large aeronautical platforms will roll up to 30 degrees typically during the ascent and descent stages of the mission. The mobile broadband system will be required to support multiple simultaneous broadband communications channels at cruising altitudes of >27,000 ft. Some reduced capability is desired during the rest of the platform's mission.

The small aeronautical platform mission consists of the same stages as the large platform although the cruising altitude will be < 15,000 ft and the mission time will range from 20 minutes to 3 hours. The mobile broadband system will only be required to support a single broadband communications channel but this capability should be provided throughout the platforms complete mission.

Maritime Mobile. The large maritime mission will support both commercial cruiseliners and maritime shipping transport vessels. The general platform mission consists of successive phases of time docked in-port (but active), transiting in and out of ports, and open water transiting. Large maritime vessel platform motion will range from relatively minor (< 1 degree in roll, pitch, and heading) during docked periods to significant (up to > 20 degrees in pitch and roll) during open water transiting periods. The relative change in platform motion during the platforms mission will depend upon platform size, weight and placement of platform load, and relative sea state conditions. Large maritime platform missions will range from 3 hours to six months (for complete mission). The mobile broadband system should provide a simultaneous multiple broadband channel capability during all phases of the large maritime mobile platform mission.

The small maritime platform mission consists of the same stages as the large maritime platform mission although the mission time ranges from 1 hour to three weeks. Platform motion conditions will also be larger during all stages of the small maritime platforms mission. The mobile broadband system should provide a multiple broadband channel capability during all phases of the small maritime mobile platform mission.

<u>Land Mobile</u>. The large land mobile platform mission will support commercial and transport railways as well as commercial buses, each with different missions. The railway mission consists of accelerating, cruising, decelerating, and stationary phases in multiple succession depending upon mission length ranging anywhere from two hours to one month. The relative motion of the railway platform will be fairly constant with gradual speed and direction changes and moderate jitter. The bus platform will include the same phases of the railway platform except that significant turns will be present during the mission and the relative frequency of the mission phases will be substantially increased.

The small land mobile platform will support emergency vehicle, trucking, and private transportation missions. All of the small land mobile missions will be similar to the bus platform mission except that mission times and frequency of phases may differ. Platform jitter can also be expected to be higher on the small land mobile platform.

Land mobile missions will include transiting over/through a variety of terrain. These missions will include blocks of time where there will not be a clear field of view to the entire skyline or in which the platform is in the presence of many RF scattering obstructions (e.g., buildings). Because of this, the land mobile platforms may not be able to support communications during the platforms entire mission cycle because of clear Line-of-Site (LOS) requirements with a satellite constellation and/or multi-path interference and fading for a microwave cellular application. It shall be acceptable from a system design standpoint that the land mobile systems may not be supportable through all user scenarios (trips through thick foliage, tunnels, etc.) although diversity schemes should be investigated during system design to maximize the availability of the land mobile system.

Fixed Remote/Hub. The fixed remote and hub terminals will support similar missions for different applications. The fixed remote terminal will act as a gateway from the mobile broadband system to fixed land sites which do not have access to a terrestrial broadband communication system. The fixed hub terminals will support user services to mobile platforms. Both applications of the fixed terminal will require missions of nearly continuous operations or at least a daily cycle of > 12 hours/day.

Portable. Portable platform missions will include those for emergency needs and those for business needs. This platform (or lack of) is unique in that the system will be stationary (i.e., fixed) at the time of system utilization but capable of mobility in between. Portable missions are assumed to be brief in utilization time (~ 20 minutes average) and infrequent (~2 missions/ day) in use based upon system setup and breakdown required. The portable mission is applicable to land applications only since a stationary platform is required. Setup with a clear LOS to the satellite or clear access to a cellular base station is assumed.

Performance Requirements - Based upon the projected user needs and subjective reasoning, the following performance objectives are defined. Because of potential physical and technological constraints and limitations, objective as well as threshold requirements are listed where applicable.

Satellite/Base Station Capacity. The communications capacity of the mobile broadband satellite and/or cellular base station will be dependent upon the number of satellites in the constellation and final orbital height (defining area of coverage) and/or coverage area of the cellular base station. A detailed analysis of current mobile communications traffic usage (narrowband) and projection of mobile broadband usage should be conducted to define a suitable number of users per square km, at a minimum. This analysis would help define the satellite coverage requirements and/or complementary cellular service required, including resulting antenna and electronics design. Due to the statistical complexity and dependency on platform, application, and location, this analysis is considered out of scope. Our current design will consider all other performance/system requirements and assume a maximization of satellite/base station capacity based upon these criteria.

Terminal Data Throughput. The mobile broadband system must provide adequate data throughput-per-user to fulfill the broadband multimedia needs of each platform and to provide integration within the future land-based communications infrastructure (information superhighway). Based on these factors and subjective projections, upper channel data rate and data throughput requirements for each user platform are listed in Table 10.

For large terminals, the objective upper channel capability should be capable of supporting DS-3 and/or STS-1 data rates, at 44.763 and 51.84 Mbps, respectively. The fixed terminal should be capable of supporting the STM-1 ATM standard data rate of 155.52 Mbps. This fixed terminal capability would provide the optimal integration with the fixed communications infrastructure and allow for a higher hub-to-mobile data rate which is desirable for hub configurations. The minimum (threshold) channel requirement is to be capable of supporting a compressed HDTV signal. Desired data throughput requirements correspond to the equivalent capability of two STM-1 or STS-1 channels respectively, which will be dependent upon platform and terminal port configuration (see below).

Table 10 - Broadband Terminal Throughput Requirements

SYSTEM APPLICATION	UPPER CHANNEL CAPACITY*		TOTAL THROUGHPUT	
	OBJECTIVE	THRESHOLD	OBJECTIVE	THRESHOLD
Aeronautical (Large)	≥ 45 Mbps	≥ 18 Mbps	≥ 310 Mbps	≥ 90 Mbps
Aeronautical (Small)	≥ 6 Mbps	≥ 1.55 Mbps	≥ 6 Mbps	≥ 1.55 Mbps
Maritime (Large)	≥ 45 Mbps	≥ 18 Mbps	≥ 310 Mbps	≥ 90 Mbps
Maritime (Small)	≥ 18 Mbps	≥ 6 Mbps	≥ 45 Mbps	≥ 18 Mbps
Land Mobile (Large)	≥ 45 Mbps	≥ 18 Mbps	≥ 310 Mbps	≥ 90 Mbps
Land Mobile (Small)	≥ 18 Mbps	≥ 6 Mbps	≥ 45 Mbps	≥ 18 Mbps
Fixed remote/hub	≥ 155 Mbps	≥ 45 Mbps	≥ 310 Mbps	≥ 90 Mbps
Pesonal Mobile (Portable)	≥ 6 Mbps	≥ 1.55 Mbps	≥ 6 Mbps	≥ 1.55 Mbps

* Terminals must also be capable of providing lower data rate channels

Small maritime and land mobile terminals should require less capability for broadband services. The upper channel objective is to support an HDTV service, while the threshold is to support the smallest data rate considered acceptable for integrated broadband multimedia at the time of system implementation. The data rate of 6 Mbps is equivalent to four ISDN Primary Rate or DS-1 interfaces at 1.544 Mbps and should support all basic multimedia services considering the compression techniques discussed earlier. The total throughput requirements for the small mobile broadband terminals correspond to DS-3/STS-1 and HDTV equivalent, respectively.

For personal/portable broadband communications, an even lower data rate of 1.55 Mbps is considered as a requirement. This data rate would be able to satisfy most personal multimedia needs while minimizing bandwidth utilization for potentially densely populated areas.

Channels. The mobile broadband terminals should be multi-channel with the capability to handle synchronous as well as asynchronous input channels. The possible number of active channels and or services per terminal will vary dependent upon terminal application and specific user needs. The mobile broadband system must be capable of providing a dynamic means of reconfiguration to suite site and multimedia configuration needs. The terminal should allow for reconfiguration of terminal ports to suite specific platform and interface requirements within the bounds of terminal throughput requirements. The mobile broadband terminal and satellite system should also provide the means of multiplexing and inverse multiplexing terminal ports where applicable to maximize system resource utilization. Other terminal and satellite channel requirements are dictated by interface and system utilization requirements listed below.

Connectivity. The mobile broadband system should provide global connectivity. The system should support point-to-point, point-to-multipoint (broadcast), and multipoint-to-multipoint (network) applications. The system shall be capable of routing individual data packets from source to destination through intelligent optimization of system resources, timing delays, congestion, and Quality of Service (QOS) parameters [35]. The system shall provide connectivity to PSDN gateways at selected fixed shore locations to provide complete connectivity from mobile to fixed users.

Accuracy. To maintain comparable performance with existing RF communications systems, the mobile broadband system should be capable of providing communications with a Bit Error Rate (BER) of at least 1×10^{-7} for clear sky conditions and 1×10^{-5} for degraded conditions (mitigation techniques for degraded conditions should be utilized). From a packet perspective, the system should maintain a cell-loss ratio of at least 1.7×10^{-9} across the network (corresponding to ATM requirements) [2].

System Delay. The performance of Multimedia services and ATM require low predictable delay due to both propagation and packet queuing at network nodes. Minimal delay and delay variation are essential for multimedia services to ensure acceptable interactive responsiveness and to maintain relative synchronization between media elements (e.g. voice and video) [36]. Because of inherent satellite propagation delay and potential digital signal processing delay, performance objectives for mobile broadband system must be relaxed from the ATM objectives (10^{-10} probability of > 250 ms) to more obtainable limits. System delay should also be on the same order of magnitude of transoceanic fiber optic delay (25 ms) to maintain marketability. Performance objectives for mobile broadband system delay are estimated as the following:

Maximum system delay	$\leq$ 90 ms	(terminal-to-terminal)
Maximum delay error	$\leq$ 10 μs	(single packet)
Maximum delay variation	$\leq$ 10 ms	(packet-packet)

Service Control. The mobile broadband system must provide an adequate call control capability to accept service requests, allocate resources, activate and deactivate services, and provide terminal numbering identification and locationing. The system must also be capable of offering different QOS levels and corresponding cost schemes (including capability of tracking usage and costs). This QOS will be capable of being applied to separate VCs from individual terminals regardless of VP. QOS must be negotiable at the time of system access or during network operations in response to system status/performance (i.e. dynamically reconfigurable). This service control capability must be compatible and integrate with the B-ISDN and AIN signaling system protocols at the time of system implementation.

Physical Requirements - Platform constraints and user needs drive physical requirements for size and weight of terminal equipment, as well as physical interfaces with baseband equipment and ancillary interfaces. Physical requirements for each application and/or platform are discussed below.

Size/Weight. To conform with platform restrictions and maintain marketability, the mobile broadband terminal configurations should conform to the size and weight constraints listed in Table 11. Exterior component sizes for the aeronautical and land mobile systems are due to the need for a low profile antenna system (particularly for the aeronautical system where drag is a major economical consideration). Interior component requirements were estimated based upon other current or planned mobile SATCOM equipment.

The mobile broadband satellite mass and payload-ready dimensions will depend upon final system design (specifically orbital height and number of satellites in constellation). Generally, the satellite system physical design should be driven by the most economical means of launching the constellation. This parameter will be a major cost driver for the entire mobile broadband system. Initial requirements are estimated at $\leq$ 500 kg for the complete satellite to lower launch costs and maintain marketability. This requirement will have to be re-assessed during system design for feasibility. The design goal is to be capable of launching multiple mobile broadband satellites at one time (as defined through a detailed LCC analysis).

Communications Interfaces. The interfaces provided and supported by the mobile broadband terminals should integrate with the future communications architecture. The terminals should provide the capability (by

Table 11 - Broadband Terminal Physical Requirements

SYSTEM APPLICATION	PLATFORM TYPE	WEGHT (lbs)			MAXIMUM SIZE	
		EXTERNAL	INTERNAL	TOTAL	EXTERNAL	INTERNAL
AERONAUTICAL	LARGE	90	100	190	≤ 6" H	19"x20"x9"
	SMALL	40	50	90	≤ 14" H	19"x16"x7"
MARITIME	LARGE	70	50	120	≤ 24" H	19"x20"x9"
	SMALL	40	50	90	≤ 14" H	19"x16"x7"
LAND MOBILE	LARGE	70	50	120	≤ 24" H	19"x20"x9"
	SMALL	30	35	65	≤ 14" H	19"x16"x7"
FIXED	LARGE	150	75	225	≤ 24" H	19"x24"x10"
PORTABLE	N/A	8	17	25	≤ 10" H	13"x15"x10"

use of separate line interface modules, if necessary) of providing some number of the following interfaces:

Medium Data Rate (MDR) Interfaces -
- EIA-530/RS-422
- RS-449
- ISDN - Primary Rate Interface

High Date Rate (HDR) Interfaces -
- FDDI Interfaces
- SONET optical interface
- B-ISDN interface
- HDTV digital interface

Support Interfaces. The mobile broadband terminals must provide support interfaces for position and stabilization information such as roll, pitch, heading, altitude, as well as latitude and longitude. This information may be provided via a digital GPS interface or through some other future position system interface. The terminal must also provide for power interfaces appropriate for each user platform which may range from 12 V DC to 208 V AC.

Utilization Requirements - The mobile broadband terminal system should be capable of continuous operation over a period of a month, in addition to being cycled on and off up to five times a day. These utilization constraints correspond to the extremes of operation (i.e. operating time within a platforms mission) of the maritime system, which may have to support a month long operations during a cruise or transport, and the sporadic daily use of a land mobile or aeronautical user. To maintain marketability, the system should be capable of operation within one minute of being turned-on and should be capable of communications within two minutes of requesting system access (satellite acquisition). Once the satellite system has been acquired, communications should be possible within 10 seconds after a request is initiated. The system shall be capable of maintaining the satellite link (acquisition, status monitoring, etc.) without the presence of active user communications (i.e., standby mode).

Operational Deployment - The complete objective for the mobile broadband system deployment would be aimed at global coverage and utilization. Complete coverage of the US and major Atlantic and Pacific ocean areas are defined as the minimum deployment. Worldwide deployment will depend upon frequency authorizations and licensing arrangements in foreign countries and the individual market demands. The support infrastructure for the mobile broadband system must also be located throughout the coverage area depending upon final market assessment and need for terrestrial gateways.

At least one System Control Facility (SCF) is required within the continental US (CONUS) for Tracking, Telemetry and Control (TT&C) of the satellite constellation as well as supervisory network management. A backup control facility maybe required within or outside of CONUS based upon final system configuration and deployment. Additional Network Management Facilities (NMFs) may also be required in multiple locations dependent upon final allocation of network management and control functionality between the space and ground segment. Fixed ground locations will also be required for network connectivity into public data networks. The number of these sites will depend upon total mobile broadband coverage, network optimization between satellite resources and ground network terminations, and communication regulatory rules at the time of implementation.

The quantity of satellites will be dependent upon final design and economic tradeoffs including number of replenishment or spare satellites. The quantity of terminals produced and deployed will again depend upon frequency authorizations and licensing arrangements as well as total market demand.

Operational Life Cycle - Based on current technology advancements and profitable electronic system life cycles, the operational life cycle of the mobile broadband system is projected at 15 years with a total development and production time of 8 years (including initial feasibility study and test phases).

Operational life-time includes initial system operation (with an incomplete constellation) through the end of usable operations as the last of the constellation dies off. Fifteen years is as long as is deemed practical for such a high dollar investment before newer more advanced technology could be deployed. The mobile broadband system satellites should be designed for a satellite lifetime of at least 5 years with the final design criteria based upon final orbital height.

Operational Effectiveness - The effectiveness of the mobile broadband system is expected to be governed primarily by the cost to utilize the system and the operational availability of the system to perform to achieve its stated performance requirements.

Usage Cost. The usage cost is perhaps the single biggest attribute of the mobile broadband system which will determine its market demand and profitability. Based on current or planned mobile communications/PCS prices, the initial usage cost target is $4/minute (in current year dollars) for continuous packet communications. This cost would be targeted to go down to $2.50/min within the first two years of system operations. This cost is comparable to or better than some of the existing or planned mobile communications systems such as INMARSAT B or P and IRIDIUM, but is considered realizable because of the decreasing cost and weight of high speed ICs and electronic components. Also, the Operations and Administrative Management (OAM) functions of the system should be configured to only charge the customer for actual packets communicated versus a flat rate. Charges for time spent acquiring the system, managing services, or being idle should be considered for separate cost schemes (e.g. flat charges per action or different rates than packet communication) such that the average cost for each platform application is comparable with corresponding land-based networks.

System Availability. System availability, within this context, includes the ability of the system to perform to its stated performance requirements (including down time for corrective actions), as well as maintain physical (LOS) and resource access to the satellite/base station system.

Because the LOS and environmental (weather degradation) conditions vary so widely for the different mobile broadband terminal configurations, the availability requirements will be listed separately for each of the systems as follows:

$$A_{o\,(aeronautical)} = 99.0\%$$
$$A_{o\,(maritime)} = 97.0\%$$
$$A_{o\,(land\ mobile)} = 95.0\%$$
$$A_{o\,(fixed)} = 98.0\%$$

These initial reliability requirements are identified considering the previous estimate of a 95% overall minimum reliability (for competitiveness), and the following individual platform considerations (i.e., estimate of how much better design can achieve above 95%). The aeronautical system availability is the highest due to normal operations at cruising altitudes where atmospheric affects are fairly constant and negligible compared to the other systems. The land mobile system availability is much lower than the others due to the probability of physical blockage to a mobile broadband satellite system and/or RF perturbations during its mobile mission profile. Land mobile availability exhibited will be higher if the mobile platform is stationary (and clear LOS) or traveling on clear terrain during its mission. Diversity techniques may need to be employed during the design of the mobile broadband system even to provide a 95% availability to the land mobile platform. All availability requirements listed above are at a 15° elevation angle to the satellite.

The Mean-Time-Between-Failure (MTBF) and Mean-Time-To-Repair (MTTR) of the terminal systems are initially set forth as the following:

MTBF = 4,380 hrs
MTTR = 1 hr

The MTBF is specified to accommodate at least six months of fault-free operation, which pertains to the longest mission of the big maritime platform (away from home port). This system MTBF would result in greater than 16 months of fault-free operation utilizing the system 10 hrs/day or less, corresponding to aeronautical and land mobile missions. The MTTR is estimated considering the complexity of the system and marketability to commercial providers. The MTTR includes time to diagnose and isolate faults to the LRU, replace, test and checkout, and reinitialize the terminal. The MTTR does not include time to obtain parts if not on-hand and assumes the utilization of Built-in-Test Equipment (BITE) to assist the maintainer in identifying and isolating the failed part to the Line Replaceable Unit (LRU).

Environmental Requirements - Environmental requirements which should be fully specified include temperature, humidity, inclination, vibration, solar radiation (satellite segment), and sea effects (e.g. salt spray) among others. Requirements should include minimum and maximum values, as well as cycles or maximum rate of changes where applicable. Requirements should take into account the Packaging, Handling, Storage, and Transportation (PHS&T) environment in addition to the operational environment. These requirements will not be specified within the scope of this limited design.

System Maintenance Concept

The maintenance concept for the mobile broadband system will be defined separately for the satellite/base station, terminal, and system control segments. This is due to unique environmental and operational conditions of each of these segments and their associated impact on system operational availability. The maintenance concept outlined below is based upon fulfillment of previously defined operational requirements, system economic/marketability projections, and subjective reasoning.

Maintenance Levels - There will be three maintenance levels for the mobile broadband system supporting each of the three system segments as shown in Figure 5. This concept will best provide for ease of operational use while fulfilling the stated operational availability requirements. Personnel expertise will be assigned to reduce the operational burden at user locations while requiring more expertise for critical maintenance support areas (e.g. system control segment).

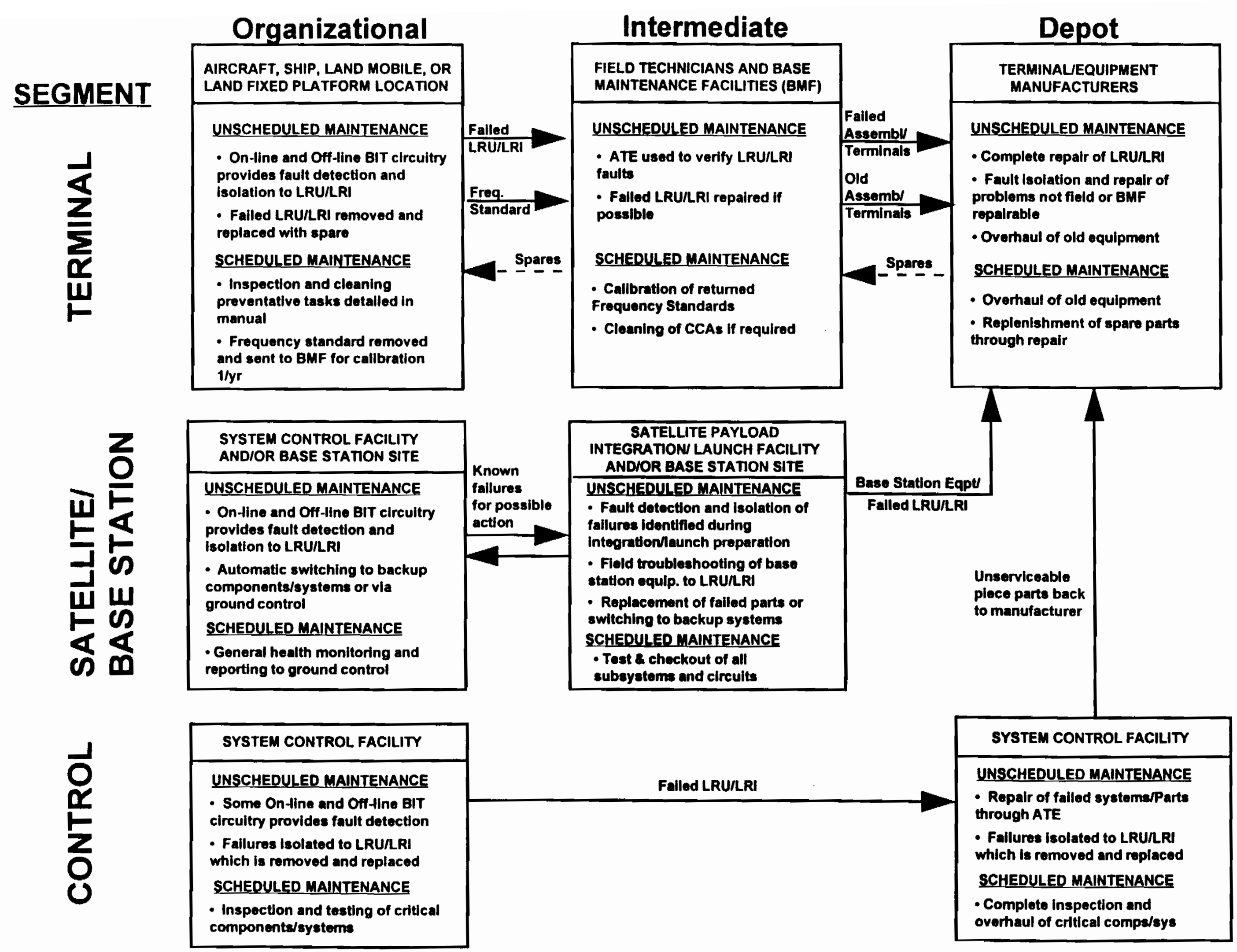


Figure 5 - System Maintenance Concept

Organizational Maintenance. Organizational maintenance would consist largely of Built-in-Test (BIT) within the equipment to perform self tests during system initialization and to provide constant on-line monitoring of subsystems and interfaces to identify and isolate failures. For terminals, specific failures requiring the replacement of Line Replaceable Units (LRUs) which do not require special testing could be performed in the field if the appropriate spare LRU is on-hand. The satellite/base station system should have adequate backup capabilities to be capable of switching to spare components and subsystems in the case of a failure. This backup switching capability should be both automatic and manual (from the system control facility) depending upon the criticality of the failed item. Organizational maintenance of the system control facility will also consist of some level of BITE. However, the system control facility should be manned with sufficiently trained technicians at all times to eliminate the need for intermediate maintenance (i.e., intermediate maintenance done at operational level).

Intermediate Maintenance. Intermediate maintenance facilities for the mobile broadband terminals would be comprised of deployable field technicians and Base Maintenance Facilities (BMFs) which could handle routine repairs on parts, components, and subsystems not repairable in the field. These intermediate BMFs and staff could be part of the terminal manufacturers field support, be part of the customers existing field support, or could be totally separate support organizations who are knowledgeable on the mobile broadband system and various terminals. Field technicians could utilize the information provided by the failed terminals BITE (via the terminals operator) to identify parts/LRUs that might be required to fix the problem. Failed parts retrieved by the field technicians would be cycled back to the depot facility for repair if not serviceable at the BMF which would have some Automated Test Equipment (ATE). BMFs would require a means of deploying field technicians to locations world-wide including at-sea. There is no intermediate maintenance required for the control system segment as qualified technicians would be on-hand operationally. The satellite system segment would consist mostly of operational maintenance through automated on-board systems or via remote control through the control segment. There would be some level of intermediate maintenance for the satellite system back from the payload integration phase which would be supported by technicians providing feedback into the operational system. Base stations for a potential cellular segment of the broadband mobile system would be periodically inspected on-site and would be repaired by field technicians in case of failure.

Depot Maintenance. The Depot level maintenance would be performed by the actual terminal manufacturers for mobile broadband terminals and transmission equipment (for cellular base stations). Failed subsystems or whole terminals would be sent to the manufacturer by intermediate maintenance facilities who could not repair a problem or directly from the user in the case of a critical failure. The reliability of the individual subsystems of the mobile broadband terminal should be such that depot level repair on whole subsystems should not be common. There would be no depot level maintenance on the space segment of the mobile broadband system. Satellites with critical failures (loss of operations) would be replaced in orbit by spare satellites. Depending upon final orbit type/height chosen, the constellation will include a specific number of on-orbit as well as on-ground spare satellites.

Logistic Support - Other logistic elements must also be considered and provided during the mobile broadband design, production and deployment. Some of these items are discussed below.

Spare Parts. Additional LRUs, parts, and sub-assemblies should be planned and manufactured to provide additional parts for the spare supply system. Sparing models should be developed and analyzed during the design of the mobile broadband terminals to identify high failure rate and critical system components which should be spared. Large commercial organizations utilizing the system may want to procure additional parts to retain on-board the platform or at central hub facilities.

Documentation. Operational and repair documentation would need to be developed by the terminal manufacturers before deployment of the system. An overall technical document on the mobile broadband system should also be developed to support the training and reference needs of the intermediate and depot facilities. Terminal operational manuals should be written at a non-technical level for the potential non-technical system operators. Operational manuals for the system control segment must also be developed. These manuals can be more technically oriented and may take the form of operational procedure manuals and wiring diagrams.

PHS&T. Packaging, Handling, Shipping, and Transportation (PHS&T) elements must also be addressed during design. This is of particular importance to the mobile broadband satellite system which must be safely transported to the appropriate launch facility and transferred into the launch vehicles payload. The satellite's physical and packaging design must take these issues into consideration. Mobile broadband terminals should be packaged such that physical and environmental conditions during shipping do not exceed those planned for operations. Terminal PHS&T from the manufacturer to sales facilities and/or users locations, as well as from users back to the BMFs and depot, must be addressed.

Training. Operations and maintenance training will be required for all three segments of the mobile broadband system. Terminal operations training could be conducted at the terminal manufacturers facility or on-site after system installation via On-the-Job Training (OJT). Maintenance training would be conducted at the terminal manufacturer's and subsequently at BMFs (after specific staff members are sufficiently trained). Operations and maintenance training for the system control and satellite segments would be taught on-site at the main system control facility.

Test Equipment. Special test equipment may need to be developed or procured to meet the unique needs of the mobile broadband system. Specifically, any RF test equipment required may not be readily available on the market since the mobile broadband frequency range may be unique. Investigation into this area should occur early enough into the mobile broadband design to identify special test equipment needed for the test and checkout, operation, and maintenance of the mobile broadband system.

Maintenance Effectiveness - The effectiveness of the system support capability should meet the MTTR of 1 hour and maintain the operational availability of each of the terminal systems. Other requirements which could be specified include supply efficiency and personnel efficiency; however, these requirements would best be set by the appropriate terminal manufacturers.

Preliminary Systems Analysis

Preliminary systems analysis for the mobile broadband system will include identification of system alternatives, definition of evaluation criteria, development of system models, and evaluation of the alternatives. The problem at hand is assumed to have been adequately defined in the previous sections.

Alternatives - Based upon the feasible approaches identified earlier and the operational requirements defined, there are four mobile broadband alternatives which will be considered:

1) LEO Satellite System
2) MEO Satellite System
3) Hybrid LEO/Cellular System
4) Hybrid MEO/Cellular System

The hybrid systems are those which utilize a cellular segment to support land and aeronautical (over land) platforms and a satellite segment to support maritime and aeronautical (over water) platforms in an integrated manner. The definition of these alternatives is based on a single company/entity solution to this deficiency (i.e., single "system" solution).

Evaluation Criteria - There are many system design and performance parameters which could be chosen to evaluate the mobile broadband system at each of the various design stages. For example, at the detailed design level, the performance of all relevant system requirements should be analyzed to ensure they are satisfied. At the system level and throughout the entire development cycle, the following key criteria are identified and will be assessed:

1) System Throughput
2) System Delay
3) System Availability
4) System Complexity
5) System Costs

These parameters encompass many other system attributes (e.g. satellite cost included in utilization cost) and are considered to be the key attributes in defining ultimate system profitability. System delay and variation encompasses all signal processing, routing, and queuing delays designed into the system and corresponding effectiveness of the network routing control. Delay variation is important in that individually routed cells should vary no more than 10 ms to ensure that audio and video components (as well as other related graphics and data) maintain sync from a user perspective. This is the type of parameter that would help determine the systems Mean Opinion Score (MOS), which is a relative user scale for assessing the quality of audio-visual communications [6]. These parameters will be utilized initially in evaluating system alternatives and should be re-evaluated at key development points for design (e.g. all design reviews) and for business (e.g. finance marketing) considerations.

System Modeling - Due to the lengthy lead-time and associated finances required before the mobile broadband system can realize profits, system modeling is a critical element of system development. Modeling must not be limited to technical system or sub-system parameters. What is needed to ensure the development of a profitable system is a complete system planning model which includes or considers the following [37]:

1) Key technical parameter tradeoffs
2) Operational capabilities/performance
3) Market Influences
4) Physical and regulatory constraints
5) All Life Cycle Cost (LCC) Components

A conceptual system model encompassing many of these elements for a SATCOM implementation of the mobile broadband system is shown in Figure 6. This model depicts the key system variables and constraints in the areas discussed above and their causal interactions. This diagram can be used to identify key decision variables and system interactions which must be considered when modifying certain aspects of the system. This model could also be used to define the impact of changes in market demands (and subsequent operational parameter changes) over the course of the development period. Since the initial system design is to fulfill projected market /operational requirements, this is considered essential.

For the sake of simplicity, the system control, satellite, and terminal complexity variables are used to include many additional design variables/decisions. These include the following:

System (all):	Modulation/Encoding Error Detection/correction scheme Access methodology
System Control:	Control Concept (centralized, distributed, etc.) Control terminal requirements (quantity, reqs, etc.) Network Management capabilities/reqs (software)
Satellite:	On-Board Processing capability Antenna technology/complexity Microwave component technology/complexity Power Subsystem complexity Command & Control (C2) system complexity
Terminal:	Built-in Processing capability Antenna technology/complexity Microwave component technology/complexity Data Interfaces

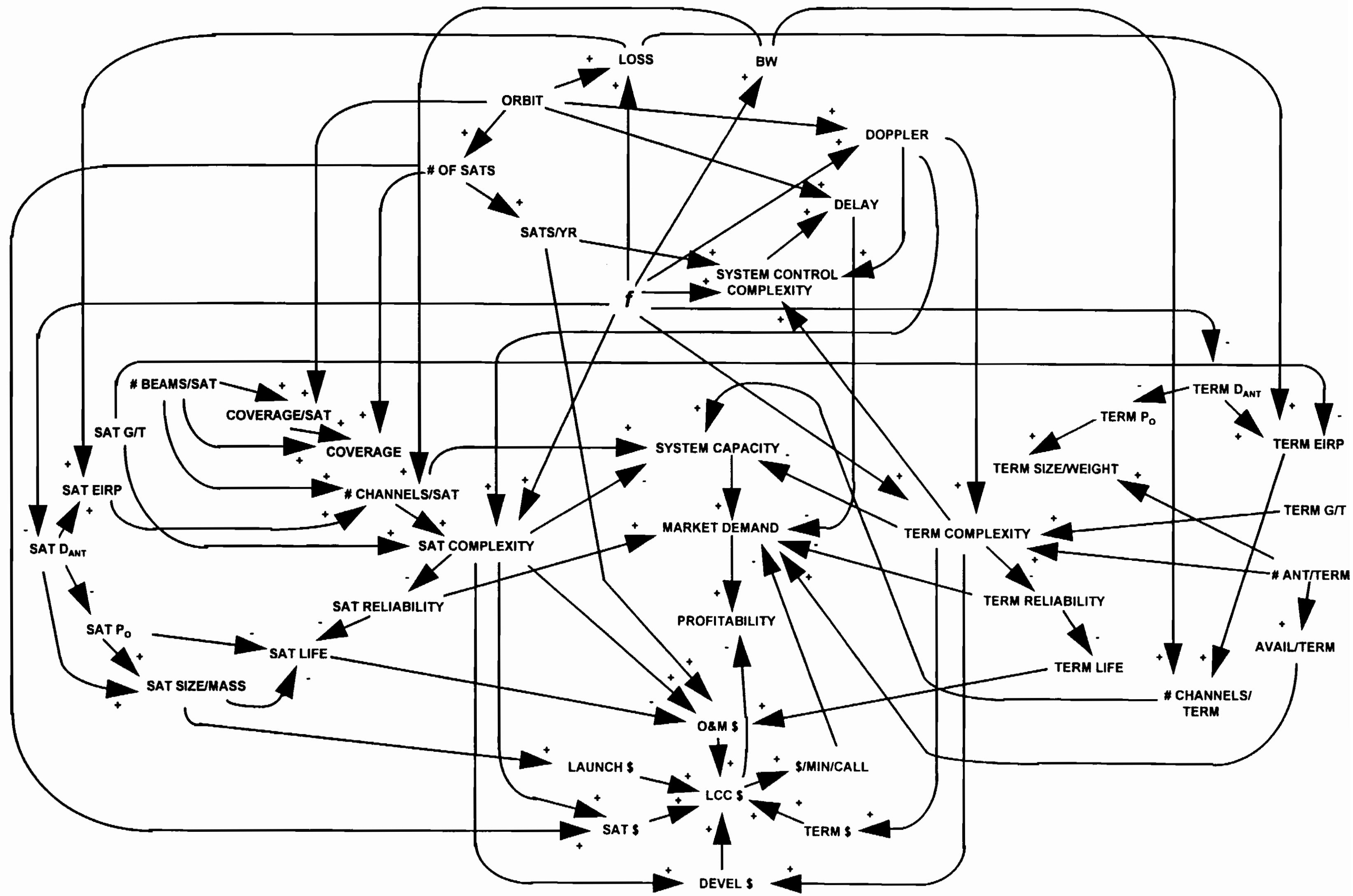


Figure 6 - System Model

This model could be fully defined during actual preliminary design and optimally solved using geometric programming methods (deemed out-of-scope for this report). The objective function of this model could be system profitability with the key variables and constraints to include the following:

Variables:	Frequency
	Orbit
	BW
	Satellite G/T
	Satellite EIRP
	Terminal G/T
	Terminal EIRP
Constraints:	Loss
	Doppler
	Delay
	Power
	Market Demand

System costs include those projected for all phases of the systems life cycle. A Life Cycle Cost (LCC) breakdown structure considering all cost elements is depicted in Figure 7 [1]. System cost can be broken out into four major categories corresponding to the four main phases of the system life cycle: development, production, implementation, and operations & maintenance. Major cost drivers expected for the mobile broadband system would be system prototype development & test, satellite launch and insurance (including replenishment), and approval/licensing fees. These and other elements will be considered during the system alternative evaluation and for development of a LCC analysis presented later.

Other mobile broadband design models should be developed to analyze and tradeoff performance parameters during the conceptual design and throughout the preliminary and detailed design phases. These include:

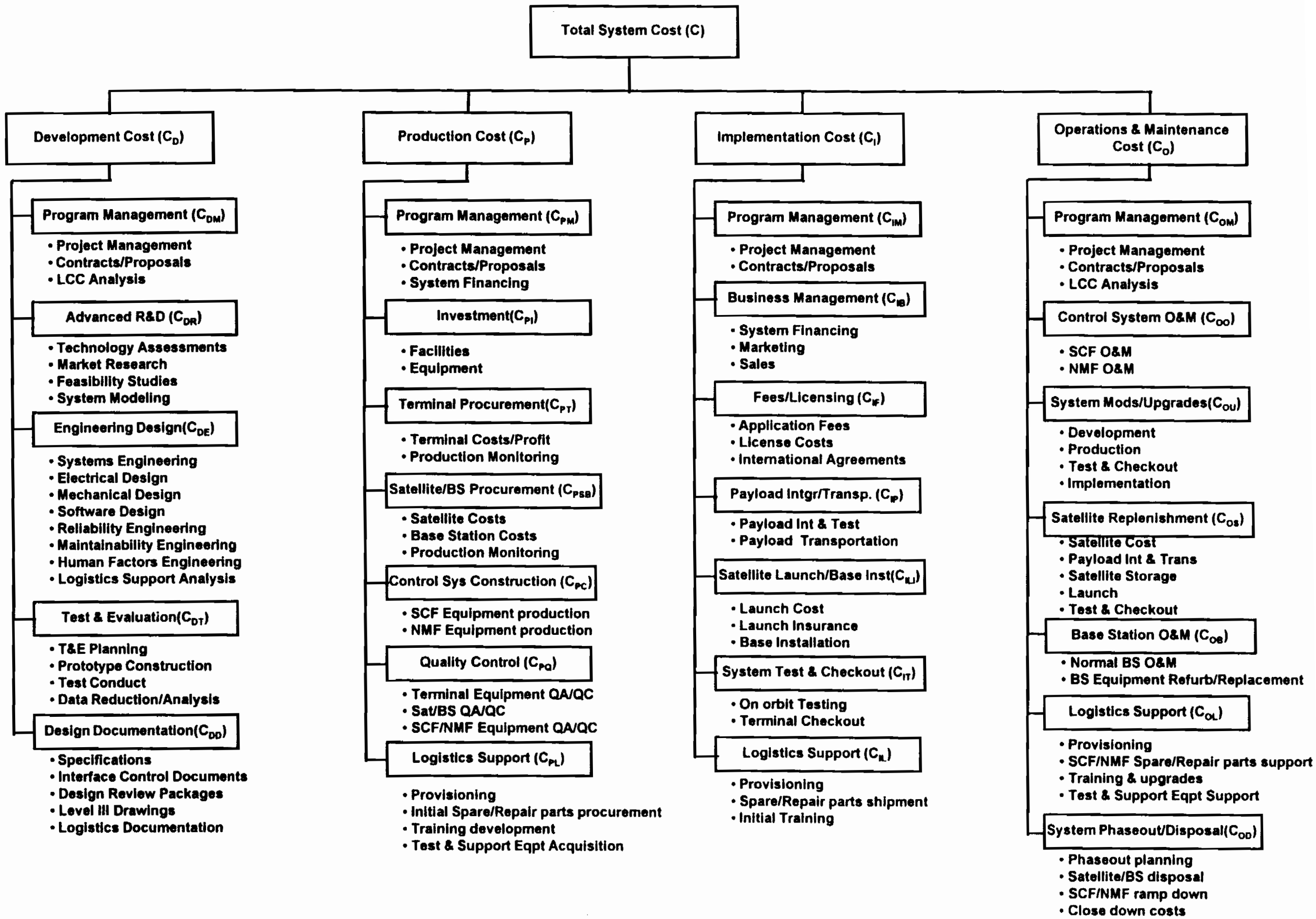


Figure 7 - Life Cycle Cost Breakdown Structure

1) Satellite constellation model (coverage, tracks, etc.)
2) Communications traffic model (throughput, blocking, delay, etc.)
3) Satellite link model (dynamic link budget analysis)
4) Acquisition/tracking performance model (pointing control and frequency/time tracking analysis)

Some elements of these models will be utilized to analyze and evaluate design tradeoffs discussed hereafter. Other tradeoffs/analyses requiring the use of these models will be identified where applicable.

Alternative Evaluation - System alternatives identified during the feasibility study phase will now be initially evaluated based upon the criteria and models developed above. This evaluation will be performed at a qualitative level through the use of relevant quantitative considerations. Table 12 depicts the results of a system alternatives evaluation based on a rating indicator from one through five (with one being the best). Each of the five major criteria have been subdivided as appropriate to fully evaluate the alternatives. An overall alternative rating is derived from this analysis (subjectively, not mathematically) considering these criteria and a single integrated system approach. A brief discussion of the alternative evaluation is provided below. It should be noted that some of the ratings derived through the evaluation are based upon educated assumptions and judicious reasoning, in conjunction with known characteristics and models. A complete quantitative evaluation would be required in order to undeniably prove the following observations and conclusions.

Based on cost and complexity and the specific needs for this system, the integrated hybrid alternatives are not selected. It is estimated (based on LCC model) that the increased cost due to required base stations and their supporting network, would not outweigh the savings found from potential reduction in number of satellites (thereby increasing costs). There is also expected to be an extremely large land-based market demand for low-end services, increasing the need for cellular service for densely populated areas. This need may best be

Table 12 - System Alternative Evaluation

Alternative	Throughput		System Delay		Avail	Complexity			System Cost				Overall Rating
	Data	#/Area	Maximum	Variation		Control	Sat/BS	Term	Dev	Prod	Impl	O&M	
LEO Satellite	2	2	1	1	2	2	2	2	2	2	3	2	1
MEO Satellite	4	4	3	3	4	1	1	1	1	1	1	1	2
Hybrid LEO/Cellular	1	1	2	2	1	5	4	5	4	4	4	5	4
Hybrid MEO/Cellular	3	3	4	4	3	4	3	4	3	3	2	4	3

Rating: 1 - 5 with one being best and five being worst satisfied by another communications system which provides single channel low quality multimedia service at data rates $\leq$ 2 Mbps as the third generation cellular system (vis-a-vis UMTS/FLMPTS). Another implementation consideration for the hybrid alternatives is that licensing would prove difficult for a hybrid system with global coverage (i.e., single system approach).

Although the MEO satellite alternative would be the least costly, there is question as to whether the throughput, delay, and availability performance would satisfy all system requirements and/or provide system profitability. The LEO satellite system is therefore chosen as the best alternative. The MEO option will be re-evaluated during preliminary design for consideration. Because we have narrowed the design selection down to a satellite-only system, we can now select a name for the system. Because of the intelligence which is assumed to be required in order to fulfill the stated operational requirements, the future mobile broadband system will hereafter be referred to as the Mobile Intelligent Broadband Satellite Communications (MIBSAT) system. A high-level conceptual diagram of the MIBSAT system is depicted in Figure 8.

Advanced System Planning

Advanced system planning for MIBSAT includes development of a Program Plan and System Engineering Management Plan (SEMP) for system management, as well as development of a system technical specification [1]. This planning and documentation development would culminate in a formal conceptual design review.

Management - The MIBSAT system would be designed and developed through a systems approach which relied heavily on concurrent engineering practices and sound program management based on continual schedule, LCC, and risk assessments and analyses. Some of these initial management areas and plans are discussed below.

Program Plan. A proposed MIBSAT system program development schedule is shown in Figure 9, taking into account the projected marketability

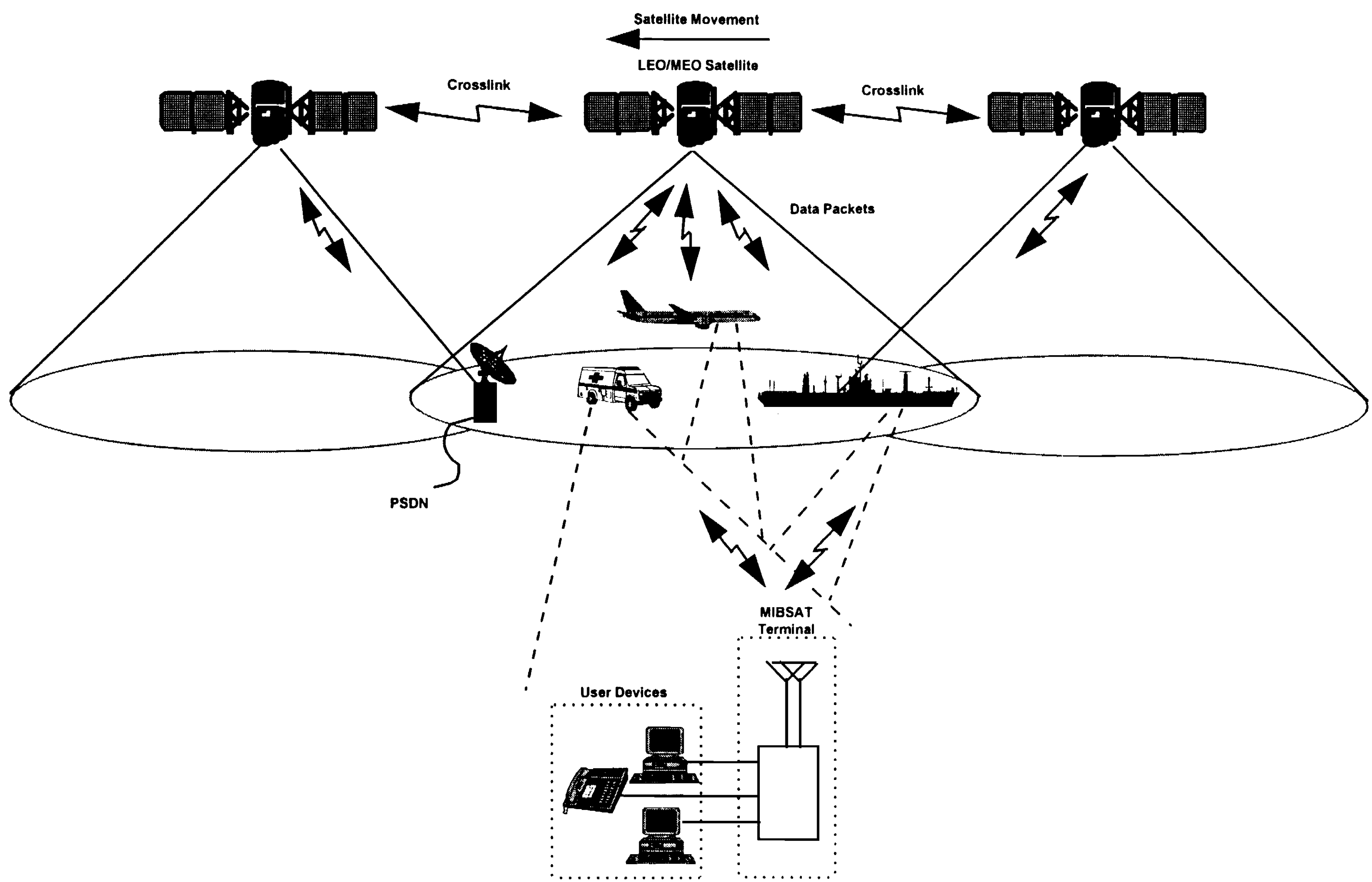


Figure 8 - System Conceptual Block Diagram

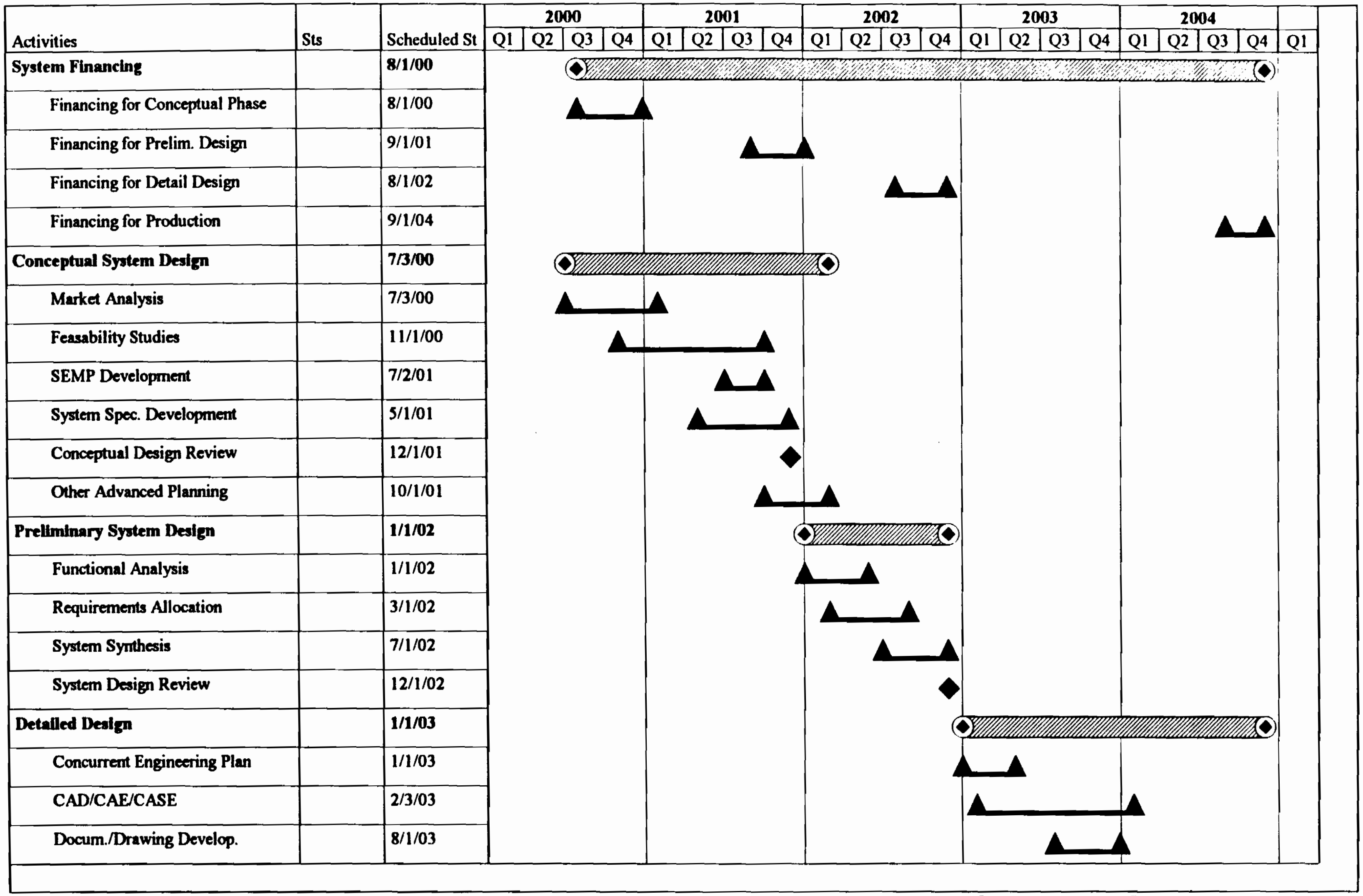


Figure 9 - System Development Schedule

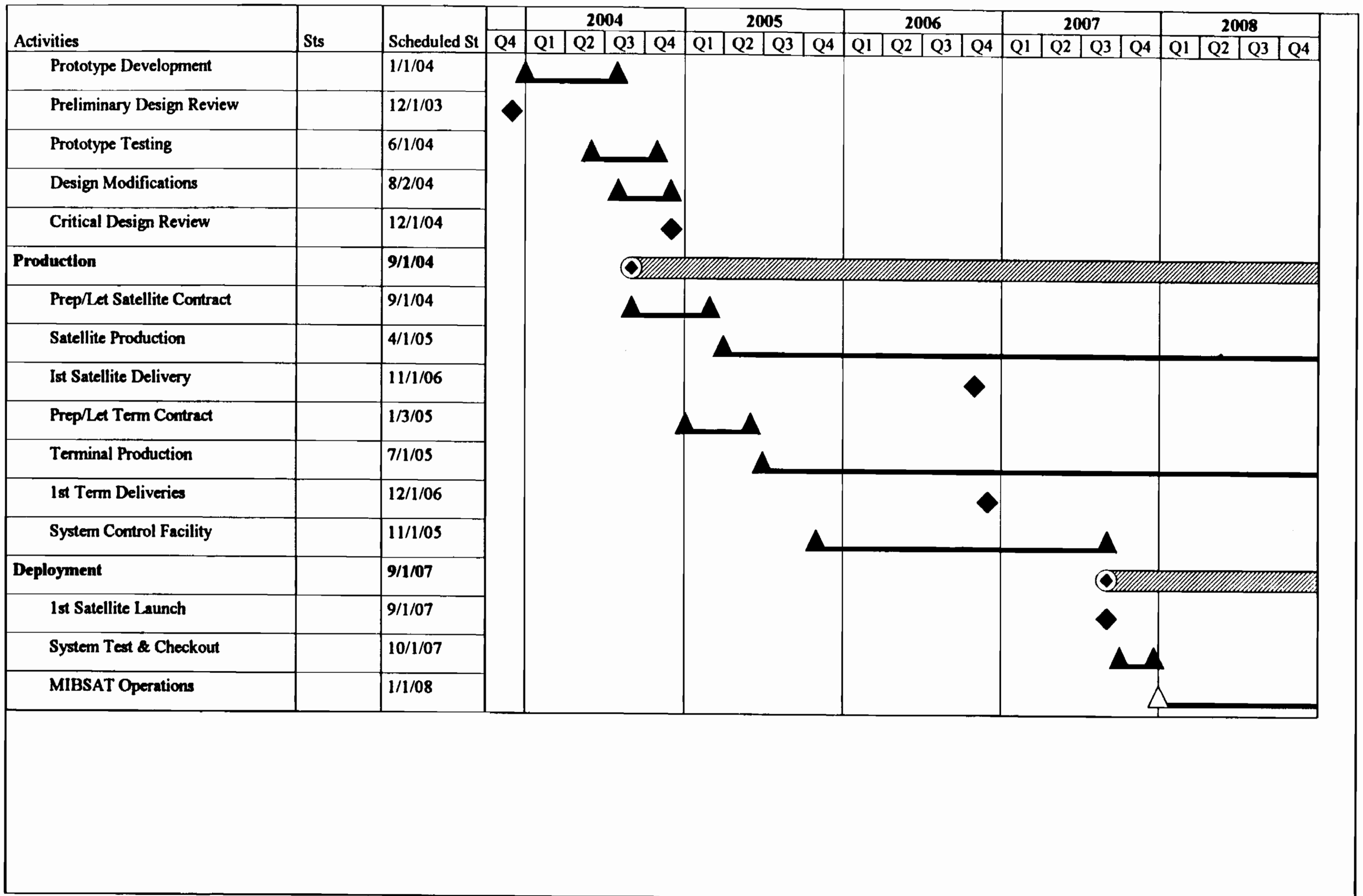


Figure 9 - System Development Schedule (cont'd)

timeframe of 2008 and assuming an eight year development period. This entire schedule could be shifted by as much as seven years later based on preliminary subjective estimates. The MIBSAT system should be designed through a phased development cycle in order to segment financing required for the system into manageable lots. This development phasing would provide a means for re-assessing MIBSAT feasibility and marketability at key development points (such as after key design reviews).

The MIBSAT system developer would design the overall system and specify requirements for both the satellite and terminal systems. Production of the satellites would most likely be contracted to a satellite manufacturer. Production of a small number of earth terminals would also be contracted out to help spur the initial introduction of the system. Quantities of each platform terminal configuration would be based on a detailed market analysis and budget constraints. Due to the expected transition of user demand (i.e., commercial transportation, government, etc.), it is not considered economical to procure portable terminals initially. Potential demand for these terminals would most likely come later. The MIBSAT developer would also design, build, and operate the system control facility, as well as control overall utilization of the system.

In order to obtain accurate design performance data and demonstrate system functionality to potential investors and customers, a prototype satellite (or satellites) would also be developed and tested during the detailed design phase. Data obtained from this test model would be used to finalize system design and specifications before final satellite and terminal production contracts were issued.

Life Cycle Cost (LCC). In considering an investment strategy for a system as significant as the MIBSAT system, a complete LCC analysis should be performed during conceptual design and throughout the rest of the MIBSAT development cycle (at key design milestones). The LCC must take into account all development, prototype production, satellite and terminal production, system control segment development, and initial launch resources. The LCC analysis must also include system operations and maintenance costs including satellite control facility operations, satellite replenishment, and system upgrades as outlined in the LCC breakdown structure. A preliminary LCC model is developed and analysis provided as Appendix B based upon cost estimates and projections of the MIBSAT design contained herein. This LCC analysis includes a sensitivity analysis of key system, satellite, and launch variables and constraints, to characterize and document the impacts of these parameters on total system cost. This data could be used when trading off system design options and considerations.

Risk Assessment. Risk assessment models should be used during initial system design and prior to major finance milestones to evaluate the overall risk of continuing with system development. These models should be continually refined during the development process to add in areas of certainty when known. Besides the general issue of system profitability, another issue requiring risk assessment early-on in system design is that of spectrum allocation, orbit allocation, and licensing agreements.

SEMP. The increasing complexity of electronic systems and competition in the global marketplace has necessitated the need to implement concurrent engineering techniques throughout the systems realization process. The System Engineering Management Plan (SEMP) would define the concurrent engineering organization and processes for efficient program planning and control, fulfillment of system engineering objectives as they relate to system requirements, and engineering specialty integration requirements. The SEMP would include details of how system development will consider design for manufacturing, test, reliability, maintainability, etc., as well as defining what communications media and support will be used to ensure the effective flow of information.

Technical - A MIBSAT System specification would be developed during the conceptual design and used as a baseline for the preliminary and detailed design phases. The system specification would be updated and refined during the development cycle through a tightly controlled Configuration Control Board (CCB). This board would be comprised of engineering and management representatives from all areas of the program. The system specification will define and control all system-level performance and effectiveness requirements. The system specification should not only consider system development changes from within, but should also monitor outside documentation and events for possible system impacts (e.g. monitor conformance to B-ISDN specifications as defined by the ITU-T/ATM Forum).

Preliminary System Design

The preliminary design phase for the MIBSAT system will include detailed functional analyses, allocation of functions and parameters to specific components of the MIBSAT system, and tradeoff and optimization of system parameters and design options. Functional analysis and allocation are presented at a high-level to demonstrate the systems engineering process as it applies to the development of the MIBSAT system.

Functional Analysis

MIBSAT functional analysis will include the definition and documentation of all operational and maintenance related actions required to perform system objectives. Functional analyses presented below concentrate on the MIBSAT terminal system.

Operational - An operational functional flow diagram for a MIBSAT terminal is shown in Figure 10. This diagram depicts the system development flow as the first level and then the highest level of operational functions for one of the MIBSAT mobile terminals. A similar functional breakdown for the satellite and control systems would be required with functional inter-relationships being defined (e.g., frequency/time tracking). The operational flow for the mobile terminal is further detailed for the communications function of operations. Not detailed in this limited flow diagram is the inter-beam and inter-satellite handoff for which continuous tracking and control would be required (this function would be detailed under function 11.2.8). Detailed diagrams charting all functions for

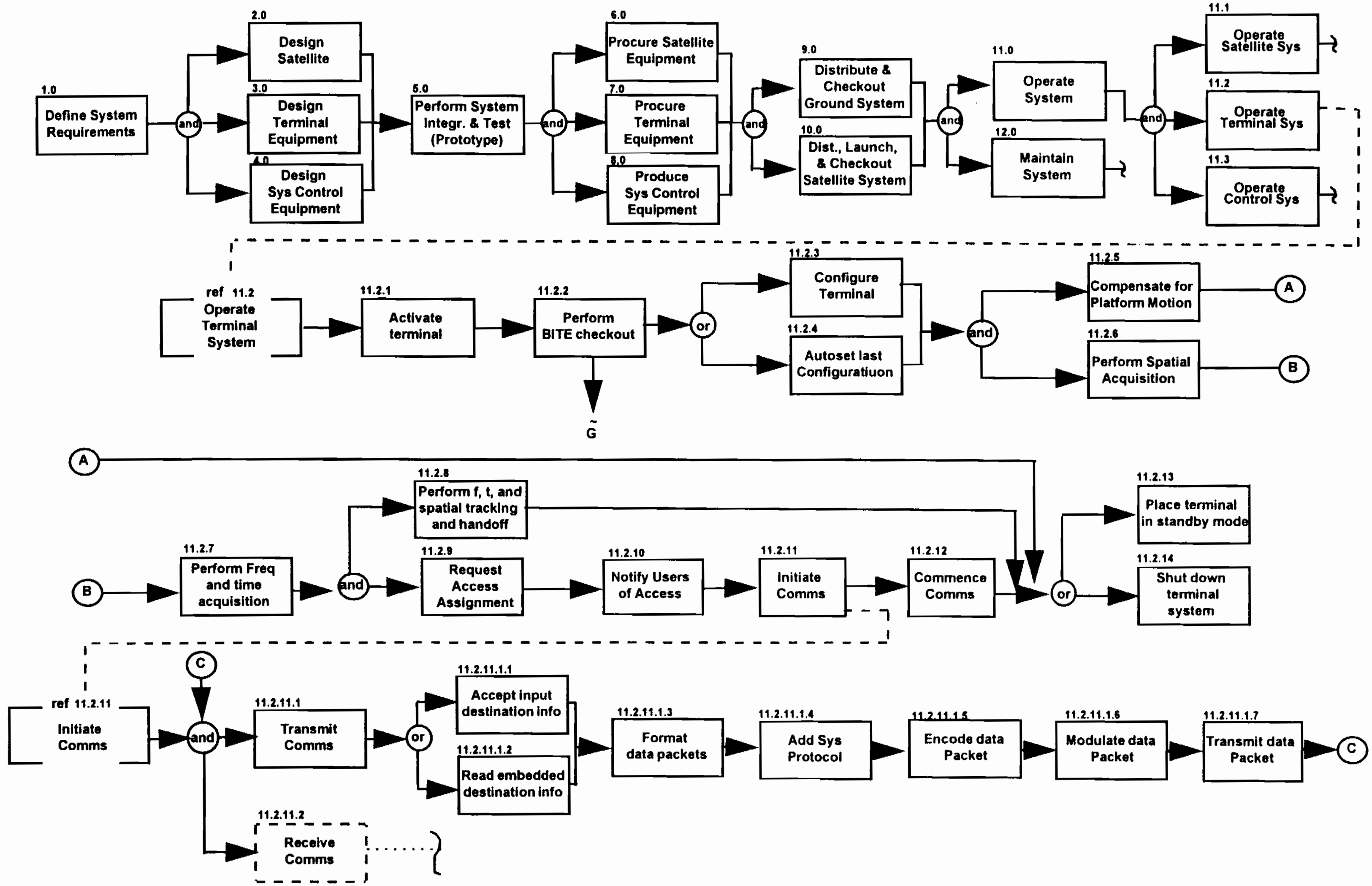


Figure 10 - Operational Functional Flow Diagram

each of the main functions shown in the figure would be required for a complete design. This high-level functional flow highlights some of the potential intelligence (software embedded) required for the terminal system in order to reduce operator requirements.

Maintenance - A maintenance functional flow diagram for a MIBSAT terminal is shown in Figure 11. This diagram details the BITE and BIT functions required for continuous monitoring and isolation of faults. Maintenance functions previously defined through the maintenance concept are incorporated into the functional flow for the identification, isolation, and repair of faulty LRUs and LRIs. Further expansion of this high level maintenance flow diagram would be used to completely define the assignment of tasks to the system (e.g., BITE), operational personnel, or maintenance personnel. Detailed diagrams charting all functions would be required for a complete design.

Functional Allocation & Packaging - The operator and maintenance functions defined in Figures 10 and 11 can be reformulated by system operational mode to perform functional allocation and develop packaging concepts. The MIBSAT terminal functional allocation and packaging scheme is shown in Figure 12. This diagram considers initialization, acquisition, and communications as the three MIBSAT terminal modes of interest. It can be seen that several of the functions required in each of these modes are similar but that each mode also contains unique functions. Providing power to each of these functions is required but not depicted since it is common to all functions.

The MIBSAT terminal will be comprised of three functionally separate groups with minor differences between the groups depending upon platform application. The need and purpose of each of the three groups can be readily explained from the functional flow diagram and based on physical restrictions in fulfilling system requirements. The MIBSAT processor group must be located somewhere close to the user or at least in a suitably manned or controlled space. The MIBSAT antenna group must obviously be located on the external of the platform to acquire and maintain access to the MIBSAT satellite segment. The MIBSAT antenna group must also be comprised of at least two antennas to

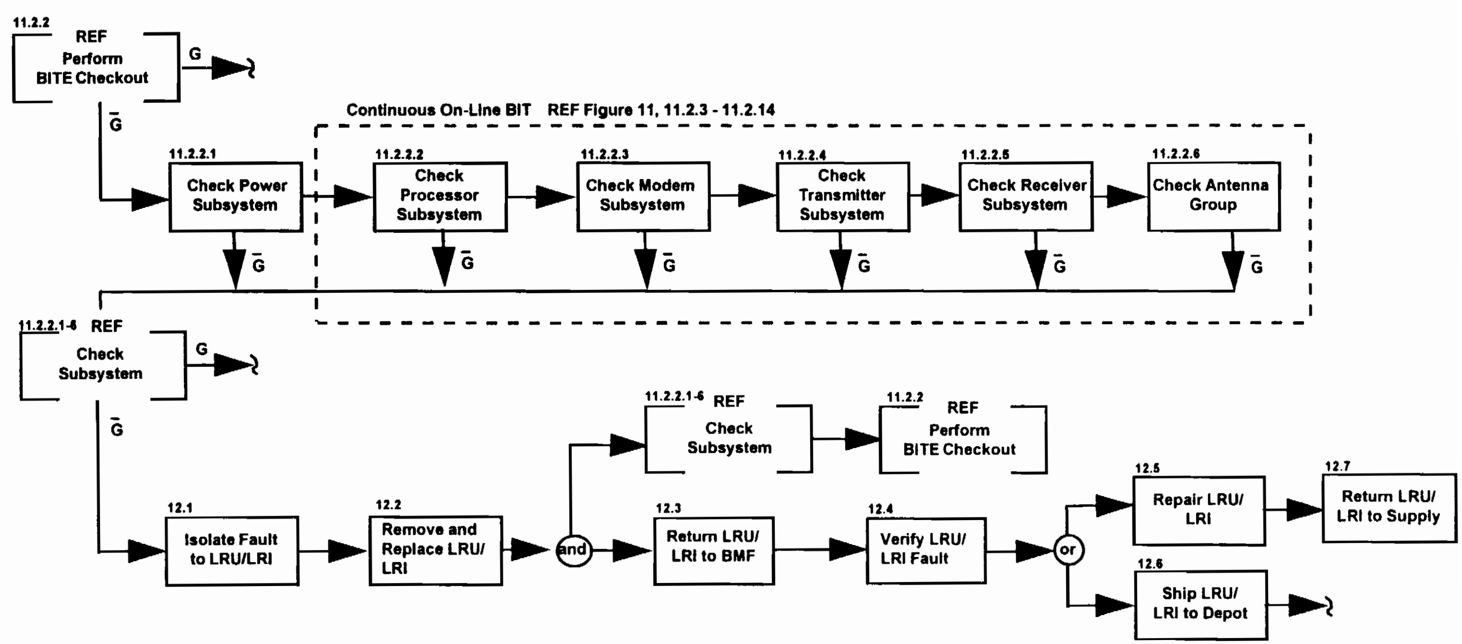


Figure 11 - Maintenance Functional Flow Diagram

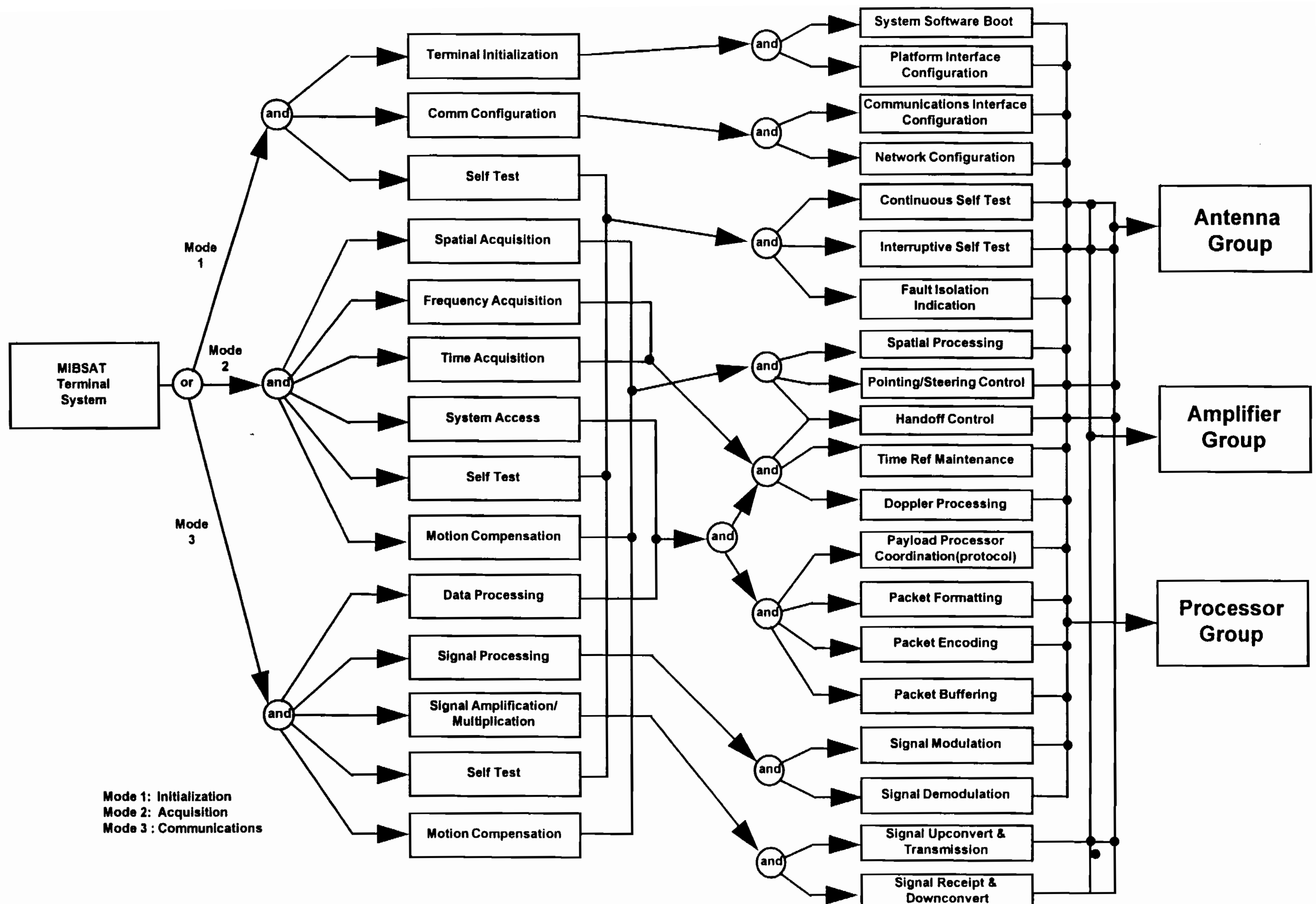


Figure 12 - MIBSAT Terminal Functional Allocation & Packaging

actively track multiple satellites simultaneously. One antenna system will always be the "active" antenna with handoff occurring between the antennas to maintain continuous communications. The amplifier unit is potentially required as a separate unit to locate close to (or be part of depending upon situation) the antenna to minimize power loss between the amplifier and the antenna. The amplifier unit could also be part of the processor unit if power loss or heat dissipation are not considered to be problems. Based upon the possibility of needing it, the MIBSAT terminal system will be defined considering a separate amplifier unit whose functions could be incorporated into other units later in the design process, if required.

Requirements Allocation

Overall system requirements must be allocated to the respective segments, systems, and subsystems of the MIBSAT system based upon the defined system requirements and results from detailed functional analyses. These requirements would be allocated to all equipment and support areas of the MIBSAT system, as applicable. A preliminary requirements allocation is shown in Figure 13. This figure displays the organization of the MIBSAT system and allocation of key design parameters from system down to subsystem requirements (breakdown shown for one terminal system only). It can be seen that different parameters are required at various levels of the allocation tree to specify but not bind subsystem requirements while still fulfilling overall system requirements. To complete the allocation, a comprehensive functional analysis would have to be conducted which is considered out of scope for this project.

System Design Tradeoffs

There are numerous design tradeoffs which would be required during the preliminary design of the MIBSAT system. Some of these key design tradeoffs and considerations are identified and discussed below at the system-level. System-level tradeoffs correspond to those parameters which affect all three segments of the MIBSAT system (satellite, terminal, and system control) and define the essential operating characteristics of the MIBSAT system. System

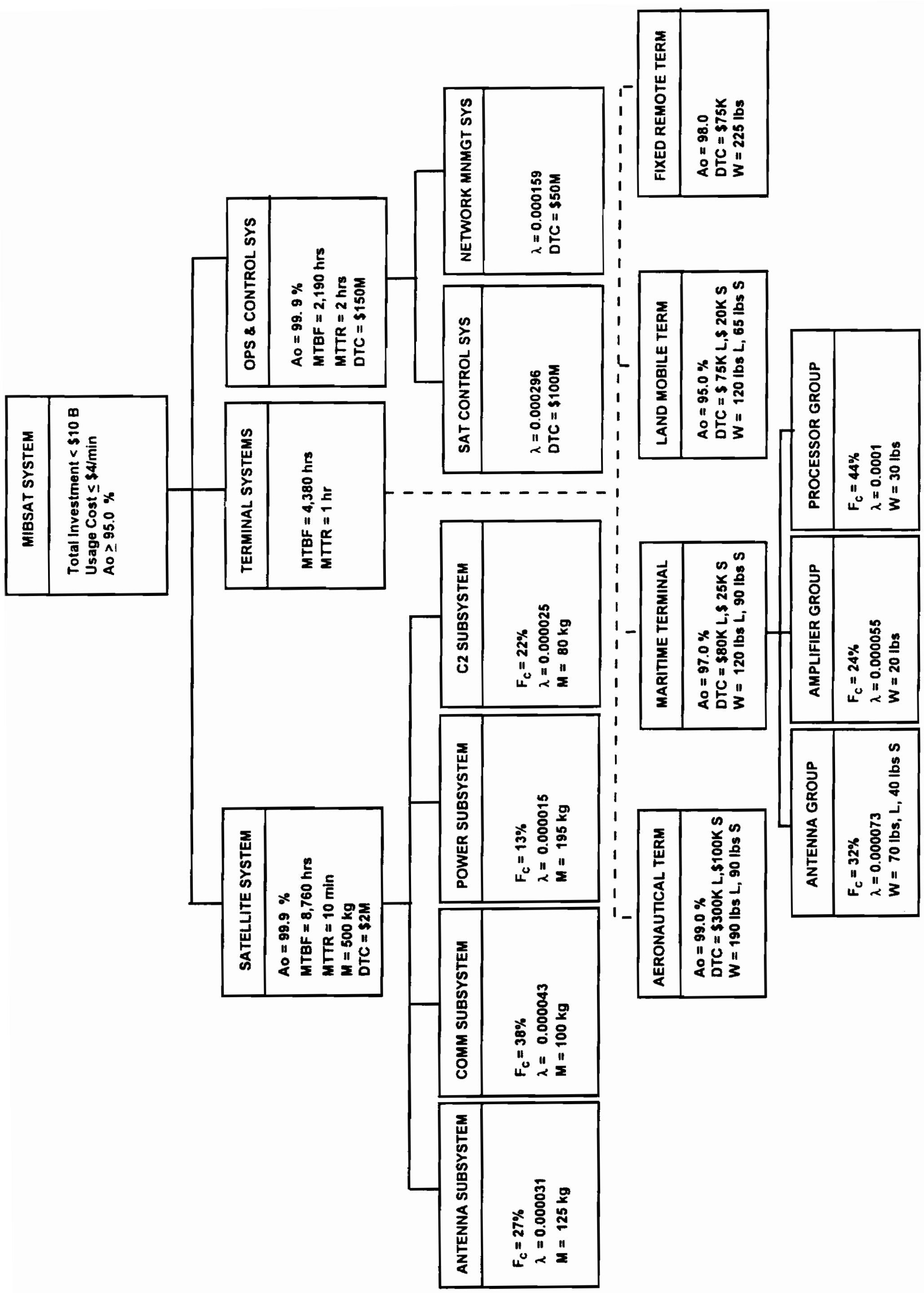


Figure 14 - MIBSAT Requirements Allocation

design tradeoffs include (among others) frequency band, satellite orbit, system connectivity, system control and management methodology, system access methodology, link budget, and rain mitigation techniques, which are addressed below.

Frequency Band - As identified previously, there are presently three bands which appear to be available to support the MIBSAT system requirements. To select which of these bands is preferred we will consider and tradeoff the following factors:

- Bandwidth provided (i.e. user capacity)
- Attenuation characteristics (free space, rain, and atmospheric)
- Relative Antenna Gain
- Antenna requirements
- Electronics technology requirements
- Locationing Potential

The frequency tradeoff analysis is shown in Table 13. Due to an increase in O_2 absorption at 71-74 GHz, there is not a significant loss due to attenuation as compared to the next higher band (with a 66% increase in channel capacity). Although bandwidth is significantly increased for the 138/97.5 GHz band, the additional atmospheric loss and increase in hardware complexity also rules out this band. Although there is some technology risk associated with antenna and electronics requirements, the best design choice for the MIBSAT frequency plan is chosen as 95-100 GHz for the uplink and 81-84 GHz for the downlink. This band also has the additional feature in that the 95-100 Ghz range is also allocated for Radionavigation satellite services. Table 13 does identify high risk factors with these bands for antenna pointing and surface roughness requirements.

Satellite Orbit - The MIBSAT satellite orbit is a critical design choice which will drive the economic feasibility and profitability of the system, as well as determine other key design parameters. The primary system requirements which must be satisfied include maximum system delay and global coverage.

Table 13 - Frequency Tradeoff Analysis

Frequency (GHz)		BW	Signal	Antenna	Antenna Reqs		Electronics	Position
Uplink	Downlink	Capacity (rel)	Loss (dB rel)[1]	Gain (dB rel)	Pointing (° error)[2]	Surface Err (rms m)[3]	Technology Risk	Service
71- 74	39.5 - 40.5	1	0	0	0.45	$3.0x10^{-5}$	Low-Med	No
95 - 100	81 - 84	1.66	3.3	8	0.18	$1.2x10^{-5}$	Med-High	Yes
134 - 142	95-100	2.66	14.2	11	0.13	$8.4x10^{-6}$	High	Yes

Notes: 1. Includes all frequency dependent losses (path, rain, atmospheric losses)
2. Pointing error based on 3-dB beamwidth/3 rule for 1 dB pointing loss
3. Surface error based on reflector surface efficiency of 0.8

The major design outcome of this choice, which will drive system economics, is the number of satellites required for complete global coverage. Other system design factors which orbital choice will affect include terminal and satellite transmit and receive requirements (i.e. EIRP & G/T), system complexity for frequency (doppler) and time tracking, and terminal tracking and satellite handoff requirements due to satellite coverage periods. Orbit type choices include the following: geosynchronous, molniya, tundra, inclined planes, meridian, or some hybrid combination. Orbit height must also be selected.

Orbit Type. A tradeoff analysis for the MIBSAT orbit type is shown in Table 14. A Geosynchronous orbit, as discussed previously, will not meet the system delay requirements and imposes EIRP requirements which are too high at the MIBSAT frequency range to support mobile terminals. Molniya and tundra orbits are primarily used for polar coverage applications although some variations have been proposed for coverage of specific non-polar areas (e.g. Sycamores coverage of the UK). These orbits also exhibit bad doppler characteristics (amplitude and variance) and expose the satellite to Van Allen Belt noise and radiation (requiring satellite hardening to these affects). Inclined planes could be chosen at an appropriate altitude for complete global coverage as in the OrbComm and Globalstar mobile SATCOM systems. This option results in areas with multiple and different satellite tracks (requiring increased terminal knowledge of satellite ephemeris unless omni-directional antennas are used) and may leave other areas with no coverage (e.g., high latitude) which would not satisfy MIBSAT system requirements.

A meridian satellite constellation (such as that to be used for the IRIDIUM system) provides for complete global coverage (with a full constellation), simplifies satellite crosslink requirements, and allows for a simple tracking algorithm since the satellite tracks can be constant. The degree of the satellite tracking complexity depends upon whether the constellation is recurrent or nonrecurrent, and phased or anti-phased. Oli et. al. [38] shows that if a meridian constellation (90° inclined planes) is chosen such that there is exactly an odd number of orbits/day from each particular satellite, the satellites will pass over the same portion of the sky twice a day (greatly simplifying tracking). This option

Table 14 - Orbit Type Tradeoff Analysis

Orbit Type	Global Cov.	Doppler Variance	Delay Variance	Power Reqs	Crosslink Complexity	Tracking Complexity	# of Sats Required	Notes
Geosynchronous	Yes	Low	Low	High	Low	Low	Low	Delay over
Molniya/Tundra	No	High	High	High	High	High	High	V.A. Radiat.
Inclin. LEO/MEO	Yes	Low	Med	AD	High	High	Med-AD	Cov. Holes
NR P Meridian	Yes	Low	Med	AD	Low-Med	Med-High	High-AD	eg IRIDIUM
NR AP Meridian	Yes	Low	Med	AD	High	Low-Med *	High-AD	
R P Meridian	Yes	Low	Med	AD	Low-Med	Med	High-AD	Limited H_e
R A Meridian	Yes	Low	Med	AD	Med	Low-Med*	High-AD	Limited H_e
Hybrid	Yes	Med-High	Med-High	AD	Med-High	High	Med-AD	Complex

Legend:

LEO - Low Earth Orbit
MEO - Medium Earth Orbit
NR - Non Recurrent
R - Recurrent
P - Phased
A - Antiphased
AD - Altitude Dependent
VA - Van Allen (Radiation Belt)

* Antiphased tracking simpler only if single antenna can be utilized to handover to rising satellite as current one sets

(meridian) does require more satellites in the constellation, but appears to best satisfy the operational requirements due to tracking simplification and capability for crosslink connectivity. The choice between phased (planes rotating in same direction) and anti-phased (planes rotating in opposite directions) orbits will be a tradeoff (considered out of scope) between crosslink and tracking complexity and performance. Feasibility of the meridian constellation option will depend upon satellite and launch costs to provide the full constellation. A hybrid system, in which satellites are in two or more different orbits, is not considered practical due to the added complexity of the terminal and system control segment to account for multiple types of satellites.

Satellite Height. The height or altitude of the satellite orbits is also chosen by trading off such factors as system delay, doppler shift, and area of coverage per satellite (driving the number of satellites per constellation, power, and coverage time requirements). Doppler shift is the apparent change in frequency of RF and sound waves transferred between mobile objects. The doppler frequency shift is given by

$$\Delta f = f_T \frac{V_T}{V_p}$$

where f_T is the transmitted frequency, V_T is the velocity of the transmitter directed towards the receiver, and V_p is the phase velocity of the wave within the medium (speed of light in this case). The velocity of a LEO satellite is a function of the period, T_s, of the satellite given by

$$V_s = \frac{2\pi\,(r_e + h_{sat})}{T_s}$$

The system delay and delay variation are a function of the minimum and maximum distance between the satellite and the earth terminal. The maximum distance is given by the slant range calculated at the system minimum elevation angle of 15° by the relationship

$$Z = [\,(r_e \sin \phi)^2 + 2r_e h + h^2]^{1/2} - r_e \sin \phi$$

The equivalent coverage of the earth's surface by the satellite is given by the relationships

$$\gamma_e = \cos^{-1} [r_e \cos\phi / (r_e + h)]$$

and

$$A_{cov} = 2\pi r_e^2 (1 - \cos\gamma_e)$$

where γ_e is the equivalent angle of coverage from the center of the earth, r_e is the radius of the earth (6,378 km), and h is the orbit height above the surface of the earth.

Using the value of γ_e for each orbital height, we can also estimate the number of satellites required for a LEO polar meridian constellation. The number of satellites in each orbital plane would be $360/2\gamma_e$ and the number of planes required would be given by $180/2\gamma_e$. This calculation would result in the worst case number of satellites since overlap at high and low latitudes is not taken into account. Fewer satellites could be utilized if look angles <15° or gaps in coverage were acceptable at latitudes of 15° S - 15° N (which is not probable due to maritime and Central America needs).

A complete orbital tradeoff analysis detailing these parameters at various orbital heights is shown in Table 15. Other considerations in choosing the orbit height include the affects of polar drag at lower altitudes (≤ 525 km), the increasing affects of radiation above ~ 600 km (becoming prohibitive above 1400km), and limitations in LEO launch vehicles at time of system implementation (≤ 2,000 km assumed). Based upon these factors, orbit heights in the range of 900-1500 km were considered (mainly due to delay requirements and number of satellites required). The three specific heights which are double lined in Table 15 represent three of the applicable recurrent meridian heights possible (representing 11, 13, and 15 orbital tracks per day, respectively).

Because one of the unique recurrent meridian heights falls within the range of interest, the initial orbit height for the MIBSAT system will be chosen as 1,236 km pending further analysis from an RF performance standpoint. This

Table 14 - MIBSAT Orbital Height Tradeoff Analysis

ORBIT (km)	Sat Per (sec)	Sat Velocity (km/sec)	Max Doppler (kHz)	Max Slant (km)[1]	Max Delay (msec)	Delay ± (usec)	Cov Elev	#of Sats/ Plane	# of Planes	# of Sats[2]	Cov Time (min)
400.00	5553.56	7.67	2617.99	1176.20	3.92	2.59	19.31	19	10	190	4.97
500.00	5676.91	7.61	2599.33	1408.27	4.69	3.03	22.83	16	8	128	6.00
541.60	5728.49	7.59	2591.70	1500.71	5.00	3.20	24.20	15	8	120	6.42
600.00	5801.16	7.56	2581.09	1626.98	5.42	3.42	26.04	14	7	98	6.99
700.00	5926.31	7.50	2563.23	1834.85	6.12	3.78	29.01	13	7	91	7.96
800.00	6052.34	7.45	2545.74	2033.72	6.78	4.11	31.77	12	6	72	8.90
900.00	6179.25	7.40	2528.62	2224.97	7.42	4.42	34.36	11	6	66	9.83
950.00	6243.04	7.38	2520.19	2318.09	7.73	4.56	35.59	11	6	66	10.29
1000.00	6307.04	7.35	2511.84	2409.68	8.03	4.70	36.79	10	5	50	10.74
1100.00	6435.70	7.30	2495.40	2588.70	8.63	4.96	39.08	10	5	50	11.64
1200.00	6565.22	7.25	2479.29	2762.73	9.21	5.21	41.24	9	5	45	12.54
1236.70	6612.97	7.24	2473.46	2825.46	9.42	5.30	42.01	9	5	45	12.86
1300.00	6695.60	7.21	2463.50	2932.34	9.77	5.44	43.30	9	5	45	13.42
1400.00	6826.83	7.16	2448.01	3097.99	10.33	5.66	45.26	8	4	32	14.30
1500.00	6958.91	7.11	2432.81	3260.09	10.87	5.87	47.13	8	4	32	15.18
1600.00	7091.82	7.07	2417.91	3418.98	11.40	6.06	48.91	8	4	32	16.06
1800.00	7360.16	6.98	2388.92	3728.27	12.43	6.43	52.26	7	4	28	17.81
2000.00	7631.80	6.90	2360.97	4027.76	13.43	6.76	55.34	7	4	28	19.55
2136.40	7818.93	6.84	2342.48	4227.17	14.09	6.97	57.31	7	4	28	20.75
3000.00	9038.16	6.52	2234.93	5420.57	18.07	8.07	67.88	6	3	18	28.40
5000.00	12078.47	5.92	2034.71	7915.82	26.39	9.72	84.44	5	3	15	47.22
10000.00	20859.39	4.93	1706.20	13525.14	45.08	11.75	105.81	4	2	8	102.19
20000.00	42635.44	3.89	1357.52	23998.49	79.99	13.33	122.99	3	2	6	242.77
35786.00	86162.69	3.07	1086.64	40061.50	133.54	14.25	133.20	3	2	6	531.33

Notes:
1. For 15° elevation angle
2. For at least one satellite in view at all times

height would maintain a one-way delay less than 10 ms and reduce the number of satellites required as compared to lower orbits. This orbit height choice will be re-evaluated during the link budget analysis. Although nine satellites are needed per plane for a minimum 15° coverage, ten would be chosen for each plane to maintain an on-orbit spare capability and provide additional overlap in coverage areas (allowing more time for handoffs). This would result in a final constellation of five planes with ten satellites each. This constellation would provide for visibility to two or three satellites for some amount of time each day, increasing the availability of the system and enhancing the position determination capability.

A plot of the MIBSAT satellite coverage and orbital track at 1,236 km is shown in Figure 14 for a 15° elevation angle. This figure displays how a constellation of ten satellites per orbit with five separate orbital planes could provide continuous global coverage with some overlap (lending to diversity). The orbital track highlighted displays one revolution of one plane which would occur twice during each day (from a specific ground terminal perspective). A particular satellite would orbit the earth 13 times each day (lending to central TT&C discussed below).

System Connectivity - The connectivity capability designed into the MIBSAT system must meet the system requirements of providing point-to-point, point-to-multipoint, and multipoint-to-multipoint (network) global connectivity, with a maximum system delay of 90 ms. The main design tradeoff here is whether to install numerous satellite gateway terminals, requiring network management processors on the ground (for "M-hops"), or to employ satellite crosslinks with intelligent on-board processors on each satellite to perform network routing. The global coverage requirement of the system and resulting area of coverage for a single satellite at 1,236 km would require an enormous number of ground terminals to support this function (# dependent upon final coverage/capacity requirements and licensing). Based on current and proposed SATCOM systems employing crosslinks and on-board processing, this option is considered both feasible and the best alternative. The on-board processors would need to have enough intelligence to have a knowledge of system users

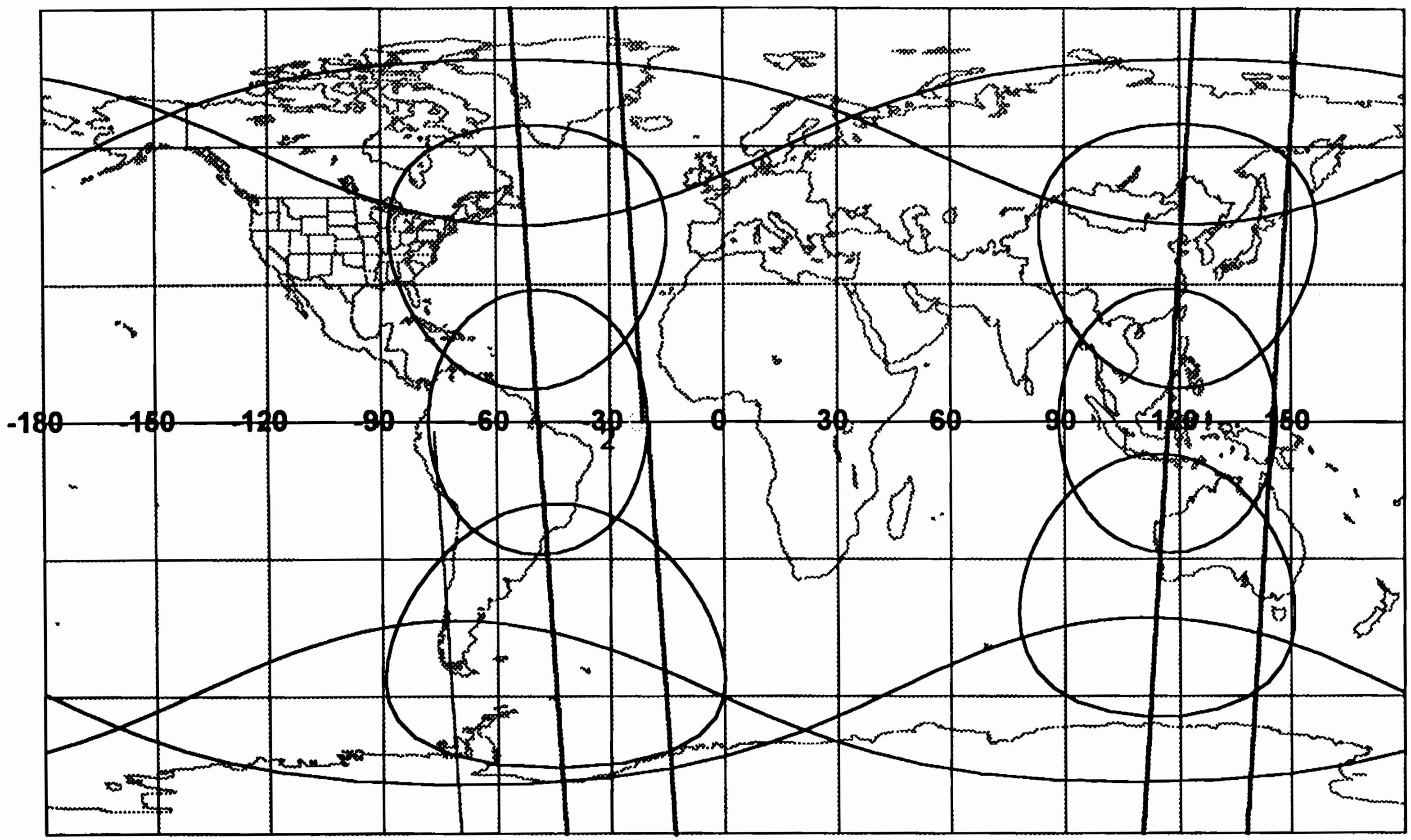


Figure 14 - MIBSAT Satellite Coverage (@ 15° el)

and locations and be capable of performing complete network and packet routing capabilities (while meeting system delay times and providing desired QOS).

The satellite crosslink antennas may best be satisfied by use of laser communication packages if the technology can be proven with low risk before MIBSAT implementation. Because the MIBSAT satellite constellation moves in a structured consistent track, LOS paths between neighboring satellites should be fairly easy to acquire and maintain. Each satellite would talk to its four closest neighbors (front, behind, and one on each side) except for the satellites on the edge of opposite orbital tracks (assuming a phased constellation). The two orbital tracks which divide the orbital rotation scheme would only talk to the neighboring satellite going in the same direction as well as the one in front and behind (this significantly reduces the tracking requirements for the lasers). Data packets needing to cross the opposite orbital track boundary would have to be routed over one of the poles until it could be passed to a satellite traveling in the same direction.

Use of laser crosslinks would allow the transfer of large data rates between satellites of the MIBSAT system. Large intersatellite link data rates are considered essential for MIBSAT due to the distributed nature of network control and probability of inter-satellite links needed for each service. Laser crosslinks would also eliminate the concern of RF bandwidth allocation and interference (60 GHz band presently in use by Military). To maintain compatibility with projected standard broadband data rates (thus increasing the availability/ reliability of processing/network components), a crosslink data rate of either 2.488 Gbps (OC-48) or 10 Gbps (OC-192) will be chosen dependent upon final network management and opto-electronics tradeoffs (considered out of scope).

System Control & Management - System control and management includes satellite position control, network & resource management, system timing control, and Operations and Administrative Management (OAM) [35]. The main tradeoff in this system feature is how to distribute the "intelligence" for system and network control such that the number of ground control terminals and system overhead for management and control are optimized to provide the highest level service to the user at a marketable price.

Satellite Control. Control is required for satellite stationkeeping and health and maintenance functions. Due to the nature of the LEO meridian constellation chosen (13 orbital tracks/day/orbital plane), one TT&C facility should be able to track all satellites if the TT&C location is properly chosen in coordination with the final constellation, and stationkeeping is not required more than twice a day for ~ 13 minutes at a time. If additional TT&C locations are needed, they could be less capable sites with terrestrial feeds back to the main facility. This function could be tied into the network control stations discussed below. Distribution of ephemeris data to mobile and fixed terminals would be greatly simplified by use of the recurrent meridian orbit. Terminals would need only know precisely where they are to calculate initial pointing vectors for system acquisition. Complete ephemeris data could then be broadcast from the satellites at pre-determined intervals. For terminals with bad initial ephemeris, distribution and input of satellite state vectors could be made possible via a floppy drive or smart card interface.

Network Control. Network control is required to efficiently manage configurations and packet routing throughout the MIBSAT network. This management includes intra-satellite, inter-satellite, and terrestrial gateway communications links [35,36]. The MIBSAT terrestrial gateways would need to be strategically located throughout the world so as to optimize the connectivity provided, while minimizing overall usage costs and delay times. It is estimated that ten to twenty gateway terminals (implemented using the standard fixed terminal) would be needed to support complete global coverage. Packet routing algorithms would be based upon the latest ATM and AIN techniques modified for MIBSAT utilization. The network management function should be largely distributed to the individual satellites to reduce overall waiting times and chance of congestion (i.e. distributed queue). The distributed nature of the network will require dedicated crosslink resources for the purpose of network coordination and control. The overall complexity of the MIBSAT network will also require a central network management system to monitor the overall network for efficiency and congestion control. The central network management function could be performed at the MIBSAT TT&C facility (to consolidate manning and reduce O&M costs). Terrestrial links between the central facility and some or all of the gateway terminals could be used to provide complete network monitoring and coordination, while minimizing the utilization of crosslinks to provide network data back to the control facility (i.e. satellites would use shortest distance algorithm to shore gateway sites or control facility).

Terminal Location. Information should be maintained on those terminals logged onto the system and the last known location of those terminals logged off of the system. The terminal would have an unique identifier code which would be transmitted as part of the acquisition process. This terminal ID (and associated location) would have to be promulgated to all satellites in the constellation for connectivity purposes. The satellite processors, in conjunction with the network management facility, would maintain an apriori knowledge of terminal location based upon orbital tracks and system acquisition information. Direct "ring-up" or paging capability to any terminal worldwide that is not logged onto the system may be impractical for MIBSAT since omnidirectional terminal antennas in a receive only mode are a practical requisite for this capability. This function would have to be accomplished through the use of a separate MIBSAT satellite and terminal antenna (small omnidirectional dipole) operating at a much lower frequency (e.g., PCS band at 2 Ghz). The only other alternative to this would be to provide this capability through another global mobile communications system (such as IRIDIUM) which is in service at the time of MIBSAT operations (i.e. notify user to log onto MIBSAT for incoming call).

System Timing. Timing synchronization will be a critical element in the realization of the MIBSAT system. Effective channel data rates as high as 155 Mbps (or higher for crosslinks) will require system synchronization on the order of several nanoseconds. The MIBSAT satellite system must provide the master timing in this scenario. The master timing would be maintained within the satellite processors through the TT&C ground link and the satellite crosslinks throughout the constellation. System timing would be conveyed to acquiring earth terminals through a timing synchronization protocol utilizing timing probes.

The satellite clock will be used as the master clock from a terminal standpoint and all delay times and variations would be compensated for considering this time source. The feasibility of providing and maintaining system timing down to nanoseconds on a globally based mobile system would be a primary consideration during the actual MIBSAT design.

Other OAM functions not discussed above include performance management, fault management, activation/deactivation, and administrative management. The satellite system would be responsible for recording specific terminal log-on duration and number of packets transferred at a specific QOS. This information would be forwarded back to the SCF for billing purposes.

Payload Processing. The payload processing capability will have to provide the following functions:

- Terminal acquisition within satellite view
- Terminal hand-off to neighboring satellite
- Network control within satellite view (i.e. intra-beam packet transfer)
- Network control hand-off to other satellites (via crosslinks)
- Complete system configuration status (via crosslinks)
- Doppler/timing correction
- ATM Functionality/Protocols
- BB switching control
- Adaptive control for rain fades
- Digital BFN control (if utilized)
- Satellite command/control

Network control in this list includes all aspects of network activation/deactivation, congestion/flow control, and other OAM functions. It is important to note that a specific earth terminal will only be in the field of view of a specific MIBSAT satellite for approximately 13 minutes. If the final design resulted in the order of 36 beams, this would mean a terminal beam transition approximately every 1.5 minutes. The data packet processing would be just as complex and continuous to efficiently route packets between satellites and beams. The satellite or system on a whole would have to predict the location (or at least direction) of each receiving terminal at the precise time. A significant amount of processing capability would be required to perform all of these functions simultaneously. Advanced parallel processing techniques should be considered during system design to accommodate this requirement. Satellite parallel processing in conjunction with neural network algorithms would lend well to the distributive intelligence architecture required for the MIBSAT system. Development of EHF three dimensional Volume Integrated Circuits (VICs) also promises to be applicable technology as it may allow computer processing directly at EHF frequencies (i.e. Gbps). Another requirement associated with this distributed intelligence architecture is ample amount of faster acting buffers which could handle temporary storage of data packets at high data rates and corresponding transmittal at the precise system time.

System Access Methodology - The satellite access methodology should maximize the number of users possible per satellite and minimize the service setup time while conserving the efficiency of actual data throughput in the presence of bursty packet data [40]. Since MIBSAT will be implemented in an ATM environment servicing multimedia networks, communications at the time can be assumed to be asynchronous in nature. Because the satellite communication channel (frequency band) must be a shared medium within each satellite beam area, a method is needed to assure access to this channel when needed. Contention based access schemes would not fulfill MIBSAT requirements due to low throughput and system delay resulting from packet collisions. A true Demand Assignment Multiple Access (DAMA) technique would also not be practical because of the time required to configure the service end-to-end (i.e. circuit switched) in relation to the data being transmitted. Reliable digital satellite communications, such as needed for MIBSAT, is inherently synchronous.

The MIBSAT access methodology must utilize a reliable assured access method for synchronous terminal-satellite communication while embedding asynchronous data and virtual packet switched data services (much as in the

SONET/ATM model). Access methods to consider are Multi-Frequency- Carrier Division Multiple Access (MF-CDMA), Frequency Division Multiple Access (FDMA), and Multi-Frequency Time Division Multiple Access (MF-TDMA).

MF-CDMA is a spread spectrum technique currently being utilized or planned for LDR mobile cellular and satellite communications. This technique requires the use of chip rates which are 10-100 times the actual data rate. This method would require chip rates on the order of (500 Mbps - 5 Gbps) for MIBSAT HDR services which is not considered feasible. Multi-rate CDMA through a processing satellite would also require a separate multiplexer-demodulator for each data rate channel.

Pure FDMA is widely in use for SATCOM applications but does not efficiently apply to multi-rate digital applications. This is because the on-board channelizer becomes increasingly complex due to reconfiguration for variable rates. FDMA also usually requires bit-interleaving which would increase system delay time. Pure TDMA has been used for digital processing satellite applications (e.g. ACTS) but requires much higher uplink burst rates than actual throughput rates (e.g., 64 kbps at 110 Mbps burst rate).

What is needed is a method where users are assigned an access frequency and use TDMA methods for different data rates. This access method is known as MF-TDMA and allows earth terminals to transmit at lower data rates than CDMA but can utilize TDM techniques to multiplex multi-rate channels. The drawback of this method is that it requires all terminals to transmit at the same effective rate regardless of interfaces. A potential modification of this method is to provide for a specific number of FDM channels at each maximum data rate configuration (i.e., 52 Mbps, 18 Mbps, 6 Mbps, and 1.55 Mbps). Users could then use TDM techniques within their channel to provide lower data rate services.). The data communicated would be bit synchronous within a given data channel but would be asynchronous within that channel. Use of MF-TDMA uplink transmission will require an uplink demodulator, decoder, and packet buffer for each uplink beam. The number of uplink beams will be chosen during the satellite design and through link budget tradeoffs to optimize power, timing, and complexity considerations.

The downlink transmission technique is chosen as Time Division Multiplexing (TDM) to provide maximum power efficiency for the satellite high power amplifier. This design also simplifies the satellite design by requiring only one downlink burst modulator per downlink beam. The number of downlink beams will be chosen during the satellite design and through link budget tradeoffs.

Satellite Link Budget - A initial MIBSAT uplink and downlink budget are shown in Tables 16 and 17, respectively [29]. This initial budget was developed by arbitrarily (but with reasoning) choosing certain system parameters to identify possible issue areas and then iteratively modifying design parameters of choice. These parameters of the satellite and terminal systems will be discussed further below. The link budget does show that MIBSAT operation is indeed feasible in clear sky conditions with additional margin to spare. A major issue highlighted is the system performance in the presence of rain which is discussed further below.

Rain Mitigation Techniques - Because of the large loss induced at MIBSAT frequencies due to rain and atmospheric attenuation, mitigation techniques must be designed into the system from conception. Power management could be used to variably control the power out of the terminal and/or satellite if the system is not overly power limited (not a likely scenario). Another technique employed by the ACTS system is to variably control the data rate and coding rate used if signal degradation falls below a certain threshold. The simultaneous reduction in data rate and increase in coding rate provides an additional 10 dB of margin. Another design consideration will be on the utilization of two terminal antennas to "switch" to another MIBSAT satellite if it is in view and the degradation is due to some localized weather cell only affecting the LOS link to one satellite.

Referring to Tables 16 and 17, we see that the system must overcome 26-28 dB of additional loss in the presence of rain (at 15° elevation for 98%

Table 16 - MIBSAT UPLINK BUDGET

Link Component	95 - 100 GHz					
	Aero	Mari (L)	Mari (S)	Land (L)	Land (S)	L Fixed
Terminal						
Po (W)	5	5	3.5	5	3.5	5
Dant (m)	Array	0.44	0.25	0.44	0.25	0.66
Gant (dB)	24	50.7	45.7	50.7	45.7	54.1
EIRP (dBW)	30.99	57.69	51.14	57.69	51.14	61.09
Point Loss (dB)	1	1	1	1	1	1
Path Loss (dB)	192.36	192.45	192.45	192.45	192.45	192.45
Edge of Beam (dB)	7.6	7.6	7.6	7.6	7.6	7.6
Atmosph. Loss (dB)	0.5	3.4	3.4	3.4	3.4	3.4
Polarization Loss (dB)	0.5	0.5	0.5	0.5	0.5	0.5
RCV Sig Strength (dBW)	-163.37	-139.66	-146.21	-139.66	-146.21	-136.26
Satellite						
Dant (m)	1	1	1	1	1	1
Gant (dB)	57.8	57.8	57.8	57.8	57.8	57.8
Satellite G/T (dB/K)	20	20	20	20	20	20
Boltzman's (dBW/Hz/K)	-228.6	-228.6	-228.6	-228.6	-228.6	-228.6
Achieved C/No (dB)	85.23	108.94	102.39	108.94	102.39	112.34
Data Rate (Mbps)	52	52	18	52	18	155
Data Rate (dB)	77.16	77.16	72.55	77.16	72.55	81.9
Received Eb/No (dB)	8.07	31.78	29.84	31.78	29.84	30.44
Required Eb/No (dB)[1]	11	11	11	11	11	11
Coding Gain (dB)	4.8	4.8	4.8	4.8	4.8	4.8
Implemen. Loss (dB)	2	2	2	2	2	2
Link Margin (Clear)	-0.13	23.58	21.64	23.58	21.64	22.24
Excess Rain Loss (dB)	1	27.9	27.9	27.9	27.9	27.9
Achieved C/No (dB)	84.23	81.04	74.49	81.04	74.49	84.44
Data Rate (Mbps)	52	18	6	18	6	52
Data Rate (dB)	77.16	72.55	67.8	72.55	67.8	77.16
Received Eb/No (dB)	7.07	8.49	6.69	8.49	6.69	7.28
Required Eb/No (dB)[2]	9.6	9.6	9.6	9.6	9.6	9.6
Coding Gain (dB)	4.8	5.2	5.2	5.2	5.2	5.2
Implemen. Loss (dB)	2	2	2	2	2	2
Link Margin (Rain) (dB)	0.27	2.09	0.29	2.09	0.29	0.88

1. For BER of 10^{-7} with rate 2/3, K=9 convolutional coding
2. For BER of 10^{-5} with rate 1/3, K=9 convolutional coding

Table 17 - MIBSAT DOWNLINK BUDGET

Link Component	81 - 84 GHz					
	Aero	Mari (L)	Mari (S)	Mobile (L	LMobile (S	L Fixed
Satellite						
Po (W)	5	5	5	5	5	5
Dant (m)	0.44	0.44	0.44	0.44	0.44	0.44
Gant (dB)	49.1	49.1	49.1	49.1	49.1	49.1
EIRP (dBW)	56.09	56.09	56.09	56.09	56.09	56.09
Point Loss (dB)	1	1	1	1	1	1
Path Loss (dB)	190.85	190.94	190.94	190.94	190.94	190.94
Edge of Beam (dB)	7.6	7.6	7.6	7.6	7.6	7.6
Atmosph. Loss (dB)	0.5	2.95	2.95	2.95	2.95	2.95
Polarization Loss (dB)	0.5	0.5	0.5	0.5	0.5	0.5
RCV Sig Strength (dBW)	-136.76	-139.30	-139.30	-139.30	-139.30	-139.30
Terminal						
Dant (m)	Array	0.44	0.25	0.44	0.25	0.66
Gant (dB)	17	50.7	45.7	50.7	45.7	54.1
Terminal G/T (dB/K)	0	17	15	17	15	20
Boltzman's (dB/Hz/K)	-228.6	-228.6	-228.6	-228.6	-228.6	-228.6
Achieved C/No (dB)	91.84	106.30	104.30	106.30	104.30	109.30
Data Rate (Mbps)	52	52	18	52	18	155
Data Rate (dB)	77.16	77.16	72.55	77.16	72.55	81.9
Received Eb/No (dB)	14.68	29.14	31.75	29.14	31.75	27.40
Required Eb/No (dB)[1]	11	11	11	11	11	11
Coding Gain (dB)	4.8	4.8	4.8	4.8	4.8	4.8
Implemen. Loss (dB)	2	2	2	2	2	2
Link Margin (Clear) (dB)	6.48	20.94	23.55	20.94	23.55	19.20
Excess Rain Loss (dB)	1	26.86	26.86	26.86	26.86	26.86
Achieved C/No	90.84	79.44	77.44	79.44	77.44	82.44
Data Rate (Mbps)	52	18	6	18	6	52
Data Rate (dB)	77.16	72.55	67.8	72.55	67.8	77.16
Received Eb/No (dB)	13.68	6.89	9.64	6.89	9.64	5.28
Required Eb/No (dB)[2]	9.6	9.6	9.6	9.6	9.6	9.6
Coding Gain (dB)	4.8	5.2	5.2	5.2	5.2	5.2
Implemen. Loss (dB)	2	2	2	2	2	2
Link Margin (Rain) (dB)	6.88	0.49	3.24	0.49	3.24	-1.12

1. For BER of 10^{-7} with rate 2/3, K=9 convolutional coding
2. For BER of 10^{-5} with rate 1/3, K=9 convolutional coding

availability). A possible mitigation scheme for MIBSAT would be to reduce the appropriate data rate by 1/3 and use 1/3 rate convolutional encoding. The BER performance requirement would also be lowered to the minimum acceptable level of 10^{-5} in the presence of rain. These considerations were incorporated into the rain cases of Tables 16 and 17 to achieve positive margins on both uplink and downlink. These link budgets are predicated upon the achievability of other design factors such as an aeronautical phased array antenna gain of 17-24 dB, satellite G/T of 20 dB, and terminal power output capabilities of 3.5 - 5 W. Because these design parameters may or may not be achievable at the time of system design, other rain mitigation techniques may have to be employed. Power management techniques could also be incorporated into the rain budget but would only add 3-6 dB of improvement at most. The other consideration in these adaptive mitigation techniques is how the terminal and/or satellite monitors the link for degradation. This function could be performed through terminal monitoring of a separate "beacon" frequency such as in the ACTS, or through in-band link quality metrics.

The other design parameter that should be taken into account is the probability that there is another MIBSAT satellite in field of view that either does not involve the weather cell in its LOS link, is at a better elevation angle thereby reducing the loss through the atmosphere, or both. Fixed MIBSAT ground terminals could also achieve higher availability and margin through multiple ground terminals sufficiently separated (ground diversity). A statistical analysis should be performed (considered out of scope) to analyze changes in system margin and availability considering all diversity schemes, different rain and atmospheric statistics, and sensitivity of link budget design parameters.

Antenna Considerations - The antenna systems required for MIBSAT include the satellite antenna configuration and separate terminal antenna configurations. Also of concern is the terminal antenna control system in the presence of platform motion.

Satellite Antenna Configuration. There are several antenna configurations which could be used to satisfy the MIBSAT requirement. Since a large number of MIBSAT satellites will have to be produced and satellite lifetime will be a critical parameter, simplicity should be a driving factor along with size and weight. The simplest antenna configuration which would satisfy the MIBSAT requirement would be separate horn elements reflecting off a parabolic dish. The resulting illumination of a set of properly organized feed horns would be a network of neatly organized beams comprising the overall field of view of the satellite. This configuration results in a structured coverage area in which communication packets can be received and transmitted to terminals within their respective beams by use of processor controlled fast RF switches. To correspond with the uplink and downlink transmissions methods, a fixed antenna network would be utilized on the uplink, while a hopping network would be used on the downlink.

One of the issues associated with this arrangement is keeping the resulting 3 dB beamwidth of each beam large enough as to not require too many hopping positions on the downlink, while still maintaining sufficient gain needed to maintain the downlink budget. For example, using the antenna relationships

$$G = \eta\ [(\pi D)/\ \lambda]$$

and

$$\theta_3^\circ \simeq \frac{75\lambda}{D}$$

the resulting 3dB beamwidth at 84 Ghz with the 16" (0.41 m) antenna downlink reflector would be 0.65° with a simple conical feed. At a satellite height of 1,236 km, there would be over 30,000 downlink beam positions required to maintain > 3 dB of loss. This situation requires that a modified antenna design be used such as a Beam Forming Network (BFN) using a phased array of radiators. The BFN appropriately weights the phase at each element to form a specific beam focused onto the reflector. Limitations in switching speeds at the modulated carrier rate and the capacity-per-area requirements will drive the number of separate beam positions required per downlink modulator. A similar situation exists on the uplink, where the number of beams required will drive the number of uplink demodulators and associated electronics needed. Again, BFN antennas can be used to shape the beams appropriately.

Digital BFN technology promises further improvements in the ruggedization, reliability, and control of phased array antennas which may provide benefit to the MIBSAT system [33]. In digital BFNs, signals are detected and digitized at the element level and then processed to form the desired beam. Digital BFN advantages include the capability of closely spaced multiple beams, antenna self calibration, ultra-low sidelobes, super resolution, and flexible power and time management. Limiting factors in digital BFNs are processing speed required and cost (as compared to analog BFN). One potential solution to the processing speed issue is the use of optically driven FFTs for phase processing. The refinement and continued implementation of MMICs and printed circuit radiators will also continue to lower the weight required for phased array antennas and may be appropriate for the MIBSAT system. The limiter on printed circuit radiators is that Electromagnetically Coupled Patch (EMCP) elements would have to be on the order of several millimeters to support MIBSAT frequencies.

Terminal Antenna Configuration. Antenna physical requirements were inherently defined earlier by exterior system constraints. Although phased array antennas offer a much smaller profile, they may not be practical for MIBSAT platforms, except for the aeronautical system which does not require antenna gains of 45-50 dB to help mitigate rain and atmospheric attenuation. The antenna system will need the capability of providing two separate uplink and downlink beams in order to acquire, track, and perform some level of soft handoff to satellites coming into view.

For the large maritime and land mobile applications, a 16" parabolic reflector antenna was specified through the link budget. This antenna is significantly smaller than what is currently available for these platforms providing significantly less data capacity. For the small maritime and land mobile applications, a 9" parabolic dish was specified. The fixed land terminals will utilize a 2' dish to support data channels at 155 Mbps. A significant issue for all of these reflecting antennas is the manufacture of the antenna to meet surface tolerance requirements at 100 Ghz. The general performance rule of $\lambda/32$ would yield surface deviation requirements of 0.1 mm at this frequency, requiring tight manufacturing process and controls.

For the aeronautical terminal, a phased array antenna would be utilized to meet the wind drag requirements. Packaging is currently the largest technology challenge in realizing affordable EHF phased array antennas for mobile SATCOM [33]. Again, electronic beam forming networks using fully integrated MMIC phase shifters could be utilized.

Antenna Control System. The added motion of mobile platforms adds another layer of complexity to the antenna control issue. Constant three directional sinusoidal motion for maritime platforms requires effective gyro systems with large enough bandwidths to track out the motion. Ring Laser Gyroscopes provide a lightweight reliable technology to realize this need. Land mobile terminals exhibit special "jolting" motion that maritime and aeronautical platforms would not typically see. Either the uplink antenna beamwidth needs to be designed larger than the maximum jolting angle or the antenna control system needs to be fast enough to respond to jolting. At 9" and 16" antenna diameters, the uplink antennas beamwidths for the small and large land mobile platforms are approximately 1° and 0.6°, respectively. This points to antenna control system as being one of the main issues for the land mobile system. The aeronautical antenna control system would be provided by the phased BFN in response to changes in pitch, roll, heading, and altitude.

A design consideration for the aeronautical terminal is the beam angle requirements for the phased array antenna and the "pointing " capability required as the platform turns.

System Configuration

The proposed MIBSAT system configuration is depicted in Figure 15. The system proposed would be comprised of approximately 50 satellites in 5 meridian polar LEO orbits at 1,236 km. The satellites would provide connection-oriented and connectionless packet data services supporting multimedia

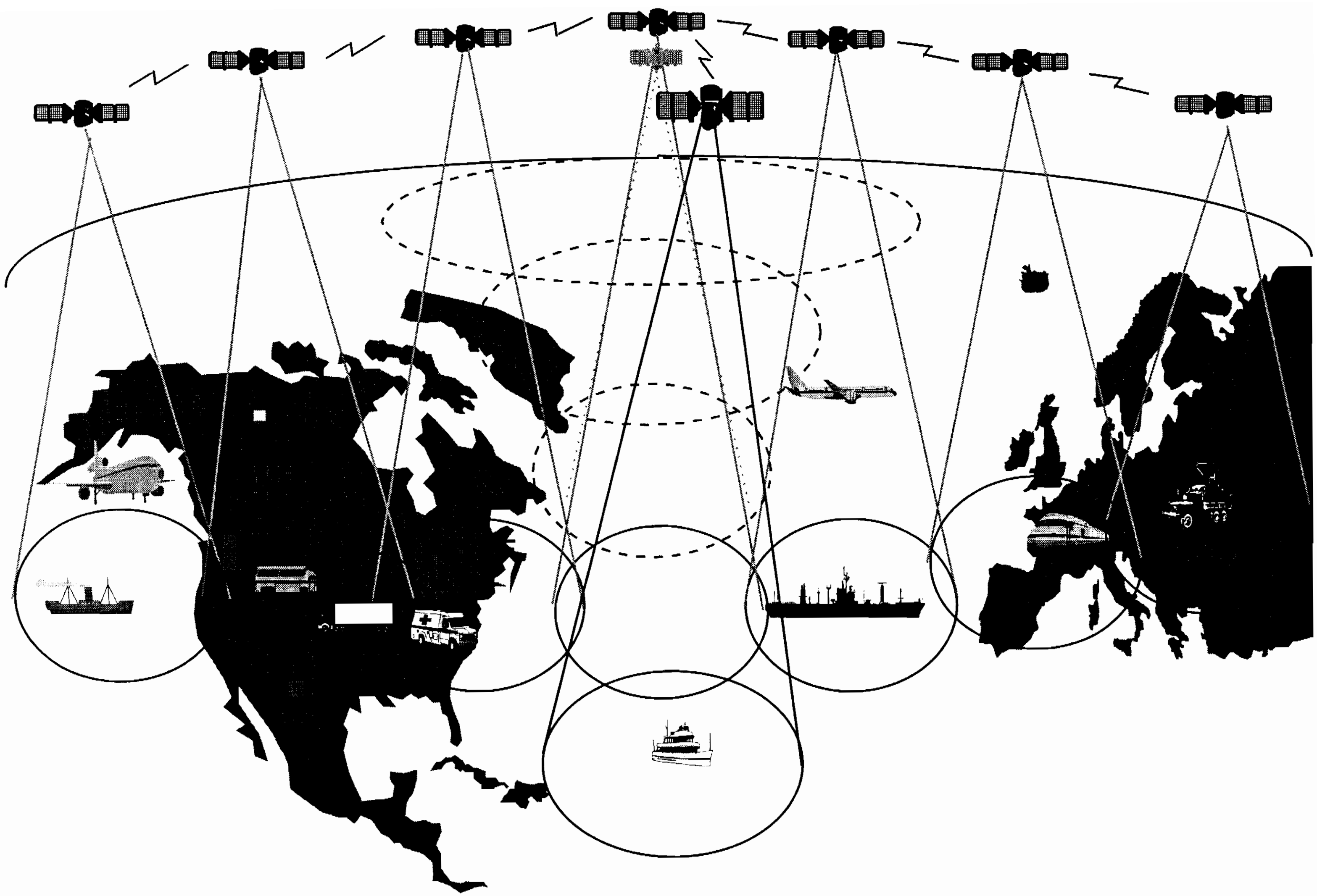


Figure 15 - MIBSAT System Configuration

applications through ATM technology, integrated satellite system crosslinks, and distributed neural network parallel processing directly embedded in the satellite system. The satellites would provide these services to land mobile, maritime, and aeronautical users of different sizes. Remote fixed users and hub terminals supporting mobile applications would also be serviced. There would be one central System Control Facility (SCF) which would include the TT&C capability and the central Network Management Facility (NMF). There would be several remote NMFs providing MIBSAT access to the PSDNs, as well as proving MIBSAT system network status back to the SCF for central monitoring, control, and management.

Additional Systems Planning

Additional systems planning considerations include the requirement for a concurrent engineering methodology to ensure Design For "X" (particularly manufacturing), an advanced production concept to mass produce space-based systems and high-tech microwave components, and sound implementation concepts to deploy a profitable system.

Concurrent Engineering Methodology

The conception and realization of electronic systems is becoming increasingly complex and now requires the expertise, coordination, and integration of many disciplines. This has lead to the development of concurrent engineering processes such as quality circles, Quality Function Deployment (QFD), and integrated communications and data exchange capabilities. During the design phases of complex systems such as MIBSAT, the emphasis of these techniques must focus on the design-to-manufacturing interface. Manufacturing must be considered much earlier in the design process to ensure overall system profitability and quality, and to result in a system which is economically and efficiently manufacturable. As the first major step in the system evolution process, design is often the main determinate in the overall system profitability. A concurrent engineering model for MIBSAT to ensure Design for

Manufacturability is depicted in Figure 16. This model utilizes advanced communications capabilities and computer tools, both within and outside the organization, and an electronic interface with a Computer Integrated Manufacturing (CIM) system.

Production Concept

Manufacturing over 150 MIBSAT satellites during the system life cycle and still maintaining a profitable system will necessitate the use of advanced production procedures and processes. The satellites would be most efficiently and reliably manufactured in a high tech manufacturing line which made maximum use of CIM technology. The successful fabrication and integration of many of these advanced technologies (such as bulk MMIC and circuit radiating phase array element fabrication) would require successful production processes. The satellites would be best produced at a constant rate (after initial production startup) until all required 50 satellites plus replenishment satellites were produced (total ~ 150). Production integration and system test procedures would have to optimize system burn-in tests to identify flawed components against system life expectancy. The MIBSAT terminals would initially be funded by the MIBSAT developer but contracted out to equipment manufacturers. Initial quantities for each of the different terminal types should also be chosen to satisfy the market projection identified earlier and such that a production line concept is feasible.

Implementation Concepts

The MIBSAT system would take a fixed amount of time to be deployed after the first MIBSAT launch. An attempt should be made to launch as many satellites at once so that revenue can be brought in immediately (as the satellites begin to die). An incomplete constellation would only be available for part of the day and would not be of substantial benefit to users unless a store and forward type of capability could be used via the NMFs.

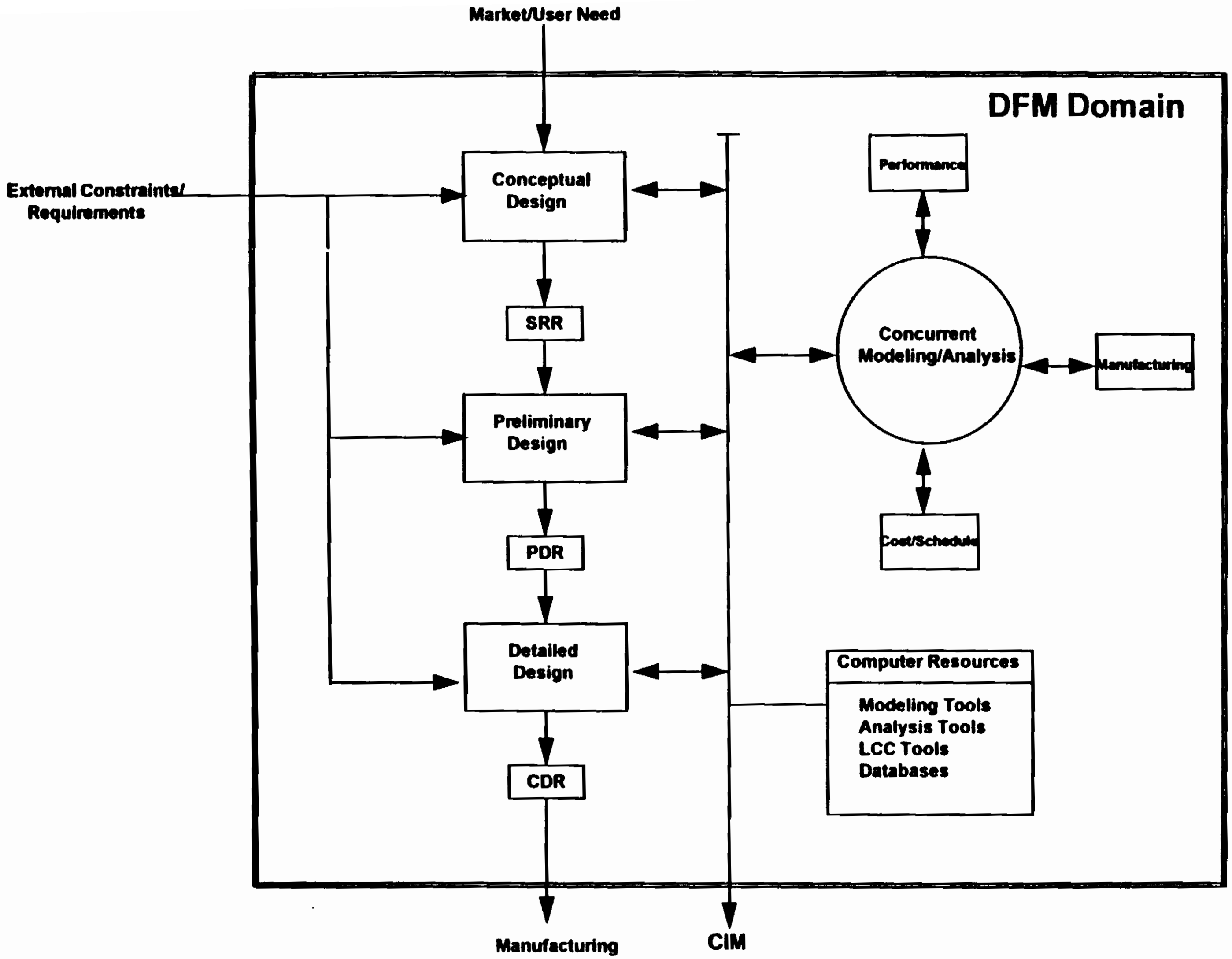


Figure 16 - Concurrent Engineering Methodology

MIBSAT terminals would first be marketed to commercial transportation companies such as airlines, cruiselines, and trains. These companies will be more willing to purchase the service since they can pass the costs off on their customers. Government would also likely show a big interest in MIBSAT due to the unique and enhanced services provided. Once the market has been stimulated with initial MIBSAT introduction, other equipment manufacturers could develop terminals in an open market place, as long as they meet documented system requirement specifications.

Conclusions

A need has been projected for a future generation (post-UMTS/FLMPTS) mobile communications system which will provide high data rate multimedia services (assumed to be available to fixed users) to mobile platforms. System requirements have been defined for this system considering the fixed communications infrastructure of the future, projected operational needs, and the systems engineering process over the systems' life cycle. This future mobile communications system was shown to be best satisfied by a LEO satellite communications system. The design presented also proposed operation in a recurrent meridian orbit and utilization of digital Asynchronous Transfer Mode (ATM) technology, high data rate satellite crosslinks, and distributed management through intelligent network concepts. A LCC model was also developed and utilized to aid in the analysis of a LEO SATCOM system based upon several design and constraint variables. The effective application of the systems engineering process, concurrent engineering methods, and advanced manufacturing techniques would be essential in realizing this system profitably.

Areas for Future Investigation

Due to the enormous scope of an actual MIBSAT design and the numerous technical and programmatic issues, there are several areas for further investigation. Among others, these include the following:

- Communications standards development
- Antenna and microwave component technology
- Spectrum allocation
- Propagation and noise in MIBSAT band
- Satellite launch technology

B-ISDN standards are currently being defined by the ITU T1 Committee and corresponding subcommittees (T1A1 on performance issues, T1E1 on physical interface issues, T1M1 on network management issues, and T1S1 on service definition and network signaling protocols). Standards are also being developed by such industry groups as the ATM Forum and the Internet Engineering Task Force (IETF). The outcome of these standards efforts will drive MIBSAT requirements to maintain compatibility and commonality where possible. MIBSAT could only achieve real profitability if it was compatible with and integral to the future B-ISDN infrastructure.

Other related projects and experiments being conducted should be investigated for technology applications. The RACE II projects being conducted in the UK are developing concepts for advanced broadband services including a Mobile Broadband System (MBS) and an interconnection service for distributed computer networks demonstrating FDDI, DBDQ, and ATM networks using over satellite services. Japan is also conducting experiments on their latest Engineering Test Satellite (ETS-VI) which includes a multibeam phased array antenna, intersatllite links, and a laser communications package.

Antenna design and fabrication technology needs to be further investigated and monitored for realization of the phased array and parabolic antenna systems, including antenna control subsystems, set forth as requirements. Microwave component design and fabrication would also have to meet MIBSAT requirements at these unique frequency ranges. It is important that these subsystems and components not only be realizable, but that the economically support a profitable MIBSAT system.

Propagation and noise analysis and measurements should be investigated in the unique MIBSAT frequency bands. Of specific interest is characterization of rain attenuation and depolarization affects. Also of interest is propagation through or around objects and foliage in both near and far fields. Specific power flux and noise density limits in the MIBSAT frequency bands should also be investigated to identify any additional terminal or satellite restrictions. Current limitations defined by the ITU and/or FCC in the US are a result of mixed terrestrial and satellite users in the same or close frequency bands (e.g. pfd $\leq$ -145dBm/sq m in 4kHz BW from 1-10 Ghz). Rules and regulations governing higher unused frequencies would have to be reviewed in conjunction with the ITU and FCC to identify other unique MIBSAT requirements.

The issue of spectrum allocation should be further investigated through review of the latest ITU regulations and WARC proceedings. The process of obtaining frequency approval should be detailed early-on in initial system conception since approvals can be expected to take some time, particularly international agreements. Specific licensing agreements in the major countries (especially US) should be reviewed and assessed for potential regulatory problems.

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APPENDIX A

ACRONYM LIST

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ACTS	Advanced Communications Technology Satellite
ADPCM	Adaptive Differential Pulse Code Modulation
ADSL	Asymmetric Digital Subscriber Line
AI	Artificial Intelligence
AIN	Advanced Intelligent Network
AMPS	Advanced Mobile Phone Service
ANN	Artificial Neural Network
APC	Adaptive Prediction Coding
ATE	Automated Test Equipment
ATM	Asynchronous Transfer Mode
B-ISDN	Broadband Integrated Services Digital Network
BB	Baseband
BER	Bit Error Rate
BFN	Beam Forming Network
BIP	Broadband Intelligent Personalized
BIT	Built in Test
BITE	Built in Test Equipment
BMF	Base Maintenance Facility
BOCs	Bell Operating Companies
BPSK	Binary Phase Shift Keying
BW	Bandwidth
C2	Command and Control
CATV	Cable Television
CCB	Configuration Control Board
CCIR	Consultive Committee International Radio
CCITT	Consultive Committee International Telegraph & Telephone
CD	Compact Disk
CDMA	Code Division Multiple Access
CDR	Critical Design Review
CIM	Computer Integrated Manufacturing
CMOS	Ceramic Metal Oxide Semiconductor
CONUS	Continental United States
CW	Continuous Wave
DA	Digital Audio
DAMA	Demand Assignment Multiple Access
DBDQ	Dual Bus Distributed Queue
DCT	Discrete Cosine-based Transformation
DE	Differentially Encoded
DECT	Digital European Cordless Telephone
DTC	Design to Cost

DTE	Date Terminating Equipment
DTM	Design to Manufacturing
DoD	Department of Defense
EC	Earth Coverage
ECMP	Electromagnetically Coupled Patch
EDFA	Erbium Doped Fiber Amplifier
EHF	Extremely High Frequency
EIA	Electronics Industry Association
EIRP	Effective Isotropic Radiated Power
FCC	Federal Communications Commission
FDDI	Fiber Distributed Data Interface
FDMA	Frequency Division Multiple Access
FFOL	FDDI Follow On
FFT	Fast Fourier Transform
FITL	Fiber in the Loop
FL	Fuzzy Logic
FLMPTS	Future Land Mobile Public Telecommunications System
FTTB	Fiber to the Building
FTTC	Fiber to the Curb
FTTH	Fiber to the Home
GPS	Global Positioning System
GSM	Global System for Mobile Users
HDR	High Data Rate
HDSL	High bit rate Digital Subscriber Logic
HDTV	High Definition Television
IATV	Interactive Television
IC	Integrated Circuit
IF	Intermediate Frequency
IM	Intermodulation
IN	Intelligent Network
INMARSAT	International Maritime Satellite Organization
ISDN	Integrated Service Digital Network
ISI	Intersymbol Interference
ITU	International Telecommunications Union
JPEG	Joint Photographic Experts Group
LAN	Local Area Network
LCC	Life Cycle Cost
LDR	Low Data Rate
LEO	Low Earth Orbit
LOS	Line of Site
LPC	Linear Predictive Code
LRI	Line Replaceable Item
LRU	Line replaceable Unit

LSI	Large Scale Integration
MDR	Medium Data Rate
MEO	Medium Earth Orbit
MF	Multi-Frequency
MHPM	Multi h-coded Phase Modulation
MIBSAT	Mobile Intelligent Broadband Satellite Communications System
MIPS	Million Instruction Per Second
MM	Multimedia
MMIC	Monolithic Microwave Integrated Circuit
MMPC	Multimedia Personal Computer
MOS	Mean Opinion Score
MPEG	Motion Picture Experts Group
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
NF	Noise Figure
NMFs	Network Management Facility
NTSC	North American Television Standard Communications
O&M	Operations & Maintenance
OAM	Operations and Administrative Management
OCR	Optical Character Reader
OJT	On the Job Training
PC	Personal Computer
PCM	Pulse Code Modulation
PCS	Personal Communications System
PDR	Preliminary Design Review
PHS&T	Packaging, Handling, Shipping, and Transportation
POTS	Plain Old Telephone Service
PSDN	Public Switched Data Network
PSK	Phase Shift Keying
PSTN	Public Switched Telephone Network
QFD	Quality Function Deployment
QOS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RACE	R&D for Advanced Communications in Europe
RF	Radio Frequency
RISC	Reduced Instruction Set Computer
ROI	Return on Investment
SATCOM	Satellite Communications
SCF	System Control Facility
SDH	Synchronous Digital Hierarchy
SEMP	System Engineering Management Plan
SHPM	Single h-coded Phase Modulation
SIF	Standard Information Format

SONET	Synchronous Optical Network
SRR	System Requirements Review
SSPA	Solid State Power Amplifier
STM	Synchronous Transfer Mode
STS	Synchronous Transfer System
TDM	Time Division Multiplex
TDMA	Time division Multiple Access
TELCOs	Telephone Companies
TT&C	Tracking Telemetry & Control
UMTS	Universal Mobile Telecommunications System
VC	Virtual Channel
VCI	Virtual Channel Identifier
VCR	Video Camera Recorder
VLSI	Very Large Scale Integration
VP	Virtual Path
VPI	Virtual Path Identifier
VSATs	Very Small Aperture Terminal
WARC	World Administrative Radio Conference

APPENDIX B

LIFE CYCLE COST ANALYSIS

LIFE CYCLE COST ANALYSIS

This LCC model and analysis is based upon the LCC Breakdown structure shown in Figure 7. A LCC model was developed in Excel to calculate the total system LCC over all years based upon input of the following variables and constraints which would pertain to the actual timeframe of system design and desired design variables:

- Satellite Cost
- Satellite life expectancy
- Satellite Height
- Launch Cost (excludes Insurance)
- # of Satellites per launch

All other costs are estimated based upon currently known costs and educated approximations. Assumptions and justification for each cost element is provided below.

Development

Program Management

- $140K/person
- Bell curve through development phase
- Personnel transition to PM of Production

Advanced R&D

- $130K/person
- First three years
- Personnel transition to engineering design

Engineering Design

- $120K/person
- Big effort second/third year (spec development)
- Some personnel transition to production; some stay for design changes
- Computer resources @ $100K/yr

Test & Evaluation

- $120K/person
- 2 Prototype Satellites (subset of functionality) @ $3M/satellite
- C2 equipment for prototype = $1M
- Prototype Terminals 7 @ $1M total (one each of seven types)
- Prototype Launch = $50M
- Test Conduct = $1M
- Data Reduction/Analysis = $300K

Design Documentation

- Admin/support costs @ $60K/person
- Documentation printing @ $30K/yr
- Documentation reproduction @150K/yr
- Drawing plot/print @ $75K/yr
- Drawing reproduction @ 200K/yr

Production

Program Management

- $140K/person
- Bell curve over production period
- RFP, proposal evaluation, and contracts year prior to production

Production Investment

- Facilities procurement = $25M
- Equipment investment = $5M

Terminal Procurement

- Terminal procurement at cost to spur demand from market forecast:
    - 120 large aeronautical terminals @ $300K/piece
    - 70 small aeronautical terminals @ $100K/piece
    - 150 large Maritime terminals @ $80K/piece
    - 110 small maritime terminals @ $25K/piece
    - 150 large land mobile terminals @ $75K/piece
    - 160 small land mobile terminals @ $20K/piece
    - 100 fixed remote terminals @ 75K/piece
- Sell terminals at cost over 8th, 9th, and 10th years

Satellite Procurement

- Satellite is selectable input cost variable in model
- Procure 40% of complete constellation satellites each of two years prior to launch; final 20% year of initial launch

Control System Construction

- Total $150M over three years prior to launch
- Includes procurement of 20 NMF terminals and site construction

Quality Control

- $100K/person
- On and off-site for terminal and satellite procurement

Logistics Support

- $90K/person
- Initial spare parts buy = $2M
- Training development = $1M
- Test equipment = $500K

Implementation

Program Management

- $140K/person
- Bell curve over implementation period
- Reassigned personnel from production

Business Management

- $120K/person finance
- $100K/person + % for sales
- Advertising/publicity = $3M/4 yrs then $200k/yr

Fees/Licensing

- $5M up front first three yrs
- $10K/operational sat/yr thereafter
- Operational fee is selectable in model

Payload Int/Transportation

- $100K/sat

Satellite Launch

- Selectable cost variable in model
- Includes insurance cost at 17% of total launch + satellites/launch
- # of launches dependent upon orbital height and satellites/launch
- Launches distributed evenly over two years (6 months before and after year of launch)

System Test and Checkout

- Initial test and subsequent test actions until constellation complete
- $90K/person

Logistics Support

- Spare parts shipment = $100K
- Initial training classes = $750K

Operation & Maintenance

Program Management

- $140K/person
- Fairly consistent over operation & maintenance period
- Reassigned personnel from production & implementation

System Operations

- Control facility personnel and technicians @ $80K/person ~ 50 people
- NMFs remote operations and field maintenance @ $2M/yr after initial ramp up
- Facility O&M @ $500K/year

System Mods/Upgrades

- Engineering support @ $120K/person
- Production/Implementation/Test & Checkout @ $1M/yr

Satellite Replenishment

- Calculated parameter dependent on input satellite cost and life, orbit height, and number of satellites/launch
- Assume satellites die exactly at satellite life; steady replenishment
- Includes comparable implementation costs for payload integration, transportation, and test and checkout
- # replenishment sats = [(system life - satellite life)/satellite life] x # of satellites in constellation
- Cost/launch = Launch cost + .17x(Launch cost + (cost/satellite)(# of sats/launch)
- # rep sats/yr = # replenishment sats/(system life - satellite life)
- Cost/yr =[[(# rep sats/yr)/(# sats/launch)] * Cost/Launch] + [#rep sats/yr * 150]

Logistics Support

- SCF/NMFs spare parts @ $300K/yr (~30 failures@10k/piece)
- Training/upgrades @ 250K/yr
- Test Equipment support @ 50K/yr

System Phaseout/Disposal

- Phaseout planning by PM personnel at $140K/person
- Close down costs @ $5M over last three years

Based on these assumptions, the attached spreadsheets were developed with this model for several cases of input variables. The cases analyzed include the following:

Case 1 - Model case
Case 2 - Increase satellite cost 2x
Case 3 - Increase cost/launch 50%
Case 4 - Reduce # sats/launch from 5 to 2
Case 5 - Increase sat life from 5 to 8 years
Case 6 - Decrease sat height from 1,237 km to 700 km
Case 7 - Best Case each variable
Case 8 - Worst Case each variable

Tables B1 through B8 provide the complete life cycle cost breakdown for each of these cases. From these tables we can get a projection of total costs per year and total costs per activity or area, as well as total cumulative costs over the system years.

Figure B1 displays the results of this analysis for the cumulative costs for each case over the complete life cycle. These totals include a 7% interest rate to account for the cost of inflation of labor and material. The cost of capital depreciation is not included for simplicity. Because no estimates for capital equipment/salvage costs or returns are considered, this figure does not represent any form of present value analysis, but merely displays the relative costs of each of the cases over the system life cycle. These cases cannot be compared and evaluated directly on cost since each will result in different system performance.

This figure does backup the original estimates for the system (estimated at \$1B to \$10B) and displays some of the variability in the LCC due to final selection of satellite and launch design parameters and constraints. Case 8 reveals that the system design could be economically unfeasible if these parameters alone are not selected appropriately.

Table B1 - MIBSAT Life Cycle Cost Analysis (Case 1)

Input Variables	System:		Satellite:		Launch:		Calculated Values:	
	Life (yrs) =	15	Cost ($k) =	2,000	Cost ($k) =	20,000	# of sats in constel. =	50
			Life (yrs) =	5	# Sats/launch =	5	# of replnish sats/yr =	10
			Height (km) =	1,237	Fee/Sat =	10		

Program Activity	Cost Desig	Cost by Program Year ($K) 2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Development	C_D	2,380	4,970	6,100	7,420	68,270	3,680	2,915	2,795	0	1,670	0	0	0
Program Management	C_{DM}	560	700	840	980	700	420	280	280	280	140	0	0	0
Advanced R&D	C_{DR}	1,690	1,950	780	0	0	0	0	0	0	0	0	0	0
Engineering Design	C_{DE}	0	1,920	4,180	4,660	2,920	2,680	2,200	2,200	1,720	1,360	0	0	0
Test & Evaluation	C_{DT}	0	0	0	1,480	64,500	480	360	240	240	120	0	0	0
Design Documentation	C_{DD}	130	400	300	300	150	100	75	75	75	50	0	0	0
Production	C_P	0	0	0	0	21,420	100,680	150,480	70,860	-2,350	-9,040	20,000	20,000	20,000
Program Management	C_{PM}	0	0	0	0	420	840	840	840	700	420	0	0	0
Production Investment	C_{PI}	0	0	0	0	21,000	9,000	0	0	0	0	0	0	0
Terminal Procurement	C_{PTP}	0	0	0	0	0	0	32,000	32,000	16,000	0	0	0	0
Terminal Sales	C_{PTS}	0	0	0	0	0	0	0	-10,000	-40,000	-30,000	0	0	0
Satellite Procurement	C_{PS}	0	0	0	0	0	40,000	40,000	20,000	20,000	20,000	20,000	20,000	20,000
Control System Constr.	C_{PC}	0	0	0	0	0	50,000	75,000	25,000	0	0	0	0	0
Quality Control	C_{PQ}	0	0	0	0	0	480	600	480	480	360	0	0	0
Logistics Support	C_{PL}	0	0	0	0	0	360	2,040	2,540	470	180	0	0	0
Implementation	C_I	0	0	0	0	0	0	620	67,330	131,240	81,230	2,380	1,740	1,660
Program Management	C_M	0	0	0	0	0	0	140	420	560	700	420	280	280
Business Management	C_B	0	0	0	0	0	0	480	1,180	1,380	1,460	1,460	960	880
Fees/Licensing	C_F	0	0	0	0	0	0	0	2,000	2,000	15,000	500	500	500
Payload Int/Trans	C_P	0	0	0	0	0	0	0	250	500	250	0	0	0
Satellite Launch	C_L	0	0	0	0	0	0	0	62,750	125,500	62,750	0	0	0
System Test & Checkout	C_T	0	0	0	0	0	0	0	630	900	720	0	0	0
Logistics Support	C_L	0	0	0	0	0	0	0	100	400	350	0	0	0
Operation & Maintenance	C_O	0	0	0	0	0	0	0	1,000	3,690	7,870	8,500	9,480	35,330
Program Management	C_{OM}	0	0	0	0	0	0	0	0	140	280	420	420	420
System Operations	C_{OO}	0	0	0	0	0	0	0	1,000	3,250	6,500	6,500	6,500	6,500
System Mods/Upgrades	C_{OU}	0	0	0	0	0	0	0	0	0	490	980	1,960	1,960
Satellite Replenishment	C_{OS}	0	0	0	0	0	0	0	0	0	0	0	0	25,850
Logistics Support	C_{OL}	0	0	0	0	0	0	0	0	300	600	600	600	600
System Phaseout/Disposal	C_{OD}	0	0	0	0	0	0	0	0	0	0	0	0	0
Total by Year		2,380	4,970	6,100	7,420	89,690	104,360	154,015	141,985	132,580	81,730	30,880	31,220	56,990
Cuml. Total		2,380	7,350	13,450	20,870	110,560	214,920	368,935	510,920	643,500	725,230	756,110	787,330	844,320
Cuml. Total +7%int		2,380	7,698	14,682	23,772	141,337	287,707	518,842	746,839	974,636	1,124,893	1,185,639	1,251,353	1,379,705

Table B1 - MIBSAT Life Cycle Cost Analysis (Case 1 Cont'd)

Program Activity	Cost Desig	Cost by Program Year 2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Total Cost
Development	C_D	0	0	0	0	0	0	0	0	0	0	0	0	100,200
Production	C_P	21,010	21,010	21,010	21,010	21,010	610	0	0	0	0	0	0	497,710
Program Management	C_{PM}	560	560	560	560	560	280	0	0	0	0	0	0	7,140
Production Investment	C_{PI}	0	0	0	0	0	0	0	0	0	0	0	0	30,000
Terminal Procurement	C_{PT}	0	0	0	0	0	0	0	0	0	0	0	0	80,000
Satellite Procurement	C_{PS}	20,000	20,000	20,000	20,000	20,000	0	0	0	0	0	0	0	300,000
Control System Constr.	C_{PC}	0	0	0	0	0	0	0	0	0	0	0	0	150,000
Quality Control	C_{PQ}	360	360	360	360	360	240	0	0	0	0	0	0	4,440
Logistics Support	C_{PL}	90	90	90	90	90	90	0	0	0	0	0	0	6,130
Implementation	C_I	1,440	1,440	1,260	1,260	500	500	500	500	500	0	0	0	294,100
Program Management	C_M	280	280	280	280	0	0	0	0	0	0	0	0	3,920
Business Management	C_B	660	660	480	480	0		0	0	0	0	0	0	10,080
Fees/Licensing	C_F	500	500	500	500	500	500	500	500	500				25,000
Payload Int/Trans	C_P	0	0	0	0	0	0	0	0	0	0	0	0	1,000
Satellite Launch	C_L	0	0	0	0	0	0	0	0	0	0	0	0	251,000
System Test & Checkout	C_{IT}	0	0	0	0	0	0	0	0	0	0	0	0	2,250
Logistics Support	C_L	0	0	0	0	0	0	0	0	0	0	0	0	850
Operation & Maintenance	C_O	61,180	61,180	61,180	61,180	61,180	61,180	61,180	58,300	54,900	2,540	1,400	1,000	612,270
Program Management	C_{OM}	420	420	420	420	420	420	420	420	380	380	240	240	6,280
System Operations	C_{OO}	6,500	6,500	6,500	6,500	6,500	6,500	6,500	4,300	1,400	460	460	460	82,830
System Mods/Upgrades	C_{OU}	1,960	1,960	1,960	1,960	1,960	1,960	1,960	980	320	200	0	0	20,610
Satellite Replenishment	C_{OS}	51,700	51,700	51,700	51,700	51,700	51,700	51,700	51,700	51,700	0	0	0	491,150
Logistics Support	C_{OL}	600	600	600	600	600	600	600	600	300	0	0	0	7,800
System Phaseout/Disposal	C_{OD}	0	0	0	0	0	0	0	300	800	1,500	700	300	3,600
Total by Year		83,630	83,630	83,450	83,450	82,690	62,290	61,680	58,800	55,400	2,540	1,400	1,000	1,504,280
Cuml. Total		927,950	1,011,580	1,095,030	1,178,480	1,261,170	1,323,460	1,385,140	1,443,940	1,499,340	1,501,880	1,503,280	1,504,280	
Cuml. Total +7%int		1,581,240	1,796,883	2,027,124	2,273,482	2,534,685	2,745,221	2,968,288	3,195,826	3,425,213	3,436,466	3,443,103	3,448,175	

Table B2 - MIBSAT Life Cycle Cost Analysis (Case 2)

Input Variables	System:		Satellite:		Launch:		Calculated Values:	
	Life (yrs) =	15	Cost ($k) =	4,000	Cost ($k) =	20,000	# of sats in constel. =	50
			Life (yrs) =	5	# Sats/launch =	5	# of replnish sats/yr =	10
			Height (km) =	1,237	Fee/Sat =	10		

Program Activity	Cost Desig	Cost by Program Year ($K)												
		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Development	C_D	2,380	4,970	6,100	7,420	68,270	3,680	2,915	2,795	0	1,670	0	0	0
Program Management	C_{DM}	560	700	840	980	700	420	280	280	280	140	0	0	0
Advanced R&D	C_{DR}	1,690	1,950	780	0	0	0	0	0	0	0	0	0	0
Engineering Design	C_{DE}	0	1,920	4,180	4,660	2,920	2,680	2,200	2,200	1,720	1,360	0	0	0
Test & Evaluation	C_{DT}	0	0	0	1,480	64,500	480	360	240	240	120	0	0	0
Design Documentation	C_{DD}	130	400	300	300	150	100	75	75	75	50	0	0	0
Production	C_P	0	0	0	0	21,420	140,680	190,480	90,860	17,650	10,960	40,000	40,000	40,000
Program Management	C_{PM}	0	0	0	0	420	840	840	840	700	420	0	0	0
Production Investment	C_{PI}	0	0	0	0	21,000	9,000	0	0	0	0	0	0	0
Terminal Procurement	C_{PTP}	0	0	0	0	0	0	32,000	32,000	16,000	0	0	0	0
Terminal Sales	C_{PTS}	0	0	0	0	0	0	0	-10,000	-40,000	-30,000	0	0	0
Satellite Procurement	C_{PS}	0	0	0	0	0	80,000	80,000	40,000	40,000	40,000	40,000	40,000	40,000
Control System Constr.	C_{PC}	0	0	0	0	0	50,000	75,000	25,000	0	0	0	0	0
Quality Control	C_{PQ}	0	0	0	0	0	480	600	480	480	360	0	0	0
Logistics Support	C_{PL}	0	0	0	0	0	360	2,040	2,540	470	180	0	0	0
Implementation	C_I	0	0	0	0	0	0	620	71,580	139,740	85,480	2,380	1,740	1,660
Program Management	C_{IM}	0	0	0	0	0	0	140	420	560	700	420	280	280
Business Management	C_{IB}	0	0	0	0	0	0	480	1,180	1,380	1,460	1,460	960	880
Fees/Licensing	C_{IF}	0	0	0	0	0	0	0	2,000	2,000	15,000	500	500	500
Payload Int/Trans	C_{IP}	0	0	0	0	0	0	0	250	500	250	0	0	0
Satellite Launch	C_{IL}	0	0	0	0	0	0	0	67,000	134,000	67,000	0	0	0
System Test & Checkout	C_{IT}	0	0	0	0	0	0	0	630	900	720	0	0	0
Logistics Support	C_{IL}	0	0	0	0	0	0	0	100	400	350	0	0	0
Operation & Maintenance	C_O	0	0	0	0	0	0	0	1,000	3,690	7,870	8,500	9,480	37,030
Program Management	C_{OM}	0	0	0	0	0	0	0	0	140	280	420	420	420
System Operations	C_{OO}	0	0	0	0	0	0	0	1,000	3,250	6,500	6,500	6,500	6,500
System Mods/Upgrades	C_{OU}	0	0	0	0	0	0	0	0	0	490	980	1,960	1,960
Satellite Replenishment	C_{OS}	0	0	0	0	0	0	0	0	0	0	0	0	27,550
Logistics Support	C_{OL}	0	0	0	0	0	0	0	0	300	600	600	600	600
System Phaseout/Disposal	C_{OD}	0	0	0	0	0	0	0	0	0	0	0	0	0
Total by Year		2,380	4,970	6,100	7,420	89,690	144,360	194,015	166,235	161,080	105,980	50,880	51,220	78,690
Cuml. Total		2,380	7,350	13,450	20,870	110,560	254,920	448,935	615,170	776,250	882,230	933,110	984,330	1,063,020
Cuml. Total +7%int		2,380	7,698	14,682	23,772	141,337	343,809	634,973	901,911	1,178,676	1,373,516	1,473,605	1,581,415	1,758,640

Table B2 - MIBSAT Life Cycle Cost Analysis (Case 2 Cont'd)

Program Activity	Cost Desig	Cost by Program Year												Total Cost
		2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	
Development	C_D	0	0	0	0	0	0	0	0	0	0	0	0	100,200
Production	C_P	41,010	41,010	41,010	41,010	41,010	610	0	0	0	0	0	0	797,710
Program Management	C_{PM}	560	560	560	560	560	280	0	0	0	0	0	0	7,140
Production Investment	C_{PI}	0	0	0	0	0	0	0	0	0	0	0	0	30,000
Terminal Procurement	C_{PT}	0	0	0	0	0	0	0	0	0	0	0	0	80,000
Satellite Procurement	C_{PS}	40,000	40,000	40,000	40,000	40,000	0	0	0	0	0	0	0	600,000
Control System Constr.	C_{PC}	0	0	0	0	0	0	0	0	0	0	0	0	150,000
Quality Control	C_{PQ}	360	360	360	360	360	240	0	0	0	0	0	0	4,440
Logistics Support	C_{PL}	90	90	90	90	90	90	0	0	0	0	0	0	6,130
Implementation	C_I	1,440	1,440	1,260	1,260	500	500	500	500	500	0	0	0	311,100
Program Management	C_{IM}	280	280	280	280	0	0	0	0	0	0	0	0	3,920
Business Management	C_{IB}	660	660	480	480	0		0	0	0	0	0	0	10,080
Fees/Licensing	C_{IF}	500	500	500	500	500	500	500	500	500				25,000
Payload Int/Trans	C_{IP}	0	0	0	0	0	0	0	0	0	0	0	0	1,000
Satellite Launch	C_{IL}	0	0	0	0	0	0	0	0	0	0	0	0	268,000
System Test & Checkout	C_{IT}	0	0	0	0	0	0	0	0	0	0	0	0	2,250
Logistics Support	C_{IL}	0	0	0	0	0	0	0	0	0	0	0	0	850
Operation & Maintenance	C_O	64,580	64,580	64,580	64,580	64,580	64,580	64,580	61,700	58,300	2,540	1,400	1,000	644,570
Program Management	C_{OM}	420	420	420	420	420	420	420	420	380	380	240	240	6,280
System Operations	C_{OO}	6,500	6,500	6,500	6,500	6,500	6,500	6,500	4,300	1,400	460	460	460	82,830
System Mods/Upgrades	C_{OU}	1,960	1,960	1,960	1,960	1,960	1,960	1,960	980	320	200	0	0	20,610
Satellite Replenishment	C_{OS}	55,100	55,100	55,100	55,100	55,100	55,100	55,100	55,100	55,100	0	0	0	523,450
Logistics Support	C_{OL}	600	600	600	600	600	600	600	600	300	0	0	0	7,800
System Phaseout/Disposal	C_{OD}	0	0	0	0	0	0	0	300	800	1,500	700	300	3,600
Total by Year		107,030	107,030	106,850	106,850	106,090	65,690	65,080	62,200	58,800	2,540	1,400	1,000	1,853,580
Cuml. Total		1,170,050	1,277,080	1,383,930	1,490,780	1,596,870	1,662,560	1,727,640	1,789,840	1,848,640	1,851,180	1,852,580	1,853,580	
Cuml. Total +7%int		2,016,566	2,292,546	2,587,349	2,902,787	3,237,906	3,459,934	3,695,298	3,935,992	4,179,457	4,190,710	4,197,347	4,202,419	

Table B3 - MIBSAT Life Cycle Cost Analysis (Case 3)

Input Variables	System:		Satellite:		Launch:		Calculated Values:	
	Life (yrs) =	15	Cost ($k) =	2,000	Cost ($k) =	30,000	# of sats in constel. =	50
			Life (yrs) =	5	# Sats/launch =	5	# of replnish sats/yr =	10
			Height (km) =	1,237	Fee/Sat =	10		

Program Activity	Cost Desig	Cost by Program Year ($K)												
		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Development	C_D	2,380	4,970	6,100	7,420	68,270	3,680	2,915	2,795	0	1,670	0	0	0
Program Management	C_{DM}	560	700	840	980	700	420	280	280	280	140	0	0	0
Advanced R&D	C_{DR}	1,690	1,950	780	0	0	0	0	0	0	0	0	0	0
Engineering Design	C_{DE}	0	1,920	4,180	4,660	2,920	2,680	2,200	2,200	1,720	1,360	0	0	0
Test & Evaluation	C_{DT}	0	0	0	1,480	64,500	480	360	240	240	120	0	0	0
Design Documentation	C_{DD}	130	400	300	300	150	100	75	75	75	50	0	0	0
Production	C_P	0	0	0	0	21,420	100,680	150,480	70,860	-2,350	-9,040	20,000	20,000	20,000
Program Management	C_{PM}	0	0	0	0	420	840	840	840	700	420	0	0	0
Production Investment	C_{PI}	0	0	0	0	21,000	9,000	0	0	0	0	0	0	0
Terminal Procurement	C_{PTP}	0	0	0	0	0	0	32,000	32,000	16,000	0	0	0	0
Terminal Sales	C_{PTS}	0	0	0	0	0	0	0	-10,000	-40,000	-30,000	0	0	0
Satellite Procurement	C_{PS}	0	0	0	0	0	40,000	40,000	20,000	20,000	20,000	20,000	20,000	20,000
Control System Constr.	C_{PC}	0	0	0	0	0	50,000	75,000	25,000	0	0	0	0	0
Quality Control	C_{PQ}	0	0	0	0	0	480	600	480	480	360	0	0	0
Logistics Support	C_{PL}	0	0	0	0	0	360	2,040	2,540	470	180	0	0	0
Implementation	C_I	0	0	0	0	0	0	620	96,580	189,740	110,480	2,380	1,740	1,660
Program Management	C_M	0	0	0	0	0	0	140	420	560	700	420	280	280
Business Management	C_B	0	0	0	0	0	0	480	1,180	1,380	1,460	1,460	960	880
Fees/Licensing	C_F	0	0	0	0	0	0	0	2,000	2,000	15,000	500	500	500
Payload Int/Trans	C_P	0	0	0	0	0	0	0	250	500	250	0	0	0
Satellite Launch	C_L	0	0	0	0	0	0	0	92,000	184,000	92,000	0	0	0
System Test & Checkout	C_T	0	0	0	0	0	0	0	630	900	720	0	0	0
Logistics Support	C_L	0	0	0	0	0	0	0	100	400	350	0	0	0
Operation & Maintenance	C_O	0	0	0	0	0	0	0	1,000	3,690	7,870	8,500	9,480	47,030
Program Management	C_{OM}	0	0	0	0	0	0	0	0	140	280	420	420	420
System Operations	C_{OO}	0	0	0	0	0	0	0	1,000	3,250	6,500	6,500	6,500	6,500
System Mods/Upgrades	C_{OU}	0	0	0	0	0	0	0	0	0	490	980	1,960	1,960
Satellite Replenishment	C_{OS}	0	0	0	0	0	0	0	0	0	0	0	0	37,550
Logistics Support	C_{OL}	0	0	0	0	0	0	0	0	300	600	600	600	600
System Phaseout/Disposal	C_{OD}	0	0	0	0	0	0	0	0	0	0	0	0	0
Total by Year		2,380	4,970	6,100	7,420	89,690	104,360	154,015	171,235	191,080	110,980	30,880	31,220	68,690
Cuml. Total		2,380	7,350	13,450	20,870	110,560	214,920	368,935	540,170	731,250	842,230	873,110	904,330	973,020
Cuml. Total +7%int		2,380	7,698	14,682	23,772	141,337	287,707	518,842	793,808	1,122,119	1,328,151	1,386,897	1,452,611	1,607,314

Table B3 - MIBSAT Life Cycle Cost Analysis (Case 3 Cont'd)

Program Activity	Cost Desig	Cost by Program Year 2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Total Cost
Development	C_D	0	0	0	0	0	0	0	0	0	0	0	0	100,200
Production	C_P	21,010	21,010	21,010	21,010	21,010	610	0	0	0	0	0	0	497,710
Program Management	C_{PM}	560	560	560	560	560	280	0	0	0	0	0	0	7,140
Production Investment	C_{PI}	0	0	0	0	0	0	0	0	0	0	0	0	30,000
Terminal Procurement	C_{PT}	0	0	0	0	0	0	0	0	0	0	0	0	80,000
Satellite Procurement	C_{PS}	20,000	20,000	20,000	20,000	20,000	0	0	0	0	0	0	0	300,000
Control System Constr.	C_{PC}	0	0	0	0	0	0	0	0	0	0	0	0	150,000
Quality Control	C_{PQ}	360	360	360	360	360	240	0	0	0	0	0	0	4,440
Logistics Support	C_{PL}	90	90	90	90	90	90	0	0	0	0	0	0	6,130
Implementation	C_I	1,440	1,440	1,260	1,260	500	500	500	500	500	0	0	0	411,100
Program Management	C_M	280	280	280	280	0	0	0	0	0	0	0	0	3,920
Business Management	C_B	660	660	480	480	0		0	0	0	0	0	0	10,080
Fees/Licensing	C_F	500	500	500	500	500	500	500	500	500				25,000
Payload Int/Trans	C_P	0	0	0	0	0	0	0	0	0	0	0	0	1,000
Satellite Launch	C_L	0	0	0	0	0	0	0	0	0	0	0	0	368,000
System Test & Checkout	C_{IT}	0	0	0	0	0	0	0	0	0	0	0	0	2,250
Logistics Support	C_L	0	0	0	0	0	0	0	0	0	0	0	0	850
Operation & Maintenance	C_O	84,580	84,580	84,580	84,580	84,580	84,580	84,580	81,700	78,300	2,540	1,400	1,000	834,570
Program Management	C_{OM}	420	420	420	420	420	420	420	420	380	380	240	240	6,280
System Operations	C_{OO}	6,500	6,500	6,500	6,500	6,500	6,500	6,500	4,300	1,400	460	460	460	82,830
System Mods/Upgrades	C_{OU}	1,960	1,960	1,960	1,960	1,960	1,960	1,960	980	320	200	0	0	20,610
Satellite Replenishment	C_{OS}	75,100	75,100	75,100	75,100	75,100	75,100	75,100	75,100	75,100	0	0	0	713,450
Logistics Support	C_{OL}	600	600	600	600	600	600	600	600	300	0	0	0	7,800
System Phaseout/Disposal	C_{OD}	0	0	0	0	0	0	0	300	800	1,500	700	300	3,600
Total by Year		107,030	107,030	106,850	106,850	106,090	85,690	85,080	82,200	78,800	2,540	1,400	1,000	1,843,580
Cuml. Total		1,080,050	1,187,080	1,293,930	1,400,780	1,506,870	1,592,560	1,677,640	1,759,840	1,838,640	1,841,180	1,842,580	1,843,580	
Cuml. Total +7%int		1,865,239	2,141,220	2,436,022	2,751,461	3,086,580	3,376,206	3,683,900	4,001,988	4,328,265	4,339,518	4,346,155	4,351,227	

Table B4 - MIBSAT Life Cycle Cost Analysis (Case 4)

Input Variables

System:		Satellite:		Launch:		Calculated Values:	
Life (yrs) =	15	Cost ($k) =	2,000	Cost ($k) =	20,000	# of sats in constel. =	50
		Life (yrs) =	5	# Sats/launch =	2	# of replnish sats/yr =	10
		Height (km) =	1,237	Fee/Sat =	10		

Program Activity	Cost Desig	Cost by Program Year ($K)												
		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Development	C_D	2,380	4,970	6,100	7,420	68,270	3,680	2,915	2,795	0	1,670	0	0	0
Program Management	C_{DM}	560	700	840	980	700	420	280	280	280	140	0	0	0
Advanced R&D	C_{DR}	1,690	1,950	780	0	0	0	0	0	0	0	0	0	0
Engineering Design	C_{DE}	0	1,920	4,180	4,660	2,920	2,680	2,200	2,200	1,720	1,360	0	0	0
Test & Evaluation	C_{DT}	0	0	0	1,480	64,500	480	360	240	240	120	0	0	0
Design Documentation	C_{DD}	130	400	300	300	150	100	75	75	75	50	0	0	0
Production	C_P	0	0	0	0	21,420	100,680	150,480	70,860	-2,350	-9,040	20,000	20,000	20,000
Program Management	C_{PM}	0	0	0	0	420	840	840	840	700	420	0	0	0
Production Investment	C_{PI}	0	0	0	0	21,000	9,000	0	0	0	0	0	0	0
Terminal Procurement	C_{PTP}	0	0	0	0	0	0	32,000	32,000	16,000	0	0	0	0
Terminal Sales	C_{PTS}	0	0	0	0	0	0	0	-10,000	-40,000	-30,000	0	0	0
Satellite Procurement	C_{PS}	0	0	0	0	0	40,000	40,000	20,000	20,000	20,000	20,000	20,000	20,000
Control System Constr.	C_{PC}	0	0	0	0	0	50,000	75,000	25,000	0	0	0	0	0
Quality Control	C_{PQ}	0	0	0	0	0	480	600	480	480	360	0	0	0
Logistics Support	C_{PL}	0	0	0	0	0	360	2,040	2,540	470	180	0	0	0
Implementation	C_I	0	0	0	0	0	0	620	155,455	307,490	169,355	2,380	1,740	1,660
Program Management	C_M	0	0	0	0	0	0	140	420	560	700	420	280	280
Business Management	C_B	0	0	0	0	0	0	480	1,180	1,380	1,460	1,460	960	880
Fees/Licensing	C_F	0	0	0	0	0	0	0	2,000	2,000	15,000	500	500	500
Payload Int/Trans	C_P	0	0	0	0	0	0	0	625	1,250	625	0	0	0
Satellite Launch	C_L	0	0	0	0	0	0	0	150,500	301,000	150,500	0	0	0
System Test & Checkout	C_T	0	0	0	0	0	0	0	630	900	720	0	0	0
Logistics Support	C_L	0	0	0	0	0	0	0	100	400	350	0	0	0
Operation & Maintenance	C_O	0	0	0	0	0	0	0	1,000	3,690	7,870	8,500	9,480	70,430
Program Management	C_{OM}	0	0	0	0	0	0	0	0	140	280	420	420	420
System Operations	C_{OO}	0	0	0	0	0	0	0	1,000	3,250	6,500	6,500	6,500	6,500
System Mods/Upgrades	C_{OU}	0	0	0	0	0	0	0	0	0	490	980	1,960	1,960
Satellite Replenishment	C_{OS}	0	0	0	0	0	0	0	0	0	0	0	0	60,950
Logistics Support	C_{OL}	0	0	0	0	0	0	0	0	300	600	600	600	600
System Phaseout/Disposal	C_{OD}	0	0	0	0	0	0	0	0	0	0	0	0	0
Total by Year		2,380	4,970	6,100	7,420	89,690	104,360	154,015	230,110	308,830	169,855	30,880	31,220	92,090
Cuml. Total		2,380	7,350	13,450	20,870	110,560	214,920	368,935	599,045	907,875	1,077,730	1,108,610	1,139,830	1,231,920
Cuml. Total +7%int		2,380	7,698	14,682	23,772	141,337	287,707	518,842	888,349	1,418,976	1,731,247	1,791,993	1,857,707	2,065,111

Table B4 - MIBSAT Life Cycle Cost Analysis (Case 4 Cont'd)

Program Activity	Cost Desig	Cost by Program Year 2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Total Cost
Development	C_D	0	0	0	0	0	0	0	0	0	0	0	0	100,200
Production	C_P	21,010	21,010	21,010	21,010	21,010	610	0	0	0	0	0	0	497,710
Program Management	C_{PM}	560	560	560	560	560	280	0	0	0	0	0	0	7,140
Production Investment	C_{PI}	0	0	0	0	0	0	0	0	0	0	0	0	30,000
Terminal Procurement	C_{PT}	0	0	0	0	0	0	0	0	0	0	0	0	80,000
Satellite Procurement	C_{PS}	20,000	20,000	20,000	20,000	20,000	0	0	0	0	0	0	0	300,000
Control System Constr.	C_{PC}	0	0	0	0	0	0	0	0	0	0	0	0	150,000
Quality Control	C_{PQ}	360	360	360	360	360	240	0	0	0	0	0	0	4,440
Logistics Support	C_{PL}	90	90	90	90	90	90	0	0	0	0	0	0	6,130
Implementation	C_I	1,440	1,440	1,260	1,260	500	500	500	500	500	0	0	0	646,600
Program Management	C_M	280	280	280	280	0	0	0	0	0	0	0	0	3,920
Business Management	C_B	660	660	480	480	0		0	0	0	0	0	0	10,080
Fees/Licensing	C_F	500	500	500	500	500	500	500	500	500				25,000
Payload Int/Trans	C_P	0	0	0	0	0	0	0	0	0	0	0	0	2,500
Satellite Launch	C_L	0	0	0	0	0	0	0	0	0	0	0	0	602,000
System Test & Checkout	C_{IT}	0	0	0	0	0	0	0	0	0	0	0	0	2,250
Logistics Support	C_L	0	0	0	0	0	0	0	0	0	0	0	0	850
Operation & Maintenance	C_O	131,380	131,380	131,380	131,380	131,380	131,380	131,380	128,500	125,100	2,540	1,400	1,000	1,279,170
Program Management	C_{OM}	420	420	420	420	420	420	420	420	380	380	240	240	6,280
System Operations	C_{OO}	6,500	6,500	6,500	6,500	6,500	6,500	6,500	4,300	1,400	460	460	460	82,830
System Mods/Upgrades	C_{OU}	1,960	1,960	1,960	1,960	1,960	1,960	1,960	980	320	200	0	0	20,610
Satellite Replenishment	C_{OS}	121,900	121,900	121,900	121,900	121,900	121,900	121,900	121,900	121,900	0	0	0	1,158,050
Logistics Support	C_{OL}	600	600	600	600	600	600	600	600	300	0	0	0	7,800
System Phaseout/Disposal	C_{OD}	0	0	0	0	0	0	0	300	800	1,500	700	300	3,600
Total by Year		153,830	153,830	153,650	153,650	152,890	132,490	131,880	129,000	125,600	2,540	1,400	1,000	2,523,680
Cuml. Total		1,385,750	1,539,580	1,693,230	1,846,880	1,999,770	2,132,260	2,264,140	2,393,140	2,518,740	2,521,280	2,522,680	2,523,680	
Cuml. Total +7%int		2,435,817	2,832,473	3,256,398	3,709,998	4,192,950	4,640,757	5,117,705	5,616,894	6,136,949	6,148,202	6,154,838	6,159,911	

Table B5 - MIBSAT Life Cycle Cost Analysis (Case 5)

Input Variables	System:		Satellite:		Launch:		Calculated Values:	
	Life (yrs) =	15	Cost ($k) =	2,000	Cost ($k) =	20,000	# of sats in constel. =	50
			Life (yrs) =	8	# Sats/launch =	5	# of replnish sats/yr =	6
			Height (km) =	1,237	Fee/Sat =	10		

Program Activity	Cost Desig	Cost by Program Year ($K) 2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Development	C_{D}	2,380	4,970	6,100	7,420	68,270	3,680	2,915	2,795	0	1,670	0	0	0
Program Management	C_{DM}	560	700	840	980	700	420	280	280	280	140	0	0	0
Advanced R&D	C_{DR}	1,690	1,950	780	0	0	0	0	0	0	0	0	0	0
Engineering Design	C_{DE}	0	1,920	4,180	4,660	2,920	2,680	2,200	2,200	1,720	1,360	0	0	0
Test & Evaluation	C_{DT}	0	0	0	1,480	64,500	480	360	240	240	120	0	0	0
Design Documentation	C_{DD}	130	400	300	300	150	100	75	75	75	50	0	0	0
Production	C_{P}	0	0	0	0	21,420	100,680	150,480	70,860	-10,350	-17,040	12,000	12,000	12,000
Program Management	C_{PM}	0	0	0	0	420	840	840	840	700	420	0	0	0
Production Investment	C_{PI}	0	0	0	0	21,000	9,000	0	0	0	0	0	0	0
Terminal Procurement	C_{PTP}	0	0	0	0	0	0	32,000	32,000	16,000	0	0	0	0
Terminal Sales	C_{PTS}	0	0	0	0	0	0	0	-10,000	-40,000	-30,000	0	0	0
Satellite Procurement	C_{PS}	0	0	0	0	0	40,000	40,000	20,000	12,000	12,000	12,000	12,000	12,000
Control System Constr.	C_{PC}	0	0	0	0	0	50,000	75,000	25,000	0	0	0	0	0
Quality Control	C_{PQ}	0	0	0	0	0	480	600	480	480	360	0	0	0
Logistics Support	C_{PL}	0	0	0	0	0	360	2,040	2,540	470	180	0	0	0
Implementation	C_{I}	0	0	0	0	0	0	620	67,330	131,240	81,230	2,380	1,740	1,660
Program Management	C_{M}	0	0	0	0	0	0	140	420	560	700	420	280	280
Business Management	C_{B}	0	0	0	0	0	0	480	1,180	1,380	1,460	1,460	960	880
Fees/Licensing	C_{F}	0	0	0	0	0	0	0	2,000	2,000	15,000	500	500	500
Payload Int/Trans	C_{P}	0	0	0	0	0	0	0	250	500	250	0	0	0
Satellite Launch	C_{L}	0	0	0	0	0	0	0	62,750	125,500	62,750	0	0	0
System Test & Checkout	C_{T}	0	0	0	0	0	0	0	630	900	720	0	0	0
Logistics Support	C_{L}	0	0	0	0	0	0	0	100	400	350	0	0	0
Operation & Maintenance	C_{O}	0	0	0	0	0	0	0	1,000	3,690	7,870	8,500	9,480	24,990
Program Management	C_{OM}	0	0	0	0	0	0	0	0	140	280	420	420	420
System Operations	C_{OO}	0	0	0	0	0	0	0	1,000	3,250	6,500	6,500	6,500	6,500
System Mods/Upgrades	C_{OU}	0	0	0	0	0	0	0	0	0	490	980	1,960	1,960
Satellite Replenishment	C_{OS}	0	0	0	0	0	0	0	0	0	0	0	0	15,510
Logistics Support	C_{OL}	0	0	0	0	0	0	0	0	300	600	600	600	600
System Phaseout/Disposal	C_{OD}	0	0	0	0	0	0	0	0	0	0	0	0	0
Total by Year		2,380	4,970	6,100	7,420	89,690	104,360	154,015	141,985	124,580	73,730	22,880	23,220	38,650
Cuml. Total		2,380	7,350	13,450	20,870	110,560	214,920	368,935	510,920	635,500	709,230	732,110	755,330	793,980
Cuml. Total +7%int		2,380	7,698	14,682	23,772	141,337	287,707	518,842	746,839	960,891	1,096,440	1,141,449	1,190,323	1,277,371

Table B5 - MIBSAT Life Cycle Cost Analysis (Case 5 Cont'd)

Program Activity	Cost Desig	Cost by Program Year 2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Total Cost
Development	C_D	0	0	0	0	0	0	0	0	0	0	0	0	100,200
Production	C_P	13,010	13,010	13,010	13,010	13,010	610	0	0	0	0	0	0	417,710
Program Management	C_{PM}	560	560	560	560	560	280	0	0	0	0	0	0	7,140
Production Investment	C_{PI}	0	0	0	0	0	0	0	0	0	0	0	0	30,000
Terminal Procurement	C_{PT}	0	0	0	0	0	0	0	0	0	0	0	0	80,000
Satellite Procurement	C_{PS}	12,000	12,000	12,000	12,000	12,000	0	0	0	0	0	0	0	220,000
Control System Constr.	C_{PC}	0	0	0	0	0	0	0	0	0	0	0	0	150,000
Quality Control	C_{PQ}	360	360	360	360	360	240	0	0	0	0	0	0	4,440
Logistics Support	C_{PL}	90	90	90	90	90	90	0	0	0	0	0	0	6,130
Implementation	C_I	1,440	1,440	1,260	1,260	500	500	500	500	500	0	0	0	294,100
Program Management	C_M	280	280	280	280	0	0	0	0	0	0	0	0	3,920
Business Management	C_B	660	660	480	480	0		0	0	0	0	0	0	10,080
Fees/Licensing	C_F	500	500	500	500	500	500	500	500	500				25,000
Payload Int/Trans	C_P	0	0	0	0	0	0	0	0	0	0	0	0	1,000
Satellite Launch	C_L	0	0	0	0	0	0	0	0	0	0	0	0	251,000
System Test & Checkout	C_T	0	0	0	0	0	0	0	0	0	0	0	0	2,250
Logistics Support	C_L	0	0	0	0	0	0	0	0	0	0	0	0	850
Operation & Maintenance	C_O	40,500	40,500	40,500	40,500	40,500	40,500	40,500	37,620	34,220	2,540	1,400	1,000	415,810
Program Management	C_{OM}	420	420	420	420	420	420	420	420	380	380	240	240	6,280
System Operations	C_{OO}	6,500	6,500	6,500	6,500	6,500	6,500	6,500	4,300	1,400	460	460	460	82,830
System Mods/Upgrades	C_{OU}	1,960	1,960	1,960	1,960	1,960	1,960	1,960	980	320	200	0	0	20,610
Satellite Replenishment	C_{OS}	31,020	31,020	31,020	31,020	31,020	31,020	31,020	31,020	31,020	0	0	0	294,690
Logistics Support	C_{OL}	600	600	600	600	600	600	600	600	300	0	0	0	7,800
System Phaseout/Disposal	C_{OD}	0	0	0	0	0	0	0	300	800	1,500	700	300	3,600
Total by Year		54,950	54,950	54,770	54,770	54,010	41,610	41,000	38,120	34,720	2,540	1,400	1,000	1,227,820
Cuml. Total		848,930	903,880	958,650	1,013,420	1,067,430	1,109,040	1,150,040	1,188,160	1,222,880	1,225,420	1,226,820	1,227,820	
Cuml. Total +7%int		1,409,792	1,551,482	1,702,594	1,864,284	2,034,892	2,175,531	2,323,808	2,471,321	2,615,081	2,626,334	2,632,971	2,638,043	

Table B6 - MIBSAT Life Cycle Cost Analysis (Case 6)

Input Variables							
System: Life (yrs) =	15	**Satellite:** Cost ($k) =	2,000	**Launch:** Cost ($k) =	20,000	**Calculated Values:** # of sats in constel. =	85
		Life (yrs) =	5	# Sats/launch =	5	# of replnish sats/yr =	17
		Height (km) =	700	Fee/Sat =	10		

Program Activity	Cost Desig	Cost by Program Year ($K) 2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Development	C_D	2,380	4,970	6,100	7,420	68,270	3,680	2,915	2,795	0	1,670	0	0	0
Program Management	C_{DM}	560	700	840	980	700	420	280	280	280	140	0	0	0
Advanced R&D	C_{DR}	1,690	1,950	780	0	0	0	0	0	0	0	0	0	0
Engineering Design	C_{DE}	0	1,920	4,180	4,660	2,920	2,680	2,200	2,200	1,720	1,360	0	0	0
Test & Evaluation	C_{DT}	0	0	0	1,480	64,500	480	360	240	240	120	0	0	0
Design Documentation	C_{DD}	130	400	300	300	150	100	75	75	75	50	0	0	0
Production	C_P	0	0	0	0	21,420	128,680	178,480	84,860	11,650	4,960	34,000	34,000	34,000
Program Management	C_{PM}	0	0	0	0	420	840	840	840	700	420	0	0	0
Production Investment	C_{PI}	0	0	0	0	21,000	9,000	0	0	0	0	0	0	0
Terminal Procurement	C_{PTP}	0	0	0	0	0	0	32,000	32,000	16,000	0	0	0	0
Terminal Sales	C_{PTS}	0	0	0	0	0	0	0	-10,000	-40,000	-30,000	0	0	0
Satellite Procurement	C_{PS}	0	0	0	0	0	68,000	68,000	34,000	34,000	34,000	34,000	34,000	34,000
Control System Constr.	C_{PC}	0	0	0	0	0	50,000	75,000	25,000	0	0	0	0	0
Quality Control	C_{PQ}	0	0	0	0	0	480	600	480	480	360	0	0	0
Logistics Support	C_{PL}	0	0	0	0	0	360	2,040	2,540	470	180	0	0	0
Implementation	C_I	0	0	0	0	0	0	620	111,430	219,440	125,330	2,730	2,090	2,010
Program Management	C_{IM}	0	0	0	0	0	0	140	420	560	700	420	280	280
Business Management	C_{IB}	0	0	0	0	0	0	480	1,180	1,380	1,460	1,460	960	880
Fees/Licensing	C_{IF}	0	0	0	0	0	0	0	2,000	2,000	15,000	850	850	850
Payload Int/Trans	C_{IP}	0	0	0	0	0	0	0	425	850	425	0	0	0
Satellite Launch	C_{IL}	0	0	0	0	0	0	0	106,675	213,350	106,675	0	0	0
System Test & Checkout	C_{IT}	0	0	0	0	0	0	0	630	900	720	0	0	0
Logistics Support	C_{IL}	0	0	0	0	0	0	0	100	400	350	0	0	0
Operation & Maintenance	C_O	0	0	0	0	0	0	0	1,000	3,690	7,870	8,500	9,480	53,425
Program Management	C_{OM}	0	0	0	0	0	0	0	0	140	280	420	420	420
System Operations	C_{OO}	0	0	0	0	0	0	0	1,000	3,250	6,500	6,500	6,500	6,500
System Mods/Upgrades	C_{OU}	0	0	0	0	0	0	0	0	0	490	980	1,960	1,960
Satellite Replenishment	C_{OS}	0	0	0	0	0	0	0	0	0	0	0	0	43,945
Logistics Support	C_{OL}	0	0	0	0	0	0	0	0	300	600	600	600	600
System Phaseout/Disposal	C_{OD}	0	0	0	0	0	0	0	0	0	0	0	0	0
Total by Year		2,380	4,970	6,100	7,420	89,690	132,360	182,015	200,085	234,780	139,830	45,230	45,570	89,435
Cuml. Total		2,380	7,350	13,450	20,870	110,560	242,920	424,935	625,020	859,800	999,630	1,044,860	1,090,430	1,179,865
Cuml. Total +7%int		2,380	7,698	14,682	23,772	141,337	326,979	600,134	921,427	1,324,823	1,581,894	1,670,869	1,766,787	1,968,211

Table B6 - MIBSAT Life Cycle Cost Analysis (Case 6 Cont'd)

Program Activity	Cost Desig	Cost by Program Year 2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Total Cost
Development	C_D	0	0	0	0	0	0	0	0	0	0	0	0	100,200
Production	C_P	35,010	35,010	35,010	35,010	35,010	610	0	0	0	0	0	0	707,710
Program Management	C_{PM}	560	560	560	560	560	280	0	0	0	0	0	0	7,140
Production Investment	C_{PI}	0	0	0	0	0	0	0	0	0	0	0	0	30,000
Terminal Procurement	C_{PT}	0	0	0	0	0	0	0	0	0	0	0	0	80,000
Satellite Procurement	C_{PS}	34,000	34,000	34,000	34,000	34,000	0	0	0	0	0	0	0	510,000
Control System Constr.	C_{PC}	0	0	0	0	0	0	0	0	0	0	0	0	150,000
Quality Control	C_{PQ}	360	360	360	360	360	240	0	0	0	0	0	0	4,440
Logistics Support	C_{PL}	90	90	90	90	90	90	0	0	0	0	0	0	6,130
Implementation	C_I	1,790	1,790	1,610	1,610	850	850	850	850	850	0	0	0	474,700
Program Management	C_M	280	280	280	280	0	0	0	0	0	0	0	0	3,920
Business Management	C_B	660	660	480	480	0		0	0	0	0	0	0	10,080
Fees/Licensing	C_F	850	850	850	850	850	850	850	850	850				29,200
Payload Int/Trans	C_P	0	0	0	0	0	0	0	0	0	0	0	0	1,700
Satellite Launch	C_L	0	0	0	0	0	0	0	0	0	0	0	0	426,700
System Test & Checkout	C_{IT}	0	0	0	0	0	0	0	0	0	0	0	0	2,250
Logistics Support	C_L	0	0	0	0	0	0	0	0	0	0	0	0	850
Operation & Maintenance	C_O	97,370	97,370	97,370	97,370	97,370	97,370	97,370	94,490	91,090	2,540	1,400	1,000	956,075
Program Management	C_{OM}	420	420	420	420	420	420	420	420	380	380	240	240	6,280
System Operations	C_{OO}	6,500	6,500	6,500	6,500	6,500	6,500	6,500	4,300	1,400	460	460	460	82,830
System Mods/Upgrades	C_{OU}	1,960	1,960	1,960	1,960	1,960	1,960	1,960	980	320	200	0	0	20,610
Satellite Replenishment	C_{OS}	87,890	87,890	87,890	87,890	87,890	87,890	87,890	87,890	87,890	0	0	0	834,955
Logistics Support	C_{OL}	600	600	600	600	600	600	600	600	300	0	0	0	7,800
System Phaseout/Disposal	C_{OO}	0	0	0	0	0	0	0	300	800	1,500	700	300	3,600
Total by Year		134,170	134,170	133,990	133,990	133,230	98,830	98,220	95,340	91,940	2,540	1,400	1,000	2,238,685
Cuml. Total		1,314,035	1,448,205	1,582,195	1,716,185	1,849,415	1,948,245	2,046,465	2,141,805	2,233,745	2,236,285	2,237,685	2,238,685	
Cuml. Total +7%int		2,291,540	2,637,502	3,007,185	3,402,745	3,823,594	4,157,633	4,512,848	4,881,784	5,262,467	5,273,721	5,280,357	5,285,430	

Table B7 - MIBSAT Life Cycle Cost Analysis (Case 7)

Input Variables

System:		Satellite:		Launch:		Calculated Values:	
Life (yrs) =	15	Cost ($k) =	1,000	Cost ($k) =	10,000	# of sats in constel. =	32
		Life (yrs) =	10	# Sats/launch =	7	# of replnish sats/yr =	3
		Height (km) =	1,500	Fee/Sat =	10		

Program Activity	Cost Desig	Cost by Program Year ($K) 2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Development	C_{D}	2,380	4,970	6,100	7,420	68,270	3,680	2,915	2,795	0	1,670	0	0	0
Program Management	C_{DM}	560	700	840	980	700	420	280	280	280	140	0	0	0
Advanced R&D	C_{DR}	1,690	1,950	780	0	0	0	0	0	0	0	0	0	0
Engineering Design	C_{DE}	0	1,920	4,180	4,660	2,920	2,680	2,200	2,200	1,720	1,360	0	0	0
Test & Evaluation	C_{DT}	0	0	0	1,480	64,500	480	360	240	240	120	0	0	0
Design Documentation	C_{DD}	130	400	300	300	150	100	75	75	75	50	0	0	0
Production	C_{P}	0	0	0	0	21,420	73,480	123,280	57,260	-19,350	-26,040	3,000	3,000	3,000
Program Management	C_{PM}	0	0	0	0	420	840	840	840	700	420	0	0	0
Production Investment	C_{PI}	0	0	0	0	21,000	9,000	0	0	0	0	0	0	0
Terminal Procurement	C_{PTP}	0	0	0	0	0	0	32,000	32,000	16,000	0	0	0	0
Terminal Sales	C_{PTS}	0	0	0	0	0	0	0	-10,000	-40,000	-30,000	0	0	0
Satellite Procurement	C_{PS}	0	0	0	0	0	12,800	12,800	6,400	3,000	3,000	3,000	3,000	3,000
Control System Constr.	C_{PC}	0	0	0	0	0	50,000	75,000	25,000	0	0	0	0	0
Quality Control	C_{PQ}	0	0	0	0	0	480	600	480	480	360	0	0	0
Logistics Support	C_{PL}	0	0	0	0	0	360	2,040	2,540	470	180	0	0	0
Implementation	C_{I}	0	0	0	0	0	0	620	19,176	34,931	33,076	2,200	1,560	1,480
Program Management	C_{M}	0	0	0	0	0	0	140	420	560	700	420	280	280
Business Management	C_{B}	0	0	0	0	0	0	480	1,180	1,380	1,460	1,460	960	880
Fees/Licensing	C_{F}	0	0	0	0	0	0	0	2,000	2,000	15,000	320	320	320
Payload Int/Trans	C_{P}	0	0	0	0	0	0	0	114	229	114	0	0	0
Satellite Launch	C_{L}	0	0	0	0	0	0	0	14,731	29,463	14,731	0	0	0
System Test & Checkout	C_{T}	0	0	0	0	0	0	0	630	900	720	0	0	0
Logistics Support	C_{L}	0	0	0	0	0	0	0	100	400	350	0	0	0
Operation & Maintenance	C_{O}	0	0	0	0	0	0	0	1,000	3,690	7,870	8,500	9,480	12,300
Program Management	C_{OM}	0	0	0	0	0	0	0	0	140	280	420	420	420
System Operations	C_{OO}	0	0	0	0	0	0	0	1,000	3,250	6,500	6,500	6,500	6,500
System Mods/Upgrades	C_{OU}	0	0	0	0	0	0	0	0	0	490	980	1,960	1,960
Satellite Replenishment	C_{OS}	0	0	0	0	0	0	0	0	0	0	0	0	2,820
Logistics Support	C_{OL}	0	0	0	0	0	0	0	0	300	600	600	600	600
System Phaseout/Disposal	C_{OD}	0	0	0	0	0	0	0	0	0	0	0	0	0
Total by Year		2,380	4,970	6,100	7,420	89,690	77,160	126,815	80,231	19,271	16,576	13,700	14,040	16,780
Cuml. Total		2,380	7,350	13,450	20,870	110,560	187,720	314,535	394,766	414,037	430,613	444,313	458,353	475,133
Cuml. Total +7%int		2,380	7,698	14,682	23,772	141,337	249,558	439,873	568,706	601,818	632,292	659,242	688,794	726,585

Table B7 - MIBSAT Life Cycle Cost Analysis (Case 7 Cont'd)

Program Activity	Cost Desig	Cost by Program Year 2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Total Cost
Development	C_D	0	0	0	0	0	0	0	0	0	0	0	0	100,200
Production	C_P	4,010	4,010	4,010	4,010	4,010	610	0	0	0	0	0	0	259,710
Program Management	C_{PM}	560	560	560	560	560	280	0	0	0	0	0	0	7,140
Production Investment	C_{PI}	0	0	0	0	0	0	0	0	0	0	0	0	30,000
Terminal Procurement	C_{PT}	0	0	0	0	0	0	0	0	0	0	0	0	80,000
Satellite Procurement	C_{PS}	3,000	3,000	3,000	3,000	3,000	0	0	0	0	0	0	0	62,000
Control System Constr.	C_{PC}	0	0	0	0	0	0	0	0	0	0	0	0	150,000
Quality Control	C_{PQ}	360	360	360	360	360	240	0	0	0	0	0	0	4,440
Logistics Support	C_{PL}	90	90	90	90	90	90	0	0	0	0	0	0	6,130
Implementation	C_I	1,260	1,260	1,080	1,080	320	320	320	320	320	0	0	0	99,323
Program Management	C_{IM}	280	280	280	280	0	0	0	0	0	0	0	0	3,920
Business Management	C_{IB}	660	660	480	480	0		0	0	0	0	0	0	10,080
Fees/Licensing	C_{IF}	320	320	320	320	320	320	320	320	320				22,840
Payload Int/Trans	C_{IP}	0	0	0	0	0	0	0	0	0	0	0	0	457
Satellite Launch	C_{IL}	0	0	0	0	0	0	0	0	0	0	0	0	58,926
System Test & Checkout	C_{IT}	0	0	0	0	0	0	0	0	0	0	0	0	2,250
Logistics Support	C_{IL}	0	0	0	0	0	0	0	0	0	0	0	0	850
Operation & Maintenance	C_O	15,120	15,120	15,120	15,120	15,120	15,120	15,120	12,240	8,840	2,540	1,400	1,000	174,700
Program Management	C_{OM}	420	420	420	420	420	420	420	420	380	380	240	240	6,280
System Operations	C_{OO}	6,500	6,500	6,500	6,500	6,500	6,500	6,500	4,300	1,400	460	460	460	82,830
System Mods/Upgrades	C_{OU}	1,960	1,960	1,960	1,960	1,960	1,960	1,960	980	320	200	0	0	20,610
Satellite Replenishment	C_{OS}	5,640	5,640	5,640	5,640	5,640	5,640	5,640	5,640	5,640	0	0	0	53,580
Logistics Support	C_{OL}	600	600	600	600	600	600	600	600	300	0	0	0	7,800
System Phaseout/Disposal	C_{OD}	0	0	0	0	0	0	0	300	800	1,500	700	300	3,600
Total by Year		20,390	20,390	20,210	20,210	19,450	16,050	15,440	12,560	9,160	2,540	1,400	1,000	633,933
Cuml. Total		495,523	515,913	536,123	556,333	575,783	591,833	607,273	619,833	628,993	631,533	632,933	633,933	
Cuml. Total +7%int		775,722	828,299	884,059	943,722	1,005,161	1,059,409	1,115,248	1,163,851	1,201,779	1,213,032	1,219,669	1,224,741	

Table B8 - MIBSAT Life Cycle Cost Analysis (Case 8)

Input Variables	System:		Satellite:		Launch:		Calculated Values:	
	Life (yrs) =	15	Cost ($k) =	10,000	Cost ($k) =	30,000	# of sats in constel. =	85
			Life (yrs) =	3	# Sats/launch =	2	# of replnish sats/yr =	28
			Height (km) =	700	Fee/Sat =	10		

Program Activity	Cost Desig	Cost by Program Year ($K)												
		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Development	C_D	2,380	4,970	6,100	7,420	68,270	3,680	2,915	2,795	0	1,670	0	0	0
Program Management	C_{DM}	560	700	840	980	700	420	280	280	280	140	0	0	0
Advanced R&D	C_{DR}	1,690	1,950	780	0	0	0	0	0	0	0	0	0	0
Engineering Design	C_{DE}	0	1,920	4,180	4,660	2,920	2,680	2,200	2,200	1,720	1,360	0	0	0
Test & Evaluation	C_{DT}	0	0	0	1,480	64,500	480	360	240	240	120	0	0	0
Design Documentation	C_{DD}	130	400	300	300	150	100	75	75	75	50	0	0	0
Production	C_P	0	0	0	0	21,420	400,680	450,480	220,860	257,650	250,960	280,000	280,000	280,000
Program Management	C_{PM}	0	0	0	0	420	840	840	840	700	420	0	0	0
Production Investment	C_{PI}	0	0	0	0	21,000	9,000	0	0	0	0	0	0	0
Terminal Procurement	C_{PTP}	0	0	0	0	0	0	32,000	32,000	16,000	0	0	0	0
Terminal Sales	C_{PTS}	0	0	0	0	0	0	0	-10,000	-40,000	-30,000	0	0	0
Satellite Procurement	C_{PS}	0	0	0	0	0	340,000	340,000	170,000	280,000	280,000	280,000	280,000	280,000
Control System Constr.	C_{PC}	0	0	0	0	0	50,000	75,000	25,000	0	0	0	0	0
Quality Control	C_{PQ}	0	0	0	0	0	480	600	480	480	360	0	0	0
Logistics Support	C_{PL}	0	0	0	0	0	360	2,040	2,540	470	180	0	0	0
Implementation	C_I	0	0	0	0	0	0	620	414,455	825,490	428,355	2,730	2,090	2,010
Program Management	C_M	0	0	0	0	0	0	140	420	560	700	420	280	280
Business Management	C_B	0	0	0	0	0	0	480	1,180	1,380	1,460	1,460	960	880
Fees/Licensing	C_F	0	0	0	0	0	0	0	2,000	2,000	15,000	850	850	850
Payload Int/Trans	C_P	0	0	0	0	0	0	0	1,063	2,125	1,063	0	0	0
Satellite Launch	C_L	0	0	0	0	0	0	0	409,063	818,125	409,063	0	0	0
System Test & Checkout	C_T	0	0	0	0	0	0	0	630	900	720	0	0	0
Logistics Support	C_L	0	0	0	0	0	0	0	100	400	350	0	0	0
Operation & Maintenance	C_O	0	0	0	0	0	0	0	1,000	3,690	7,870	8,500	9,480	281,080
Program Management	C_{OM}	0	0	0	0	0	0	0	0	140	280	420	420	420
System Operations	C_{OO}	0	0	0	0	0	0	0	1,000	3,250	6,500	6,500	6,500	6,500
System Mods/Upgrades	C_{OU}	0	0	0	0	0	0	0	0	0	490	980	1,960	1,960
Satellite Replenishment	C_{OS}	0	0	0	0	0	0	0	0	0	0	0	0	271,600
Logistics Support	C_{OL}	0	0	0	0	0	0	0	0	300	600	600	600	600
System Phaseout/Disposal	C_{OD}	0	0	0	0	0	0	0	0	0	0	0	0	0
Total by Year		2,380	4,970	6,100	7,420	89,690	404,360	454,015	639,110	1,086,830	688,855	291,230	291,570	563,090
Cuml. Total		2,380	7,350	13,450	20,870	110,560	514,920	968,935	1,608,045	2,694,875	3,383,730	3,674,960	3,966,530	4,529,620
Cuml. Total +7%int		2,380	7,698	14,682	23,772	141,337	708,473	1,389,827	2,416,098	4,283,474	5,549,906	6,122,799	6,736,511	8,004,698

Table B8 - MIBSAT Life Cycle Cost Analysis (Case 8 Cont'd)

Program Activity	Cost Desig	Cost by Program Year 2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Total Cost
Development	C_D	0	0	0	0	0	0	0	0	0	0	0	0	100,200
Production	C_P	281,010	281,010	281,010	281,010	281,010	610	0	0	0	0	0	0	3,847,710
Program Management	C_{PM}	560	560	560	560	560	280	0	0	0	0	0	0	7,140
Production Investment	C_{PI}	0	0	0	0	0	0	0	0	0	0	0	0	30,000
Terminal Procurement	C_{PT}	0	0	0	0	0	0	0	0	0	0	0	0	80,000
Satellite Procurement	C_{PS}	280,000	280,000	280,000	280,000	280,000	0	0	0	0	0	0	0	3,650,000
Control System Constr.	C_{PC}	0	0	0	0	0	0	0	0	0	0	0	0	150,000
Quality Control	C_{PQ}	360	360	360	360	360	240	0	0	0	0	0	0	4,440
Logistics Support	C_{PL}	90	90	90	90	90	90	0	0	0	0	0	0	6,130
Implementation	C_I	1,790	1,790	1,610	1,610	850	850	850	850	850	0	0	0	1,686,800
Program Management	C_{IM}	280	280	280	280	0	0	0	0	0	0	0	0	3,920
Business Management	C_{IB}	660	660	480	480	0		0	0	0	0	0	0	10,080
Fees/Licensing	C_{IF}	850	850	850	850	850	850	850	850	850				29,200
Payload Int/Trans	C_{IP}	0	0	0	0	0	0	0	0	0	0	0	0	4,250
Satellite Launch	C_{IL}	0	0	0	0	0	0	0	0	0	0	0	0	1,636,250
System Test & Checkout	C_{IT}	0	0	0	0	0	0	0	0	0	0	0	0	2,250
Logistics Support	C_{IL}	0	0	0	0	0	0	0	0	0	0	0	0	850
Operation & Maintenance	C_O	552,680	552,680	552,680	552,680	552,680	552,680	552,680	549,800	546,400	2,540	1,400	1,000	5,281,520
Program Management	C_{OM}	420	420	420	420	420	420	420	420	380	380	240	240	6,280
System Operations	C_{OO}	6,500	6,500	6,500	6,500	6,500	6,500	6,500	4,300	1,400	460	460	460	82,830
System Mods/Upgrades	C_{OU}	1,960	1,960	1,960	1,960	1,960	1,960	1,960	980	320	200	0	0	20,610
Satellite Replenishment	C_{OS}	543,200	543,200	543,200	543,200	543,200	543,200	543,200	543,200	543,200	0	0	0	5,160,400
Logistics Support	C_{OL}	600	600	600	600	600	600	600	600	300	0	0	0	7,800
System Phaseout/Disposal	C_{OD}	0	0	0	0	0	0	0	300	800	1,500	700	300	3,600
Total by Year		835,480	835,480	835,300	835,300	834,540	554,140	553,530	550,650	547,250	2,540	1,400	1,000	10,916,230
Cuml. Total		5,365,100	6,200,580	7,035,880	7,871,180	8,705,720	9,259,860	9,813,390	10,364,040	10,911,290	10,913,830	10,915,230	10,916,230	
Cuml. Total +7%int		10,018,075	12,172,389	14,477,008	16,942,950	19,579,108	21,452,063	23,453,920	25,584,762	27,850,684	27,861,938	27,868,574	27,873,647	

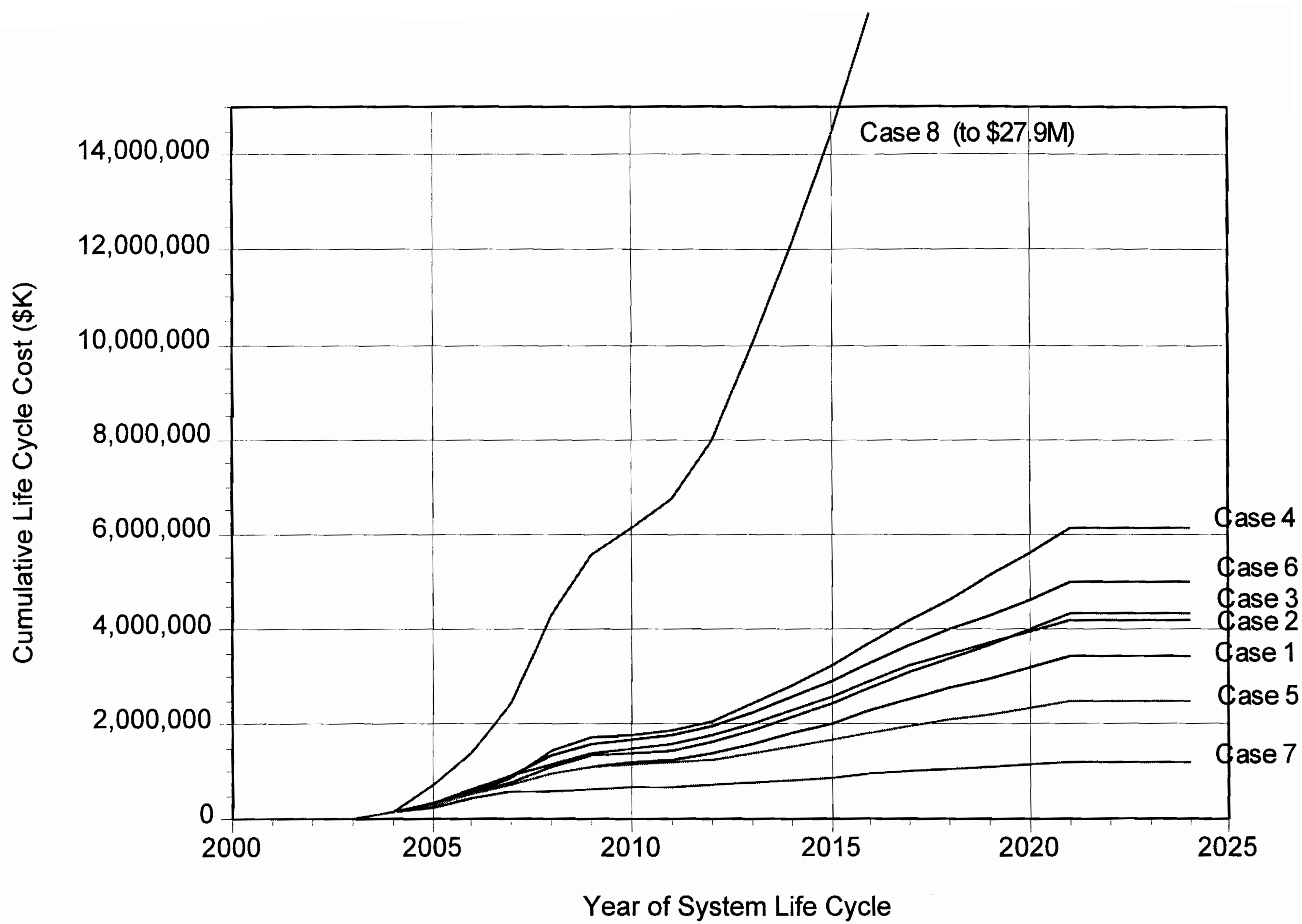

Figure B1 - Cumulative Life Cycle Cost Results

Figure B2 displays a sensitivity analysis based upon this model for each of the design/constraint variables. All of the variable multipliers are shown on one figure to aid in a comparison. It should be noted that the satellite height profile is not centered on the "model" case (case 1) LCC because of the design selection to include an additional satellite in each orbital plane. The slope depicted for this multiplier is still valid.

From this sensitivity analysis, we can rank the variables under review in order of importance from a LCC standpoint:

1) Satellite height
2) Satellite life
3) # of satellites/launch
4) Launch cost
5) Satellite cost

This information would be used during early design phases to help select DTC parameters and required constraint costs (e.g., launch costs) for system economic feasibility and profitability. The LCC model could also be used throughout the development phase to confirm and refine cost elements and recalculate overall LCC.

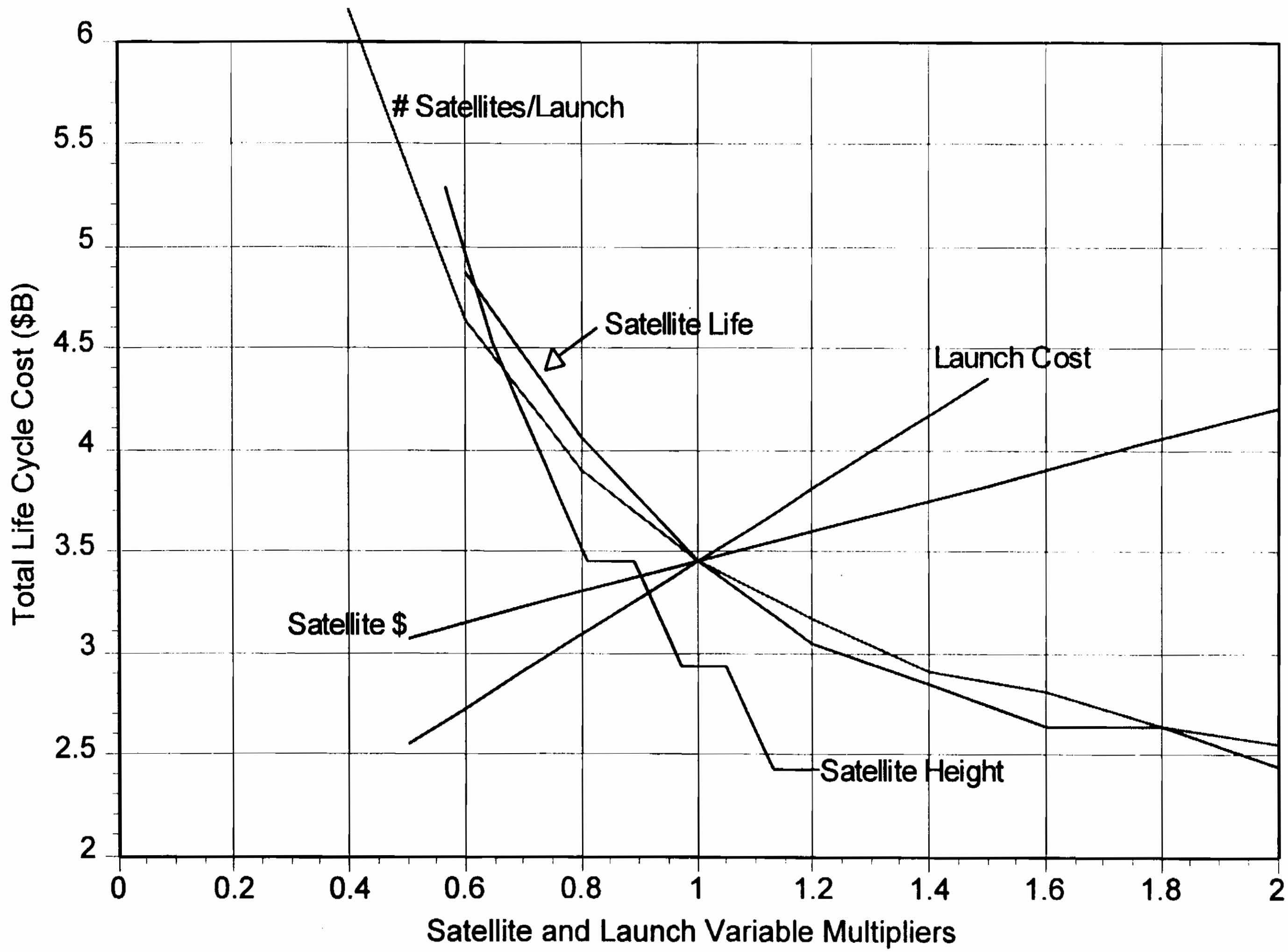

Figure B2 - Life Cycle Cost Sensitivity Analysis