PERSPECTIVES ON THE SATELLITE SERVICES INDUSTRY: ANALYSES OF CHALLENGES AND OPPORTUNITIES IN THE MARKET, POLICY AND REGULATORY ENVIRONMENTS

by

Juan Pablo Torres-Padilla

Ingénieur diplômé de l'École Polytechnique, Paris, France, 2002

Submitted to the Engineering Systems Division
in partial fulfillment of the requirements for the degree of

Master of Science in Technology and Policy

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Abstract

This thesis focuses on Space Communications and combines engineering, economics, market, and policy analyses to identify challenges and opportunities in the industry that are beyond the scope of any one isolated discipline.

This work is divided in two parts. The first part begins by discussing the background of the communications satellite industry, its value-chain, service applications, history and evolution, and then explores two questions of significant importance to the survival and sustained growth of this industry: 1) are satellite communications solutions competing or complementary alternatives to terrestrial networks–in what context and for what service applications? And 2) what are the characteristics of the regulatory and policy environments and how do they affect the satellite communications industry? In order to address the first question, a framework to analyze the tradeoffs associated with satellite versus terrestrial solutions is developed around three axes: type of solution, service application, and geographic market. It is then argued that satellite solutions and terrestrial networks have a dual character: they are simultaneously competing and complementary technologies. The case is made that satellite solutions have important competitive advantages for voice and data transmission in rural markets and urban areas where terrestrial networks are not available. It is found that consumer video applications represent the most dynamic market with the highest potential of growth for satellite operators. Then, to assess the impact of the regulatory and policy environments, two key regulatory issues are discussed: spectrum/orbit allocation and spacecraft disposal. First, major conflicting issues in frequency bandwidth allocation are discussed. Second, it is argued that there is a critical need to enforce space debris regulations, even though such regulations would have short-term negative financial implications for satellite operators. The case is made that a single collision in geostationary orbit (GEO) is likely to create a cascading debris field that can impact the entire fleet of spacecraft in GEO, resulting in significant loss of satellite communications services. In addition, it is found that the U.S. space communications policy is highly flexible, while on the European side there is a need to consolidate and further ease the regulatory environment in order to promote competition. It is argued that more international cooperation in regulatory issues is desirable.

The second part of this thesis focuses on the lifeblood of the satellite industry: the satellite itself (as opposed to the industry-context explored in Part I). In particular, part II explores issues associated with satellite design lifetime. Qualitative arguments are presented for reducing or extending a spacecraft design lifetime, as seen from different stakeholders' perspectives (the manufacturer, the customer, and society at large). Quantitative analyses are then conducted from an operator's perspective, and preliminary results indicate that optimal design lifetimes do exist that maximize a satellite financial/value metric. These results disprove the traditional assumption that satellite operators (customers) are always better off acquiring spacecraft designed for the maximum technically achievable lifetime. Additionally, it is argued that design lifetime is a powerful lever that can impact the market size as well as the financials of the key players in the space sector. Overall, it is shown that the specification of a system's design lifetime requires much more attention than it has received so far in the literature, as it can impact an entire industry value chain.

Thesis Supervisor: Dr. Joseph H. Saleh
Executive Director, Ford-MIT Alliance

A Dios Padre,
por haberme dado vida y por haberme tratado siempre mejor de lo que merezco,
así como por los innumerables retos y oportunidades que me ha puesto en el camino.

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† Part Two of this thesis is based on two papers accepted for presentation at the AIAA Space 2005 Conference (chapter 5) and for publication at the AIAA Journal of Spacecraft and Rockets (chapter 6). This work was done in collaboration with different co-authors that are properly referenced in each chapter.

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"For the advent of communications satellites will mean the end of the present barriers to the free flow of information; no dictatorship can build a wall high enough to stop its citizens listening to the voices from the stars. It would be extremely difficult, if not impossible, to jam satellite broadcasts [...]"

The influence of satellite communications "will be like that of air transport, though on a much larger scale and affecting whole nations rather than a relatively few favored individuals. The inexorable force of astronomical facts will destroy the political fantasies that have so long fragmented our planet. For when all major artistic productions, entertainments, political and news events can be viewed simultaneously by the whole world, the parochialism and xenophobia of the past will be unable to survive."

Adapted from Arthur C. Clarke. *Voices from the Sky*. 1962

Chapter 1

Introduction

1.1. Background and Motivation

Technological advances in two major fields in the twentieth century changed the way people live: transportation and communications.[1] Before the proliferation of the automobile, people traveled on foot or by horse. A trip of 100 kilometers was an adventure. Prior to the invention of the telegraph and the telephone, people had to travel in order to communicate with someone in a different urban area. Traveling was onerous and could required days or weeks. The airplane provided us with an incredible mobility that nowadays is often taken for granted, but was unimaginable just a century ago. In addition, the development of advanced telecommunication technologies has made it possible to communicate with virtually anyone, anywhere, at anytime. Artificial Earth satellites have been used for more than 40 years and satellite communications form today a unique part of our every-day life, serving billions of people and granting access to a vast range of voice, data and video telecommunication applications.

At the beginning of the commercial space era, satellites were designed to deliver long-distance telephony services.[2] Since then, new satellite technologies have emerged, and today a variety of spacecraft is capable of providing diverse service applications to various types of end-users with different communication needs. As a result, several industries have developed around satellite communications. In fact, the entire space enterprise value-chain has become a key foundation of the economy and one of the engines of economic growth and development. In the United States, for instance, the aerospace industry generated in 2003 the largest positive trade balance of any manufacturing sector. This represented over 15 percent of the U.S. Gross Domestic Product (GDP) and translated into a total of over 15 million high quality jobs.[3] In addition, the enabling technologies generated by the space-based communications industries, such as overnight parcel delivery and just-in-time manufacturing, literally have an impact on almost all aspects of our daily living.

Within the commercial space sector, three central stakeholders are directly related to the satellite communications industry, namely: the satellite manufacturers, the launch service providers, and the satellite operators (also called satellite services providers). In addition to these three main stakeholders, there is a significant number of industries and institutions indirectly related to the space-based communications industry. The entire space enterprise value-chain includes suppliers of equipment, engine manufacturers, government agencies, regulatory bodies, banks and investment organizations, insurance companies, and of course, the different types of end-users (i.e., the satellite operators' customers), namely telecom operators, TV and radio broadcasters, government organizations, corporate users, and others. Figure 1.1 provides a comprehensive view of the entire space enterprise value-chain.

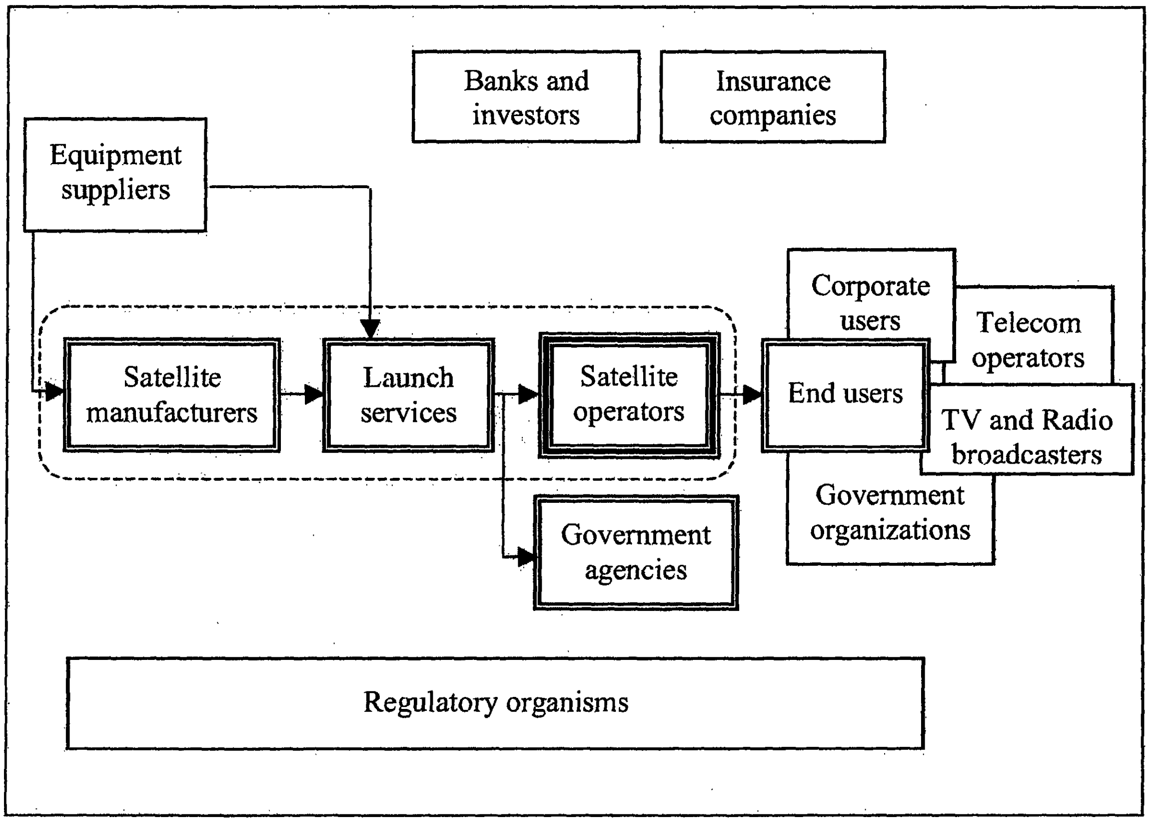

Figure 1.1: Comprehensive view of the entire space enterprise value-chain (Adapted from Euroconsult)

1.2. Thesis objectives

As stated above, satellite operators are major stakeholders (probably the most important ones, since they provide the service itself) within the satellite communications industry. The main objective of this work is to provide a comprehensive perspective on the space-based communications industry including the analysis of challenges and opportunities in the market, policy and regulatory environment, as well as linking engineering considerations to business/strategic issues. This thesis focuses on the key stakeholders of the satellite communications industry, i.e., satellite service providers. Yet, it also provides noteworthy insights on the dynamics of the interactions between the operators and the end-users, as well as different perspectives on the influence of some regulatory bodies in the industry.

Satellite operators can in turn be classified into three categories: Fixed-Satellite Service providers (FSS), Mobile-Satellite Service (MSS) providers, and Direct Broadcast Service providers (DBS). Although this thesis focuses on the FSS operators, it presents an overview of the industry that includes all commercial communication satellite services. In addition, some of the findings identified in Chapters 3 and 4 are also applicable to the DBS and MSS sector. Furthermore, Chapters 5 expands the scope of the thesis and proposes to analyze issues related to spacecraft design lifetime from two perspectives: the operator's and the manufacturer's perspective.

In fact, the first contribution of this thesis is precisely the broad perspective that it introduces. In the academic and business literature, one can find various reports and studies on different topics related to the satellite communications industry. However, the author believes this is the first time that the members of the commercial space sector are presented with a wide and comprehensive analysis of the structure and the dynamics of the satellite operators industry, including the current opportunities, challenges, competing technologies, and financial and regulatory issues faced by major stakeholders. The second major contribution of this thesis is the multidisciplinary approach that is proposed. It is divided in two parts combining engineering, economics, industry analysis and policy in a way that identifies insights beyond the reach of any one isolated discipline. The specifics of both Parts and each Chapter are described below.

1.3. Thesis Outline

This thesis is divided into two parts. Part I, On the Market Dynamics of the Satellite Communications Industry, consists of Chapter 2, Overview of the Satellite Communications Industry, Chapter 3, Satellite Communications and or versus Terrestrial Networks: Competing or Complementary Technologies, and Chapter 4, The Regulatory Environment for Satellite Operators and the Policy-making process for Space-based Communications.

The objective of Chapter 2 is to provide the reader with the necessary background about the subject matter of this thesis, as well as with an overview of key issues and indicators of the satellite communications market. It provides a summary of the evolution of the industry and introduces the key definitions of satellite services used by the International Telecommunication Union (ITU), in order to effectively and clearly discuss the subject. In addition, Chapter 2 presents a snapshot of the current financial state of the industry and the concept of satellite applications. A classification and a brief description of these applications are presented here. Finally, Chapter 2 provides the highlights of some of the most important satellite operators.

Chapter 3 presents a thorough discussion of the dual character of satellite technologies when confronted to terrestrial networks: competing and or complementary solutions. The author of this thesis believes that satellite technologies have yet to conquer potential new markets and that satellite operators might find it useful to forge partnerships with some of their terrestrial competitors. Chapter 3 provides arguments that support this assertion. Firstly, it presents a comprehensive analysis of satellite communications as a competing or complementary technology to terrestrial networks. Secondly, it summarizes the challenges that satellites face as a solution to providing telecommunications in urban areas. Next, it discusses the opportunities that rural areas represent for the satellite services industry. Brief descriptions of Aramiska and the Twister projects (two satellite-based solutions) are provided as examples for rural connectivity. An analysis of the trans-oceanic communications market is also provided. Finally, Chapter 3 closes with an overview and outlook for a new technology, the Worldwide Interoperability for Microwave Access (WiMAX), which might considerably impact or disrupt the satellite service industry in the near future.

Chapter 4 discusses the regulatory environment for satellite service providers. It also delineates what, in the opinion of the author, might be the shape of the space communications policy in the near future. The chapter starts with an historical summary of international regulatory bodies, followed by an overview of what the author considers to be two of the most important regulatory issues, namely frequency/orbit allocation and space environmental pollution. The second section of Chapter 4 is devoted to the description of the space policies implemented by the United States and the European Union in order to promote and develop satellite communications.

In sum, the first part of this thesis discusses the market dynamics and the regulatory environment of the satellite industry. While market and policy issues play a central role in shaping the structure of the satellite services industry, economic and engineering considerations provide decisive insights that can significantly alter the dynamics of the sector. The second part of this thesis combines economic and engineering analyses within a multidisciplinary approach and focuses on the lifeblood of the satellite industry: the satellite itself (as opposed to the industry-context explored in Part I). In particular, part II explores issues associated with spacecraft design lifetime and the impact that it may have on the whole industry value-chain. Part II, Economic and Engineering Issues in Spacecraft Design, consists of Chapter 5, To Reduce or To Extend a Spacecraft Design Lifetime?, and Chapter 6, Utilization Rates of GEO Communication Satellites.

Chapter 5 investigates issues associated with the selection and specification of a communications satellite's system design lifetime, as seen from the perspective of different stakeholders.. It involves a qualitative and a quantitative study that explores the engineering and economic issues at stake for reducing or extending a complex system's design lifetime, using spacecraft as example. The study examines these issues from both an operator (customer) and a manufacturer's perspective, as well as from the perspective of society at large. The question of whether there is an optimal design lifetime for complex engineering systems in general (and spacecraft in particular) is addressed here. In addition, at the level of the entire space industry value chain (i.e., the spacecraft manufacturers, launch industry and the operators), the case is made that design lifetime is a powerful lever that can significantly impact the whole industry's performance, financial health, and employment.

Satellites are correctly described as the lifeblood of the space industry. A key metric for the performance and outlook for the commercial space communications sector is the utilization rate (or load factor) of a satellite. Chapter 6 introduces the basic definitions of this key metric, and provides the reader with some figures about the load factor of geostationary orbit (GEO) communications satellites in recent years. Load factor data of twenty-one communication satellites was collected and analyzed. Time series analyses and statistical models describing the evolution of utilization rates (or loading dynamics) of a communication satellite are presented here. The chapter exposes the results of theses time series analyses showing three different loading patterns that are consistent within groups of satellites launched in different time periods. Finally, Chapter 6 also presents a discussion of the factors that drive satellite loading dynamics.

Chapter 7 contains the conclusions and recommendations for future work.

References – Chapter 1

[1] T. Pratt, C. Bostian, J. Allnutt. *Satellite Communications.* Wiley and Sons, 1996. pp. 1-6

[2] T. Pratt, C. Bostian, J. Allnutt. *Satellite Communications.* Wiley and Sons, 1996. p.1

[3] J.P. Torres-Padilla, "European Efforts to Challenge US Aviation Global Leadership". FAA Office of the Associate Administrator for International Aviation, August 2004.

PART I: ON THE MARKET DYNAMICS OF THE SATELLITE COMMUNICATIONS INDUSTRY

Chapter 2

Overview of the Satellite Communications Industry

The objective of this chapter is to provide the reader with background information about the subject matter of this thesis and to present an overview of key issues and indicators of the satellite communications market. It is organized as follows: Section 1 starts with a historical overview of the evolution of the industry. Section 2 introduces the key definitions of satellite services used by the International Telecommunication Union (ITU). Section 3 presents a snapshot of the current financial state of the industry. Section 4 introduces the concept of satellite applications, which are then classified and a described. Section 5 is devoted to satellite service providers. It provides a synopsis of five of the biggest global satellite operators and describes two examples of regional service providers.

2.1. From a modest "beep-ing" satellite to a $100 billion industry in four decades

The origins of satellite communications can be traced back to an article written by Arthur C. Clarke in the British radio magazine *Wireless World* in 1945.[1] In this visionary paper, Clarke describes a world communication and broadcasting system based on geosynchronous space stations. Clarke was a member of the British Royal Air Force and interested in long-distance radio communication. He suggested the fundamental principle of a GEO (geostationary orbit) satellite: the spacecraft would remain stationary with respect to the Earth's surface if it was orbiting on an equatorial plane with a period of twenty-four hours.* At that moment, there were no satellites in orbit nor rockets powerful enough to launch them. Twelve years later, in October 1957, satellite communications became a reality with the launch by the USSR of a small

* More precisely, in 23 h 56' 4,091" (86164 seconds) or 1 sidereal day

rudimentary satellite called *Sputnik 1*. This was the first artificial Earth satellite; it carried only a beacon transmitter and did not have two-way communications capability, but demonstrated that satellites could be placed in orbit by powerful rockets. The next significant step toward the development of a satellite communication system took place in 1965: the first commercial geostationary satellite INTELSAT I (*Early Bird*) heralded the commercial space era[2]. In the same year, the USSR launched MOLNYA I, the first Soviet communications satellite.[3] Only eleven years passed between the launching of *Sputnik 1* and the implementation of a fully operational global satellite communications system (INTELSAT - III) in 1968. Since then, GEO satellites have grown steadily in weight, power, size, lifetime, and capacity. In 2000, there were approximately 200 GEO satellites in operation. Today, the world satellite industry consists broadly of four sectors: satellite manufacturers, launch services, satellite operators, and ground services; the industry generates almost $100 billion per year in revenues.[4]

GEO satellites have always been the backbone of the commercial satellite communications industry. Radio waves travel in straight lines at the microwave frequencies used for wideband communications, so a *repeater* is needed to transmit signals over long distances.[5] Satellites are a good place to locate a repeater, since they can link places on the Earth that are thousands of kilometers away, and large GEO satellites can serve one-third of the Earth's surface. Non-GEO satellite systems with lower attitude, such as those operating at highly elliptical orbit (HEO), low-Earth or medium-Earth orbit (LEO or MEO), have been utilized to deliver few applications in special circumstances.[6] Two examples of such systems are the Russian Molnya satellites and the Global Positioning System (GPS). The Molnya satellites operate at HEOs, an egg-shaped orbit inclined approximately 60 degrees to the equator with a high apogee over the northern hemisphere and a low perigee over the southern hemisphere. In this type of orbit, the satellite makes one revolution around the Earth approximately every 12 hours. The satellite swings low and fast over the southern hemisphere and then slows as it rises toward its apogee in the northern hemisphere, making it appear to "hover" in the sky over northern territories for long periods of time. This type of orbit is therefore suitable for communications services in the high-latitude areas. Such satellites systems (i.e., the Molnya satellites) were designed to serve the communication needs of the former USSR. They are appropriate to cover most of the territory of the former USSR, at higher latitudes.[7] The GPS is a worldwide MEO satellite navigational system formed by 24 satellites. These satellites orbit the Earth at approximately 19,000 kilometers (12,000 miles) above the surface and make two complete orbits every 24 hours. However, the majority of communication satellites are in geostationary Earth orbit, at an altitude of around 36,000 km (22,500 miles).

2.2. Satellite communications: ITU classification and definitions

Radio Regulations are necessary to ensure an efficient and economical use of the radio-frequency spectrum. The International Telecommunication Union (ITU) is the entity within the United Nations that publishes the Radio Regulations (RR). The RR refer to the following space radiocommunication services, defined as transmission and/or reception of radio waves for specific telecommunication applications:[8]

- Fixed Satellite Service (FSS)
- Mobile Satellite Service (MSS)
- Broadcasting Satellite Service (BSS)
- Earth Exploration Satellite Service (EES)
- Space Research Service (SRS)
- Space Operation Service (SOS)
- Radiodetermination Satellite Service (RSS)
- Inter-Satellite Service Satellite Service (ISS)
- Amateur Satellite Service (ASS)

Different frequency bands are allocated to each of the above services to ensure compatibility of use. The bands can be either exclusive for a service or shared by several services.[9]

The following subsections discuss the three major types of services, namely the Fixed Satellite Service (FSS), the Mobile Satellite Service (MSS), and the Broadcast Satellite Service (BSS). Table 2.1 shows the frequency allocations for these three services.

Table 2.1: Frequency allocations (Data Source: ITU)[10]

Radiocommunications service	Typical frequency bands for uplink/downlink	Usual terminology	Mainly used by:
Fixed Satellite Services (FSS)	6 / 4 GHz	C band	Fixed service terrestrial microwave
	8 / 7 GHz	X band	Military communication / Digital Radio feeder links
	14 / 12-11 GHz	Ku band	Fixed service terrestrial microwave
	30 / 20 GHz	Ka band	Local multichannel distribution service (LMDS)
Mobile Satellite Services (MSS)	1.6 / 1.4 GHz	L band	Studio television links / cellular phone communications
	30 / 20 GHz	Ka band	LMDS / Intersatellite links (ISL)
Broadcasting Satellite Services (BSS)	2 / 2.2 GHz	S band	Digital Radio / NASA and deep space research
	12 GHz *	Ku band	Direct-to-User transmissions

* The BSS use a frequency of about 12 GHz for downlinks. The uplinks transmissions are carried by FSS operators (these uplinks are called feeder links).

2.2.1. Fixed Satellite Services (FSS)

According to the Radio Regulations of the ITU, "FSS is a radiocommunication service between given positions on the Earth's surface when one or more satellites are used. These stations located at given positions on the Earth's surface are called Earth stations for the FSS. The given position may be a specified fixed point or any fixed point within specified areas. The stations located on board the satellites [...] are called space stations of the FSS".[11] In other words, FSS refers to the applications that involve communication links between a satellite and any *fixed* point on Earth. It does not include links between a satellite and a *mobile* receiver on Earth, or *broadcast* services, i.e., transmissions from a satellite to several end-users simultaneously. Figure 2.1 shows a generic representation of Fixed Satellite Services.

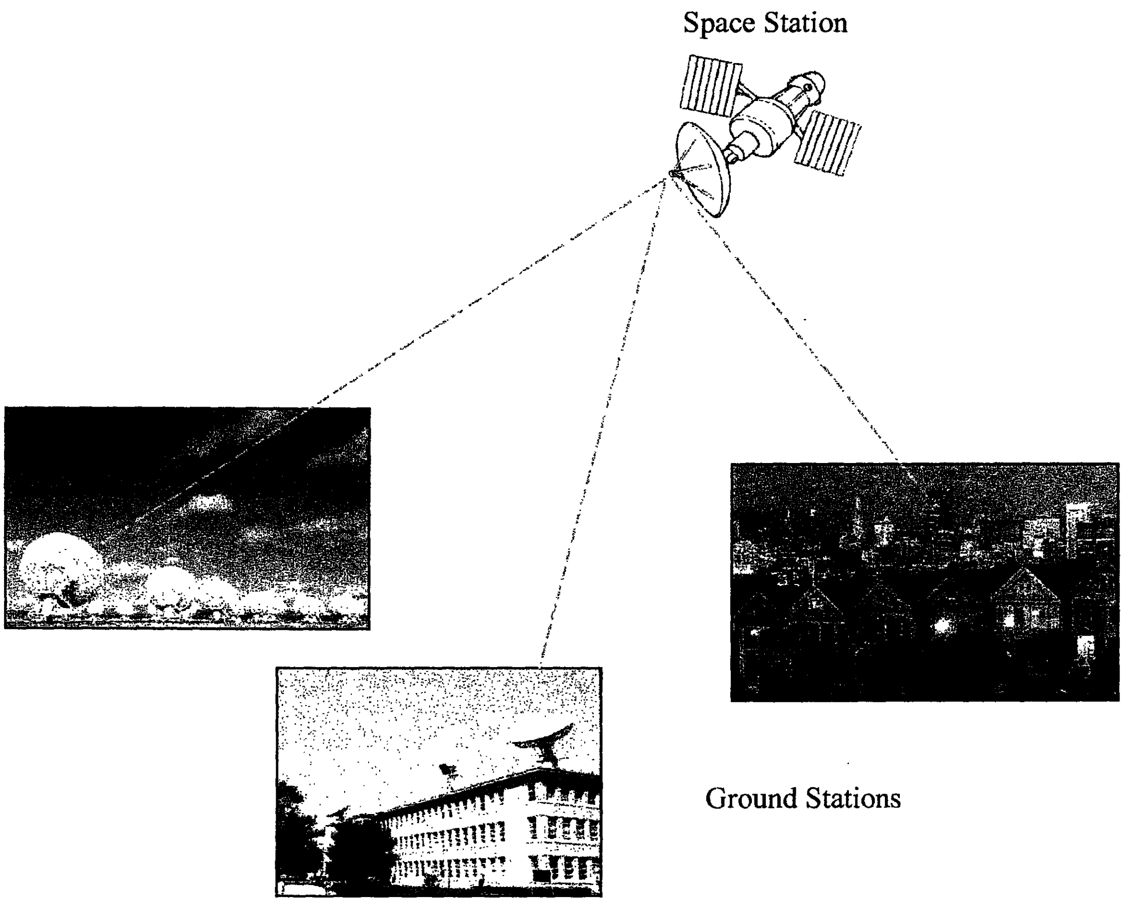

Figure 2.1: Generic illustration of FSS (links between a fixed point on Earth and a space station)

Currently, most of the transmissions between two earth stations are achieved through a single satellite. This link can be separated in two parts: an uplink between the ground transmission station and the satellite, and a downlink between the satellite and the ground receiving station. However, in the near-future links between two earth stations using satellite-to-satellite links are likely to be utilized. This multi-satellite link will be part of the Inter-Satellite Service (ISS) as defined by the ITU.

The FSS also includes other types of links called *"feeder links"*. These are uplinks from an earth station at a fixed point to a space station transmitting information for a service other than the FSS.

Some examples of this category include uplinks to the satellites of the broadcasting satellite service (BSS), as well as up and downlinks between fixed earth stations and satellites of the mobile satellite service (MSS).[12] In this cases, the FSS satellite and ground station are used to provide part of the BSS or MSS applications.

2.2.2. Mobile Satellite Services and Broadcast Satellite Services

The communication satellite services described in this section use different frequency bands than the ones allocated to the FSS.

Mobile-satellite services (MSS): According to the regulations of the ITU, "MSS is a radiocommunication service between mobile earth stations and one or more space stations, or between mobile earth stations by means of one or more space stations".[13] This type of services include maritime, aeronautical and land applications. Figure 2.2 provides a schematic view of mobile-satellite services (MSS).

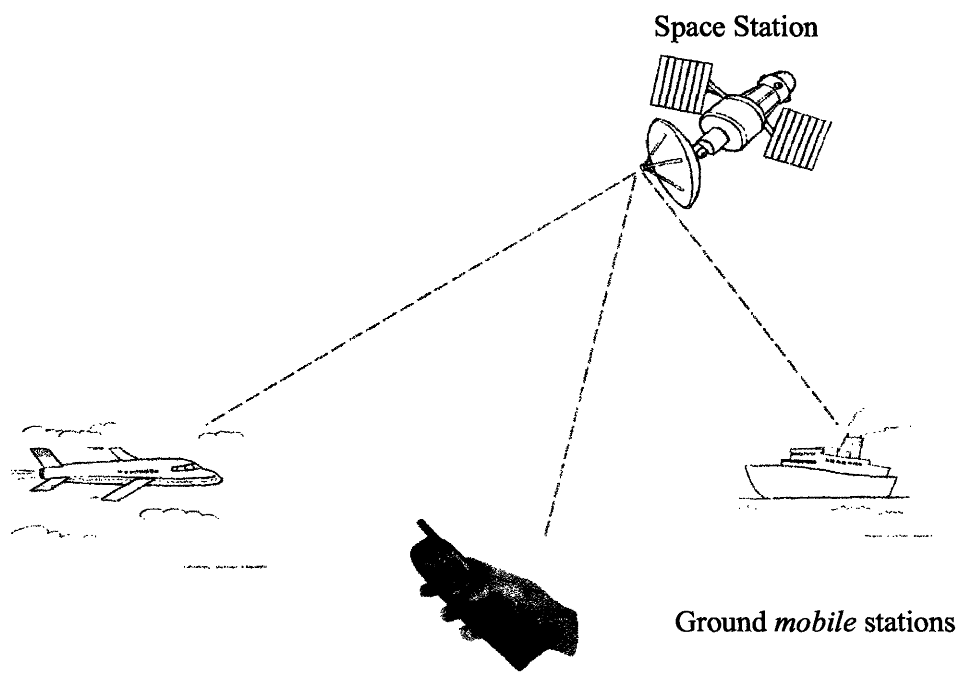

Figure 2.2: Generic illustration of MSS

MSS provide key communications services to the maritime and aeronautical sector. Before the advent of communication satellites, it was not rare for merchant navy ships and other vessel in high seas to be lost in the oceans under difficult weather conditions due to lack of means of communication. The first effort to address this issue was made by COMSAT (an entity specifically created to act for the United States within Intelsat, the International Telecommunications Satellite Organization), over the Navy satellite called Marisat in the late 1970s.[14] Its success culminated in the formation of Inmarsat (International Maritime Satellite Organization) in 1979, an international treaty organization similar to Intelsat, but focused on connectivity to and from ships in the seas. Inmarsat has provided communication services to ships and aircraft for several decades, although at a high price. LEO satellites were seen as one way to create a satellite telephony system with worldwide coverage; three systems were eventually deployed (e.g., Iridium and Globalstar). However, the implementation of a LEO and MEO satellite system for mobile communication has proved much more costly than anticipated, and the capacity of the systems is relatively small compared to GEO satellite systems, resulting in higher costs per transmission. Satellite telephony systems were therefore not able to compete with cellular telephone systems, mainly because of the high costs and low capacity of the space segment.[15] Other ventures have entered this market and the lack of success of most of them has been well documented and analyzed. The reader is referred to Ref. 16 or Ref. 17 for a thorough discussion of these topics.

Broadcasting-satellite services (BSS): The ITU defines BSS as "a radiocommunication service in which signals transmitted or retransmitted by space stations are intended for direct reception by the general public using very small receiving antennas" (television receiving only, or TVRO).[18] The satellites utilized by the BSS are often called direct broadcast satellites (DBS). The TVRO needed to receive the signal from a BSS is usually smaller than the one needed to receive an FSS signal. Furthermore, the direct reception shall include both individual reception (e.g. Direct-to-Home (DTH) applications) and community reception (e.g. Cable Television Network (CATV) or satellite master antenna TV (SMATV)).

Direct Broadcast Satellite (DBS) television was developed in the United States to overcome "blind spots" in the coverage area of traditional terrestrial systems. Today, a DBS (or Direct-to-User, DTU) system is capable of transmitting digital video signals from high-powered geostationary satellites directly to individual subscribers via small receiving dishes, without the need for additional ground receiving or distribution equipment. Two examples of DTH pay-TV satellite broadcasters in the United States are DirecTV and Echostar. Together they operate a total of 16 satellites and will launch three new ones in coming years.[19]

This sector, the Pay-TV broadcast services, has generated a rapid growth in this segment of the satellite industry, with further expansion expected from the introduction of interactive TV services. Communication satellites are also being used to deliver commercial radio DTU services. One example is the Worldspace project, which involves three satellites to provide radio services to around 5 billion people living in Africa, the Middle East, the Caribbean, and Central and South America.[20] In the U.S., the FCC announced a spectrum auction for nationwide digital radio. The two winners of this auction in April 1997 were American Mobile Radio Corporation (AMRC) then in partnership with WorldSpace, and CD Radio, now known as XM Radio and Sirius Radio, respectively. Both systems are now in operation and had a total of 3.2 million subscribers as of October 2004, targeting 4 million by January 2005.[21,22] Table 2.2 shows the revenues generated by the biggest Non-FSS Satellite Operators in 2003.

There are other services that are mainly focused on specific applications, such as radionavigation-satellite (notably the Global Positioning System, a constellation of satellites that has revolutionized navigation and surveying systems) or meteorological-satellite service (e.g. EUMETSAT, the European Organization for the Exploitation of Meteorological Satellites).[23] The description of those systems is outside the scope of this thesis.

Table 2.2: Revenues of Non-FSS Satellite Operators in 2003. (Source: Euroconsult)[24]

Company	Revenue (in USD million)	Market Share (%)	Cumulated Market Share (%)
Mobile Satellite Service Providers (MSS)			
Inmarsat	504	50 %	50 %
Thuraya	290	28.8 %	78.8 %
Iridium	80	7.9 %	86.7 %
Globalstar	51	5 %	91.7 %
Others	83	8.3 %	100 %
Total MSS	**1,008**	**100 %**	
Direct Broadcasting Satellite Service Providers (DBS)			
DirecTV	7,700	58.6 %	58.6 %
Echostar	5,400	41.1 %	99.7 %
BSat	30	0.3 %	100 %
Total DBS	**13,130**	**100 %**	
Digital Audio Broadcasting by Satellite (DAB)			
XM Satellite Radio	92	86.8 %	86.8 %
Sirius Radio	13	12.3 %	99.1 %
WorldSpace	1	0.9 %	100 %
Total Digital Audio Radio System (DARS)	**106**	**100 %**	

2.3. Current status and financial performance of the satellite industry

This section is organized in two parts: the first one presents key indicators about the financial performance of the satellite industry. The second part describes some recent and important changes in the ownership structure of the sector.

The revenues generated by the entire satellite industry (satellite manufacturers, launchers, satellite operators, and ground services) experienced continuous growth between 1996 and 2002. The average annual growth during this time period was 13%.[25] In 2003, however, the growth of the entire satellite industry slowed to about 6%, considerably lower than the record high of almost 30% in 1997.[26] Figure 2.3 shows the revenues generated by the entire satellite industry between 1996 and 2003. This revenue growth was due almost entirely to the growth in the satellite services providers sector. Government spending and strong consumer demand for video services (mainly for DBS applications) were responsible for much of this growth. This trend can be clearly observed in Figure 2.4, where the reader will find the satellite operators' revenues generated by each type of service provided, namely FSS, MSS, and DBS.

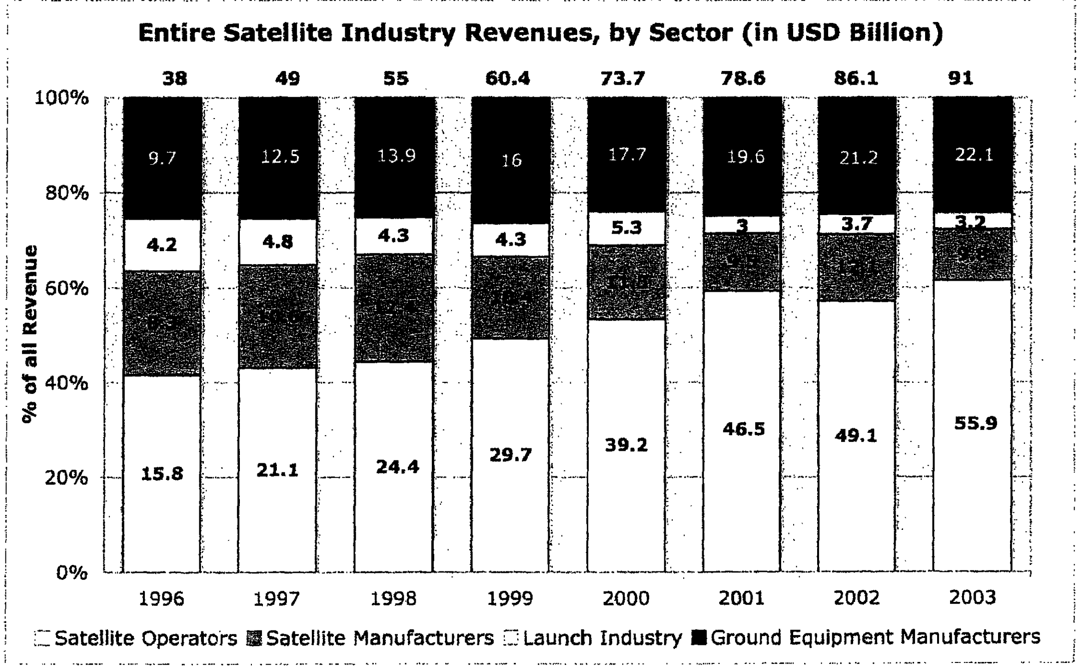

Figure 2.3: Entire Satellite Industry Revenues, by Sector (Source: Futron Corporation) [27]

The satellite operators sector has experienced considerable changes over the past 25 years: going from 6 service providers operating 24 GEO satellites in 1979 to 45 companies operating over 220 satellites in 2004.[28] This sector has more than tripled in size from 1996 to 2003 (see Figure 2.3). Its share of the entire commercial space industry revenues has grown from 42% to over 60% during the same period of time. In 2003, satellite services revenues reached $ 55.9 billion. [29] Subscription and Retail Services have witnessed the greatest growth of all industry sectors in 2003, with a 15% growth rate. The service that continues to drive overall growth is Direct-to-Home satellite pay-TV. This sector represented a market of over $13 billion in the United States. [30] In 2003, revenue growth of over 400% occurred in the digital audio radio broadcasting satellite market, even though this still accounts for less than 1% of the total satellite services revenues. [31] This application has been developed predominantly in the United States. The following figure shows the revenues generated by satellite operators, for each type of service provided from 1996 to 2003.

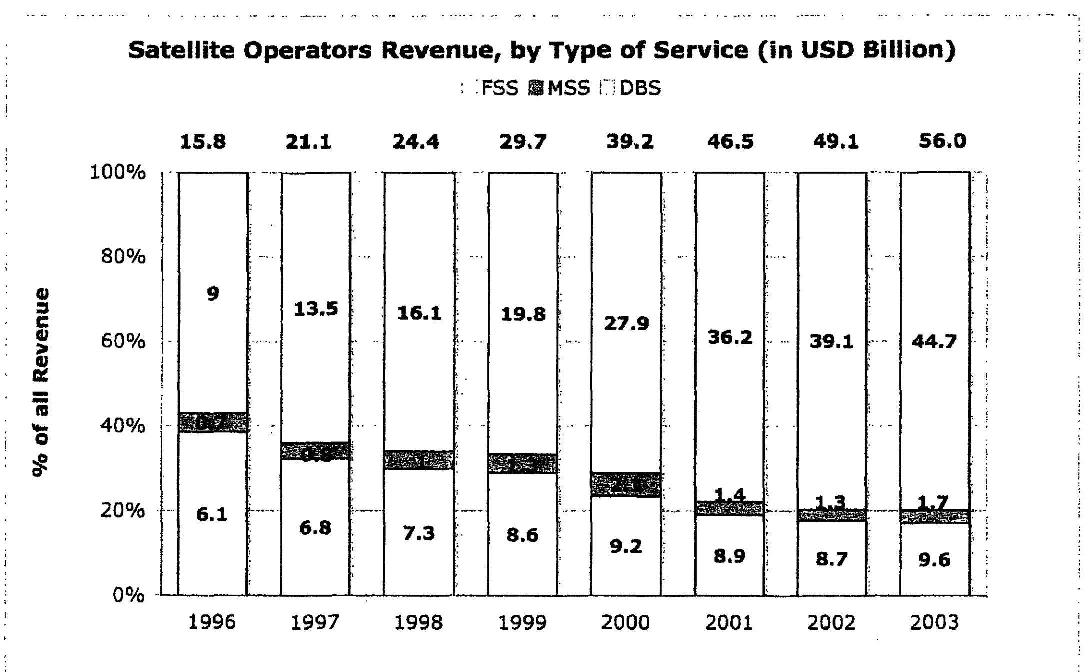

Figure 2.4: Satellite Operators Revenues, by type of service provided (Source: Futron Corporation) [32]

Fixed satellite services have always been a stable and strong component of the space industry. In 2003, FSS revenues attained $ 9.6 billion.[33] Despite falling prices of transponder leases, the FSS sector still enjoys considerably high operating margins (between 70 and 80% in 2003).[34] While competition on point-to-point applications has increased (terrestrial services have important advantages in capacity over satellite services as will be discussed in the following chapter), satellite's particular point-to-multipoint distribution advantages are allowing broadcast services to remain a prominent source of revenues for the satellite industry.[35]

Even though FSS generated $ 9.6 billion in revenues in 2003, some operators (the ones that have less capacity than their customers' demand) lease capacity from other operators. Consolidated revenues of FSS operators reached $ 6.6 billion in 2003 (increasing 3% with respect to the previous year). Yet, most of this growth was the result of currency exchange rates (a weak U.S. Dollar), since two of the largest operators (SES Astra and Eutelsat) operate in Euros (the U.S. Dollar devaluated about 16% during 2003). At a constant exchange rate, the FSS industry consolidated revenues actually decreased by 3% to about $ 6.2 billion. For the first time, the FSS industry experienced three consecutive years of negative growth since 2000 (with a consolidated revenue of about $ 7 billion).[36] This decrease is mainly due to a decline in transponder lease price together with a lack of growth in demand. Satellite operators have been forced to concede in price in order to maintain a higher load factor (or utilization rate). As a result, even if the number of transponders leased has slightly increased, this small growth has not compensated for the decline in prices.

The revenues of the FSS sector have traditionally been concentrated: in 2003, four operators held 60% of the market, and the top ten FSS providers shared about 85% of the total revenues. Despite a decrease in revenues and lower profitability margins, the FSS still enjoys an average industry margin of 70% for EBITDA[†], 31% for operating profitability (EBIT), and a net profit average of about 20%. Furthermore, the recent decrease in EBIDTA margins slowed down in 2003. The EBITDA is a key indicator for the industry, since the FSS sector generates high depreciation and amortization costs, while operational costs are relatively low with respect to the revenues generated. Therefore, any decline in revenues reflects directly on the EBITDA margin (assuming no significant decreases in sales and operational costs). Additionally, the average net profit

[†] Earnings before interest, tax, depreciation and amortization. EBITDA is a financial measure defined as revenues less cost of good sold and selling, general, and administrative expenses. It is a common way to measure the profitability of a company

margin became constant in 2003 at 20%, coming down from a high record of 31% in 2000.[37] Table 2.3 shows the typical cost structure of a FSS satellite operator.

Table 2.3: Typical cost structure of a FSS satellite operator (Data Source: Euroconsult) [38]

Typical cost structure of a FSS satellite operator	
Depreciation and Amortization (D and A)	50 % to 60 %
Cost of sales and cost of operations	20 % to 34 %
Selling, general and administrative expenses (SG&A)	16 % to 20 %

Recurrent capital expenditures by the operators are unavoidable in order to maintain a competitive fleet of transponders and to provide reliable services to satellite customers. Even though the satellite fleet of most of the large service providers is currently young (an average age of less than 6 years) as satellites become obsolete and less productive, they have to be replaced. Persistent capital expenditures and long-term contracts result in predictable cash flows. This, together with the characteristic high operating profitability margins of the satellite operators, makes FSS companies attractive to private equity firms.

A description of some of the biggest satellite operators is provided in a forthcoming section. However, recent changes occurred in the ownership structure of the FSS industry that are worthy of note. Four acquisitions of satellite operators by private equity firms took place in 2004. These operations reached a transaction value of over $13 billion:

- PanAmSat, one of the leading providers of video, broadcasting and network distribution and delivery services, was acquired by a group of equity firms (Kohlberg Kravi Roberts, The Carlyle Group, and Providence Equity Partners) in April 2004 for $ 4.3 billion; [39]
- New Skies Satellites was acquired by the Blackstone Group in July 2004 for $956 million; [40]
- Intelsat, the pioneering commercial satellite company, owned and governed for most of its 40 years by companies representing 145 governments around the world, has recently

been acquired (August 2004) by a conglomerate of four private equity groups reunited under Zeus, a newly formed consortium for $ 5 billion.[41]

- In March, November and December 2004, five private equity firms (Texas Pacific Group, Spectrum Equity Investors, Cinven Ltd, Eurazeo, and Goldman Sachs Capital Partners) paid a total of over $ 2.8 billion for an overall stake of 85.1% of Eutelsat, the leading European satellite operator.[42]

In addition to these acquisitions, Intelsat acquired Loral Skynet's North American satellite assets in March 2004, for $ 960 million.

The interest of private equity firms for satellite operators is not new, but it has considerably grown since 2003. When these types of transactions occur, the acquirer has often funded the buyout by issuing more bonds and debt. In the case of PanAmSat, KKR paid $3.55 billion cash and sold 54% interest to two the two other private equity firms: the Carlyle Group and Providence Equity Partners.[43]

Since the rationale of the industry is based on economies of scale and access to large capital market, more consolidation is expected in the coming years. The industry will probably undergo another wave of Mergers and Acquisitions soon, where large operators (e.g. Intelsat, Eutelsat) and smaller regional operators may be involved. A more detailed profile of regional and global operators is provided in section 2.5 of this chapter.

2.4. Satellite applications

In section 2.1, I introduced and discussed the concept of *satellite services* and the main types of services that a communication satellite can provide (FSS, MSS, BSS). In this section I discuss the different types of satellite *applications*. Stakeholders and analysts of the commercial space sector use different classifications and definitions of *satellite applications*. Even the term "application" itself is frequently understood and interpreted differently. It is not rare to find classifications in the business and scientific literature that do not make a difference between satellite "services" and "applications", and often refer to one or the other concept with either term indistinctly. For the purposes of this thesis, I define a *satellite service* as the type of transmission link between the ground station and the space station, namely FSS, MSS, or BSS (see section 2.2), and a *satellite application* as the specific task or purpose that the satellite service is delivering.

There are several ways of classifying telecommunications applications. Some of the most commonly found in the scientific and business literature are: [44]

1) By direction:
    a. One-way (such as uplink only or downlink only); and
    b. Two-way (e.g., typical of voice services)
2) By bandwidth:
    a. Narrow-band (e.g. telegraph and low-speed data);
    b. Voice frequency band; and
    c. Wideband (56KHz to hundreds of megahertz)
3) By type of network:
    a. Switched (public telephone, telegraph, and some complex private networks);
    b. Demand access or dedicated (point-to-point services such as private lines or private networks);
    c. Broadcast (radio, television, weather warnings)

For the purpose of this thesis, I define the following classification of telecommunications applications, grouped into three main categories: the transmission of voice (telephony), video and digital radio, and data. Each of these types of applications can be subdivided in several submarkets:[45]

a) Voice
    - International telephone relay
    - Domestic telephone relay
    - Fixed telephony

b) Video and digital radio
    - TV relay (cable and broadcast)
    - Direct to Home (DTH) TV
    - Digital Audio Radio System (DARS)
    - High Definition TV
    - Digital Cinema

c) Data

- Private networks (VSAT[‡] and others)
- ISP-to-Internet backbone
- End-user internet (SOHO[§] and residential)
- Air Telecom (In-flight entertainment)
- Caching
- Multicasting

Each of these submarkets of the three main types of applications is discussed in this section. A description of "traditional" communications satellites markets is presented in the first subsection. The second subsection is devoted to the discussion of some emerging markets within the video and data types of applications.

2.4.1. Traditional markets

i) Voice:

This market includes domestic and international relay (trunking) as well as fixed telephony services such as satellite mainlines and satellite phone booths. International and domestic trunk services were the prime engines for the early evolution of communication satellite applications. Following the introduction and proliferation of high-capacity optical fibers, the trunking markets have since been steadily shifting away from satellite to fiber-optic cables, particularly on the transoceanic routes. However, the telephone trunking (also referred to as point-to-point) market has experienced a modest growth as telecommunications traffic with and among less developed markets increases.[46] Large carriers (as well as ISPs -Internet Service Providers) backhauling traffic to the U.S. or European backbones are using satellite operators more heavily for access to developing regions. There are essentially no market opportunities for point-to-point satellite services between "Tier 1" cities (major cities in developed countries), since even the need for the satellite service as a backup for fiber-optics has declined as fiber routes have diversified and increased internationally. The voice transmission as a satellite application has low revenue growth potential and is currently a small market. Yet, it is perhaps interesting to note an anticipated growth of the fixed telephony services (a consumer market). This includes the satellite

[‡] Very Small Aperture Terminal
[§] Small Office / Home Office

"phone booths" and other rural networking infrastructure unlikely to be served by terrestrial alternatives.[47]

Figure 2.5 shows the share of satellite in the outgoing international traffic of U.S. carriers.

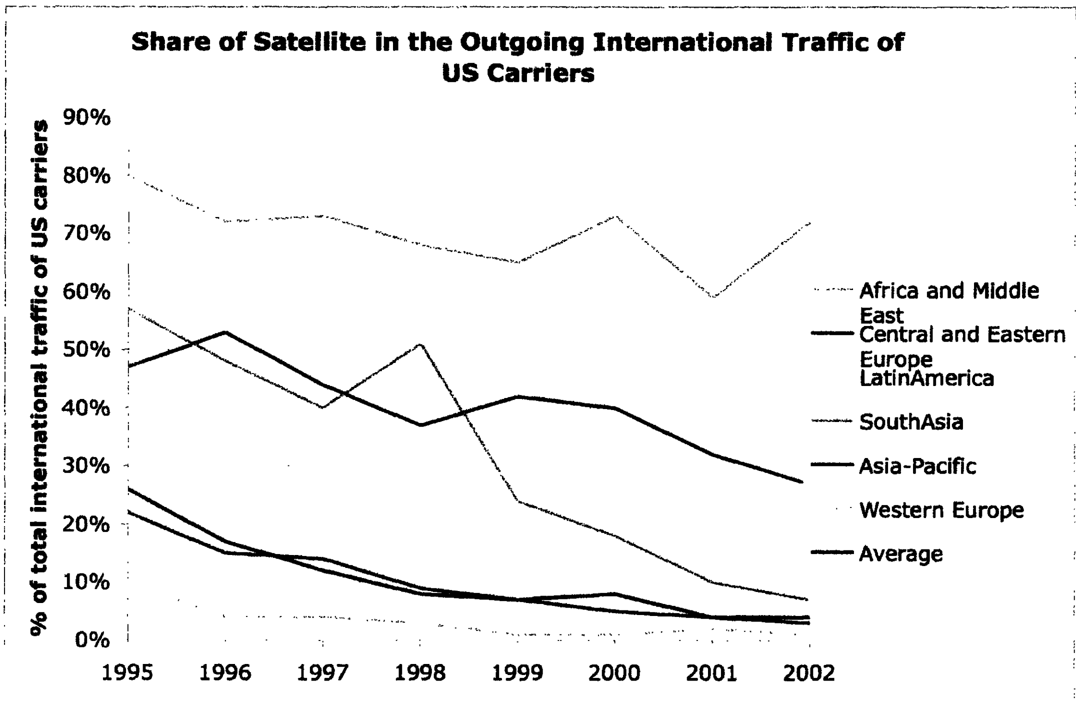

Figure 2.5: Share of Satellite in the Outgoing International Traffic of US Carriers (Source: Euroconsult / FCC)[48]

The reader may find interesting to analyze this chart. The general trend that is observed is clearly a decrease in the percentage of the U.S. outgoing international communications carried by satellites. The world average, for instance, has experience a steady decline from 22% in 1995 to 3% in 2002. However, the reader can also notice three interesting patterns: a) the share of outgoing communications carried via satellite to more developed regions in the world (such as Western Europe and Asia-Pacific) was relatively low even in 1995 (between 10% and 20%); since then, it has decreased at a small rate to 3% to 5% in 2002; b) the share of satellite in the outgoing traffic to Latin America presents a similar behavior; this can be explained by the fact that it is easier to develop terrestrial networks across continents than it is across the oceans; c) the share of communications going to South-Asia was relatively high in 1995 (almost 60%); yet it has decreased at a much higher rate than (a) and (b), this can be explained by the fact that South-

Asia has experienced a high economic growth, a rapid infrastructure development, therefore new technologies such as or underwater cable networks have been implemented during the past 10 years; finally, d) regions such as Africa, Middle East, and Eastern Europe, have experienced a slower economic development, therefore the implementation of terrestrial networks has been slower, and consequently the share of outgoing communications carried via satellite from the U.S. to these regions has decreased at a slower rate.

ii) Video:

The transmission of video (TV relay, including both broadcast and cable markets) remains the core business and the greatest source of revenue for satellite operators. Recent forecasts analysis suggest that this sector will continue to experience a reasonably constant growth rate, although the most dynamic market is being observed on the consumer side of the video transmission, i.e., DTH (direct-to-home).[49]

There are three types of video distribution and radio satellite transmissions:

- Contribution (exchange of video contents between broadcasters);
- Feed of cable TV head-ends, and broadcast of free-to-air TV channels;
- DTU broadcast of TV and radio channels (DTH TV and DARS).

Video distribution is likely to continue to grow and dominate over satellite communication links in the FSS sector. Technological improvements in C- and Ku- bands together with a lower cost per use of transponder are likely to support this growth. Transponder demand for video and radio broadcasting has tripled over the past 12 years from around 1,000 transponders in 1991 to almost 3,000 in 2003. That year, the nearly 3,000 transponders used for video transmission accounted for more than 55% of the total satellite services demand. Video represents at least 50% of the revenue source for eight out of the top ten satellite operators.[50]

Video broadcasting services and the digital revolution have changed the relationship between video service providers and satellite operators: the latter have been changing the way they market services and fix prices to attract more video broadcasters as their customers. Today, the introduction of interactive entertainment, High Definition TV (HDTV) channels, the new compression format MPEG-4, and the consolidation of satellite TV broadcasters, might have an impact on the structure of the video transmission market.[51]

As discussed in a previous section of this chapter, growth in the number of video transponders has been mainly due to the progress of satellite TV ventures (Echostar, DirecTV, SkyDigital and SkyperfecTV, and recently Galaxy Satellite Broadcasting and Dish TV). Furthermore, the DTH pay-TV sector is still observing some growth despite the fact that there has been a consolidation of satellite broadcaster in middle-sized markets.[52] Figure 2.6 shows the growth of the world video transponder fleet between 1991 and 2003.

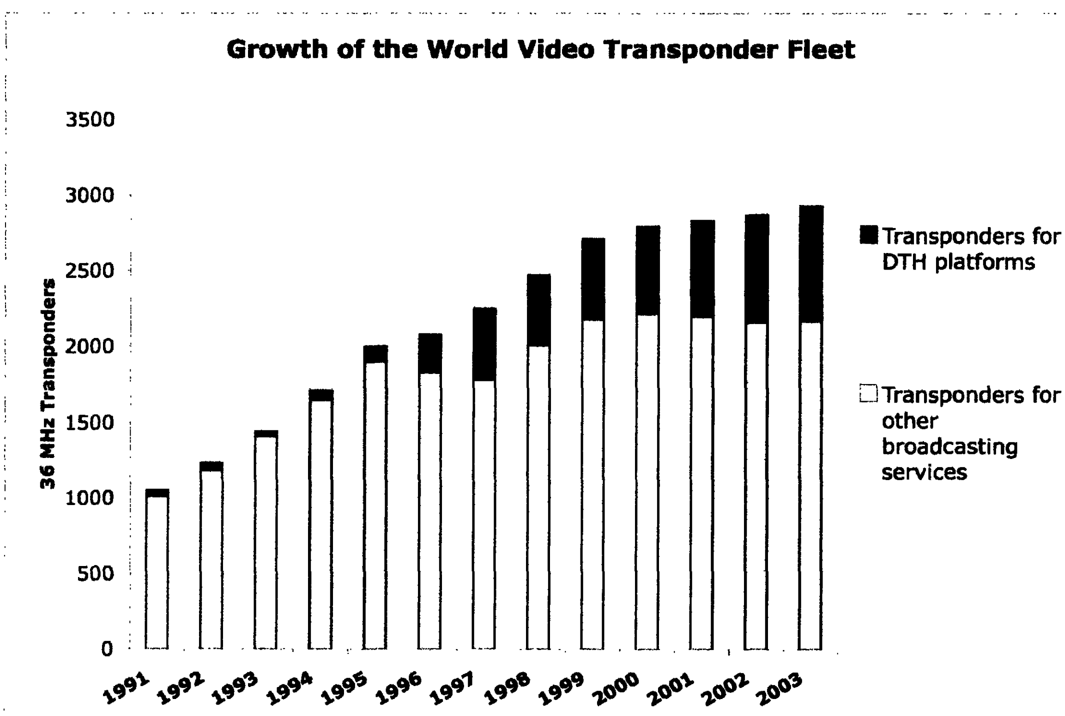

Figure 2.6: Growth of the world video transponder fleet between 1991 and 2003 (Source: Euroconsult)[53]

Finally, another significant issue in this market is the fact that independent channels are using lower compression rates than the DTH ventures. The use of compression has accelerated in recent years, growing from 2.5 channels per 36-MHz equivalent transponder in 2000 to 3.8 in 2003. As a result, the number of transponders dedicated to independent channels has been decreasing.[54]

iii) Data:

Video broadcast is indeed the primary revenue source for the FSS sector. In fact, several DBS operators lease significant capacity from FSS operators to deliver their service. Yet, it would be wrong to assume that the DTH TV sector is enough to sustain the FSS industry. Voice and data services represented around 45% of the total transponders leased in 2003. Data (and voice) transmission is the historical market of the satellite operators, and it remained their main source of revenues for years.[55] In the following paragraphs a brief description of some of the submarkets associated with the data application is presented.

Private networks (VSAT and others):

A Very Small Aperture Terminal (VSAT) is an earthbound station used in satellite communications of data, voice and video signals, excluding broadcast television. A VSAT consists of two parts, a transceiver that is placed outdoors in direct line of sight to the satellite and a device that is placed indoors to interface the transceiver with the end user's communications device, such as a PC. The transceiver receives or sends a signal to a satellite transponder in the sky. The satellite sends and receives signals from a ground station computer that acts as a hub for the system. Each end user is interconnected with the hub station via the satellite, forming a star topology. The hub controls the entire operation of the network. For one end user to communicate with another, each transmission has to first go to the hub station that then retransmits it via the satellite to the other end user's VSAT. This submarket continues to be the dominant application within the data market. It is also the only one that has experienced strong and steady yearly growth. VSAT devices are typically used to extend corporate networks with ubiquitous and uniform communications infrastructure. The main users of VSAT include customers in the retail industry (e.g., gas stations or small supermarkets); banking, finance and assurance (e.g., Visa, Nomura Securities, etc.); automotive and others.[56] Hundreds of gas stations can be connected to a central data facility to process transfers, inventory, billing, etc. In general, the Private Corporate Networks sector includes a variety of closed data communication networks for businesses with multiple locations. The increase use of networked applications suggests that corporate VSAT will continue to grow. End-users (such as corporations with branches in remote locations) seek in VSAT networks a cost-effective and flexible solution to connect its business when terrestrial alternatives are unavailable or unreliable. This is a stable market and, even if it is not as stunning as newer applications, it accounts for the majority of current data services demand. North America is the largest market for this application, although Asia is currently experiencing the highest growth rates, both in terms of total number of terminals sold and transponders utilized.[57] Table 2.4 shows the evolution (from 1999 to 2003) of revenue generation from VSAT networks for three major satellite operators.

Table 2.4: Revenue from VSAT networks for three of the biggest satellite operators (Data Source: Euroconsult)[58]

	1999	2000	2001	2002	2003
	millions of US dollars (except installed VSATs)				
Eutelsat	45.0	60.6	65.0	112	100
Intelsat	n.a.	274.3	292.7	327.4	352.5
PanAmSat	186.7	207.9	208.8	194.9	207.8
Total	**n.a.**	**543**	**566**	**634**	**660**
Number of installed VSATs	431,000	530,000	642,000	n.a.	700,000

ISP-to-Internet backbone:

This market includes the direct connection to the fiber backbone for national operators serving ISPs and ISPs serving individual users. It has experienced a surprisingly high growth rate since satellites started to provide this service in the mid-1990s, although it is starting to peak in many markets. Like other point-to-point applications, it represented a good business opportunity when the optic fiber was unavailable. In some areas where fiber is not yet available (such as Eastern and Central Europe), this market is likely to continue showing some growth.[59] This sector, IP trunking, represented about 9% of the overall transponder demand in 2003, with Asia-Pacific as the leading market.

2.4.2. Emerging markets

In this subsection a discussion of some emerging markets within the video and data types of satellite application is presented.

i) Video and Digital Radio:

Interactive services:

Most satellite TV platforms are planning to provide improved services in addition to the TV programming. The number of interactive services has experienced a significant growth from 176 in 2000 to 388 in 2003.[60] Typically, these applications are delivered by using very high compression rates and will gradually be broadcast in the new MPEG-4 format, supporting even higher compression rates. The development of this market is an important stake for the satellite TV ventures in order to compete with the triple package of services offered by TV cable operators: a unique application that includes TV, telephony and Internet services.

HDTV:

Some analysts of the industry estimate that HDTV channels would require three times the bandwidth used by a digital standard TV channel.[61] The development of High Definition television is expected to generate an increase in transponder demand in the short-term, although the HDTV market contributes still marginally to the industry, with less than 1% of the total of satellite TV channels in 2003, most of them available in North America. The second biggest market is Asia, including both Japan and Australia. Because of higher transmission and production costs than Standard Definition Television (SDTV), HDTV is expected to be only a small niche with premium content such as movies or sports events, where viewers are ready to pay for high-quality pictures.

Digital Cinema:

This market represents a new form of satellite contribution service to provide cinemas and theaters with better-quality digital movies at lower costs than with physical copies of films. Despite a decline in the price of digital projectors, most of the operators of cinemas or theaters are not ready to pay for an upgrade of their equipment. However, the number of theaters equipped for digital cinema has tripled since 2001, with 161 in 2003, out of a total of about 115,000 worldwide.[62] In addition to this, uncompressed movies require a lot of bandwidth and time to download, as well as storage infrastructure. The technical standards that will be developed and used for compression might have an impact on the future of this market. However, this impact is not likely to be experienced in the mid-term, since ventures created to promote digital cinema via satellite are not making commercial progress (leading operators in this market, such as Boeing Digital Cinema, are considering a sale as an exit option due to the low rate of theaters equipped with the necessary technology).

Digital Audio Radio System (DARS):

In the satellite DTU market, television came first and digital radio only started in 2001. Worldspace is one of the first DTU Digital Radio venture, and it involves three satellites to provide radio services to around 5 billion people living in Africa, the Middle East, the Caribbean, and Central and South America.[63] In the U.S., rapid growth in this market has been recently observed. Today, XM Radio and Sirius Radio are the two main DARS in operation nationwide. Despite a late start and some adverse business conditions, several of these systems are currently operating around the world. The technology has an important potential, given the large number of radio listeners around the world in cars, homes and other environments.[64] Figure 2.7 shows the revenues generated by DTH radio operators in 2003.

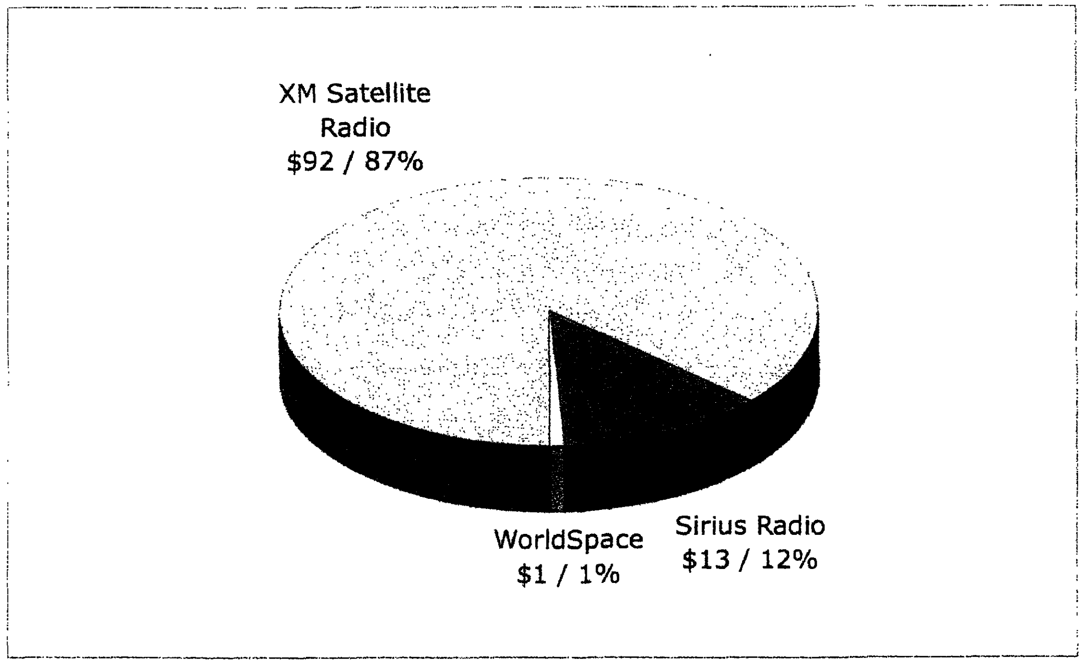

Figure 2.7: Revenues generated by DARS operators in 2003 (in million USD) (Data Source: Euroconsult) [65]

ii) Data:

End-user Internet (Enterprise, SOHO and residential):

This sector encompasses a mix of diverse sub-markets: last mile access to the Internet for residences, Small-Offices/House-Offices (SOHOs), Small/Medium Enterprises (SME), and Large Enterprise. The key drivers for all the last mile access sectors are broadly the same:

- Exponential growth in content availability and individual user bandwidth needs
- Price competitiveness of satellite delivery, including user equipment and bundling
- Ka-Band introduction reducing the number of transponders needed to serve still-growing bandwidth demand

These factors, however, don't affect all regions similarly. There are some short-term opportunities in entering the market of developed regions that have a need for broadband. However, this market is closing to the satellite services due to the deployment of terrestrial broadband. Similar opportunities in developing countries are likely to be found in forthcoming years, as demand outpaces availability of terrestrial infrastructure.[66]

Air Telecom (In-flight entertainment):

Six companies are currently planning to offer in-flight services (Tenzig Communications, AirShow 21, Live TV, Connexion by Boeing, AirTV, and In-Flight Network). Live TV is owned by JetBlueAirways and is equipping its airplanes for the reception of the existing satellite TV platforms. Connexion by Boeing announced lease contracts for about 16 transponders for the trans-Atlantic airline traffic, and is looking to expand in Asia. About three hundred airplanes are expected to be equipped with this application by 2005.[67] In the opinion of the author, the necessary transmission capacity for this application is likely to be leased by DBS and FSS operators. This service seems to focus more on broadband capabilities than on video contents, and the outlook for this application is not very clear at the time this thesis is being written.

Caching:

This application consists of taking the most popular content of the Web and push it to edge devices located in hundreds of "points of presence" (POPs) owned by a number of carriers to allow quick content access and easier streaming. Software developed in-house by the Content

Delivery Networks (CDNs) streamlines content distribution and automatically ranks content to be put on the POPs. However, caching services have not been able to sustain all of the competing CDNs, and the ones that are still in the market have refocused their portfolios to include large file transfers and content aggregation. [68] This has resulted in a lower number of potential customers for FSS providers, but an increase in demand for bandwidth capacity to provide these additional services can be experienced in the short term.

Multicasting:

The term *multicasting* refers to "the delivery of information to multiple destinations simultaneously using the most efficient strategy to deliver the messages over each link of the network only once and only create copies when the links to the destinations split".[69] Multicast satellite services are highly efficient delivering IP content when a combination of satellite and fiber is used. Point-to-point long-haul transport is usually done through fiber between content aggregation points. Point-to-multipoint satellite services deliver then content from these aggregation points to the edge servers in the POPs. The resulting one-step distribution over the satellite network, rather than the multiple steps necessary with terrestrial networks, provides the customer with a higher-quality service. A key differentiator for satellite-based services is their ability to scale for a large number of users, allowing service providers to reach a larger audience and to deal efficiently with demand peaks. Although this application is not truly being commercially exploited, it might represent a significant potential for satellite operators.

2.5. Regional and global satellite operators

This section is devoted to the description of five global and two regional satellite operators. For the purposes of this thesis, a *global satellite operator* is defined as a satellite service provider that has service covering more than one of the three main geographic regions on Earth: Atlantic Ocean Region (AOR), Indian Ocean Region (IOR), and Pacific Ocean Region (POR).[70] The top five –by revenue- global satellite service providers are: Société Européenne des Satellites (SES Global through its subsidiaries SES Astra and SES Americom), Intelsat, Eutelsat, PanAmSat and Loral Skynet.

Table 2.5: 2003 Revenues and Market Shares of FSS Satellite Operators (Source: Euroconsult)[71]

Company	2003 Revenue (in USD million)	2003 Market Share
SES Global	1,352	20.5 %
Intelsat	953	14.5 %
Eutelsat	886	13.4 %
PanAmSat	831	12.6 %
JSAT	371	5.6 %
Loral Skynet	259	3.9 %
New Skies Satellite	215	3.3 %
Total	**4,867**	**73.8 %**

The following tables provide the highlights of the global satellite operators mentioned above. [72]

SES Global

Ownership	SES Global operates through two wholly owned subsidiaries: SES Astra and SES Americom. In addition, SES Global has some partnerships in which it holds interests. Some examples of these partners include AsiaSat, Nahuelsat, Star One, and Satlynx. GE Capital owns a 25 percent stake of SES Global. The Luxembourg government together with two state-owned banks owns another third of SES Global.
Head Office	Château de Betzdorf, Luxembourg
Satellite Capacity	A total of 29 satellites. Twelve of them are operated by SES Astra, and located primarily in two orbital positions: 19.2 degrees east and 28.2 degrees east.
Main services provided:	-Consumer Internet access via Advanced Codec (AVC) Broadband -Business services provided through Satlynx, a joint venture between SES Global and Gilat Satellite Networks -Corporate/small and midsize enterprise broadband (through a product called Systar advantage) -Broadband interactive system based on a Ku/Ka hybrid system -Remote system connectivity, through Satlynx. -IP and multicasting services -Communications solutions to broadcasters, cable programmers, ISP, government agencies, and private corporate networks

Intelsat

Ownership	Zeus, a private equity consortium.
Head Office	Washington, D.C., USA, with Asia/Pacific regional offices in Chennai (India) and Singapore
Satellite Capacity	The global system includes 27 satellites under several series (Intelsat V-A, VI, VII, VII-A, VIII, VIII-A, and IX). IS-907, at 332.5 degrees east, one of Intelsat's most recent launches (2003) provides C-band coverage for the Americas, Africa, and Europe, as well as Ku-band spot beam coverage for Europe and Africa.
Main services provided:	-Video transmission (satellite news gathering, television broadcasting, and DTH broadcasting) -Satellite master antenna television (SMATV) -Internet backbone and enterprise connectivity -VSATs and private network services -Transponder leasing for occasional use -High-speed internet access -Multicasting -Training and technical assistance

Eutelsat

Ownership	Five private equity firms (Texas Pacific Group, Spectrum Equity Investors, Cinven Ltd, Eurazeo, and Goldman Sachs Capital Partners) held stock for more than 80% of Eutelsat.
Head Office	Paris, France
Satellite Capacity	Operates a fleet of 24 satellites. The "hot Bird", a constellation of five satellites, located at 13 degrees east, provides full coverage of Europe. Eutelsat II-F3, located at 21.5 degrees east, covers Western Europe. Most of the spacecrafts are constructed by Alcatel Space Industries. Three satellites, the Atlantic Bird 1, 2 and 3, cover the Americas, Europe, the Middle East and Africa.
Main services provided:	-Television and radio broadcasting for the consumer public -Professional video broadcasting -Corporate networks connectivity -Intranet services mostly to European corporations -IP services and multicast file delivery -Home internet (through a product called OpenSky) -IP trunking

PanAmSat

Ownership	A private equity consortium composed of the following corporations: Kohlberg Kravi Roberts, The Carlyle Group, and Providence Equity Partners.
Head Office	Greenwich, Connecticut, USA, with Asia/Pacific regional offices in Tokyo (Japan), and additional offices in Hong Kong, Sydney (Australia), Mumbai (India), Mexico, and Peru.
Satellite Capacity	PanAmSat's global system comprises 25 satellites (as of January 2004), covering the main business centers across North and Latin America, Europe, Africa, the Middle East, and Asia.
Main services provided:	-Transponder leasing for occasional use -DTH broadcasting capability -Video transmission -Internet backbone services -Internet content distribution network and Internet access -Private business networks and VSATs -Telephony and radio -Network design and engineering -Special event and ad hoc services such as new customized applications

Loral SkyNet

Ownership	The main shareholder is Loral, which owns 39 percent. Intelsat owns LoralSkyNet's NorthAmerican assets. Lockheed Martin owns 15 percent.
Head Office	New York City, NY, USA.
Satellite Capacity	A total fleet of 12 satellites (as of January 2004) covering Europe, the Americas, and parts of Asia and Africa. Their Europe Star 1 satellite, at 45 degrees east, provides the highest-powered Ku-band cross connection between South East Asia and Europe, and is the first satellite to provide interconnections between Asia, India, Africa, Europe and the Middle East.
Main services provided:	-IP broadband data transmission -Global telephony services via its subsidiary GlobalStar -Internet access -DTH broadcasting

The following tables present the highlights of two *regional satellite operators*: New Skies Satellite (The Netherlands) and JSAT (Japan). For the purposes of this thesis, a *regional satellite operator* is defined as either a satellite service provider that does not have global coverage, or as a satellite operator whose satellite fleet is considerably smaller than that of a *global satellite operator*.

New Skies Satellite

Ownership	Originally a public-listed company, recently acquired by Blackstone group, a private equity company.
Head Office	The Hague (Netherlands), with offices in London (UK), New Delhi (India), Sao Paulo (Brazil), and Washington, D.C., USA.
Satellite Capacity	Five satellites. Covering predominantly AOR with one POR and one IOR satellite.
Main services provided:	-Transponder leasing for occasional use -Digital and analog video distribution -Multicasting -High-speed IP backbone connections: "multihoming satellite links" enable ISPs to offer one-hop connections from the internet backbone

JSAT

Ownership	Privately owned. First private-sector satellite operator in Japan.
Head Office	Tokyo (Japan), with offices in Los Angeles, CA, USA.
Satellite Capacity	Nine satellites covering the Asia / Pacific Region and parts of North America.
Main services provided:	-Uplink services for SkyPerfecTV (DTH TV) -Two-way satellite communications (VSAT) -Live coverage of special events through SNG (Satellite News Gathering) services -Digital video transmission -IP-based content distribution over North America using the Horizons-1 satellite.

2.6. Summary

This chapter provided an extensive overview of key issues and indicators of the satellite communications industry. Establishing a sound framework and setting coherent definitions constitutes already a significant contribution that is often taken for granted or simply not reached. I therefore started this chapter by summarizing the evolution of the industry and introduced the key definitions of satellite services used by the International Telecommunication Union (ITU). The distinction was made between FSS, MSS and BSS. Chapter 2 presented as well a snapshot of the current financial state of the satellite industry in general, and the FSS operators in particular. The first substantial contribution of this thesis was the identification, classification, and outlook assessment of the different types of service applications (markets) delivered by communication satellites. Finally, the highlights of some of the most important satellite operators were presented at the end of the chapter. The next chapter will address the central question of Part One of the thesis: are satellite communications solutions competing or complementary alternatives to terrestrial networks–in what context and for what service applications?

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Chapter 3

Satellite Communications and or versus Terrestrial Networks: Competing or Complementary technologies?

In order to better understand some of the issues associated with the future of the satellite industry, it is important to be aware of the context in which the satellite operators provide their services. Communication satellites are part of *telecommunication* networks. Telecommunication refers to the science and technology of communication at a distance by electronic or optical transmission of impulses.[1] The term "telecommunications" refers to all kind of data transmissions, including voice, video, and different pieces of information usually formatted in a variety of specific ways. Telecommunications is therefore a set of *services*, while satellites are *tools* for providing some of these services.[2] In general, services are present in a market for a much longer period of time than tools. Yet, satellites have been used for more than 40 years now and they have demonstrated an exceptional adaptability to the evolving challenges and new types of telecommunications services. In early 2001, in the midst of the then-ongoing telecommunications and satellite industry downturns, there was a recurrent debate and discussion about the satellite business outlook. "Does the satellite industry have a future?" was the question that a number of experts and analysts of the sector attempted to address. The author of this thesis believes that the answer to this query is positive, and this chapter will provide some of the arguments that support this assertion.

The chapter is organized as follows: The first section presents a comprehensive analysis of satellite communications as a competing or complementary technology to terrestrial networks. Section 3.2 summarizes the challenges that satellites face as a solution to providing telecommunications in urban areas. Section 3.3 discusses the opportunities that rural areas represent for the satellite industry. Brief descriptions of Aramiska and the Twister projects (two satellite-based solutions) are provided as examples for rural connectivity. Section 3.4 is devoted to the analysis of the trans-oceanic communications market. Finally, section 3.5 closes the chapter with an overview and outlook for a new technology, the Worldwide Interoperability for Microwave Access (WiMAX) that might considerably impact the satellite service industry in the near future.

3.1. In what context, service application or geographic market, are satellites a competing and or a complementary alternative to terrestrial networks?

This section focuses on the tradeoffs associated with choosing satellite communications versus terrestrial solutions to deliver telecommunication services. The goal is to understand in what context satellites represent a competing technology or a viable alternative to terrestrial networks, and vice-versa. More generally, as the title of the section suggests, the discussion presented here is about comparing the two types of solution in different contexts. The analysis is structured around three axes: type of solution, service application, and geographic market. Figure 3.1 shows a graphic representation of the three perspectives from which the analysis is developed. The type of solution refers to satellite versus terrestrial networks. The service application perspective divides the satellite communications market in two categories: transmission of voice and data, or transmission of video contents. The third axis compares both solutions (satellite and terrestrial) in three major geographic markets: urban areas in developed markets, urban areas in emerging regions, and rural areas in general.

This section is divided in three parts: subsection 3.1.1 provides an overview of the alternative technologies to satellite communications, i.e., other types of technologies capable of providing the same telecommunications services that a satellite provides. Currently, the main competing technologies to satellite communication solutions are Optical Fiber Cables and Digital Subscriber Lines (DSL). The major advantages associated with these technologies are briefly discussed in this subsection. The second subsection, 3.1.2, is devoted to the analysis of the advantages of satellite communications over terrestrial networks. Subsection 3.1.3 presents a description of the tradeoffs associated with the use of both solutions (satellite and terrestrial) to deliver a specific service application (the transmission of voice and data, or video) in the three different types of geographic markets, namely urban-developed, urban-emerging, and rural in general.

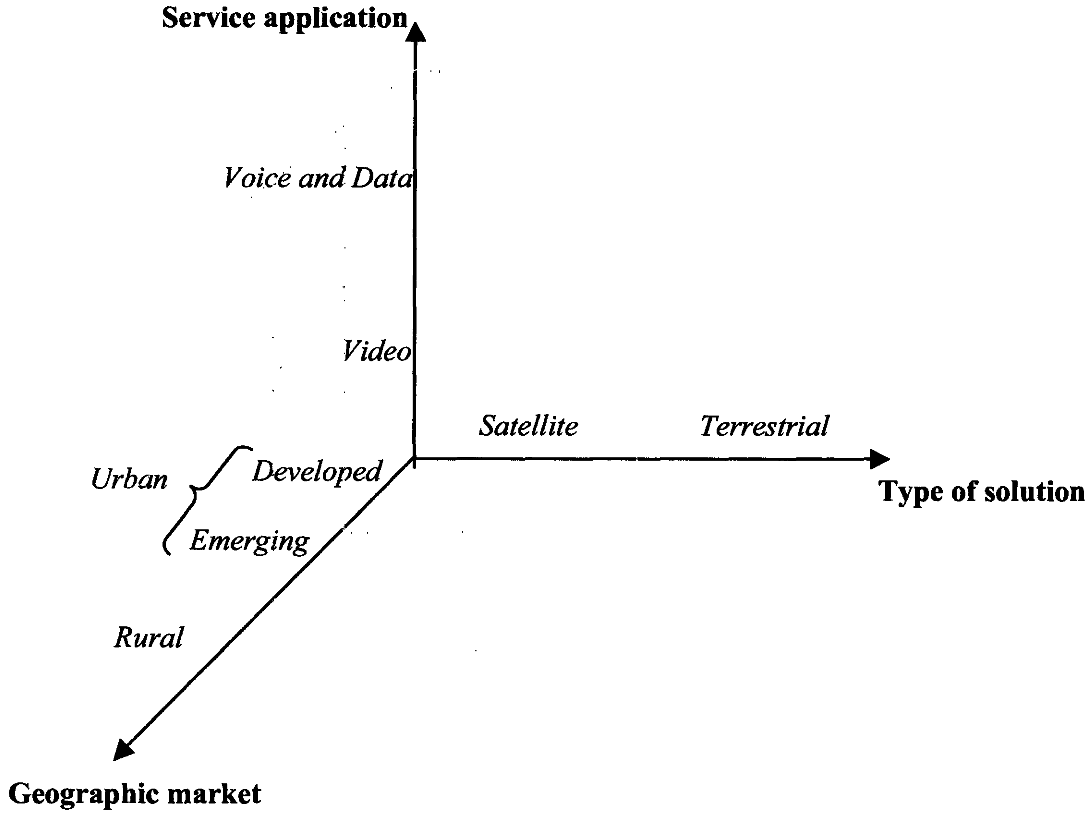

Figure 3.1: Graphic representation of the perspectives used for the comparative analysis of satellite versus terrestrial solutions to provide telecommunication services.

3.1.1. Overview of competitor markets

This subsection provides the reader with an overview of the competitor markets of satellite communications, i.e., other types of technologies that are capable of providing the same telecommunications services that a satellite provides. There are currently two main competitor technologies to satellite communication solutions, Digital Subscriber Lines (DSL) and Optical Fiber Cables.

3.1.1.1 Digital Subscriber Lines (DSL)

DSL refers collectively to all types of digital subscriber lines, the two main categories are Asymetric DSL (ADSL) and Symetric DSL (SDSL). DSL technologies use modulation schemes to pack data and transmit it over copper wires. They are sometimes referred to as last-mile technologies because they are used only for connections from a telephone switching station to a home or office, not between switching stations. DSL operates over existing copper telephone lines (plain old telephone service, or POTS), and requires short runs to a central telephone office (usually less than 20,000 feet). DSL offers high speeds of data transmission: up to 32 Mbps for upstream traffic, and from 32 Kbps to over 1 Mbps for downstream traffic.[3]

DSL is often understood, in most regions of the world, as synonymous with broadband access. The DSL infrastructure began to be deployed in the late 1990s, and this market represents now approximately 60 percent of the world's broadband subscribers.[4] ADSL is the dominant DSL technology, although new technologies such as Very-High-Data-Rate DSL (VDSL) and Global-Standard High-Bit-Rate DSL (GSHDSL) are emerging.

In North America, cable continues to dominate DSL and it maintains a two-to-one advantage in the number of new customers. Europe and Asia, however, are much better suited markets for higher-speed DSL broadband access. In comparison with North America, the lengths of the loop between the central offices (CO) of a telephone company and the customer are much shorter. They also have newer and cleaner copper that minimizes loss and interference.

DSL is currently perceived as a technology that will deliver not only high-speed Internet access, but also video services. Several telecommunication companies (telcos) across the world (such as Bell Canada, and Aliant, also in Canada) are providing television services via ADSL or VDSL.[5] In addition to this, telcos are using DSL to offer Voice over IP (VoIP) services, and although there are currently some technical barriers to be overcome, ADSL is likely to deliver this kind of connectivity in the near future. In North America, there is an ongoing competition on price between telcos and cable providers to attract customers within the markets of providing Internet access and data transmission services. Finally, DSL is being gradually considered more as a platform that provides a package of services than as a simple ISP; its availability is growing globally. The potential market that DSL might penetrate in Europe is more than 90%, although in North America it remains approximately 60%.

3.1.1.2 Optical Fiber Cable

A fiber-optic system is similar to the traditional copper wire system that it replaces. The difference is that "fiber-optics use light pulses to transmit information down fiber lines instead of using electronic pulses to transmit information down copper lines".[6] The optical fiber can be used as a medium for telecommunication and networking because it is flexible and can be bundled as cables. Because of the remarkably low loss and excellent linearity and dispersion behavior of optical fiber, data rates of up to 40 gigabits per second are possible in real-world use on a single wavelength.[7] Modern fiber cables can contain up to a thousand fibers in a single cable, so the performance of optical networks easily accommodates today's demands for bandwidth on a point-to-point basis. It is estimated that no more than 1% of the optical fiber installed in recent years is actually in use. [8] In recent years, fiber-optic cables have been steadily replacing copper wire as a suitable technology to transmit communication signals. Currently, fiber-optics extend over the long distances of local phone systems, and provide the infrastructure for the backbone of many network systems. Other users of optical fiber cable are cable television services, universities, office buildings, industrial infrastructure, and electric utility companies.

Worldwide, DSL is the largest broadband access technology, followed by cable. In North America, however, cable dominates the residential broadband access market. American Multiple System Operators (MSO), or cable services providers, invested billions of dollars to upgrade their previous infrastructure for two-way services. Abroad, where satellite pay-TV is more present, and where video is not the main product of consumer services, cable operators have had more difficulties upgrading their cable network.[9] Global cable operators continue to grow their broadband subscribers base, and are investing in new technologies (such as Voice over IP) aiming to increase their revenue per user, and to add value to their services. Major cable operators in the United States and Canada dominate the market, and better network availability is helping the operators to remain as the leaders in the consumer market.

The next subsection provides an analysis of the advantages of satellite communications over the terrestrial solutions that were described above, namely DLS and cable.

3.1.2. Satellite advantages over terrestrial networks

Since the beginning of the commercial space era in the 1960s, satellite communications have provided a variety of broadcasting and telecommunication services. They made possible the creation of a global and automatically-switched telephony network. Today, even though the deployment of advanced optical fiber submarine cables across the oceans and across the continents have considerably lowered telephony costs and have significantly increased transmission capacity, only satellite communications have the capability to provide reliable transmission links over all types of terrestrial obstacles, regardless of the distance or of how remote the locations to be connected might be.[10]

The main and inherent strength of a satellite is thus its ubiquity. Unlike any other communication technology, their position gives them a radio visibility across vast areas of the Earth that is almost impossible to match. From the beginning of the commercial era of the satellite communications industry, this characteristic played a fundamental and strategic role in the deployment of defense systems. As a result of this military role, the commercial applications experienced an accelerated technology development process.[11]

In addition, satellite communication systems have three properties that are not found in terrestrial networks (or only to a lesser extent):[12]

- Multiple access capability, i.e., point-to-multipoint, or multipoint-to-multipoint connectivity.
- Distribution capability, in particular in the case of point-to-multipoint transmission.
- Flexibility for changes in traffic and in network architecture, and ease of reconfiguration.

These intrinsic characteristics of a satellite system make it particularly well suited to provide communication services over large or dispersed areas.[13] Vast territories, natural obstacles (forest, mountain ranges, deserts), scattered population, or an undeveloped infrastructure are some of the situations where communication satellites can play a unique role by allowing the rapid establishment of a telecommunications network, typically capable of providing high-quality and low-operational-cost links (especially in rural areas) for the transmission of data, voice and video.

A brief discussion of each of the most specific characteristics of satellite networks is presented below:

⇒ *Coverage:*

A satellite system enables communication links between any two points on Earth independently of the geographical distance between these points, and provided that they are located within the satellite coverage area. This communication link can be established without any intermediary infrastructure. In the case of GEO satellites, a single spacecraft has geometric visibility of approximately 40% of the Earth's surface.[14] The points to be covered must be situated within the geographical areas covered by the beams of the satellite antennas; these areas are called the *coverage areas* of the satellite system. The antenna beams can be configured to form customized coverage areas that respond to the specific needs of the customer and the region that will be served. Satellite coverage can therefore easily reach the rural areas that terrestrial solutions are not capable of serving. This characteristic gives customers of satellite operators the possibility to use their service applications homogeneously across their network.

⇒ *Multiple access:*

This is an exceptional feature used in FSS telecommunication links. Multiple access is defined as the ability of a satellite transponder to receive data from several ground stations simultaneously. The most important consequence of this feature is that it allows any ground station located in the satellite coverage area to receive transmissions from several other ground stations through one satellite transponder. This allows a transmitting ground station to group several transmissions into a single-destination link.[15] There are several common types of multiple access protocols, such as frequency division multiple access (FDMA) and time division multiple access (TDMA). Their description is outside of the scope of this thesis. The reader is referred to Ref. 16 for a thorough discussion of this topic.

⇒ *Distribution:*

The distribution capability of a satellite is the ability to transmit data from one point to multiple points on Earth. It is used when the data to be transmitted is emitted by a single ground station towards stations that are assigned for reception only (in general several stations are scattered throughout the coverage area). This capability is particularly useful for television (specifically DTH TV) and for some data transmission services (e.g. data banks).[17]

⇒ *Flexibility:*

The implementation of the ground segment of a satellite network is relatively simple in comparison to other terrestrial solutions. Technologies such as optical fiber require the installation of thousands of miles of cable, for which the right-of-way has to be secured from governments or other organizations, hundreds of sites have to be build, provided with shelter and power, and maintained regularly to guarantee a reliable service.[18] Therefore, **rapid installation** and bringing into service of ground stations represents an **important advantage of satellite systems**. Provisioning times for satellite services vary, but initial service can be offered within weeks instead of months (typical delay of other solutions such as T1 or T3 lines, i.e., DSL technologies). Another important feature that makes communication satellites attractive is the flexibility for changes of services and traffic, such as "bandwidth-on-demand". Once the service is established, bandwidth can be provided immediately up to 45 Mbps. In the case of traditional terrestrial private lines services, upgrading from a 1.5Mbps DS1 line to a 45Mbps DS3 line may require several months. Finally, another advantage of satellite systems is the **relative low cost of installation**. Once the satellite is in-orbit, service providers and end-users can deploy the necessary equipment with low costs in comparison with the capital expenses necessary to pull fiber cables to a new location.[19]

Table 3.2, presented at the end of this section, summarizes the advantages and disadvantages of satellites solutions.

3.1.3. Service applications

This subsection discusses the tradeoffs associated with the use of satellites versus terrestrial solutions to deliver a specific service application (transmission of voice and date, or video) in different geographic markets (urban-developed, urban-emerging, and rural in general). For the purposes of the analysis presented here, issues related to the transmission of voice and data are grouped in one category, while the tradeoffs associated with the transmission of video are considered under a second category.

3.1.3.1 Voice and Data

The telecommunications traffic has been steadily moving from analog transmissions to digital technology during the past decades. This tendency, together with the high capacity of both optical fiber and satellites, has resulted in a lower cost of long-distance telephone calls and therefore in an increase in the number of circuits available. Prior to the commercial development of communication satellites, in 1960, communications from the United States to Europe had to be handled by an operator and many hours of waiting time to establish a call was not rare. In 2000, international calls could be dialed directly by end-users and rates had decreased at least by a factor of ten.[20] A capacity superior to that of the copper cables across the oceans and continents was, in the early years of satellite communications, a decisive advantage that made international and domestic trunk traffic services the main engine of the satellite industry. However, the implementation of optical fibers and their higher capacity rapidly challenged the satellite trunking services, first across the continents, and then across the oceans. In the future, this sector (voice transmission) will clearly not be one of the main drivers of the satellite communications industry, although satellite's ease of reconfiguration of coverage and capacity to match peaks in demand (e.g. for dealing with natural disasters or government needs) might sporadically translate into a small benefit to the sector. Satellite communications also provide a reliable alternative (as a back-up solution) to submarine cables when for any reason the service is disrupted (e.g., if the anchor of a ship damages the underwater cable). In other words, satellite and cable can be sold as a bundled solution, with submarine cable as the primary technology and satellite communications as a back-up alternative should the cable connectivity suffers a disruption for any reason.

Figure 3.2 shows the usage trends by service application between 2000 and 2003. Figure 3.3 shows the percentage of change in capacity used by type of service application from 2000 to 2003.

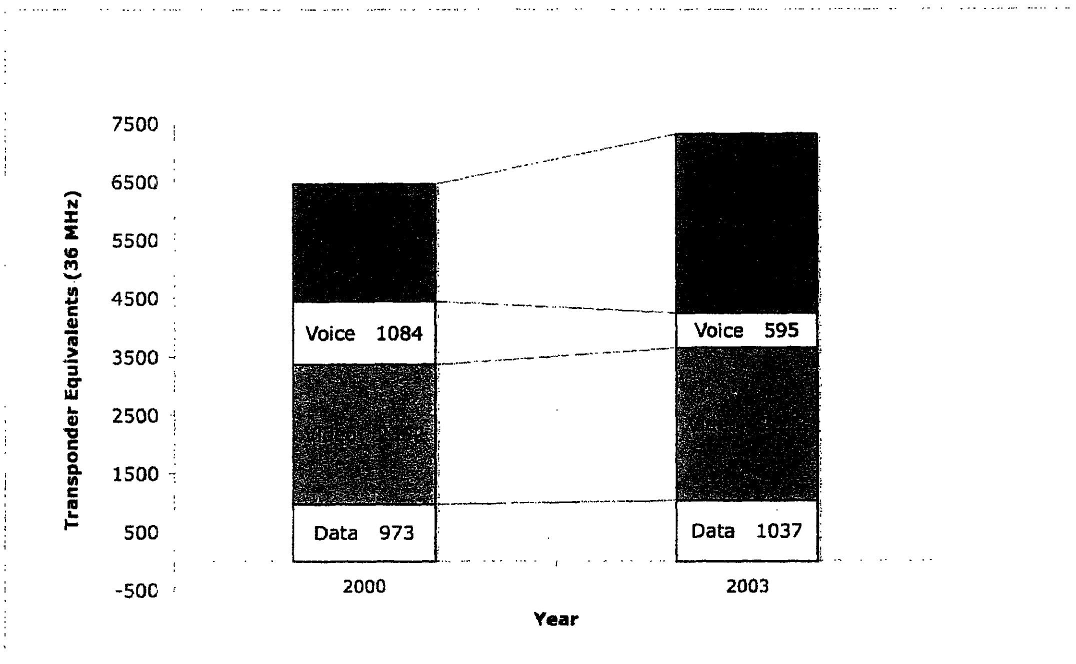

Figure 3.2: Usage Trends by Service Application. Years 2000 to 2003. (Data Source: Futron Corporation)[21]

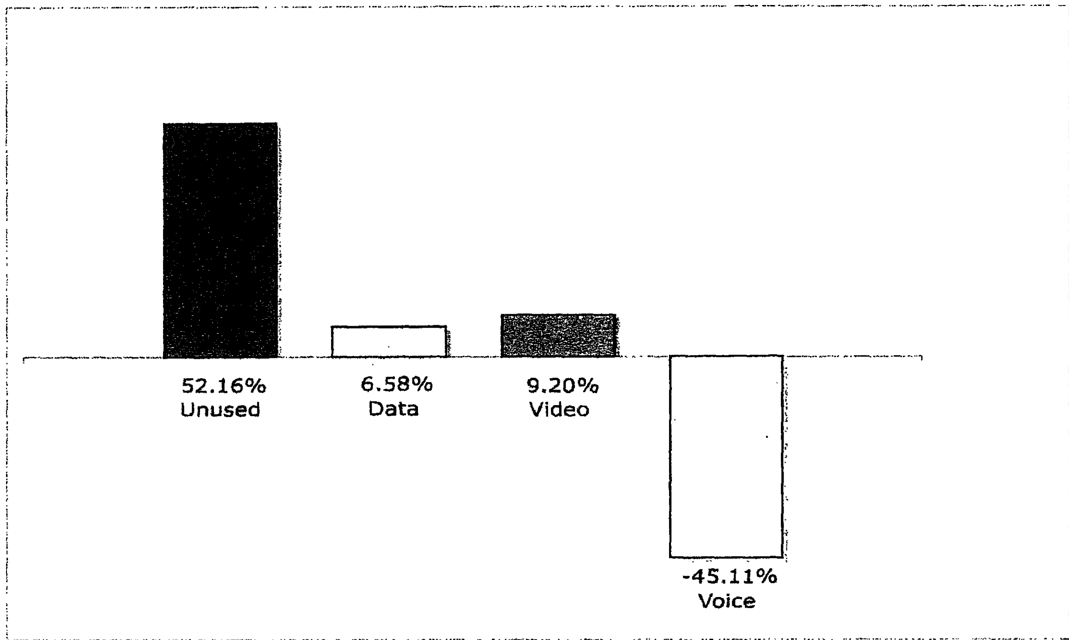

Figure 3.3: Percentage of change in capacity used by application 2000-2003 (Data Source: Futron Corporation) [22]

In the near future, data applications are likely to experience the strongest growth, mainly driven to increases in both demand for bandwidth per user, and the numbers of users. Figure 3.4 shows the data applications market share for private networks, ISP-to-Internet- backbone, and end-user Internet access.

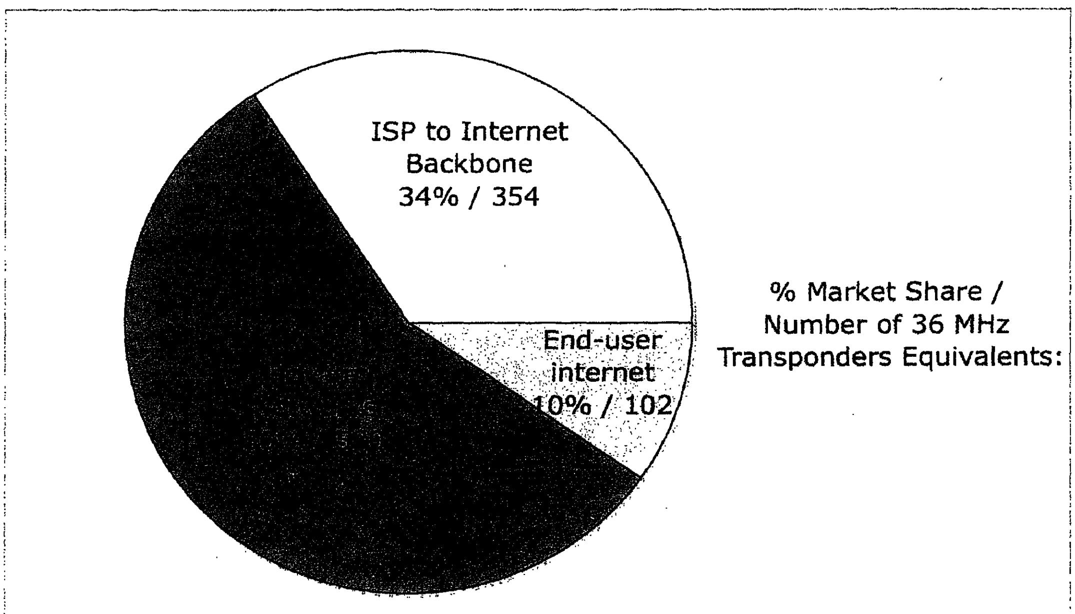

Figure 3.4: Data applications: Market shares in 2003[23] (DataSource: Futron Corporation)

In 2004, some satellite operators, such as Spaceway by Hughes, Shin Satellite, and Telesat, launched Ka-band satellites, and more are scheduled for launch in 2005. These new high-capacity satellites are likely to change the landscape of the satellite services industry. Higher speeds and lower service costs should be the natural consequence of making more frequency in the Ka-band available. As a result, satellite services might be at the reach of new customers that have not yet been able to take advantage of this technology, and new markets of satellite applications might become a real opportunity for satellite operators. As a result, there is an ongoing debate about weather broadband satellite solutions will be a competing or a complementary technology to DSL and cable. Different stakeholders within the satellite services industry are at odds about this question. For example, the belief that satellite services can compete as an alternative to DSL and cable underlies Spaceway's strategy.[24] In contrast, Alcatel Space is looking at its "DSL in the Sky" broadband satellite solution as a complementary option to existing terrestrial infrastructure. Alcatel is combining its solution with its existing DSL network and management services.[25] In addition, Alcatel believes it can persuade customers to use this solution by bundling services such as DTH TV with broadband connectivity.

Approximately 40% of the 7 million businesses in the United States are out of the reach of terrestrial networks.[26] Remote offices represent a large market for satellite operators. Some of these companies in remote locations have chosen satellite solutions as the best alternative because of the ubiquity, the relatively low cost of installation, as well as the quick deployment of this solution. Another advantage of this structure is the fact that it implies less complex service contracts and billing issues, since a single service provider delivers connectivity to all of the company's locations. Other customers have preferred to use DSL or cable solutions in urban locations and use satellite to cover only their remote locations.[27] Satellite solutions are also appealing for the Small and Medium Business (SMB) and the SOHO markets, where often the DSL alternative is limited by degradations in speed that become insurmountable when the customer is beyond a specific distance from the central office (CO). In addition, satellite's "bandwidth-on-demand" (i.e., customers pay for bandwidth use as opposed to paying for a flat monthly rate) is a potential source of cost-savings, especially for SMB.

Hybrid solutions that integrate both terrestrial and satellite technologies have recently started playing an important role in the industry. This has resulted in partnerships between satellite operators, system integrators and carriers. An example of these new hybrid service solutions are

Gilat's Connexstar product, which is integrating terrestrial (DSL) and satellite based communications. Another example is Intelsat, which has partnered with L3 Communications to provide its GlobalConnex hybrid Internet trunking service to enlarge existing terrestrial networks. This product registered a 329% increase in revenue in 2003.[28] Satellite operators are likely to search for new opportunities and partnership in order to avoid a role of "commoditized transport provider". Their goal, in order to remain profitable, should be to become a solutions provider rather than a satellite service provider. By expanding their portfolio of products and including new access tools, satellite operators may intend to become a neutral network-access provider.[29]

In conclusion, it is certainly true that satellite broadband has yet to make an impact in the satellite services industry. In 2005, as new Ka-band satellites are launched, more capacity will be available.[30] This higher capacity will allow two-way access and an increase in the number of subscribers. However, satellite broadband differentiators from fixed-line broadband solutions (ubiquity and low upfront installation costs) will essentially allow satellite service providers to remain competitive, but in no way satellite broadband will represent a strong competitive advantage over terrestrial networks. The success of this new technology will mostly depend on the creativity of satellite operators to upgrade and sell their services. Satellite service providers must concentrate their efforts on markets already using satellite solutions. Some opportunities to succeed and grow are, for example, to up-sell Internet services to existing residential DTH TV customers, or to up-sell two-way broadband satellite services to business VSAT customers that already know the benefits of this technology and are looking for a more solid and complete solution.[31] In most cases, because the costs of customer premises equipment (CPE, or upfront installation cost) are higher than those of DSL or cable modem,[32] satellite services are used only if other alternatives are not available. Therefore, satellite operators should also create a strategy to reduce CPE and monthly service costs.

3.1.3.2 Video

The transmission of video (TV relay, both broadcast and cable) continues to be the main market of the satellite services industry. Eight out of the ten top satellite operators generate at least 50% of their revenue from video services, which are estimated to account for 59% of the total revenues of the satellite operators in 2003.[33] The consumer side (primarily DTH services) has provided the most dynamic market within the video satellite application. In most geographic regions, DTH TV continues to take market share away from terrestrial pay-TV providers.[34] In some of these regions, the fact that the deployment of cable has been slow (given the physical geography and related difficulties) has generated a steady growth for DTH pay-TV platforms.

As the author defined in chapter 2, there are three major types of video broadcasting services:

- ⇒ Contribution (i.e. backhaul* of video contents,[35] or the exchange of video contents between broadcasters);
- ⇒ Feed of cable TV head-ends, and broadcast of free-to-air TV channels;
- ⇒ DTH broadcast of TV channels (previously referred to as the consumer market).

The main applications of the contribution market are feeds to head-ends of cable for terrestrial broadcasting and exchanges of video contents. This market can be divided into two categories:[36]

- ⇒ Permanent broadcasting of TV channels to the head-ends of cable.
- ⇒ Occasional broadcasting of TV programs and video contents for live broadcast or integration into TV channels.

In recent years, the demand for video transponders used for contribution services has increased continuously in some geographic markets, such as Asia.[37] This tendency has been mainly generated by an increase in the number of TV channels in the region, not only satellite pay-TV, but also cable and over-the-air channels. In this context, even if cable is a competitor of satellite pay-TV, it also generates a positive impact on FSS providers performance, since cable providers need to feed their head-ends using satellite links, mostly due to difficult geographic conditions in the region and to the lack of cable infrastructure for the backhaul segment.

In North America, video contribution is a key market, considering the importance of the media industries and of cable TV penetration. Approximately 83 million households subscribed to cable TV in 2003.[38] As a result, the feeding of cable networks head-ends is a robust business. During the past 3 years, all cable platforms have recently increased the number of programs offered, driving demand for satellite capacity up. In addition, the United States hosts the world's largest producers of video content for TV; consequently, the exchanges of programs are growing between North America and other markets, and this results in an increase in the number of satellite transmissions.

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* In satellite technology, backhaul refers to the transmission of data to a point from which it can be uplinked to a satellite.

In Latin America, video broadcasting represents half of total transponder demand.[39] In 2003, there was a limited growth in demand for video transponder, and it was generated mostly by demand for broadcasting TV channels independent of the satellite pay-TV platforms. Video contribution, however, has been a stable market in the region, with an annual average of 40 transponders in service for the feeds of cable TV networks and video content exchanges during the past five years.

Western Europe is a heterogeneous market with significant differences in culture, business practices, and competition, especially in the cable and free-to-air TV market (cable TV can reach 50% penetration in the northern countries, while it remains at less than 20% in France and the UK). Approximately 67% of total transponder demand of the region comes from video services. Transponder demand for video contribution and backhaul applications has decreased around 30% since 1996, mostly because of an increase in compression rates, and because of the growing competition of optical fiber. This decrease stopped in 2003, since a large number of live feeds, cable feeds and programs exchanges were generated mainly by geopolitical events, especially the Gulf War. In this context, satellite solutions are well suited for the live coverage of such events. Growth in this sector should continue as long as major events (such as the European Football Cup or the Soccer World Cup in Germany) and other news in the region continue to generate demand for transponder capacity.

In 2003, transponder demand for video services in the Asia-Pacific region experienced an increase of 8.5%.[40] This growth in demand was mainly generated by video contribution and backhaul services. Asia is the largest TV base with 470 million TV households. Most of the video transponders in the region are used to broadcast TV channels independent of the satellite TV platforms. The increase in transponder demand in 2003 for video contribution and backhaul applications can be explained by the international geopolitical context, with several global news and live video content of interest for the region, as well as content originating in the region that is of interest for broadcasters around the world. Again, in this context, satellite services are in a much better position to cover the broadcaster needs than terrestrial networks.

In general, providing satellite contribution services has become an inclusive industry where broadcast companies benefit of the complementary of optical fiber and satellite networks to backhaul and broadcast video content. Broadcast companies usually prefer fiber-optic cables to transmit high volume and permanent video traffic routes. Nevertheless, satellite services remain the primary solution for remote and far geographic market,[41] as well as for service applications that require a higher degree of flexibility, such as live coverage of global news or major massive events. Table 3.1 shows the optical fiber recently leased or bought by major satellite broadcast service providers.

Table 3.1: Optical Fiber used by some satellite broadcast service providers[42] (DataSource: Euroconsult)

Globecast (France Telecom)	Paris / London; Transatlantic
BT Broadcast Services (BT)	Paris / London; Transatlantic New York / Washington / Los Angeles North America / Latin America Transpacific and Asian loop
Verestar (SES Americom)	10 points of presence (POP) in the US; Transatlantic
Williams Vyvx	Traffic inside the US; Transatlantic (through partnerships); Transpacific (through partnernships)

From a broader perspective, as a summary of this section, three elements can be identified that are key to ensure that satellites as *tools* will continue to be resilient and deliver services in the telecommunications industry. Firstly, the strong attribute of multiple access that satellites provide. Secondly, the fact that satellites service providers continue to adapt to the evolving needs of the market by providing more complete solutions and enhanced services. Finally, an important issue to ensure the longevity of these tools will be that satellite businesses and ventures are managed precisely as what they are: business, and not as technological experiments.[43] In addition, the recent partnerships between satellite operators and telecommunication companies are likely to play an important role within the sector. If well managed, they might prove to be a new successful business model in the satellite services industry. In this direction also, some of the recent changes in the ownership structure of the satellite service providers are likely to bring a more strict financial discipline within the major operators. Table 3.2 presents a summary of the tradeoffs associated with the use of satellite and terrestrial networks.

Table 3.2: Summary of issues associated with the use of terrestrial and satellite solutions.[†]

		Terrestrial Solutions		Satellite solutions
Competing technologies	+	Higher capacity	+	Ubiquity in coverage: a) *Voice and data*: Rural regions and urban emerging markets (where there is no terrestrial network infrastructure deployed) represent a large market for satellite operators b) *Video*: Remote locations, where the deployment of cable has been slow, are a potential market for DTH TV applications as well as for the backhaul segment
	+	Reliable and modern network infrastructure already deployed in urban developed markets	+	Higher degree of flexibility: ideal for applications that require immediate implementation (such as live coverage of global news, major massive events, or natural disasters). Ease of reconfiguration of coverage and capacity allows to easily match peaks in demand.
	+	Lower price per unit of capacity	+	"Bandwidth-on-demand" as a potential source of cost-savings
			+	Quick initial deployment
	-	Degradations in speed beyond a specific distance from the central office (CO) for DSL	+	Less complex service contracts and billing issues (a single service provider delivers connectivity to all of the company's locations)
	-	Remote locations out of the reach of terrestrial networks (e.g. 10% of the 150 million households in Europe)[44]	-	Lower capacity (although broadband capacity delivered by new Ka-band satellites launched in 2004 and 2005 is expected to allow satellite solutions to remain competitive)
	-	High installation costs	-	Higher cost of customer premises equipment (CPE)

[†] The + or – refer to characteristics that are perceived as advantages or disadvantages, respectively.

Table 3.2 (continued): Summary of issues associated with the use of terrestrial and satellite solutions

	Terrestrial *and* Satellite solutions
Complementary alternatives	Bundled solution with cable as the primary technology and satellite as a back-up in case of disruption of the terrestrial service
	For satellite operators, partnerships represent a good opportunity to avoid a role of "commoditized transport provider", and therefore to become a *solutions* provider instead of only a *service* provider.
	Contribution services as an inclusive industry where broadcast companies benefit of the complementary of optical fiber and satellite networks to backhaul and broadcast video content
	Capability to persuade customers to use hybrid solutions by bundling services such as DTH TV with broadband connectivity

3.2. Challenges in urban areas

This section is devoted to the description of the challenges faced by satellite operators to implement satellite solutions in urban areas.

The satellite services market is different in each region: every area presents its own challenges and opportunities. The ultimate service provider will know how to develop added-value services and implement flexible product strategies that will fit to each region's constraints and will allow the operator to take advantage of the different business opportunities. As discussed in the previous section of this chapter (3.1), satellite services have been pushed out of major cities in developed countries (Tier 1 cities) and trans-oceanic routes by optical fiber cable and other terrestrial technologies.[45] This is resulting in a redirection of satellite operators' strategies. Four main challenges that the operators face, especially in urban areas, are identified and discussed below:

A) To sell their added-value services and new products over the already well-established terrestrial access alternatives.[46] In the case of new broadband services, for example, enterprises have more flexibility to afford satellite services than residential customers, yet most of them are concentrated in urban areas, where DSL and cable solutions are usually available. As a result, satellite operators will need to offer strong value propositions in order to convince firms to use satellite as its complete solution for connectivity.[47]

B) To reduce customer premises equipment (CPE) and monthly services costs.[48] Residential broadband satellite services represent a significant opportunity for potential growth for satellite operators, especially in Tier 2 and smaller cities where terrestrial solutions are not yet available. Nevertheless, the lack of other alternatives will not drive end-users to adhere to satellite services if the price is not competitive. Consumers in this sector are price-sensitive, and with CPE costing around US$300 (as of July 2004)[49], the development of this market is not likely to happen soon if satellite operators cannot find a way to lower the initial cost, especially in urban regions where the income distribution dynamics have a stronger impact on customer decision (such as Latin America or Asia-Pacific). Until broadband satellite services become more affordable, their market will be restrained to less cost-sensitive users such as SOHO.

C) Within the broadband Internet access market, one of the challenges is **to develop a technological solution for the lack of a return path (one-way versus two-way satellite services).**[50] Even though one-way satellite services have some advantages (such as the fact that the one-way service is considerably much cheaper to deploy than two-way services, and that it covers most of the residential customer needs), it leaves customers with larger connectivity needs dependent on a dial-up connection and an ISP account for uplink traffic (which is costly and problematic). This is a serious disadvantage for customers that require more downstream transmission capacity than the average residential user.

D) Finally, another downside in urban areas is **the lack of clear DTH reception because a clear view of the southern sky (or of the northern sky in the South Hemisphere) is not available** (for instance, if a tree, a building or any other object blocks the line of sight between the mini-dish and the satellite). Although this problem currently occurs only in a small percentage of the cases, it might condemn the broadband satellite services to remain a niche market with the necessity to differentiate itself from other existing access solutions, by focusing on its unique attributes (such as video content delivery and multicasting services).[51]

In order to respond to these challenges, satellite operators have a number of alternatives. Some examples of strategies that they could implement, or new services they could deploy, are recommended below:

1. DSL and cable will certainly help increase the penetration of broadband access into businesses and consumers of Tier 1 cities. Satellite operators have therefore an opportunity to increase their penetration outside those Tier 1 cities for **last-mile solutions, where terrestrial alternatives are not yet available**. On the other hand, the DSL/cable phenomenon within Tier 1 cities will also help drive traffic onto satellite and backhauling/backbone services. Tier 2 cities represent an opportunity for potential growth as the overall communications market grows.[52] This market, however, represents short-term opportunities in developing economies that are pushing for a large-scale deployment of terrestrial networks. On the other hand, it is also likely that this window reopen in the future, as demand outpaces terrestrial broadband availability in emerging economies.[53] An example of a broadband satellite service provider is WildBlue, a Colorado-based company that is planning to deliver two-way satellite broadband access to residential and SOHO markets, both in urban areas out of the reach of terrestrial solutions and in rural areas. They plan to start operations in the second quarter of 2005[54], serving what they believe is a large underserved market where wired broadband access is not available. Low-price CPE and installation costs are critical for the success of the venture.[55] Finally, satellite solutions are highly appealing to SMB and SOHO because DSL is often subject to possible degradations in speed depending on the distance to the CO and, although the cost of satellite services is slightly higher, satellite solutions offer SMBs and SOHOs the guaranty of quality and constant speed.[56] Satellite operators should therefore target markets outside of Tier 1 cities, i. e. rural areas (with little or no terrestrial infrastructure) and urban areas out of the reach of terrestrial solutions.

2. Satellite operators have the opportunity to **situate themselves as a complementary alternative to terrestrial networks**. By offering cost-effective bandwidth in smaller cities (Tier 2 cities and smaller urban areas) and providing end-to-end solutions, they can enlarge the range of their services and offer added value solutions. Some operators have already implemented this strategy, one example is PanAmSat. This company purchased transatlantic fiber that will be integrated with its satellite network to provide video and data services.[57] Offering this type of end-to-end services will probably bring the satellite operators to direct competition with several of their customers that lease transponder capacity. As a result, a new satellite service provider business model should be emerging soon: operators need to choose where they want to add value across the value chain and

identify new opportunities and partnerships that prevent them from being relegated to a "transport provider" commoditized role.[58] Partnerships with system integrators, telecommunications companies and other customers are likely to be necessary in order to build complete solutions that will satisfy customers' needs. Satellite operators need to become a *solutions* provider instead of a *services* provider, i.e. they need to be a service and network integrator.

3. **Wi-Fi (wireless fidelity)**[59] technology might represent a unique business opportunity for satellite operators. To date, a lack of affordability (since the satellite's upfront installation cost is considerable higher than those of terrestrial technologies) has prevented the satellite solution to become the third main technology in the broadband access market (the first two being DSL and cable). Satellite service providers must therefore find ways to offer affordable prices for their customer premises equipment (CPE). Using a mixed Wi-Fi–satellite service could be a successful choice. This solution involves the use of broadband satellite access for the backhaul, and Wi-Fi technology for local connectivity. A VSAT terminal receives the satellite link and connects it to a Wi-Fi access point. A wireless LAN can then be implemented and connect multiple users to the Internet.[60] An immediate application of this solution can be found in the market of wireless access points (or *hot spots*). Common places for these hot spots include airports, restaurants, hotels, and stores. Hughes Network Systems (HNS) is an example of the implementation of this strategy. HNS launched DIRECWAY Wi-Fi Access, a solution that provides customers with Internet access across North America.[61] This type of solutions represents an option for SMB (such as retailers and the leisure travel sector) to generate a new revenue stream. The most likely candidates to benefit from this technology will be companies that already use VSAT terminals, so that they don't incur in high up-front CPE costs.

4. In order to **lower costs**, the recent developments in Ku-band technology and the launch in 2004 and 2005 of satellites with transponders operating in Ka-band frequencies should allow satellite operators to provide their customers with more reliable and cheaper access.[62] Nevertheless, the problem of high upfront CPE costs is likely to restraint the development of the broadband services market to residential users. WildBlue expects to drive down their CPE costs to below US$400.[63] This will be a key element for the

success of their business model and for the deployment of the broadband satellite access market, and the market response to this cost is uncertain.

5. Finally, satellite operators could develop a **wholesale strategy through partnerships with telcos or cable operators** to increase their services' reach and reputation.[64] In markets where satellite services are not yet provided, a wholesale strategy would allow operators to complement their retail markets. The rationale behind this strategy is that it should be easier to sell an unknown satellite service through firms that are already established and have customers' loyalty, such as telecommunications companies or cable operators.

The goal of this section was to discuss the most important issues faced by satellite services providers in urban areas. The next section introduces the reader to issues related to the deployment of satellite services in rural regions.

3.3. Opportunities for rural connectivity (e.g., Aramiska and Twister project in Europe)

This section provides an overview of the current business opportunities that satellite operators have in the rural telecommunications market. Two examples of current undergoing projects that promote rural connectivity, namely the TWISTER project, and Aramiska, are also discussed herein.

As stated in the previous section, the expansion of optical fiber in the backbone infrastructure and last-mile solutions such as DSL have accelerated the development of the telecommunications industry in developed regions. As a result, fewer business opportunities are available for satellite operators in urban areas. However, a young telecommunications market in rural areas is creating new potential business prospects. These opportunities include broadband services and voice applications. The voice market in developing regions, such as Latin America and Asia-Pacific, includes fixed telephony services (both satellite mainlines and satellite phone booth), as well as other rural networking facilities that are unlikely to be served by terrestrial alternatives due to the high costs of deploying terrestrial network infrastructure from scratch. These are mostly consumer markets, and some forecast studies suggest a small but steady growth rate within the next ten years.[65]

The other satellite application that is considered to have a significant growth potential in the rural market within the near future is the provision of broadband satellite services. Broadband Services Providers (BSP)[66] see the satellite alternative as a cost-effective solution to provide consumers out of the reach of terrestrial networks with a comparable service to DSL and cable. The biggest obstacle to fully deploy satellite broadband services has been the high cost of implementing bi-directional access (i.e. two-way data transmissions). However, the great coverage provided by satellite communications allows a quick deployment of broadband access to customers out of the reach of terrestrial solutions.[67] All in all, satellite operators have a potential market in this sector, and some of them (such as Astra and Eutelsat in Europe)[68] have already started to expand their broadband service offering in rural areas, that have high demand for advanced services. The most important submarkets are consumers, SMB, and enterprises with remote locations dispersed over vast geographic areas.[69] In the United Sates, WildBlue Communications (supported by the National Rural Telecommunications Cooperative) is planning to provide two-way satellite broadband access in rural areas across North America, by using a high-powered spot beam technology and standards-based end-user terminals that employ the Data-Over-Cable Service Interface Specification (DOCSIS) technology in order to reduce CPE costs.[70]

Another recent hybrid technology that offers satellite service providers a distinctive market opportunity is the use of Wi-Fi and satellite to provide broadband access to the Internet in small rural communities, where terrestrial broadband solutions are not easily available. The rural area receives the satellite signal at a VSAT terminal located within the community, from where residents and small business can receive the data through a wireless access point. This solution significantly lowers the cost of a satellite-only alternative, since wireless adaptors are considerably less expensive than satellite receivers.[71] As a result several customers share the cost of the satellite service.

In general, rural connectivity by satellite represents a good opportunity for satellite operators around the world. Every geographical region has vast areas out of the reach of terrestrial networks, either because of the topology of the area, or because of the high implementation costs.[72]

In Europe, the broadband services industry is still evolving. The market is fragmented and European Union's member and non-member countries face regulatory problems. Nevertheless, approximately 15 million households are out of the reach of DSL/cable,[73] making the broadband industry a market with great potential for satellite operators. Service providers have the greatest potential in rural and peripheral areas. The European Commission (EC) launched the *eEurope 2005 Action Plan*, which aims to bring broadband connectivity at competitive prices to rural communities, in order to stimulate information availability and economic revival.[74] Broadband access is considered to be a key factor for the deployment of modern public services such as e-government, e-health, and e-learning.

The EC has strongly supported broadband access through alternative technologies. It is currently subsidizing the TWISTER (Terrestrial Wireless Infrastructure Integrated with Satellite Telecommunication for E-Rural) project. Launched in February 2004, this venture will provide broadband services through satellite and Wi-Fi technology to approximately 100 rural areas across Europe (Spain, France, Sweden, Poland, Greece, Malta) over a period of three years.[75] The project consists in providing free broadband access for 18 months, and then charging the access at rates similar to those of DSL services.[76] The objectives of the European Commission are to reduce the digital gap between urban and rural areas, to increase the numbers of broadband subscribers, and to force costs down.[77] The project is led by EADS Astrium, and is partially funded under the Aeronautics and Space priority of the EU's Sixth Research Framework Programme (FP6). From a total budget of €8.5 million, €5 million will be provided by the EC.[78] The TWISTER consortium involves several stakeholders of the telecommunications value chain, including satellite operators, satellite and wireless equipment manufacturers, universities, and research organizations.

Aramiska is a satellite service provider that started offering broadband access solutions in Europe in 2003. It offers high-speed Internet access, mainly to businesses, using a two-way satellite technology.[79] This type of solution provides customers with cost-effective, high-speed and "always-on" connections. Aramiska is one of the satellite service providers that are leading the broadband satellite access industry, positioning the satellite solution as an alternative to terrestrial providers. Furthermore, Aramiska's strategy follows a new business model that focus on delivering customized global solutions for the customer's specific needs. Aramiska's main customers today are local rural businesses and large multi-site enterprises with locations spread across Europe.

3.4. Trans-oceanic satellite traffic and underwater cable

This section discusses the key issues associated with trans-oceanic communications. A comparative analysis of the two technologies, namely satellite and underwater cable, is presented here, followed and supported by some figures about the current trends in capacity and usage of trans-oceanic satellite networks.

Before the deployment of underwater optical fiber cable, point-to-point trunking service applications were the main source of revenue for satellite services providers within the international satellite business (mostly trans-oceanic). Since the advent and installation of the higher-capacity cable infrastructure, there has been a recurrent debate and discussion about whether the two types of solutions are competing or complementary technologies, and to what extent satellite can compete against underwater cable.

Trans-oceanic satellite and cable traffic demand have similarities and differences. Both markets often experience similar trends. For instance, in the early 2000s, there was a shift towards private line and data traffic from voice traffic carried on the trans-Atlantic networks.[80] Later, satellite started conveying a substantial part of the trans-Atlantic Internet traffic, offering other data transmission services as well. A difference between both technologies is the fact that around 20% of the trans-oceanic satellite transponder capacity is used to transmit video and other miscellaneous services (such as occasional video),[81] whereas video represents an insignificant percentage in underwater cable traffic. This trend, however, is changing as telcos are seeking to use underwater optical fiber cables to transmit video contents on specific routes.

An important advantage of underwater cable over satellite networks is the capacity. It is evident that trans-oceanic cable networks have a much greater capacity. In 1997, for instance, trans-Atlantic satellite capacity represented about 2% of cable capacity.[82] Nevertheless, it is difficult to estimate the exact available bandwidth that some underwater cable systems provide. The reason is that, often, it is not clear how much capacity is reserved to handle emergency reconfigurations and how much is actually available for regular service.[83]

In any case, nowadays it is rather clear that in the long-term satellites will hardly be a substitute or a competitor to trans-oceanic underwater cable, because it would be extremely difficult to match or exceed the capacity of optical fiber cables that telcos and cable operators have been deploying since the 1990s. The U.S. Federal Communications Commission (FCC) stated, in a report of the trans-oceanic communications market in the late 1990s, that satellite systems do "not appear to be an adequate substitute for submarine capacity".[84]

There are, however, some engineering challenges faced by underwater cable operators that might allow satellite systems to remain in this market (the trans-oceanic communications) as a complementary alternative to fiber cable. The shape and behavior of the deep ocean bed is for the most part unknown. Some studies suggest that there is more known about the surface of the moon than about the ocean floor.[85] The layout of underwater cable is therefore technically challenging, and its operation involves important risks of disruption. Some of the physical obstacles that submarine cables have to avoid are hundreds of volcanoes and seismic activity beneath the sea floor. Another important source of incidents with underwater cables come from artificial elements such as anchors or fishing nets. Cable damages such as compression, dragging or breakage are not rare. A preventive solution involves using armors or shield and burying the cables to protect them from anchors that can penetrate the sea floor by several meters.[86] Satellite operators may therefore get some benefit from the trans-oceanic communications market by providing a backup solution, should disruptions in the underwater network occur. In the near future, however, this role as backup to cable might be threatened, since modern underwater cable systems are intended to be "self-restoring".[87] New systems are designed as long loops, linking pairs of continental stations. In other words, under this design, two points on one side of the ocean (separated some hundreds of km) are connected to two similar points on the other side of the ocean. The signals are usually transmitted through the primary cable, and they are switched to the secondary path (within milliseconds) if there is any disruption on the main line. The cables are usually laid out several hundreds of kilometers apart. This reduces considerably the probability of having both cables affected by one potential incident, and improves the overall availability of the system (the cable "ring"), making the system "self-healing" or "self-restoring".[88]

Yet, there is still another advantage of satellite systems over underwater networks that is allowing satellite service providers to keep a share of the trans-oceanic communications market, and it is the ease of reconfiguration. Cable traffic is concentrated at landing sites on both sides of the ocean, while satellite traffic can be easily redirected to any spots within the coverage area of the satellite. In other words, once the underwater cable is installed between two landing stations, the traffic going through it cannot go anywhere else, whereas satellite solutions can be adapted to different needs, such as a shift in traffic between the U.S. and Western Europe, to Eastern Europe, or the Middle East or Africa.[89] In addition to this, underwater cable operators also realize that satellite solutions have an unambiguous competitive advantage for point-to-multipoint broadcast and low-volume transmissions.[90]

In the 1990s, as a result of a steady demand for transmission capacity of video content, together with forecasts of unconstrained growth in Internet traffic, several satellite operators launched satellites to mid-ocean slots. The excessive forecast of growth in Internet traffic and the parallel deployment of trans-oceanic optical fiber cables shifted most of the trans-oceanic point-to-point traffic away from satellite systems. The trans-oceanic communications business became a niche market for satellite operators: as of early 2004 it represented only 8% of the total satellite demand.[91] The market is largely served by 39 satellites in slots over the Pacific and the Atlantic. As of early 2004, these satellites were experiencing an average utilization rate of 58%, and 60% of the utilized capacity was serving regional continental markets rather than the trans-oceanic routes.[92] Figure 3.5 shows the usage of trans-oceanic satellite capacity in 2003, by service application.

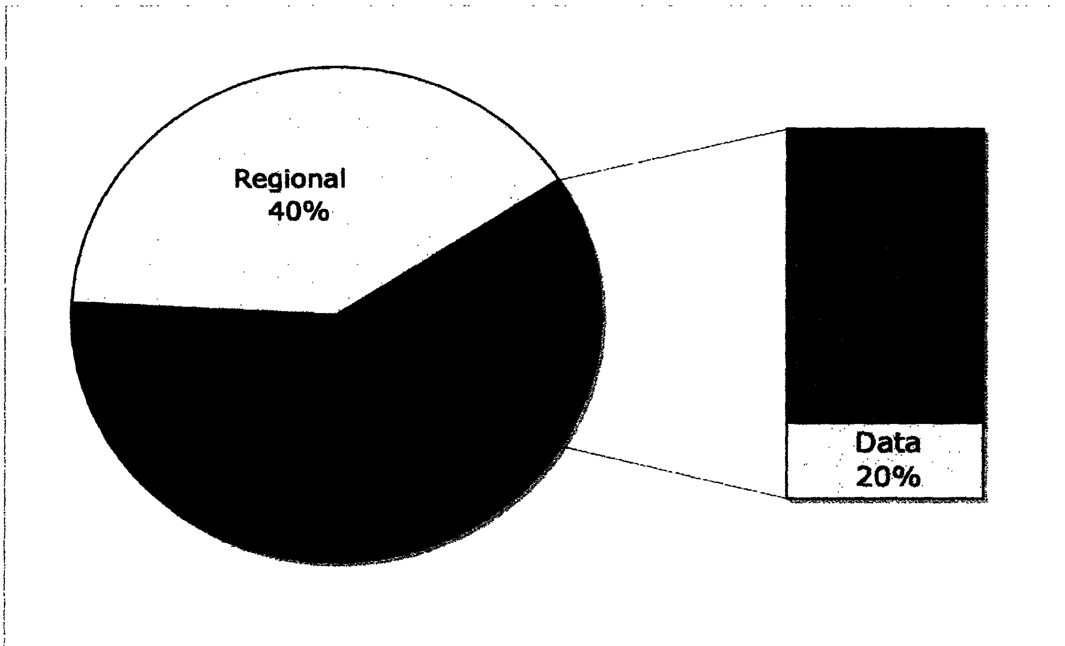

Figure 3.5: Usage of Trans-oceanic satellite capacity in 2003[93]
(Data Source: Futron Corporation)

3.5. WiMAX, a disruptive‡ technology? [94]

This section provides a brief description of WiMAX, an emerging broadband technology that might play a key role in the telecommunications industry within the next few years (timeframe 2005-2007).

extensive

Consumers and telecommunication service providers are encountering an increasing number of broadband access technology options. After some telcos (such as AT&T and MCI) ruled out the fixed-wireless strategies several years ago, the development of wireless technologies slowed down. Yet, vendors kept on developing a new generation of wireless solutions to eliminate key technological problems such as issues related to line-of-sight, and to expensive upfront installations (cost of CPE).[95]

WiMAX, short for Worldwide Interoperability for Microwave Access, is a wireless technology based on the standard 802.16d of the Institute of Electrical and Electronics Engineers (IEEE 802.16d). This essentially means that WiMAX technology is compatible with the WiFi technology. WiMax provides "high-throughput broadband connections over long distances",[96] and has the potential to be used as a "last-mile" solution to deliver high-speed connectivity to enterprises and the residential market. This new technology will offer metropolitan area network (MAN) broadband access at speeds up to 75 Mb per second, and it can be used to transmit data to locations up to 30 miles away (although under the current deployment plans by Intel and the WiMAX Forum, a WiMAX base-station will cover an average of three to five miles). [97]

Currently, last-mile connections are provided by cable, DSL and satellite networks. The two main problems with these existing broadband technologies are cost (high cost of deployment or high cost of CPE) and coverage (locations out of the reach of terrestrial networks). On the other hand, the essential issue that has prevented the WiFi technology to develop as a solution to broadband connectivity is that access spots cover only small areas (rooms or buildings). WiMAX is a technology that would provide high-speed broadband access, wireless access (therefore with significant lower deployment costs than DSL or cable), and broad coverage (similar to a cell

‡ A disruptive technology is a new technological innovation, product or service that eventually overturns the existing dominant technology in the market. A disruptive technology comes to dominate an existing market by either filling a role in a new market that the older technology could not fill or by successively moving up-market through performance improvements until finally displacing the market incumbent. The term was defined by Clayton M. Christensen in 1997. The reader is referred to Ref. 94 for a more extensive definition of the concept.

phone network).[98] As a result, it represents both an opportunity (to the customers) to reduce the cost of providing these services and a threat to the competitor technologies (satellite solutions included).

Intel Corporation is driving the development of WiMAX networks. The deployment is planned in three phases: the first one (by June 2005) will deliver "fixed wireless connections via outdoor antennas".[99] This type of access is likely to be used for high-throughput enterprise connectivity (similar to T1 services), backhaul and cellular networks (and probably also for premium residential services). By the second half of 2005, indoor installations will be deployed by using smaller antennas similar to current Wi-Fi access points. Within this model, since the technology will be "user installable), WiMAX is likely to be offered to large consumer residential markets, and is expected to lower installation costs for carriers. Finally, by 2006, Intel is planning on integrating WiMAX solutions into portable devices "to support roaming between WiMAX service areas".[100] This technology should prove useful and attractive in particular to emerging markets, where terrestrial networks are poorly or not deployed. High-speed Internet access to customers with currently no access (or even with little access to wired phones) might be a reality at lower or similar costs to those of DSL, cable and satellite broadband access. Regions such as India, Mexico, and China, should find WiMAX particularly attractive, since the cost of deploying wire networks around the countries would make broadband connectivity too expensive.[101]

At the time this thesis is being written, there is no clear outlook or forecast of the impact that the development of WiMAX will have in the telecommunications market. Nonetheless, it is clear that in order to remain competitive, broadband access operators (satellite service providers included) will have to offer complete solutions and not only to provide a telecommunication service. Strategic partnerships in order to offer a mix of broadband access technologies (such as DSL, cable, Satellite, WiMAX, and WiFi) that allows operators to provide bundled voice, video and data transmission services will be fundamental.[102]

3.6. Summary and Conclusions

The central question of the first part of this thesis was exposed in this chapter: Are satellite communications competing or complementary technologies to terrestrial networks –in what context and for what service applications? The chapter started with what is one of the conceptual contributions of this thesis: the definition of a framework designed to develop a comparative analysis between satellite and terrestrial telecommunication services. This framework is structured around three axes: type of solution, service application, and geographic market. The type of solution refers to satellite versus terrestrial networks. The service application perspective divides the satellite communications market in two categories: transmission of voice and data, or transmission of video contents. The third axis is about comparing both solutions (satellite and terrestrial) in three major geographic markets: urban areas in developed markets, urban areas in emerging regions, and rural areas in general. Then, Chapter 3 presented an overview of the major terrestrial competitor technologies to satellite solutions, namely Fiber Cable and DSL networks. The most important advantages of satellite technologies over terrestrial networks were investigated: coverage, multiple access, distribution and flexibility. Afterwards, the chapter continued with a thorough discussion of the tradeoffs associated with the use of satellites or terrestrial solutions to deliver a specific service application (transmission of voice and date, or video) in different geographic markets (urban-developed, urban-emerging, and rural in general). Challenges and opportunities in urban and rural areas were also explored. Specific examples (i.e. projects such as WildBlue, TWISTER, Aramiska) of rural opportunities for connectivity were provided and discussed.

In conclusion, the case was made that in general, a) satellite solutions have important competitive advantages for the transmission of data (and or voice) in rural areas as well as in urban regions in emerging markets, where terrestrial networks have not been deployed and the option of deploying these networks today makes terrestrial solutions less financially and technically attractive than space-based solutions; b) in the market of video transmission, the DTH applications represent the most dynamic market, in both urban and rural areas in developed and emerging countries, and it also has the most potential growth for satellite operators. Other video service applications such as contribution (video contents exchange between broadcasters) and feed of cable TV head-ends should prove to be a steady market for satellite service providers. On the other hand, the author of this thesis believes that satellite operators might find it valuable to forge partnerships with some of their market competitors (i.e., DSL and cable providers), in order to exploit the dual character (competing/complementary) of the telecommunication networks. Lastly, Chapter 3 closed with an overview and outlook for a new technology, the Worldwide Interoperability for Microwave Access (WiMAX), which might considerably impact the satellite services industry in the near future, although at the time this thesis is being written, the WiMAX technology is too early in its commercial development stage in order to assess the consequences it might have on satellite operators.

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Chapter 4

The Regulatory Environment for Satellite Operators and the Policy-making process for Space-based Communications

At the beginning of the space era, the role of space-based communications was to provide a means to connect people located in distant fixed points on Earth. Since then, satellite communications have evolved to a situation where they play a central role in promoting and developing different types of human activities (such as entertainment, business, and education) across the globe.[1] Issues related to communications satellites have therefore transcended national and regional boundaries. Currently, the dynamics of international communications are shaped by several factors and by the interests of different stakeholders (that are not necessarily always aligned). In the last two decades, the main stakeholders of the FSS industry, namely the satellite operators, have gone from being publicly-owned regulated monopolies to competitive international corporations. The main sources of influence and market power in the satellite communications industry have therefore shifted from publicly-controlled companies, to multinational firms who have experienced a period of deregulation in the last few years.[2] At the time this thesis is being written, however, the industry shows traits of a new period of regulation and control by privately-owned companies. These firms, with significant influence on the behavior of the market, are playing an increasingly decisive role when it comes to the negotiation of international regulatory treaties.[3] As a result, the legal context of space communications has gradually become a more complex set of international and regional agreements, worldwide and national regulations, and intricate relationships between private corporations, regulatory bodies, governments, and international organizations.[4] This chapter provides an overview of the regulatory environment for satellite service providers. It also delineates what, in the opinion of the author, might be the shape of the space communications policy in the near future. A detailed analysis of the legal context mentioned above is out of the scope of this thesis. The reader is referred to Ref. 5 [Stalin, 2000] for a comprehensive discussion of the complexity of satellite communications regulations.

The first section of this chapter provides an historical background on international regulatory bodies, followed by an overview of what the author considers to be two of the most important regulatory issues, namely, frequency/orbit allocation and space environmental pollution. The second section of the chapter is devoted to the description of the space policies implemented by the United States and the European Union in order to promote and develop satellite communications.

4.1. Satellite communications regulations

This section is devoted to the description of some key issues within the regulatory context of the satellite services industry. The first subsection provides the reader with a historical perspective on the origins of international regulatory bodies. The subsequent subsections introduce what the author considers to be two of the most important issues in satellite communication regulations: subsection 4.2 discusses the spectrum/orbit allocation and the orbital spacing policy implemented by the Federal Communications Commission (FCC) in the United States. Subsection 4.3 focuses on matters related to space environment pollution, i.e., the disposal of spatial debris.

4.1.1. The need for regulation

The origins of space-based communications regulations can be traced back to the 1960s. The first space treaty was developed after the first U.S.S.R. and United States satellites were launched.[6] Space activities were still a duopoly formed by these two countries. In fact, satellite communications were born as a product of a deterrent strategy implemented during the Cold War.[7] Space-based communications laws are therefore international in nature, where governments and sovereign states are the law-makers. Since international telecommunications were seen as an extension of national telecommunications, the publicly-controlled monopolies (e.g., COMCAST) that represented national interests in a international satellite organization (e.g., INTELSAT) had control over the regulatory framework of satellite communications.[8]

The International Telecommunications Union (ITU) is the largest international regulatory body for telecommunication issues. It started as the International Telegraph Union in 1865 with 20 founding members.[9] At that time, its mission was to define standards to facilitate international interconnection through telegraph networks. The first regulations of wireless telegraphy were issued in 1906 during the first International Radiotelegraph Conference in Berlin.[10] These regulations evolved and expanded their scope throughout the years. Today, they are known as Radio Regulations and, together with other international conventions, they establish recommendations and standards for the use of radio frequencies and satellite orbits. The ITU took its current name in 1932, when the International Telegraph Union decided to combine the International Telegraph Convention of 1865 and the International Radiotelegraph Convention of 1906 to form the International Telecommunication Convention. The scope of the responsibilities of the ITU was expanded and by that time it covered "all forms of wireline and wireless communication".[11] The first international regulations concerning satellite communications were issued in 1963. They were the product of the ITU Extraordinary Administrative Radio Conference, and they allocated frequencies to the different space-based communication services.[12] These conventions and regulations are the result of different interests, complex relationships among the countries members, technical constraints, and national legal restrictions. The role of the ITU is often considered to be that of a regulator, but it is in fact more the role of a coordinator.[13] The two basic conventions related to activities in the Outer Space are the Liability and the Registration conventions. They state that a) the country members have full responsibility of the activities carried by any of their national institutions that are also members of the ITU, and b) the country member itself has to conduct a registration procedure in order to place a satellite in a geo-stationary orbit. In addition to the ITU regulations, any organization that wishes to provide satellite services or to establish a satellite network has to comply with the current regulations of its home country in order to launch, implement and operate any system or network.[14] It is important to note that after the last trend of "de-regulation" (started in the U.S. in 1972 with the "Open Skies" decision, but really implemented since the 1980s)[15], a large number of the regulations and restrictions to the operation of satellite systems has been eased or eliminated in many countries (at least from a legal perspective, although from a market perspective, the satellite services industry is one with relatively high barriers to entry). The second section of this chapter provides a more detailed analysis of the telecommunication policies implemented in the United States and Europe. In the next subsection, the reader will find a discussion of one of the fundamental issues in satellite communication regulations: frequency and orbital allocation.

4.1.2. Spectrum and orbit allocation

In Chapter 1 the author defined three main types of commercial satellite communication services were defined, namely Fixed Satellite Services (FSS), Direct Broadcast Services (DBS), and Mobile Satellite Services (MSS). From a technical perspective, however, the ITU Radio Regulations define 38 different types of radio communication services. Satellite networks can provide 17 of these 38 types defined by the ITU.[16] In order to provide these services, satellite operators use frequency spectra allocated by the ITU Radio Regulations. The allocation of these frequencies usually takes place during the World Radio Conferences (WRC), and is done on a world and regional basis.[17] Satellite services require two frequencies, one for "uplink" communications and another one for "downlink" communications. New services that are intended to deliver high-speed data require a wider bandwidth than traditional services. The allocation of the frequency spectrum for satellite communication services started in 6/4 GHz or C-band, with an allocation of 500 MHz that was also used by terrestrial microwave links.[18] As more transmission capacity was demanded, the GEO orbit slots were filled up with satellites operating at C-band, and satellites were then built to operate in the next available frequency, 14/12-11 GHz or Ku-band.[19] In the early 2000s, there was an increasing demand for a wider bandwidth in order to provide new high-speed services (e.g., broadband access to the Internet). This has resulted in the use of the Ka-band (30/20GHz) and higher frequencies, although these bands are subject to high meteorological attenuation of the signal and other elements of interference (above 20 GHz of frequency, attenuation caused by thunderstorms can be strong enough to make the link fail)[20]. Throughout different World Radio Conferences (WRC), the allocation of different frequencies has included bands L, S, C, Ku, K, Ka, V, and Q bands. FSS and DBS services provided by GEO satellites use frequencies that range from 3.2 to 50 GHz, while Mobile Satellite Services use frequencies ranging from 0.137 to 2.5 GHz, or L- and S-bands.[21] Table 4.1 shows the allocation of frequencies for FSS and DBS (also called BSS).

Table 4.1: Frequency allocations for FSS and DBS (also called BSS). DataSource: ITU[22]

Radiocommunications service	Typical frequency bands for uplink/downlink	Usual terminology	Mainly used by:
Fixed Satellite Services (FSS)	6 / 4 Ghz	C band	Fixed service terrestrial microwave
	8 / 7 Ghz	X band	Military communication / Digital Radio feeder links
	14 / 12-11 GHz	Ku band	Fixed service terrestrial microwave
	30 / 20 GHz	Ka band	Local multichannel distribution service (LMDS)
Broadcasting Satellite Services (FSS)	2 / 2.2 GHz	S band	Digital Radio / NASA and deep space research
	12 GHz *	Ku band	Direct-to-User transmissions

* The BSS use a frequency of about 12 GHz for downlinks. The uplinks transmissions are carried by the FSS (feeder links).

In 1993, the ITU created the Radiotelecommunication Sector (ITU-R Sector). The objective of the ITU-R Sector is to "ensure rational, equitable, efficient and economical use of the radio-frequency spectrum and satellite orbits".[23] The Radiocommunication Bureau (BR) coordinates and manages the work of the ITU-R Sector. The BR is also in charge of registering frequency assignments and orbital parameters of space-based communication services. It also maintains the Master International Frequency Register (MIFR). In order to promote the efficient use of the spectrum, many frequencies are allocated to more than one service. These frequency bands are therefore "shared" by several services. Typical examples of services sharing frequencies are the FSS and the fixed service (FS) or radio-relay links.[24] This sharing is possible because the GEO orbit arch is far above the "local horizon", and since the FS links travel at that level, the problem of interference can be easily managed. During the WRC in 1997, the Radio Regulations (RR) were revised in order to establish "procedures and limits to prevent harmful interference form affecting the proper operation services sharing the same frequency bands or networks of a certain service operating in the same frequency bands".[25] In addition to the frequency allocation, one of the key regulatory issues in satellite communications is the effective use of the spectrum in order to avoid interference in the transmission of signals. There are different types of interference and different measures have to be taken to avoid them. The most common types of interference are: a) between different networks (providing the same service) operating in the same band, b) when a band is shared by more than one service, interference between the Earth or space stations of different services.

The radio-frequency spectrum and the GEO orbit are limited resources and it is necessary to ensure an efficient and economical use of them. They are considered to be a natural resource and, as stated above, they are regulated by a complex set of international and multilateral agreements and conventions adopted during international conferences organized by the ITU.[26] The spectrum/orbit are two inherent characteristics to the satellite communication services and, today, they are considered as part of a common humankind heritage. The RR Resolution 2 introduces principles stating the "equitable use, by all countries, with equal rights, of the GSO and of frequency bands for space Radiocommunication services".[27] According to these principles, all countries should have equal rights in the use of both resources (frequency and orbit). A constant source of international negotiations and disputes however is the acquisition or allocation of orbital slots (the position in the GEO orbit arc where the commercial satellites orbit around the Earth). Most orbital slots are "available" on a "first come, first served" rule.[28] A country only has to file a "notice of intention" to the ITU in order to launch a satellite to a specific orbital position. Priority is therefore given on the so-called "first come, first served" basis. However, this should not translate into a nation having the exclusive right to use a specific slot. To a certain extent, "priority" means that any satellite to be launched to the same slot (or a near one) in the future has to be operated in a way that it does not cause interference to the transmissions of the previous satellite, but it should not prevent the use of the same slot to any other country.

Demand for voice, data, and video transmission capacity was steadily increasing in the United States domestic satellite communications market in the 1980s.[29] Additional domestic satellites were needed in order to meet the demand, but the orbital slots available were limited. In order to promote a more efficient use of the GEO orbit, the FCC in the United States implemented an "orbital spacing" policy in 1983. Prior to this date, domestic satellites launched to a GEO orbital slot needed to comply with a minimum separation of 4 degrees at 6/4 GHz and 3 degrees at 12/14 GHz. Such orbital separations were large enough to guarantee no interference between different services or networks operating in the same range of frequencies. The FCC reduced the orbital separations to 2 degrees in both bands and implemented technical constraints and regulations in order to guarantee that there would be no interference in satellite transmissions.[30] These resulted in an increase in transmission capacity that allowed satellite operators to meet the growing domestic demand at that time. In recent years, as demand continued to grow, it has been proposed to further reduce this separation. However, analysts of the industry think that this separation would create interference problems hard to solve with the existing transmission and reception technology. This, together with the dynamic allocation of the frequency spectrum, is one of the central issues in the satellite communications regulatory environment nowadays. Another important issue that needs to be regulated is the space environment pollution. The next subsection provides an overview of the current state of regulations in that matter.

4.1.3. Orbital Debris

This subsection briefly discusses the existing legal framework related to the disposal of space debris, from both an international and a U.S. perspective.

A simple definition of orbital debris includes a) spacecraft that is no longer in operation, b) spent rocket parts, and c) materials released during space operations. Space debris are certainly scattered at different altitudes, but the majority of the debris are concentrated in altitudes where there is an intense space activity, i.e. between the 800-1000 km of LEO and around the 36,000 of GEO. Over 30,000 artificial space bodies have been detected by ground radars,[31] and the consequences of a collision could be extremely serious (a debris of 10cm with a relative speed of 10km/sec., for instance, has "a destructive power greater than 1kg of TNT" [32]).

Several simulation models provide different results about the probability of an impact for any given object at LEO or GEO. They all agree, however, that if no regulation is implemented, by 2100 the number of collisions with an impact on any of the satellite networks that are currently operating in GEO could be up to 50, and it could be up to 15 even if all spatial launches were stopped after 2025.[33] Unlike satellites in LEO (which sooner or later fall back to Earth due to the atmospheric drag), GEO satellites do not naturally spiral back to Earth: they remain in the geostationary ring forever, cramming and endangering what must be considered as a precious piece of real state. However, the situation in GEO is far more delicate. A serious concern about GEO satellites is that, once they are abandoned up there, they don't stay in their allocated orbital slot. The "non-uniform nature of Earth's gravity creates two stable orbit points in the geostationary ring: one above India at longitude 75 degrees east and one over the Pacific at 105 degrees west".[34] Any abandoned object in the GEO ring will therefore float towards the nearest stable point and swing through (like a pendulum). A survey by the European Space Agency (ESA) in 2004, revealed that out of 34 satellites abandoned between 1997 and 2003, 22 are oscillating over India and 10 over the Pacific.[35] This situation not only increases significantly the risk of collision, but should a collision occur, it is likely that it will trigger a chain reaction. One collision could easily result in the destruction of all of the objects currently orbiting in half of the slots in the geostationary ring. Should two collisions occur, the entire GEO ring could be wiped out! In the words of an ESA executive, "if we don't make some dramatic changes in the [enforcement of space debris policy in the] geostationary ring now, [...] we will end up with a garbage ring like Saturn's".[36] This would obviously have devastating consequences not only for satellite operators but also for the future of the telecommunications on Earth.

Although several methods to control and reduce the density of debris around the LEO and GEO have been proposed, most of them are not possible to implement with today's technology. The only real solution is to legislate and regulate spacecraft disposal in a way such that operators have to propel them to orbits far from LEO and GEO. This, however, will certainly have a financial impact on satellite service providers. For instance, in order to propel a standard GEO satellite to an orbit where it cannot cause damage as debris, around 6 kg of fuel are needed. This represents something between two and three months of revenue-earning operation.[37] In 2003, out of 13 geostationary satellites that were put of operation, only 5 were propelled to safe "graveyard" orbits.[38]

Until recently, the FCC had not issued any regulation related to spatial debris. In June 2004 it established a regulation that forces all U.S.-licensed satellites launched after March 2002 to be propelled to a "graveyard" orbit between 200 and 300 kilometers above the GEO orbit.[39] This regulation set the path for other standards around the world, since no other nation with space activity, or international regulatory body, has regulated about spatial debris. Prior to that regulation, there were only "soft recommendations" about the disposal of unused spacecraft that were ignored most of the time. Both commercial and government satellites operators agree that if no action was taken to control de disposal of spatial debris, objects around the GEO "could ultimately shut down the space industry".[40] The new regulation established by the FCC is based on recommendations issued by the Inter-Agency Space Debris Coordinating Committee (IADC), an international organism that includes representatives from 11 of the world's most space-active countries.[41] Under the new rules, satellite operators are required to commit to propel their satellites to a safe orbit at the end of their lifetime in order to obtain a license to provide satellite services in the United States.

On the other hand, in the international arena, regulation about spatial debris has not yet been issued. Nevertheless, in an effort to control the damage that might be caused by spatial debris, the United Nations Committee on Peaceful Uses of Outer Space (UN-COPUOS) initiated a study about the issue. The committee has already finished its technical study. However, "its legal Sub-Committee is yet to formulate a Spatial Debris Treaty to be signed by all member states".[42]

4.2. Space communications policy

The regulatory environment, especially the allocation of spectrum and orbit, plays often a fundamental role in determining the success of any satellite-based venture. Satellite regulations, however, are only a means to implement a broader plan or course of action developed (most often by governments) to influence and shape the dynamics of the communications industry. The set of goals and actions specified in this type of plans constitutes what is known as a *space communications policy*. While the previous section provided an overview of regulatory issues associated with satellite operators, this section introduces the reader to some of the key policies associated with satellite communications. The first subsection presents a summary of the evolution of the space telecommunications policy in the United States, paying especial attention to the "Open Skies" policy. The second subsection is devoted to the description of the space policy implemented by the European Union in order to promote and develop satellite communications.

4.2.1. The "Open Skies" and the U.S. telecommunications policy.

The United States government started to develop a space communications policy in the 1960s. President John F. Kennedy delineated the general principles of U.S. policy "in regard to satellite communications and made the first unambiguous references to a single worldwide system"[43] Months later, the U.S. Congress suggested that the International Telecommunications Union revised the portion of satellite communications where international collaboration was going to be necessary. In 1962, the U.S. Congress passed the *Communications Satellite Act*, which lays the ground for a commercial investment in an international satellite organization. [44] Two years later, representatives of 12 countries signed an agreement to form an organization that would later become the International Telecommunications Satellite Organization (INTELSAT). A company was then created in the U.S. to represent national interests within Intelsat: Comsat. At that time, the Bell System was a monopoly in the long-distance telephone communications market within the United States. The Bell System was excluded from any direct participation in satellite communications.

In the United States, the Federal Communications Commission (FCC) is the government agency that has authority over the satellite communications market. However, the U.S. Congress and other organizations within the administration exert important influence in shaping the telecommunications policy of the country. The monopoly of AT&T, the only telecommunications operator in the U.S., started to be dismantled in the 1960s. The FCC was originally in favor of conserving the monopoly, but became later a strong supporter of open competition in the telecommunications industry.[45] In 1970, President Nixon asked the FCC to design a strategy to liberalize the satellite communications market. The FCC issued therefore the "Open Skies Decision" in 1972, opening to competition the market of communications by satellite. Since then, the industry has experienced a significant growth in the United States, especially in the radio and television broadcasting sectors (both FSS and DBS).[46] The first set of satellite regulations was developed by the FCC in the 1980s. These regulations concerned mostly the FSS using GEO satellites.

In regard to the FSS industry, one can identify two key impacts of deregulation on satellite operators. Firstly, the implementation of the Open Skies policy in 1972 naturally resulted in a consolidation of satellite manufacturers and satellite operators.[47] This consolidation was further promoted by the decision of the Federal Trade Commission, in 1995, of approving the merger of two of the largest satellite operators in the industry: Lockheed Corporation and Martin Marietta Corporation. In the opinion of some industry analysts, the FTC policy was helping "the aerospace industry to reconstitute itself".[48] Secondly, another set of satellite regulations were issued by the FCC in 1994 in order to promote "the creation of innovative new global broadband satellite services (Ka-band)".[49]

Another important piece of legislation related to the industry was the Telecommunications Act of 1996. As stated in its introduction, its goal was "to promote and reduce regulation in order to secure lower prices and higher quality services for American telecommunications consumers and encourage the rapid deployment of new telecommunications technologies".[50] Although this legislation has little impact on competition within the satellite services industry, it has two important implications for satellite communications. Firstly, it lays the ground to "equate" satellite operators to common carriers. In other words, it states that "the proposed space segment services are likely to be offered to the public indifferently, a basic characteristic of common carrier service".[51] In addition to this, it recognizes that "the imposition of common carrier requirements [to space segment operators] may have an adverse effect on the development of this service",[52] which gives satellite operators the possibility of having access to foreign funding (therefore foreign ownership). The possibility of foreign participation increased the probability of obtaining orbit resources (orbit slots) from foreign regulatory agencies. Secondly, the Act promotes measures to increase competition in the telecommunications market by promoting investment in new technologies, such as satellite services, to transmit high-speed voice, data and video. It also reaffirms the U.S. government commitment to help U.S. satellite operators having access to foreign markets.[53]

Effective January 1996, to continue with the deregulation trend, the FCC had also issued rules that allowed foreign telecommunications operators to enter the U.S. market. This was in order "to develop effective competition in the U.S.", "to prevent anticompetitive conduct in the provision of international services or facilities", and "to encourage foreign governments to open their telecommunications markets to US companies"[54]

The latest legislation issued to promote open competition in the satellite telecommunications industry was the ORBIT* Act, in March 2000. It amends the Communications Satellite Act of 1962 and paves the ground to ensure the privatization of satellite communications.[55] This Act had a deep impact in Comcast, and some industry analysts consider it to have extraterritorial implications for Intelsat. The Act's goal is to promote *"a fully competitive global market for satellite communication services for the benefit of consumers and providers of satellite services and equipment by fully privatizing the intergovernmental satellite organizations, Intelsat and Inmarsat"*.[56]

Currently, as a result of the deregulation of the industry started in 1972 with the "Open Skies" policy, the United States have probably one of the most flexible regulatory environments for satellite communications. The "Open Skies" policy was originally created to promote the

* The Open Market Reorganization for the Betterment of International Telecommunications Act.

development of the industry with minimal regulations. As previously stated, some examples of regulations and policies associated with this deregulation trend are the "orbital spacing policy" and the reduction in the time to process space station licenses. For most industry analysts, the high number of spacecrafts (especially Ka-band satellites) launched in recent years is an irrefutable proof of the effectiveness of these policies.[57]

Finally, it is important to evoke the current context of the U.S. space-based communications policy from an international perspective. Most analysts of the satellite services industry suggest that more international cooperation, especially in the licensing process of new telecommunication satellites (which includes orbit and frequency allocation), would result in a more beneficial relationship for both the U.S. and the rest of the world (especially Europe). With the last trends of complete deregulation and open competition promoted by the U.S. (in the opinion of some analysts,[58] driven mostly by the U.S. wish to ensure and support strategic positions in the space industry business), there is indeed a risk of trade war with Western Europe. As stated by the Outer Space Treaty of 1967, "advocating cooperation and a shared interest between all countries"[59] should result in a more sound and healthy satellite communications industry.

In the next subsection the reader will find an overview of recently implemented policies related to satellite communications in the European Union.

4.2.2. An expanding European Union

In regard to satellite communications regulations and policy, the European Union is an emerging system and, in that respect, Europe is the "young" continent when compared to the United States.[60] There is no European organization or institution serving as one common authority over space-based communications issues. In contrast with the United States, Europe is a mélange of different nations, histories, identities, cultures and languages, with different political interests, governments and regional or local markets.[61] As such, it represents vast market opportunities, but it also encloses significant organizational and administrative challenges. In addition to this, in Europe there are two types of stakeholders when it comes to shaping the space communications environment. Firstly, there are nations (Members States of the ITU), which are allotted space resources (spectrum and orbit slots in the GEO). Secondly, there are international and regional organizations that are also allotted their own space resources. These organizations are formed by representatives of the nation members of the ITU.[62] Furthermore, in order to fully understand the

European context, one has to be aware of the several regulatory and government bodies that have influence over space communications matters. The most important are, besides the national regulatory agencies, the European Commission, the European Council, the European Parliament, the European Space Agency, and other organizations with special authority over telecommunications issues, such as the European Radiocommunications Committee (ERC), the European Telecommunications Standard Institute (ETSI), the *Conférence Européenne des Postes et Télécommunications* (CEPT), or Eurocontrol. The necessity of a global European body with authority over telecommunication issues (a "*European FCC*") has been expressed by different industry and government leaders since the 1990s. Regulatory obstacles and different interests have prevented its creation, but work has been done towards the development of such organization at a European level.[63]

Until the late 1980s, little or nothing had been done about a legal structure for the development of satellite communication at a European level. The Member States had national authority and control over telecommunication issues. Four major documents laid the ground to develop a satellite communications policy in the European Community up to the 1990s: the 1987 Green Paper on Telecommunications, the 1990 Green Paper on Satellite Communications, the 1991 Guidelines on competition rules within telecommunication services, and the 1992 Maastricht Treaty.

The Green Paper on Telecommunications of 1987 ("*Green Paper on the Development of the Common Market for Telecommunications Services and Equipment*") encloses the intention of harmonizing the diverse set of national regulations within the European Community. It delineated an action plan to transform the regulatory environment in order to meet the dual challenge of a) the Common Market of 1992, and b) rapid technological developments".[64] This document delineates several action lines to promote the development of satellite communications. More specifically, it proposes the creation of the European Telecommunications Standards Institute (ETSI), the adoption of a "definition of a coherent position regarding the future development of satellite communications in the European Community", and a single "definition of telecommunication services and equipment with regard to relations with non-EC countries".[65]

Three years later, in 1990, the European Commission published a document called the "Green Paper on a common approach in the field of satellite communications in the European Community". Indeed, in the 1990s, Europe became more active in developing policies that focused directly on satellite communications matters. This paper specifically set the development of a common position on satellite communications as one of the primary objectives within the European telecommunications policy. Satellite communications in Europe are perceived as a key factor in achieving the European commercial success needed to develop a strategic position in the space industry. Therefore, the 1990 Green Paper became the foundation stone of the new space-based communications policy of the European Community. It introduced four main lines of action to promote the development of satellite communications: a) ensuring that satellite technologies are considered in the development of network and services, optimizing the potential complementary character of terrestrial and satellite solutions; b) fostering an adequate political and regulatory environment in order to develop new services and equipment, ensuring maximum utilization of space networks; c) promoting the implementation of satellite solutions when applying European-level public policies, especially in sectors like education and training; d) increase the level of research and development to support the growth of space-based applications.[66]

The *Guidelines on the Application of European Economic Community (EEC) Competition Rules in the Telecommunications Sector* were issued by the European Commission in 1991. These guidelines present directives about anticompetitive agreements that "could not be granted exemptions from EU competition rules and address specific issues such as distributorship agreements for satellite services, uplink services and joint venture agreements between TOs [telecommunication companies] and private parties".[67] Even though this document deals more with regulations than with policy issues, it does delineate a strategy created to promote competition within the telecommunications industry, specifically in the satellite service providers sector.

The *Maastricht Treaty on the European Union* was signed in February 1992, and it was developed in order to give a new "impetus" and a solid basis for the creation of a more integrated Europe. The spirit of the Treaty was not to supplant previous European agreements (such as the Rome Treaty). Instead, the main purpose of the Treaty was to "expand the reach of all pervious EC Treaties and Agreements by subtle alterations to the former provisions and by adding new provisions to their global aggregated content".[68] As a result, many provisions of the Treaty have indirect impact on space communications. Yet, among the new additions by the Maastricht Treaty, one that has a clearer and more direct impact on space-based communications is the Trans-European Networks (TEN) provision. The development of TENs focuses on transportation, telecommunications and energy issues. Title XII of the Treaty states that "trans-european telecommunication networks should play an important role in the move towards EU, especially when viewed as part of the internal market's infrastructure". The Treaty also expands the power of the European Community to support private investments in the industry. It recognizes that this expansion of the EC power "will have an impact on European space policy in matters of telecommunication infrastructure and particularly, communication satellites, with respect to several crucial aspects: interconnection, interoperability, access to networks and financial support".[69]

In 1995, the European Industry Council raised the need to define a *European Space Policy*, specially considering "whether it would be necessary to envisage a more autonomous EU policy for satellites", since until now, many European services use North American satellites, creating a certain dependency on the United States in a field that is "so important for the future of the information society".[70] As a result, the European Commission has issued several documents delineating a new European Space Policy. Two of the most important are the EU Action Plan on Satellite Communications (1997) and the White Paper "Space: a new frontier for an expanding Union. Action Plan for Implementing the European Space Policy" (2003). The former introduced an action plan in order to strengthen the "role of European services and manufacturing in global advanced broadband and multimedia satellite systems, services and applications [...] ".[71] It recognized the quick development of satellite services and underlined the necessity of a strong, coherent satellite communications industry in Europe.

The White Paper on Space Policy is the most recent document on European Space policy (2003), and it proposes the implementation of an "extended European Space Policy to support the achievement of the European Union's policy goals: [...] faster economic growth, job creation and industrial competitiveness, enlargement and cohesion, sustainable development and security and defense".[72] One of the policy changes that this document proposes is to "invest in the knowledge economy to strengthen economic growth job creation and competitiveness and make a success of enlargement by supporting cohesion and economic, industrial and technological growth throughout all Member States".[73] The paper proposes the use of satellite communications as part of a technology portfolio that might be used to bring broadband access to the 20% of the inhabitants in Europe that are out of the reach of terrestrial networks in the medium term. This action is conceived as part of a global strategy to close the "digital divide" [†,74] with new Member States and beyond.[75] Specifically, the document states that broadband access can be delivered through a variety of solutions such as DSL, cable, satellite, and wireless. It recognizes that these technologies can be perceived as substitutes (competing solutions), but also as "complementing, completing, and co-existing with each other according to local geographical needs".[76] This White Paper concludes by asserting that the EU has a key role to develop space activities in Europe, especially in order to expand the European share in fast-growing markets where space-based services are fundamental.[77]

It is important to stress the fact that most of the stakeholders within the satellite services industry recognize a need for an international more concerted approach to develop satellite communications policies and regulations. The relationship between the United States and the European Union, in regard to space-based communications and space business in general, is a sensitive matter. In addition, due to the political and economic influence of both the U.S. and the E.U., their relationship is currently playing a major role in shaping the evolution of space law and regulations.[78] In fact, the evolving nature of the U.S. – E.U. aerospace-related interactions has become part of the set of major factors that influence the geopolitical dynamics and the structure of international relations.

4.3. Summary and Conclusions.

Chapter 4 provided an overview of the regulatory environment for satellite operators. Starting with an historical perspective on international regulatory bodies, I followed with a discussion of what I consider to be two of the most important regulatory issues for satellite operators, namely spectrum/orbit allocation and space environmental pollution (i.e., the disposal of space debris). With respect to the first issue, international regulatory bodies have allocated different frequencies and bandwidths to FSS, MSS and DBS applications. In practice, however, most of the latest generations of communication satellites operating in FSS frequencies carry high-power transponders that open the possibility (to FSS operators) of implementing direct broadcasting services (DBS) through FSS satellites. As a result, the regulatory environment for satellite operators has become surprisingly dynamic; with continual behind-the scenes maneuvering by both terrestrial and satellite services interests as well as by other stakeholders in the industry, in

[†] The "digital divide" is defined as "the inequality in the capability of access by broadband technology connectivity (i.e. Internet services) to knowledge society. It is measurable in terms of widespread availability of the connection or in cost of the connection in comparison to a benchmark".

practice, frequency allocations are not necessarily always respected. While the commercial battle for spectrum/orbit allocation is often engaged with a much less open approach, different conventional and less conventional practices shape the actual state of the industry. With respect to the second regulatory issue, Chapter 4 identified a need to legislate and regulate spacecraft disposal in a way such that operators have to propel unused satellites to orbits far from the geostationary orbit (where they cannot cause damage to operating GEO satellites). This, however, will certainly have a short-term financial impact on satellite service providers. Currently, the only existent regulations related to space debris were issued in 2004 by the FCC in the U.S., forcing all U.S.-licensed satellites launched after March 2002 to be propelled to a "graveyard" orbit above the GEO. This regulation set the path for other standards around the world, since no other nation with space activity, or international regulatory body, has regulated about spatial debris. An important contribution of this work is the clear identification of a critical need to enforce space debris regulations. The geostationary orbit must be recognized as a precious real-state resource that is likely to become useless should a collision occurred. Such an incident might have extremely negative consequences for the development of telecommunication services on Earth.

This chapter also delineated what might be the shape of the space communications policy in the near future. In the United States, as a result of the deregulation of the industry started in 1972 with the "Open Skies" policy, the regulatory environment for satellite operators is probably one of the most flexible in the world. The "Open Skies" and the "orbital spacing" decisions are examples of policies that were originally created to promote competition and the development of the industry with minimal regulations. On the other hand, in regard to satellite communications regulations and policy, the European Union is an emerging system and, in that respect, Europe is the "young" continent when compared to the United States. Although in a much more measured manner, Europe has also been moving toward deregulation. Yet, analysts coincide in the need to further ease the current regulatory environment to promote competition among satellite operators (today, the duopoly Eutelsat/SES exerts a decisive influence on regulatory issues in Western Europe). The EU acknowledges a key role in developing space activities in Europe, and has clearly implemented a strategy to expand the European share in fast-growing markets where space-based services are fundamental. From a global perspective, however, more international cooperation is desirable, since it would result in a more beneficial relationship amongst space faring countries, eliminating a risk of trade war between the U.S. and Western Europe. In fact, the evolving nature of the U.S. – E.U. aerospace-related interactions has become part of the set of major factors that influence the geopolitical dynamics and the structure of international relations.

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PART II: ECONOMIC AND ENGINEERING ISSUES IN SPACECRAFT DESIGN*

The first part of this thesis focused on the market dynamics and policy drivers of the satellite communications industry. Specifically, two questions were addressed: 1) Are satellite communications competing or complementary technologies to terrestrial networks, in what context and for what service applications? And, 2) what is the impact of the regulatory environment and the policy-making process on the satellite communications industry?

While market and policy issues play a central role in shaping the structure of the satellite services industry, economic and engineering considerations can provide decisive insights that might significantly alter the dynamics of the sector. The second part of this thesis combines economic and engineering analyses in a multidisciplinary approach and focuses on the lifeblood of the satellite industry: the satellite itself (as opposed to the industry-context explored in Part I). In particular, part II explores issues associated with satellite design lifetime and the impact it may have on the whole industry value-chain. Part II consists of Chapter 5, To Reduce or To Extend a Spacecraft Design Lifetime?, and Chapter 6, Utilization Rates of GEO Communication Satellites.

* Part Two of this thesis is based on two papers accepted for publication at the AIAA Journal of Spacecraft and Rockets (chapter 5) and for presentation at the AIAA Space 2005 Conference (chapter 6). This work was done in collaboration with different co-authors that are properly referenced in each chapter.

Chapter 5 [*]

To Reduce or to Extend a Spacecraft Design Lifetime?

What is at Stake, for Whom, and How to Resolve the Dilemma

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The attitude towards systems design lifetime has often been ambiguous, and at times uninformed. Although the issue has received almost no attention in the technical literature, there have been a few qualitative arguments fraught with subjectivity for or against extending a system design lifetime. In this chapter, the authors explore the engineering and economic issues at stake for reducing or extending a complex system's design lifetime using spacecraft as example. The study examines these issues from an operator/customer's perspective, a manufacturer's perspective as well as from the perspective of society at large. We address the question of whether there is an optimal design lifetime for complex engineering systems in general, and spacecraft in particular, and what it takes to answer this question. Our approach constitutes a fundamental addition to the traditional thinking about system design and architecture, and involves quantitative analyses of both dynamics and volatility of the market the system is serving in the case of a commercial venture, and the obsolescence of the system's technology base. Preliminary results indicate that optimal design lifetimes do exist that maximize a system's financial/value metric. Therefore even if it is technically feasible to field a system or launch spacecraft with a longer lifetime, it is not

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necessarily in the best interest of an operator, and definitely not in the interest of the manufacturer, to do so. Preliminary results also show that the design lifetime is, in the case of a spacecraft, a key requirement in sizing various subsystems–and consequently has a significant impact on the overall cost of the spacecraft. Additionally, at the level of the entire space industry value chain, i.e., the spacecraft manufacturers, launch industry and the operators, the design lifetime is a powerful lever that can significantly impact the whole industry's performance, financial health, and employment. Overall, we show that the specification or selection of a complex engineering system's lifetime begs careful consideration and requires much more attention than it has received so far in the literature as its impact will ripple throughout an entire industry value chain.

5.1. Introduction: From Product Durability to System Design Lifetime

There is a popular belief that manufacturers of durable goods (e.g., automobile tires, light bulbs, batteries) often deliberately reduce the time period for which their products remain operational in order to increase their sales and profits. For instance, it seems that the electric lamp industry in the United States in the 1960s "has served to limit, and frequently reduce, lamp life in order to increase sales" when consumers' interests were generally thought to be better served by bulbs of much longer life.[1] This hypothetical practice has sparked environmental concerns among ecologists and policy makers, and created interest in the contribution that extended product design lifetime can make towards reducing the waste management and other environmental problems.[2] Several industries however strongly denied having a concealed policy of either deliberately limiting product operational life, or of accelerated product obsolescence, i.e., introducing upgrades or new functionalities in a product in order to promote consumer dissatisfaction with existing products and promote sales of new products.[3]

The example discussed above, the relevance of which is heightened in the era of planned obsolescence of hardware and software, is used for two purposes: First, it introduces the three main stakeholders that should be taken into account when analyzing issues of product durability and system design lifetime, namely the consumer, the manufacturer, and society at large. Second, the example portrays tension between the stakeholders as each is affected differently by an extended or reduced product lifetime, and shows that the interests of the one are not necessarily aligned with the interests of the other. We therefore recognize that when exploring the issues at stake in reducing or extending a product durability, or when asking whether there is an optimal design lifetime for complex engineering systems, it is necessary to first specify from which stakeholder perspective the analysis is carried out as the interests and trade-offs can be substantially different.

Academic interest in product durability peaked in the 1970s and early 1980s then temporarily faded out only to resurface in the 1990s and grapple with issues of planned obsolescence of computer hardware and software. But beyond product durability, emerge questions pertaining to engineering system design lifetime. Product durability and system design lifetime are similar in that they both characterize an *artifact's* relationship with *time*. The difference however is one of complexity and scale, and the issues related to system design lifetime are much more involved–and interesting–than those associated with product durability. In the following we define system design lifetime as a requirement that specifies to the manufacturer the duration for which a system should remain operational. This requirement can be specified either by the customer or by the designer, or imposed by the market or by society. Design lifetime differs from product durability in that it is mainly used to characterize the duration of intended operation for complex engineering systems, as opposed to products of limited complexity and functionalities.

System design lifetime, unlike product durability, has received almost no attention in the technical literature, either from academics or from industry professionals. For instance, the design lifetime requirement in the case of satellites is "assigned rather arbitrarily"[4] with an understanding of the technical limitations that prevent further extension of this requirement, and a vague intuition regarding the economic impact of extended design lifetimes. The engineering and economic issues associated with system design lifetime do offer a rich field of investigation for academics and industry professionals. In the following, we show that the design lifetime is a key requirement in sizing various subsystems–using a spacecraft as an example–and that its specification begs careful consideration and requires much more attention than it has received so far in the literature as its impact is substantial and can ripple throughout an entire industry value chain.

5.2. Qualitative Arguments for Reducing or Extending Product Durability or System Design Lifetime

In the following, we discuss the qualitative implications and trade-offs associated with reducing versus extending a product durability or a system design lifetime, as seen from the perspective of the three stakeholders introduced in the previous section, namely the customer, the manufacturer, and society at large. Table 5.1 synthesizes our findings.

Table 5.1: Implications scorecard for reducing or extending a system design lifetime

To Reduce (Reduced) Design Lifetime			To Extend (Extended) Design Lifetime		
Customer's perspective	**Manufacturer's perspective**	**Society's perspective**	**Customer's perspective**	**Manufacturer's perspective**	**Society's perspective**
1A. Family of products more likely to be improved through more frequent iterations of fielding and feedback to the manufacturer, than products with longer lifetimes	1A. Ability to improve subsequent products through more frequent iterations of fielding and customer feedback	1A. Shorter design lifetime can stimulate faster innovation and technological progress	1A. Smaller volume of purchasing	1A. Service contracts have the potential to generate higher profits that the mere sale of the product or system	1A. Products with longer design lifetimes result in less waste during a given time period than those with shorter lifetimes
	2A. Potential for higher sales volume	2A. Potential for maintaining and boosting industry employment level through higher sales volume	2A. Potentially smaller cost per operational day	2A. Increased design lifetime acts as a magnifier of reliability as a competitive advantage. Product reliability is less critical for short lifetime than for products with longer lifetime	2A. Longer design lifetime can stimulate the creation of a secondary market for the products
	3A. Heightened obligation for employees to remain technically up-to-date and attentive to the voice of the customer	3A. "Old products" are easier to replace than repair. Hence the likelihood of more state-of-the-art products in use than with products with longer lifetimes			
1D. Need to purchase more products for a given duration	1D. Fewer opportunities for revenues from services	1D. Adverse environmental effect as a result of more product disposal during a given time period	1D. Increased risk the product will be technically or commercially obsolete before the end of its lifetime, hence loss of revenues	1D. Extended warranty needed, which may result in higher levels of unpaid services	1D. Increased risk of technological slowdown, potential increase in an industry's unemployment

5.2.1. Implications of reducing (or a reduced) design lifetime

In this section, we discuss the qualitative implications for reducing product durability or system design lifetime. We have tagged each implication with a numeral followed by an "A" or a "D" for what appeared to us more as an advantage or a disadvantage, even though some of the implications did not necessarily carry a positive or a negative connotation.

From an operator or a customer's perspective, a product or a family of products with a shortened lifetime is more likely to be improved upon, during a given time period, through more frequent iterations of fielding and feedback to the manufacturer, than products with longer lifetimes. One disadvantage however the customer could perceive if the duration of the needed service exceeds the system design lifetime is the need to purchase increasingly more products as their lifetimes decreases. This observation leads to the suggestion that customers are perhaps better off purchasing products or system with design lifetime that match the duration of their service needs. This suggestion however is not necessarily true, as we will show later.

From a manufacturer's perspective, the two points raised above translate into advantages: First, manufacturers of products or family of products with shortened lifetime have an increased ability to improve their products through more frequent iterations of fielding and customer feedback. Second, shorter lifetime can stimulate sales since customers need to buy more volume in order to sustain the same level of service during a given time period. For example, in the sports industry, "Professional teams constantly update their merchandise to keep the public spending uniformly".[5] Another implication of shortened lifetime, which we classified as an advantage to the manufacturer, is a heightened obligation for the employees to remain technically up-to-date and attentive to the voice of the customer in order to fend off competitors. This we believe is the case since customers of systems with short design lifetime are not locked in for as long of a duration as customers who acquire longer lived products; these customers can therefore more frequently recommit resources to acquiring new products or systems from the competition, if the incumbent is not constantly offering best value products. One disadvantage for manufacturers of reducing system design lifetime is the limited opportunities they have to generate revenues from service contracts. This can represent a substantial opportunity loss. However, this opportunity loss should be analytically compared to the increased volume of sale and revenues associated with it before manufacturers decide whether they are better off reducing or extending the product durability or system design lifetime.

From a society's point of view, short design lifetime present several advantages. First, shorter design lifetime can stimulate a faster pace for innovation and technological progress. Planned obsolescence or short-lived products but fast innovation may be preferred, from a society's perspective, to long-lasting products and a slow pace for innovation. Second, if the assumption we discussed above is true, namely that products with shorter lifetime can stimulate sales since customers need to buy more volume in order to sustain the same level of service during a given time period, then this increased sales volume has the potential to maintain or boost industry employment. Third, "old" products are likely easier to replace than to repair than products with longer lifetimes. More state-of-the-art products therefore are likely to be found more in use at any given time than if these products were designed for longer lifetime. We classified this implication as an advantage for society, but we recognize that other people or groups might not consider this to be so. One adverse environmental effect however associated with shortened lifetimes results from an increased number of products to dispose of during a given time period.

5.2.2. Implications of extending (or an extended) design lifetime

In this section, we discuss the qualitative implications for extending product durability or system design lifetime. The reader will notice that some of the stakeholders' advantages in reducing a system design lifetime transform into disadvantages when longer design lifetime are considered, and vice-versa.

From a customer's perspective, purchasing products or systems with long lifetime offers mainly two advantages. First, customers have to purchase fewer products for the duration of their service needs as the product design lifetime increases. Second, it is more likely that the product or system's cost-per-operational-day decreases as the system's design lifetime increases. This point will be discussed in more detail in the following analytical sections. One disadvantage a customer will encounter with longer-lived systems in an increased risk that these systems will be technically and commercially obsolete before the end of their lifetimes, hence an increased risk of loss of revenue.

From a manufacturer's perspective, there are two main implications associated with an increased system design lifetime. First, systems with long design lifetime offer manufacturers a heightened ability to generate additional revenues, and higher profits, from service contracts than from the mere sale of the system (it is worth noting that for satellites, manufacturers normally do not have service contracts, but usually provide anomaly support through the contracted life on-orbit at no cost to the operator. If the satellite lasts longer than the planned contract life, then on-orbit support service contracts are feasible, bur are generally not big dollar items. In today's buyer's market, operators can demand that these additional services are also provided at no extra cost). There is limited potential for additional revenues from services with system of short design lifetime. The second implication, which is neither an advantage nor a disadvantage, merely an observation is the following: increased design lifetime acts as a magnifier of system's "reliability as a competitive advantage." That is the reliability of a system is increasingly more valuable for customers as the system design lifetime increases. Therefore, manufacturers with core competencies to produce highly reliable systems have some incentives to increase their systems design lifetime in order to augment the quality gap with manufacturers of less reliable systems, and therefore augment their market share at the detriment of the competition. One risk manufacturers have to deal with when extending their system design lifetime is the need to offer equally extended warranty, which may result in higher levels of unpaid services. This risk is heightened for manufacturers of lesser reliable systems. In other words, manufacturers who do not have a track record in designing distinctively reliable systems should carefully consider before engaging in "design lifetime extension behavior" to differentiate their systems from the competition's. This risk should be weighted against, or can be mitigated by, the service contract advantage discussed above.

From a society's point of view, one clear environmental advantage of systems with long design lifetime is that the use of such artifacts result in less waste to be disposed of during a given time period than shorter lived products or systems. Another implication, which we classified as an advantage for society, is that long design lifetime can stimulate the creation of a secondary market for products, hence an increased economic activity. One disadvantage however that can result from fielding systems with increasingly longer lifetime is that, while short design lifetime can stimulate a faster pace for innovation, long design lifetime can increase the risk of technological slowdown and adversely impact an industry employment level.

In the previous sections, we synthesized and discussed the different qualitative implications associated with reducing versus extending a product durability or a system design lifetime, as seen from the perspective of three stakeholders, namely the customer, the manufacturer, and society. The purpose of this qualitative discussion was to illustrate the complexity of the choice in reducing or extending a system's design lifetime–not to take a position for reducing or extending this requirement–and to lay the ground for the quantitative discussion to follow.

5.2.3. Example: to reduce or to extend a spacecraft design lifetime? An operator's perspective

In recent years, manufacturers of high-value assets (e.g., rotorcraft, spacecraft) have chosen to increase their systems design lifetime. Over the last two decades, telecommunications satellites for instance have seen their design lifetime on average increase from seven to fifteen years. In this case, increasing the space segment lifetime was driven by both the desire of satellite operators to maximize their return on investment, and by the determination of manufacturers to offer spacecraft with longer lifetime as a competitive advantage for their spacecraft in the hope of increasing their market share (it is legitimate however to ask whether this competitive behavior is not locking the players in a Nash-like equilibrium with the end result of a reduced market for all manufacturers).

Extending satellite design lifetime however has several side effects. On the one hand, it leads to larger and heavier satellites as a result of several factors such as additional propellant for orbit and station-keeping or increased power generation and storage capability. This in turn increases the satellite's development and production cost. On the other hand, as the design lifetime increases, the risk that the satellite becomes obsolete, technically and commercially, before the end of its lifetime increases. This trade-off is illustrated in Figure 5.1.

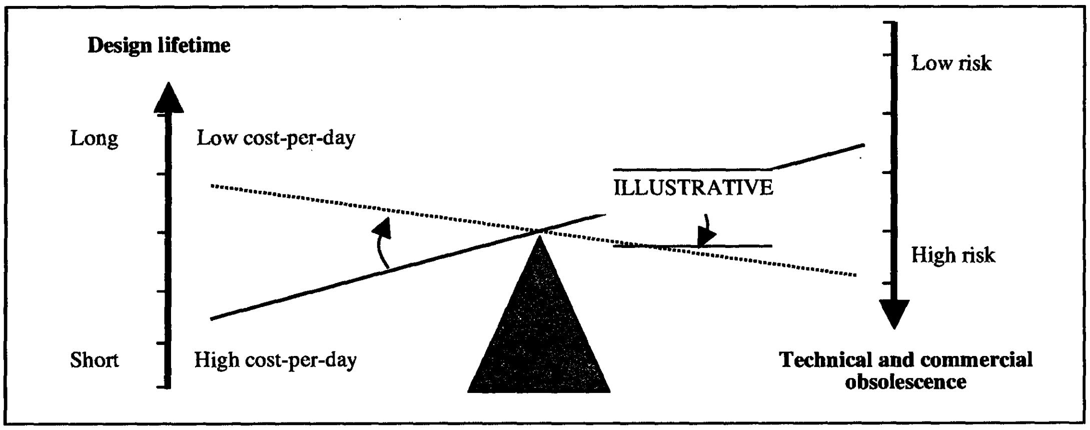


Figure 5.1: Design lifetime trade-offs: keeping a satellite cost-per-operational day low through long design lifetime but risking that the satellite becomes obsolete before the end of its lifetime.

The discussion above indicates that in specifying spacecraft design lifetime requirement, operators have to assess the risk of loss of value due to both obsolescence of their spacecraft technology base as well as the likelihood of changing or shifting market needs after the satellite has been launched (volatility of the market the system is serving). For example it is not obvious to be in the best interest of a satellite operator to make the contract life of a spacecraft too long: new or enhanced capabilities, e.g., better spatial resolution for an optical instrument, might be developed and become available within a couple of years following the launch, hence the need to launch a new satellite or risk losing market share to a competitor who launches later with newer or more advanced capabilities. So how can we capture the value of a system (or the loss of it) as a function of its design lifetime? The following sections offer some suggestions towards this goal.

5.3. Is There an Optimal Design Lifetime for Complex Engineering Systems? A Customer's Perspective

Questions regarding the design lifetime requirement of complex engineering systems can be grouped into three categories:

1. What limits the design lifetime? How far can designers push the system's design lifetime? What is the lifetime "boundary" and why can't it be extended?
2. How do the different subsystems scale with the design lifetime requirement, and what is the total system cost profile as a function of this requirement?
3. What does (or should) the customer ask the contractor or manufacturer to provide for a design lifetime, and why?

Although related, these questions cover nevertheless different realities. The first question is purely a technical/engineering one and addresses the issue of lifetime boundary. For instance, what prevents engineers from designing a spacecraft for say a hundred years? Current satellites are launched with design lifetime of twelve to fifteen years. Solar array degradation due to thermal cycling in and out of eclipses, micrometeoroid strikes, radiation damage and material outgassing offer serious challenges for engineers to overcome if the current fifteen-year mark of spacecraft design lifetime is to be extended. Other limitations result from battery technology (number of charge/discharge cycles possible), inertial systems degradation and failure, as well as electronics degradation both in the Telemetry, Tracking and Control subsystem (TT&C) of a spacecraft as well as its payload due to space radiation (increased electronic shielding is costly and does not scale up effectively).

The second question, closely related to the first one, focuses on the effects of varying the design lifetime requirement on each subsystem. We explored in a previous work[6] how different spacecraft subsystems scale as a function of the design lifetime requirement, then aggregated the results and derived total spacecraft mass and cost profiles as a function of this requirement. We found that the design lifetime is a key requirement in sizing various subsystems, and that typically 30%–40% mass and cost penalty are incurred when designing a spacecraft for 15 years instead of 3 years, all else being equal. More generally, the answer to this second question in the case of any complex engineering system constitutes a mapping between a system design lifetime and the investment necessary to develop or acquire such a system. The answer to this second question also provides another confirmation of the old adage, from a different angle though, that "Time is Money", that is more system lifetime requires more money to develop or acquire!

The third question builds on the two preceding ones and is mainly a management decision that should be supported by engineering and market analyses as well as financial evaluation: given the maximum achievable design lifetime (answer to Question 1), and given the impact of the design lifetime on the system cost (answer to Question 2), what should the customer ask the contractor to provide for a design lifetime? Is there a value metric that can be maximized through the selection and specification of an *optimal* design lifetime? What should be taken into account when evaluating this metric? These questions are addressed in the following sections. We first discuss what it takes in order to answer the design lifetime optimality question.

5.3.1. Prerequisite: a mindset change

How can we capture the value of a system (or the loss of it) as a function of its design lifetime? In order to do so, we first need to augment our understanding of system design architecture(-ing). System architecture is defined as the fundamental and unifying structure, in terms of system elements, interfaces, and constraints, of a system.[7] System architecting is traditionally viewed as a matching between two (vector) quantities, resources and system performance. One traditional design paradigm fixes the amount of available resources and attempts to optimize the system performance given this constraint. The other approach constrains the system performance to a desired level and strives to find a design that will achieve this performance at minimal cost.[7] The first approach operates with–and attempts to maximize–a performance per unit cost metric; the second approach seeks to minimize a cost per function (or performance) metric. In order to (quantitatively) discuss issues related to the design lifetime, which we consider to be a fundamental "component" of system architecture although we cannot see it or touch it, it is imperative that we view in a system the flow of service (or utility) it will provide over a given period of time. We therefore need introduce cost, utility, and value per unit time metrics in order to guide the selection the design lifetime.

5.3.2. Value of a system as a function of its design lifetime

In order to specify the design lifetime requirement, a customer needs to be able to express the present value of a system as a function of its design lifetime. We propose Eq. (1) as a means for capturing this value.

$$V(T_{Life}) = \int_0^{T_{Life}} \left[u(t) - \theta(t)\right] \times e^{-rt} dt \; - C(T_{Life}) \qquad (1)$$

T_{Life} : System's design lifetime

$V(T_{Life})$: Expected present value of a system architecture as a function of its design lifetime

$u(t)$: Utility rate of the system (e.g., revenues per day for a commercial system)

$\theta(t)$: Cost per day for operating the system

$C(T_{Life})$: System cost profile as a function of its design lifetime

r : Discount rate

Equation 1 is conceptually analogous to the continuity equation (or conservation of mass) in fluid dynamics, which in its integral form looks as follows:

$$\frac{\partial}{\partial t}\int_V \rho dV + \int_S \rho U dS = 0 \qquad (2)$$

ρ : Fluid density

V : Control volume

S : Closed surface bounding volume V

U : Flow velocity vector

dS : Elemental surface area vector

The analogy between the two equations is illustrated in Fig. 5.2. The control volume becomes a time bin–the system's design lifetime. The flow entering the control volume is analogous to the aggregate utility or revenues generated during the time bin considered, and the flow exiting the volume corresponds to the cost of acquiring a system designed for this time bin, T_{Life}, plus the cost to operate it during the same period.

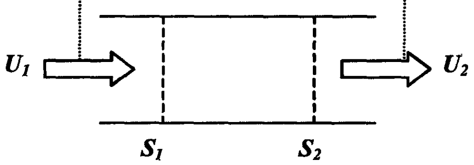
	Flow in	**Accumulation**	**Flow out**
Fluids	$\int_{S_1} \rho U_1 dS_1$	$\frac{\partial}{\partial t}\int_{V} \rho dV$	$\int_{S_2} \rho U_2 dS_2$
			
System architecture	$\int_{0}^{T_{Life}} u(t)\, e^{-rt} dt$	$V(T_{Life})$	$C(T_{Life}) + \int_{0}^{T_{Life}} \theta(t)\, e^{-rt} dt$

Figure 5.2: Analogy between the expected present value of a system as a function of its design lifetime (Eq. 1) and the continuity equation in fluid dynamics.

Two time characteristics can be readily derived from Eq. 1: the minimum design lifetime for a system to be profitable, and the time of operations for a system to break even given a design lifetime. These are discussed below.

5.3.2.1. Minimum design lifetime for a system to be profitable

The minimum design lifetime for a system to become profitable can be computed by setting $V(T_{Life})$ equal to zero:

$$V(T_{Life\text{-}min}) = \int_0^{T_{Life\text{-}min}} [u(t) - \theta(t)] \times e^{-rt} dt - C(T_{Life\text{-}min}) = 0$$

$$V(T_{Life}) > 0 \quad for \quad T_{Life} > T_{Life-min} \qquad (3)$$

While technical considerations limit the upper bound of system design lifetime, as we discussed previously, the lower bound on the design lifetime, as seen from a customer perspective, is dictated by economic (value) considerations, and is given by the solution to Eq. 3. The dynamics of $T_{Life\text{-}min}$ and the parameters driving it will be discussed shortly. It should be noted that the minimum design lifetime for a system to be profitable is NOT identical to the "time to break even". This second time characteristic of a system is discussed below.

5.3.2.2. Time to break even given a design lifetime

The time for a system to break even is given by the solution of Eq. 4 in which T_{Life} is fixed. In other words, once the system's design lifetime is specified, time is allowed to vary until the discounted revenues cover the cost to design the system for T_{Life}, $C(T_{Life})$, in addition to the discounted cost to operate the system until $t_{break\text{-}even}$:

$$V(T_{Life}, t_{break-even}) = \int_0^{t_{break\text{-}even}} [u(t) - \theta(t)] \times e^{-rt} dt - C(T_{Life}) = 0 \qquad (4)$$

The comparison between the time to break-even and the minimum design lifetime is summarized in Table 5.2.

Table 5.2: Time to break even and minimum design lifetime

When	$T_{Life} < T_{Life\text{-}min}$	$T_{Life} = T_{Life\text{-}min}$	$T_{Life} > T_{Life\text{-}min}$
	$t_{break\text{-}even}$ does not exist	$t_{break\text{-}even} = T_{Life\text{-}min}$	$t_{break\text{-}even} > T_{Life\text{-}min}$

How can these equations be useful? Let us assume for instance that the management of a company about to acquire a large complex system wants to break even in $t_{break\text{-}even}$ years, what is the average revenue per day u_0 that the company should guarantee from the system in order to do so? This is one instance of the mindset change we advocated previously about seeing in a system the flow of service (or utility) that it will provide over a given time period. The answer is readily given by Eq. 5 and 6:

$$\int_0^{t_{break-even}} u_0 \times e^{-rt} dt = C(T_{Life}) + \int_0^{t_{break-even}} \theta(t) \times e^{-rt} dt \qquad (5)$$

Therefore

$$u_0 = r \times \frac{C(T_{Life}) + \int_0^{t_{break-even}} \theta(t) \times e^{-rt} dt}{1 - e^{-rt_{break-even}}} \qquad (6)$$

Assuming that the cost to design the system is larger than the cost to operate it, i.e., $C(T_{Life}) >> \int_0^{t_{break-even}} \theta(t) \times e^{-rt} dt$ and recalling that $e^x = 1 + x + \varepsilon(x^2)$, we get:

$$u_0 \approx \left[\frac{C(T_{Life})}{T_{Life}}\right] \times \left(\frac{T_{Life}}{t_{break-even}}\right) \qquad (7)$$

In a previous work,[6] we introduced the concept of cost-per-operational day for a spacecraft. We defined this metric as the ratio of the spacecraft cost to Initial Operational Capability and its design lifetime, expressed in days:

$$Cost_{/ops\_day} = \frac{Cost\ to\ IOC}{design\ lifetime\ (days)} \qquad (8)$$

More generally, we can define an engineering system's cost-per-operational day as follows:

$$Cost_{/ops\_day} = \frac{C(T_{Life})}{T_{Life}\ (days)} \qquad (9)$$

This definition corresponds to uniformly amortizing the cost of a system–excluding the cost to operate it–over its intended design lifetime. Going back to Eq. 7 and the question that prompted that analysis, namely what is the average revenue per day u_0 that a company should guarantee from the system in order to break even in $t_{break\text{-}even}$ years? We found the answer in Eq. 7, the first term of which is the system's cost-per-operational day. This result can prove useful in feasibility studies or back-of-the-envelope calculations. For instance, assume a company that is acquiring a \$100m system designed for ten years wishes to amortize its investment in two years. In order to do so, the company should guarantee average revenues per day at least five times more than the system's cost per operational day:

$$u_0 \approx \left(\frac{100\times10^6}{10\times365}\right)\times\frac{10}{5} \approx \$55{,}000/day$$

Conversely, if market analysis indicates that the service provided by this system can at best generate \$30,000/day, considering the market size and the presence of other players in this market, then the time to amortize the investment is:

$$t_{break-even} \approx \left(\frac{100\times10^6}{10\times365}\right)\times\frac{10}{30{,}000} \approx 9.1 years$$

It is likely, given this result that the senior management of the company will reconsider before acquiring the system with its ten years design lifetime.

5.3.3. Quantitative analyses required for answering the optimality design lifetime question

We set up to investigate whether an optimal design lifetime exists for complex engineering systems, optimality as seen from the customer's perspective. In order to answer this question, the discussion first led us to advocate a mindset change about system design and architecture: namely to view in a system the flow of service it will provide over a given time period. This led us to recognize the need for system-level metrics as functions of time, such as cost, utility, and value per unit time. Second, optimality presupposes a metric that is minimized or maximized; we therefore proposed Eq. (1) as a means for capturing the present value of a system as a function of its design lifetime. We can now mathematically formulate our question regarding the existence or not of an optimal design lifetime for complex engineering systems, as seen from the customer's perspective:

$$V(T_{Life}) = \int_{0}^{T_{Life}} [u(t) - \theta(t)] \times e^{-rt} dt \;\; - C(T_{Life})$$

Is there a T^{*}_{Life} such that $V(T^{*}_{Life}) \;>\; V(T_{Life})$ for all $T_{Life} \neq T^{*}_{Life}$? (10)

In order to investigate this problem, several analyses and models are required:

Engineering and cost estimate analyses of the system cost profile $C(T_{Life})$
Market analyses and forecast of system expected revenue model $u(t)$
Technical analysis and estimate of cost to operate and maintain the system $\theta(t)$
Financial analysis of the investment riskiness, usually referred to as beta, which in turn is used to derive the appropriate risk-adjusted discount rate for the investment, r

We performed some of the above analyses in the case of commercial spacecraft wherever possible, and used proxies or generic models in other cases. We briefly discuss our methodology and findings in the following.

5.3.3.1. Spacecraft cost profile $C(T_{Life})$

How does the design lifetime requirement impact the sizing of the different subsystems on-board a spacecraft? Consider the solar arrays for example. Life degradation is a function of the design lifetime. It occurs for a number of reasons, e.g., radiation damage, thermal cycling in and out of eclipse, and is estimated as follows:

$$L_d = (1 - degradation / year)^{T_{Life}} \qquad (11)$$

The degradation-per-year is a function of the spacecraft orbital parameters (position with respect to the Van Allen belts) as well as the solar cycle. It varies typically between 2% and 4%.[4] The solar array's performance at the end of life (EOL), compared to what it was at beginning of life (BOL) is given by:

$$P_{EOL} = P_{BOL} \times L_d \qquad (12)$$

Given a power requirement at EOL, the power output of the solar arrays at BOL scales inversely with life degradation, and the solar arrays have to be over-designed to accommodate this performance degradation. This over-design of the solar arrays translates into mass and cost penalty as the design lifetime increases. Batteries, which can constitute up to 15% of the dry mass of a typical communications satellite,[8] are also significantly impacted by the spacecraft design lifetime requirement. The amount of energy available from the batteries, or depth of discharge (DOD), decreases with the number cycles of charging and discharging. To first order, the number of charge/discharge cycles is equal to the number of eclipses a satellite undergoes during its design lifetime. Typically, a satellite in GEO undergoes two periods of 45 days per year with eclipses, hence 90 cycles of charging and discharging per year. As the design lifetime increases, the number of charging/discharging cycles a battery has to undergo increases. Therefore its depth-of-discharge decreases. For example, for a 3-year spacecraft lifetime in GEO, the average DOD for a Nickel-Cadmium battery is approximately 76%, but it drops to 62% for a spacecraft lifetime of 10 years. Battery capacity scales inversely with the DOD, therefore as the spacecraft design lifetime increases, batteries have to be over-designed to compensate the reduction in DOD. This result again in a mass and cost penalty for the spacecraft as its design lifetime increases.

The design lifetime is a key requirement in sizing all the subsystems on-board a spacecraft, not just the solar arrays and batteries. When we aggregate the direct and indirect impact of the design lifetime on all subsystems, we generate typical spacecraft mass profiles as a function of the design lifetime. Then, using spacecraft Cost Estimate Relationships (CER) developed over the years by various organizations–relating subsystem cost to physical or technical parameters–we generate spacecraft cost profiles as functions of the design lifetime, our sought-after $C(T_{Life})$. Typical results of $C(T_{Life})$ and spacecraft cost-per-operational day are shown in Fig. 5.3 and 5.4. We see cost penalties of 30% to 40% when designing a spacecraft for 15 years instead of 3 years. A more elaborate discussion these results, along with their limitations, is provided in Ref. 6.

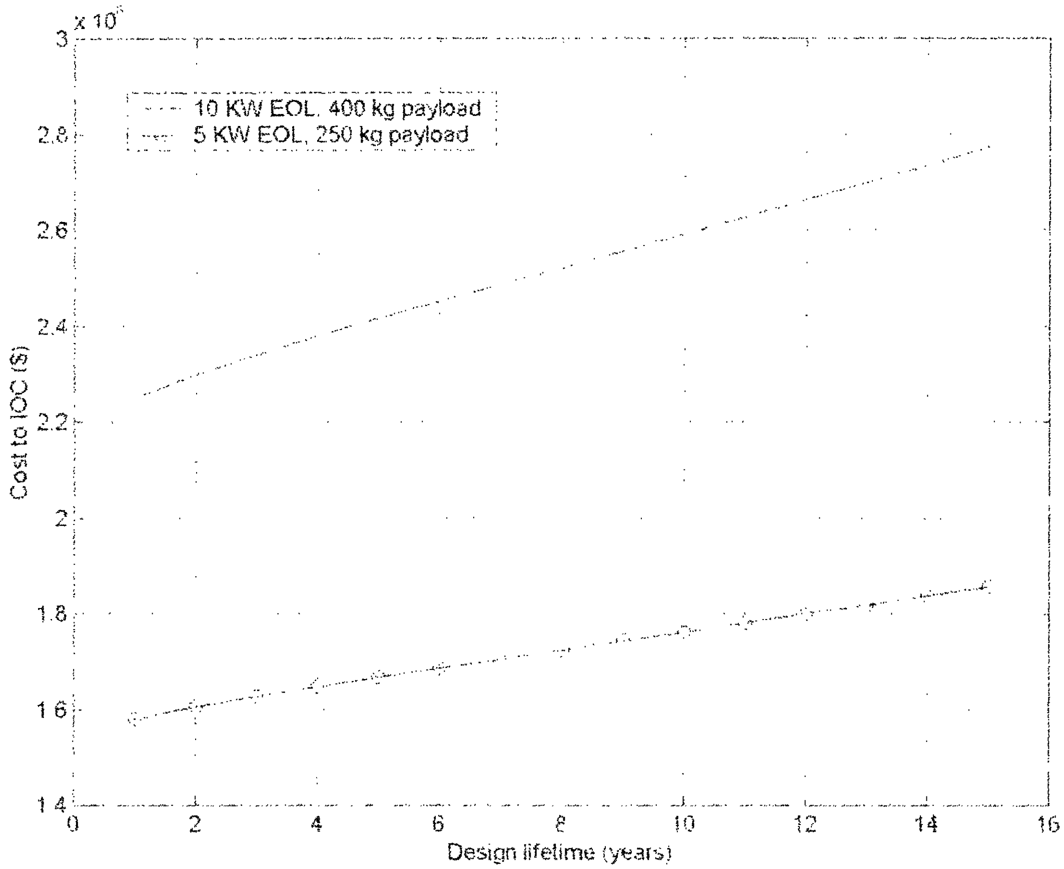


Figure 5.3: Spacecraft $C(T_{Life})$ or Cost to IOC as a function of the design lifetime requirement (spacecraft in GEO, mission reliability = 95%, GaAs cells, Ni-H2 batteries).

The spacecraft cost-per-operational day decreases monotonically. In other words, the additional cost (to get more "life" out of the system) scales up at a slower pace than the additional number of days the spacecraft is designed to remain operational. In the absence of other metrics, this behavior of the cost-per-operational day may justify pushing the boundary of the design lifetime and designing spacecraft for increasingly longer periods. It also suggests that a customer is always better off requesting the contractor to provide the maximum design lifetime technically achievable:

$$T_{Life-best} = T_{Life-\max} \qquad (13)$$

This may be valid in a "cost-centric" environment, but is not necessarily true in a "value-centric" environment as we will show later.

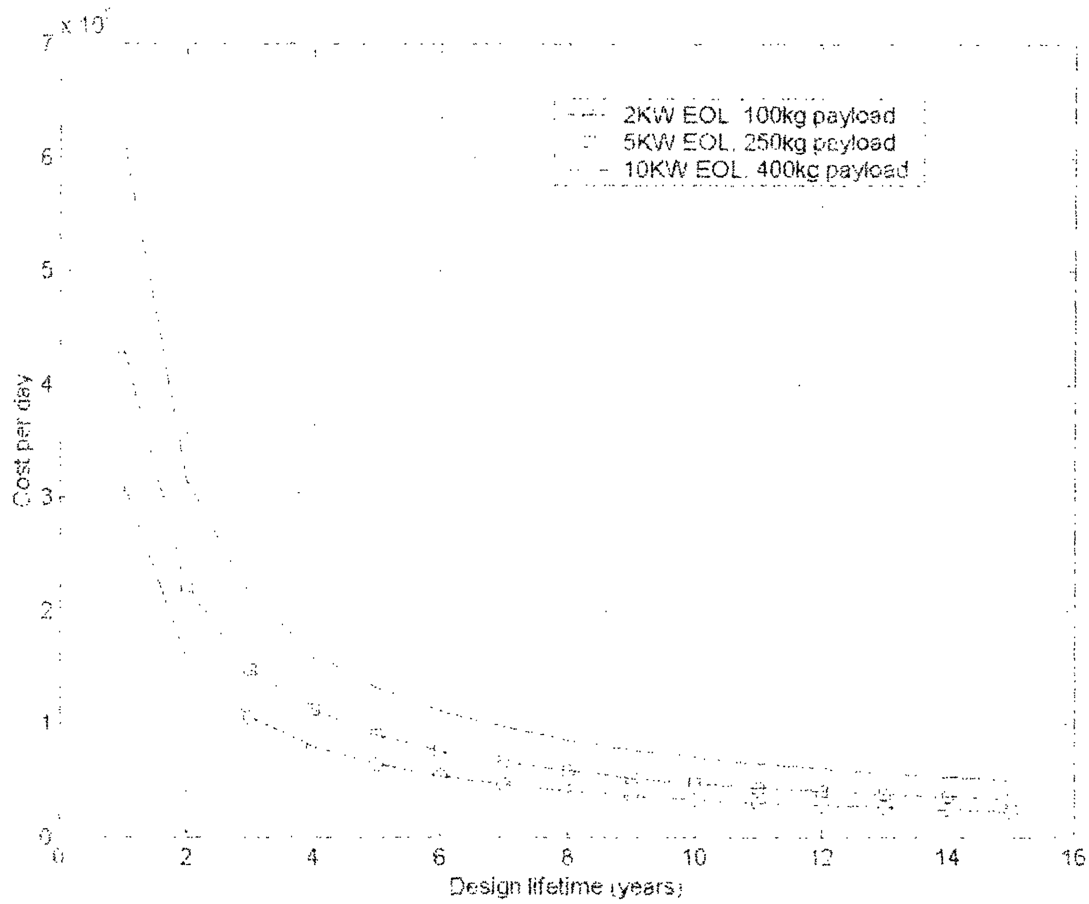


Figure 5.4: Spacecraft cost-per-operational day ($/day) as a function of the design lifetime (same parameters as in Fig. 5.3)

5.3.3.2. Spacecraft revenue models *u(t)*

After the system cost profile $C(T_{Life})$, the second model required in order to demonstrate the existence or not of an optimal design lifetime consists of market analyses and forecast of the system's expected revenue model *u(t)*. In the case of a non-commercial system, the revenue model can be replaced by an expected utility profile of the system as a function of time. For a communications satellite in GEO, the revenue model should depend on the following:

$$u(t) = u(longitude,\ \#\, of\, Tx,\ service\ mix,\ market\ volatility,\ technology\ obsolescence,\ ...) \qquad (14)$$

The spacecraft longitude provides both an indication of the market size the operator can tap into as well as the competitive intensity over this market (which in turn drives the service price). Spacecraft prime locations have traditionally been over the Americas, Europe, as well as Trans-Atlantic longitudes. The number of transponders as well as the service mix (audio, video, data) are also important parameters that define a communications satellite revenue profile. Finally, the volatility of the market the satellite is intended to serve and the obsolescence of the system's technology base have to be factored in when forecasting a satellite revenue profile as a function of time, $u(t)$.

When we set up to investigate communications satellite revenues, we were surprised to find that, while numerous spacecraft cost models exist and are widely available, used and taught in academic environments, no (individual) spacecraft revenue models exist, to the best knowledge of the authors. The data required in order to build these models is not easy to access (tracking the revenue of an individual satellite on a monthly basis along with its utilization rate and service offered). In addition, one can presume that satellite operators are not necessarily eager to share this financial information. We are currently working with industry partners on developing communications satellites revenue models that appropriately capture the dependencies shown in Eq. 14. For this paper, we use two simple spacecraft revenue models based on back-of-the envelope calculations and generic obsolescence models.

The simple case: we consider the revenues per day generated by the satellite to be constant over its design lifetime–no ramp-up/fill rate, market volatility, or obsolescence issues taken into account. The numbers, based on simple calculations using satellite operator's Income Statement, average transponder lease ($M/year), average number of transponders per satellite and utilization rate typically vary between $50,000 and $100,000 per day:

$$u_1(t) = u_0 \qquad (15)$$

Technology obsolescence case: In the second case, we consider the impact of the technology obsolescence on the spacecraft revenue model. We assume a model exists that relates component obsolescence to system's obsolescence, and that a time scale of obsolescence affects the system's revenues as follows:

$$u(t) = u_0 \times \exp\left[-\left(\frac{t}{T_{obs}}\right)^2\right] \qquad (16)$$

The reader is referred to Ref. 7 and 9 for a more elaborate discussion of this model's rationale, assumptions, and limitations. Time to obsolescence can be modeled in the simple case as a deterministic variable, or more appropriately as a random variable with a lognormal probability density function:[9]

$$p(\hat{T}_{obs}) = \frac{1}{(\sigma\sqrt{2\pi})(\hat{T}_{obs} - \tau)} \times \exp\left[-\left(\frac{\log((\hat{T}_{obs} - \tau)/m)}{\sigma\sqrt{2}}\right)^2\right] \qquad (17)$$

σ : Standard deviation

m : median

τ : Waiting time or shift parameter

Figure 5.5 illustrates the lognormal density function as well as the cumulative density function of the Time to Obsolescence for a typical microprocessor.

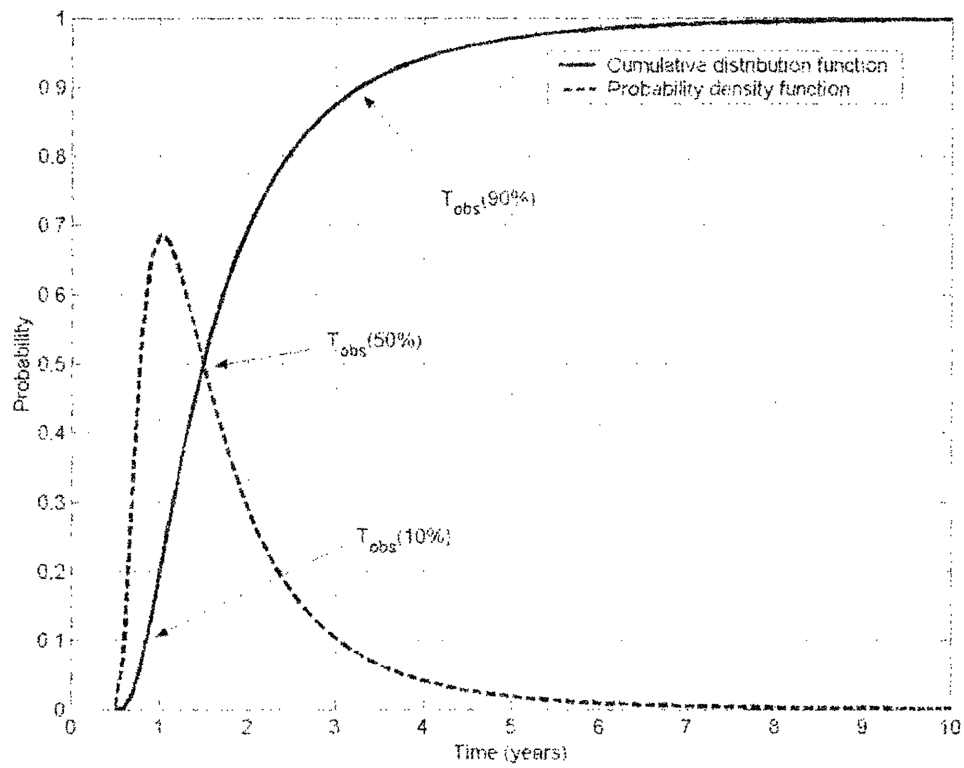


Figure 5.5: Cumulative distribution function and probability density function of the Time to Obsolescence for a microprocessor (m=1.5 years, σ = 0.8 years, τ = 0.5 years).

5.3.3.3. Operations cost and discount rate

The last two models or parameters needed in order to demonstrate the existence or not of an optimal design lifetime consists are estimates of the cost to operate and maintain the system $\theta(t)$, and the risk-adjusted discount rate that the company may wish to use for its investment in the system, r.

In the case of spacecraft, mission operations are described in detail in Ref. 10. The cost per year to operate a satellite typically varies between 5% and 15% of the spacecraft cost to IOC. In our analysis, we consider the cost of operations $\theta(t)$, to be constant and equal to 10% of $C(T_{Life})$ and perform our sensitivity analysis around this value. The assumption of a constant cost of operations over the spacecraft design lifetime can be easily amended to incorporate different cost profiles for operations as a function of the mission phase (e.g., e.g., operations during the launch and deployment phase may require more personnel, hence be more expensive than operations after the spacecraft has been delivered to orbit and tested to full functionality). This assumption however has little effect on our results, and bears no consequences on our conceptual findings as we will show in the following.

We use a discount rate, r, of 10%–this is a commonly used figure and a few percent points above the risk-free rate of return–and perform a sensitivity analysis around this value.

5.3.4. Illustrative results

Using the models and assumptions discussed previously, we can now explore the solution to Eq.10, namely whether an optimal design lifetime exists for a satellite–as seen from a customer's perspective–that maximizes the expected present value of a system as a function of its design lifetime, $V(T_{Life})$. The results are shown on Fig. 5.6 and 5.7.

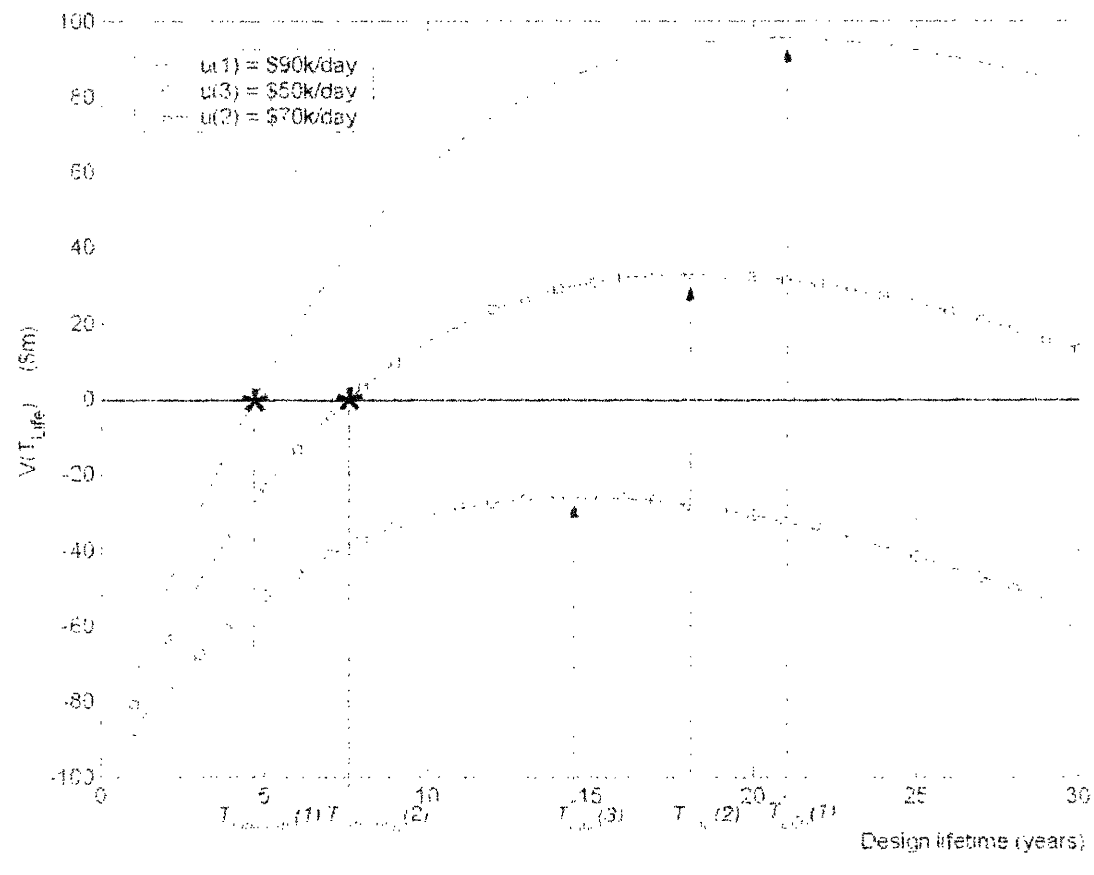


Figure 5.6: Expected present value of a satellite as a function of its design lifetime $V(T_{Life})$, assuming constant revenues per day over its design lifetime.

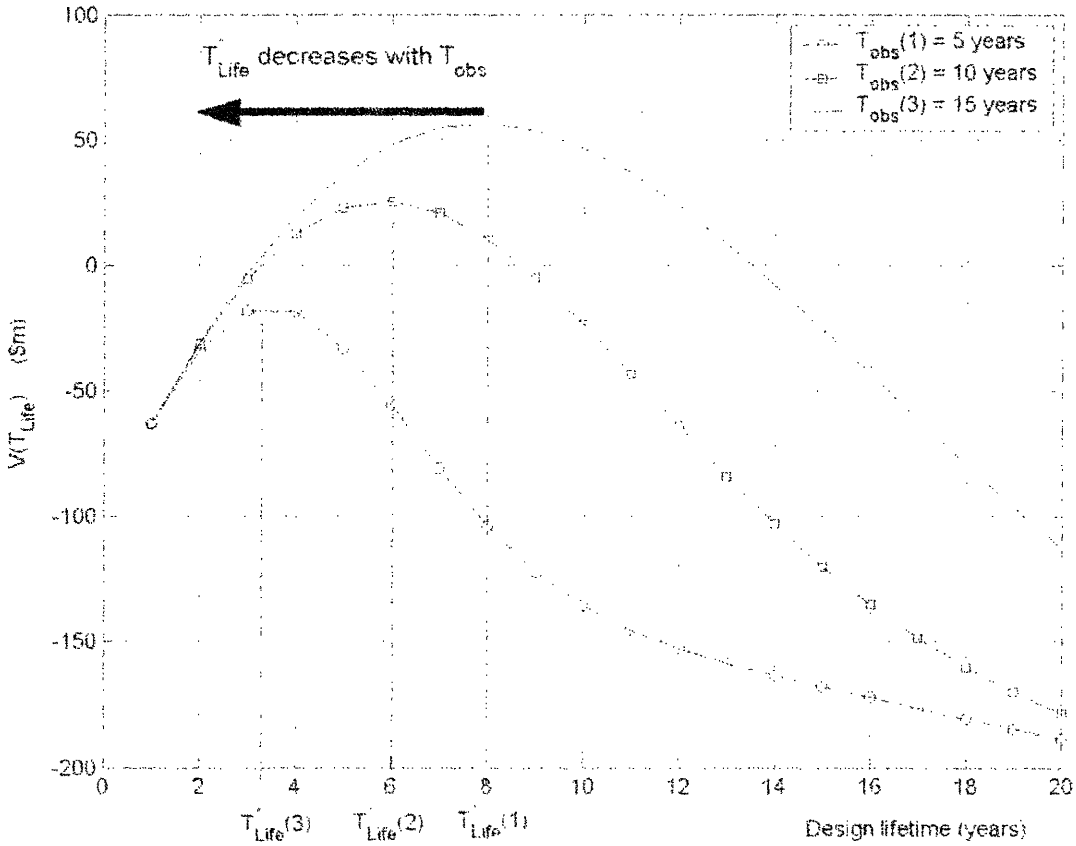


Figure 5.7: Expected present value of a satellite as a function of its design lifetime, assuming revenues per day affected by system's obsolescence (Eq. 16). Optimal design lifetime deceases as the expected Time to Obsolescence decrease.

Several observations can be made:

1. Given our assumptions, an optimal design lifetime exists that maximizes the expected present value of a satellite as a function of its design lifetime $V(T_{Life})$. In other words, even if it is technically feasible to design a spacecraft for an extended lifetime, it is not necessarily in the best interest of the customer to ask the contractor to provide a spacecraft designed for the maximum achievable lifetime. This result, i.e., the existence of an optimal design lifetime, disproves the implications of Eq. 13 that the customer is always better off requesting the contractor to provide a spacecraft designed for the

maximum achievable lifetime. We recall that this latter conclusion was reached by considering only cost factors, namely the monotonic decrease of the cost-per-operational day metric as a function of the design lifetime (see Figure 5.4).

2. The optimal design lifetime increases as the expected revenues per day increase (e.g. from 14 to 21 years as the revenues increase from \$50k/day to \$90k/day). In other words, the more revenues customers expect to generate from a system, the longer they would want the system to remain operational. This of course is an intuitive result; Eq. 10 and Fig. 5.6 provide a quantitative basis for it.
3. In Fig. 5.7, we note that the optimal design lifetime deceases (from 8 to 3.5 years) as the expected system's Time to Obsolescence decreases (from 15 to 5 years). In other words, the sooner customers expect a system to become obsolete, the shorter they should require its design lifetime to be. While this result is intuitive, Eq. 10 and 16 provide a quantitative justification for it.

Caveat and limitations: The above results DO NOT prove the existence of optimal design lifetimes for complex engineering systems. They merely illustrate the fact that, under certain assumptions, satellites have optimal design lifetimes that maximize a value metric. Caution and – given the complexity of the task and analyses needed–humility are required before extrapolating these results beyond their domain of applicability. The results however do show the importance of undertaking the engineering, market, and financial analyses we described above as their integration (Eq. 10) can significantly impact the choice for the design lifetime of the system the customer is contemplating acquiring. More generally, our results show that intuition is not necessarily a good guide in selecting or specifying a complex engineering system design lifetime, and that customers are not always better off requesting the contractor to provide a system with a maximum lifetime technically achievable.

In another work, we explored the impact of the probabilistic case of Time to Obsolescence, as well as the market volatility. The results show that the less the customers know about the dynamic characteristics of the system's underlying technology base as well as its market, i.e., the larger the standard deviation of the expected Time to Obsolescence as well as the market volatility, the shorter customers should require their system or investment design lifetime to be (staging the design lifetime); however, the more valuable it becomes to contract options for the system's life extension, upgrade or modification. It is worth noting that our findings are in accord with a fundamental lesson from finance and the real option approach: namely that there is increasing value in breaking up large projects in uncertain markets or staging investments in volatile environments:[11] the analysis of a spacecraft cost profile as a function of its design lifetime, $C(T_{Life})$, and Fig. 5.2, show a direct mapping between investment and design lifetime. The background and analytics for these results are beyond the scope of this paper; the reader is referred to Ref 7 and 12 for a more comprehensive discussion.

5.3.5. Sensitivity analysis

We now perturb the assumptions underlying the analyses discussed previously and explore the impact on the optimal design lifetime. Four models or parameters affect the solution of Eq. 10, namely the system's expected revenue model $u(t)$, its cost profile $C(T_{Life})$, the discount rate r, and the cost per year to operate and maintain the system $\theta(t)$.

Our nominal case is the following:

$$\begin{cases} u_n(t) = \$70{,}000/\text{day} \\ r_n = 10\% \\ \theta_n(t) = 10\% \text{ of } C(T_{Life}) \\ C_n(T_{Life}) = \$200 \text{ million designed for 15 years with an average slope of } 4\%/\text{year} \end{cases}$$

The results of the sensitivity analysis are displayed in Fig. 5.8. The plot reads as follows: a 10% increase in the satellite expected revenues for instance, results in an 8.4% increase in the optimal design lifetime. Conversely, a 10% increase in the investment discount rate results in a 7.9% decrease in the spacecraft optimal design lifetime.

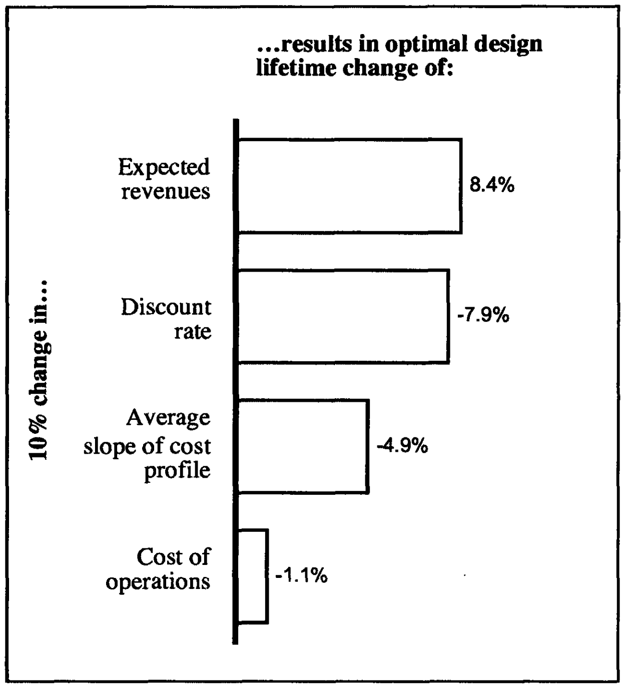


Figure 5.8: Sensitivity analysis of the optimal design lifetime to variations in underlying models and assumptions.

Given our assumptions and the nominal case considered, we find that the "location" of the optimal design lifetime is most sensitive to the expected revenues of the satellite over its design lifetime $u(t)$, as well as the investment discount rate, r. Equally important is the spacecraft cost profile $C(T_{Life})$ and how it scales with T_{Life}. Of minor importance however is the impact of the cost of operations $\theta(t)$ on the optimal design lifetime. These results, while illustrative, indicate where potential customers should invest resources and conduct careful modeling before selecting a design lifetime for their system, and where they can make do with limited accuracy of their models: of prime importance are the market analyses and forecast of the system's expected revenue model, as well as financial analysis of the investment riskiness. Equally important are the engineering and cost estimate analyses of the system's cost profile. Of lesser importance to the selection of the design lifetime is the technical analysis and estimate of the cost to operate and maintain the system.

5.4. Are Satellite Manufacturers Driving Themselves Out of Business by Designing for Increasingly Longer Lifetime?

The discussion about optimal design lifetimes in the previous sections was conducted from a customer-centric perspective. What about the manufacturers? More generally, what about the entire industry value-chain? How are all the players involved in the manufacturing, fielding, and operation of a complex engineering system affected by the system's design lifetime? Satellites for example are the lifeblood of the space industry and it is only fitting to ask how does increasing or decreasing their design lifetime affect the manufacturers, the launch services, and the operators?

The results in this section are preliminary; they will be developed further in a forthcoming paper. We chose nevertheless to share them because they make a strong case for the spacecraft design lifetime as a powerful yet overlooked lever that can significantly impact the entire space enterprise value chain.

5.4.1. Adapting Augustine's "First Law of Impending Doom" to the commercial space sector

Norman Augustine, former Chairman and CEO of Lockheed Martin, half-jokingly calculated that the cost of a tactical fighters quadrupling every 10 years, by 2054, the entire defense budget would be able to purchase just one aircraft! We contend there is somewhat similar dynamics in the commercial space sector, a geometric increase in satellite capability that will herald the "Second law of impending doom" of the commercial space sector. What are these dynamics and what is the "Second law of impending doom"?

Over the past ten years, communications satellites have continued to grow in terms of size, power, and design lifetime. The average number of transponders (36 MHz transponder equivalent) for example has increased from 26 in 1992 to 48 in 2002. The increase in power and design lifetime is shown in Table 5.3. We also include in the table the Compounded Annual Growth Rate (CAGR) over the 10-year period.

Table 5.3: Trend in GEO satellite size, power, and design lifetime (Data Source: Futron Corporation)

	1992	*2002*	*CAGR (1992-2002)*
Average number of 36 MHz transponder equivalent (TE)	*26*	*48*	*6.3%*
Average power level	2.2	*7.6*	*13.2%*
Average design lifetime	*8*	*14*	*5.8%*

The increase in number of transponders on-board a spacecraft, along with enhanced data compression techniques and increase in design lifetime have contributed to make satellites ever more powerful. According to the Futron Corporation, "the average satellite of today is approximately 900% more capable than the average satellite launched in 1990. In other words, the average satellite launched today is doing the equivalent work of 9 average satellites launched in 1990."[13] Assuming this trend will maintain its momentum, we can state our "Second law of impending doom" of the commercial space sector:

The capability of a communications satellite doubling every 4 years, the entire demand for satellite services and bandwidth in 2021 will be satisfied by just one satellite!

5.4.2. The space sector financial scorecard

There is a large discrepancy in the financial health and performance of the different players in the space industry value chain. We only consider in this section the satellite manufacturers, launch services, and satellite operators; equipment manufacturers, end users, insurance companies, regulatory agencies and others who play a role in the space industry value chain are not discussed here.

There is a myriad of metrics to describe the financial performance and outlook for a company or an industry; we choose for this section a reduced financial scorecard with two measures: the sector's revenue growth over the past five years as well as its operating profitability or EBITDA margin. These two measures provide a good indication of the sector's past financial performance, as well as its financial attractiveness, outlook, and valuation.

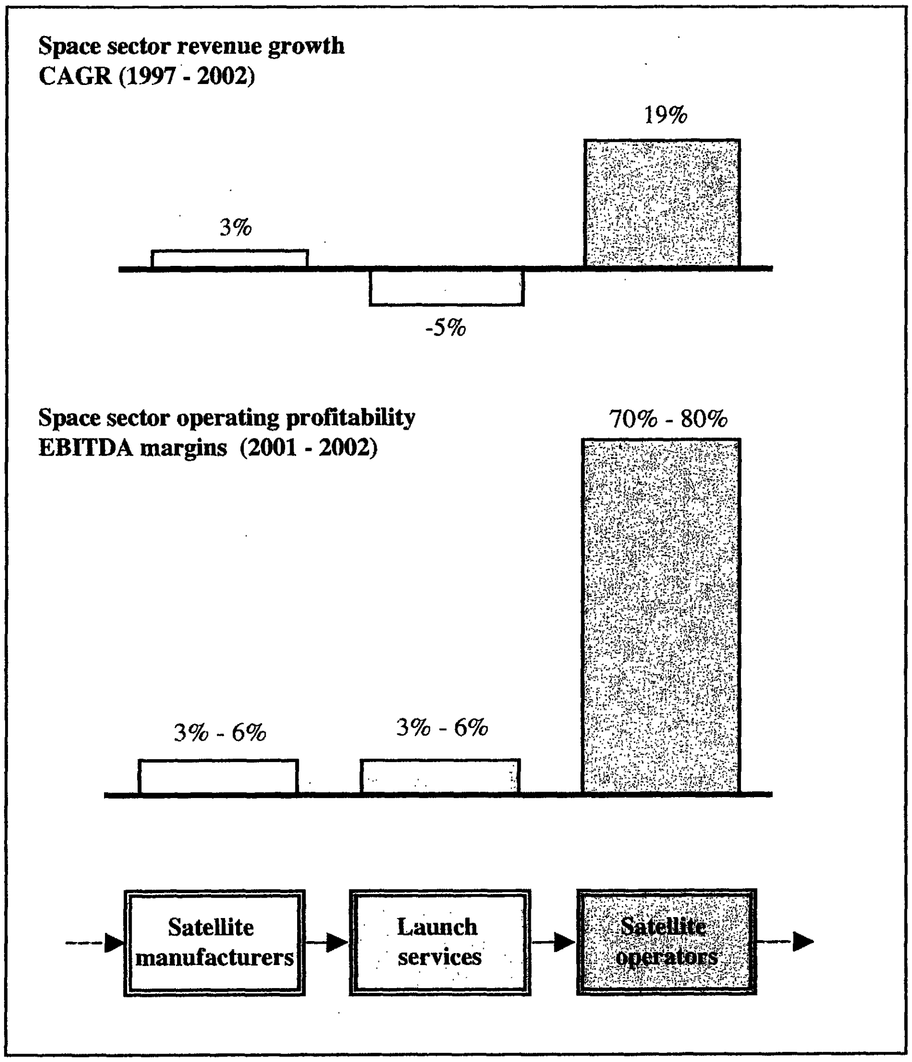


Figure 5.9: Financial scorecard for the key players in the space sector (Data sources: Futron Corporation, IDATE, annual reports).

The results are shown in Fig. 5.9. They merely confirm what is already known in the industry, namely that:

Satellites are "cash-cows" for the operators! Satellites operators are posting excellent profitability compared to any other economic sector. In fact the EBITDA margins we found show little variation and have been hovering over the past 5 years between 70% and 80% (e.g., AsiaSat, EutelSat, IntelSat, PanAmSat, SES Global)

The combined effect of several factors has decreased the demand for GEO satellites, and dramatically limited the growth potential as well as the profitability of satellite manufacturers and launch services. Among those factors, first and foremost, there is the substantial overcapacity in satellite manufacturing and launch services. This overcapacity is driving a heightened competition among manufacturers, putting downward pressure on prices and allowing operators to set aggressive terms and conditions for procurement. All these effects results in the very small margin we see in Fig. 5.9. The relatively flat demand for GEO communications satellites results from another set of factors: on the one hand, there is no, or not yet, a "killer app" that will revitalize the market and spur demand for new satellites that can provide broadband access and compete with cable and DSL. On the other hand, there is the fact that manufacturers are designing spacecraft ever more capable, with increased number of transponders, enhanced data compression techniques and extended design lifetime, thus limiting the need for additional spacecraft (see the "Second law of impending doom" of the commercial space sector discussed above).

Figure 9 also suggests that the current industry structure is not sustainable, and that we will likely witness consolidation, vertical integration, and/or business unit divestiture in the near future. In a forthcoming publication, we discuss the emergence of a new space industry structure, and the possibility of a duopoly in the world satellite manufacturing business.

5.4.3. Design lifetime impact on the forecast for satellite orders

The satellite is the lifeblood of the space industry. Unfortunately, unlike other industries that can generate additional revenues, and higher profits, from service contracts in addition to the sale of their systems, e.g., jet engines, satellite manufacturers do not have this option given the particular feature of GEO satellites of being physically inaccessible for maintenance or upgrade. On-orbit servicing remains to date a stalled idea of limited practicality; Ref. 12 provides a comprehensive discussion of this subject matter. We therefore are left with the number of satellites ordered as a defining metric of the industry's financial performance and health.

How does changing the design lifetime affect the demand for communications satellites going forward? In order to answer this question, the global demand for telecommunication services (telephony, video, data) must first be estimated. Second, terrestrial competition must be assessed as well as the demand that can be captured by terrestrial networks. We are then left with the demand for satellite bandwidth, which can be translated into demand for actual satellites given the inputs of satellite size (number of transponders), utilization rate, and design lifetime. There are numerous financial analysts' reports, as well as consulting companies that provide the data for the first and second step discussed above. We have relied in this section on the forecast for satellite bandwidth over the period of 2004 to 2012 provided by the Futron Corporation; using a design lifetime of 15 years, a utilization rate of 60% to 80%, and an average of fifty 36 Mhz Transponder-Equivalents, Futron forecasts a dramatic decline in the demand for communications satellites. The company estimates there will be a need for barely 8 to 15 commercial GEO satellites for the next several years. We have relied on Futron's estimate for satellite bandwidth, and used the current average satellite utilization rate (60%) and number of Transponder-Equivalents (48). However, we varied the design lifetime between 5 and 15 years. Our results are shown in Fig. 5.10.

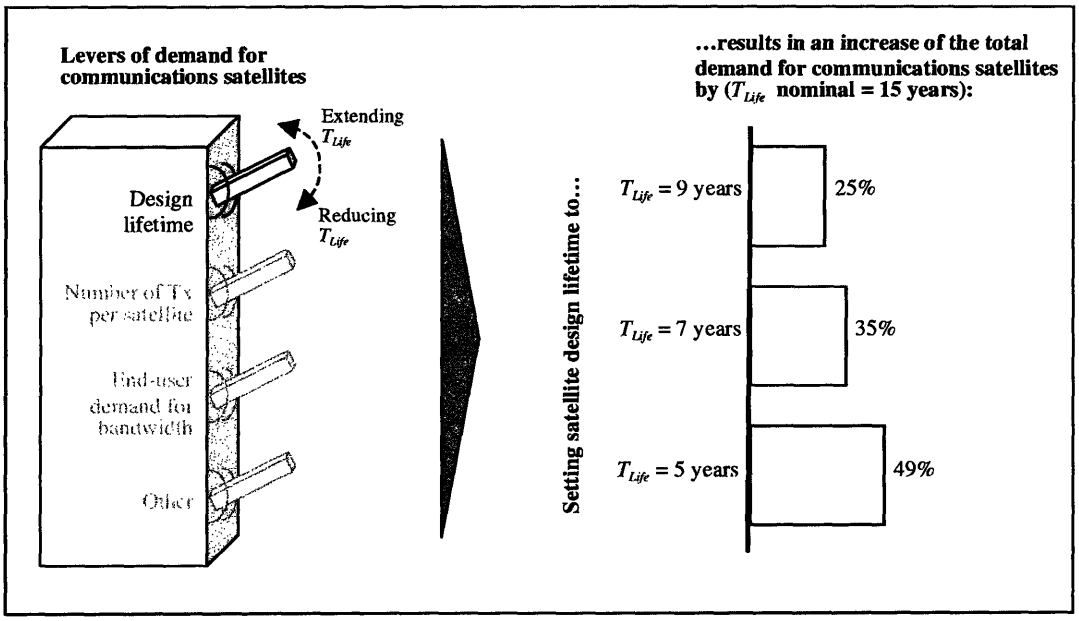


Figure 5.10: Impact of the design lifetime lever on the total demand for communications satellite over the period 2004 – 2012. The nominal design lifetime is set 15 years.

The results show for instance that, should manufacturers set the design lifetime of their communications satellites to 9 years instead of 15 years, there would be a 25% increase in the demand for communications satellites over the next several years (2004 to 2012), compared to demand resulting for a design lifetime set at 15 years.

Though preliminary, these results show nevertheless that a spacecraft design lifetime is a powerful, yet overlooked lever that can significantly impact the market size for commercial communications satellites. In addition, it is likely that these results will affect the financials of the key players in the space sector, and can result in a redistribution of growth and margins, other than the one displayed in Fig. 5.9. We explore these issues in a forthcoming paper.

5.5. Summary and Conclusion

We set up to explore the engineering and economic issues at stake for reducing or extending a complex system's design lifetime, using spacecraft as example. In the first section of this paper, we came to recognize that when exploring these issues, or when asking whether there is an optimal design lifetime for complex engineering systems, it is necessary to first specify from which stakeholder's perspective the analysis is carried out as the interests and trade-offs can be substantially different. We then synthesized and discussed the different qualitative implications associated with reducing versus extending a product's durability or a system's design lifetime, as seen from the perspective of three stakeholders, namely the customer, the manufacturer, and society. The purpose of this qualitative discussion was to illustrate the complexity of the choice in reducing or extending a system's design lifetime–not to take a position for reducing or extending this requirement–and to lay the ground for the quantitative discussion that followed. Following the qualitative discussion, we asked whether there is an optimal design lifetime for complex engineering systems, as seen from the customer's perspective. In order to answer this question, we first made the case for a mindset change regarding system's design and architecture: we discussed the need on the one hand to view in a system the flow of service (or utility) that it will provide over its design lifetime, and on the other hand, to introduce metrics per unit time such as cost, utility and value as functions of time. Second, optimality presupposes a metric that is minimized or maximized; we therefore proposed Eq. (1) as a means for capturing the present value of a system as a function of its design lifetime. After discussing the quantitative analyses required in order to answer the design lifetime optimality question, we show that, under certain assumptions, satellites do have optimal design lifetimes that maximize the value metric we introduced. Theses result disproves the traditional implicit assumption that satellite operators are always better off requesting the manufacturer to provide a spacecraft designed for the maximum technically achievable lifetime. Caution, however, and–given the complexity of the task and analyses needed–humility are required before extrapolating these results beyond their domain of applicability and generalizing them to other complex engineering systems. The results nevertheless demonstrate the importance of undertaking the engineering, market, and financial analyses we described in this paper, and illustrate using spacecraft as example, as their integration can significantly impact the choice for the design lifetime of the system the customer is contemplating acquiring. In the last section, we ask provocatively if satellites manufacturers are driving themselves out of business by designing for increasingly longer lifetime? We review the trends in GEO communications satellites in terms of power, number of transponders, and design lifetime and conclude half-jokingly, that should these trends maintain their momentum, the entire demand for satellite services and bandwidth in 2021 will be satisfied by just one satellite; we called this result the "Second Law of impending doom" of the commercial space sector, in deference to Augustine's "First law of impending doom" regarding the rising cost of tactical fighters and the ability of the DoD to purchase just one aircraft in 2054! More seriously, we showed that the design lifetime is a powerful, yet overlooked lever that can significantly impact the market size for commercial communications satellites as well as the financials of the key players in the space sector.

Our main claim in this paper is that issues pertaining to the selection and specification of a an engineering system design lifetime are much more complex–and interesting–than those related to a simple product's durability; and that these issues beg careful consideration and require much more attention than what they have received so far in the literature as the impact of a system's design lifetime is substantial and can ripple throughout an entire industry value chain.

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Chapter 6 *

Utilization Rates of GEO Communication Satellites

Statistical analysis of loading dynamics

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Satellites have been rightfully described as the lifeblood of the space industry, and the number of satellites ordered per year is to a large extent the defining metric of the industry's level of activity. Similarly, the case can be made that a key metric for the commercial space communication sector is the utilization rate, or load factor, of a satellite or a fleet of satellites. For this paper, we collected and analyzed load factor data of twenty one communication satellites launched between 1980 and late 1990s. We conducted time series analysis and built statistical models for the evolution of utilization rates, or loading dynamics, of a communication satellite that broadly address three questions: First, how fast does a satellite get "filled up" after it has been launched? Second, does a satellite load factor reach a steady-state level? Third, if a steady-state load factor is reached, does it remain at that level or does it decline (when and how fast if so) as the satellite ages? We found consistent results that exhibit three different loading patterns: these patterns are consistent within groups of satellites launched in the early 1980s, in the late 1980s, and in the mid 1990s (load factor ramp-up in three to four years; a steady-state load factor between 80% and 100%; and a decline in load factor after five to seven years on-orbit for satellites launched in the mid 1990s). We further discuss these results and the factors that drive satellite loading dynamics, from the supply/demand (im)balance of on-orbit bandwidth over the

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last two decades to customer churn from aging transponders and switching towards newer more powerful and reliable units. Results should prove useful to satellite operators and industry observers; they also inform the estimation and specification of financially optimal satellite design lifetimes.

Nomenclature

$A_{Tx}(t)$	=	Number of added transponders during year t.
D_{Tx_global}	=	Global demand for transponders.
$f(.)$	=	Probability density function.
$L(t, i)$	=	Load factor of satellite i at time t. Also known as the utilization rate or fill rate.
$\bar{L}(t)$	=	Instantaneous average load factor of $L(t, i)$.
$\bar{L}_{BOL}$	=	Beginning-of-life average load factor of $L(t, i)$.
$\bar{L}_{EOL}$	=	End-of-life average load factor of $L(t, i)$.
$\langle L \rangle_{global}$	=	Average load factor of the entire GEO fleet of communications satellite at any given year.
$\langle L \rangle_{operator}$	=	Average load factor for the fleet of satellites of a given satellite operator at any given year.
$\langle L \rangle_{region}$	=	Average load factor of all satellites serving a given geographical region, e.g., North America, at any given year.
$n_{Tx\_active}(t, i)$	=	Number of active transponders on-board satellite i at time t.
$N_{Tx\_total}(i)$	=	Total number of transponders on-board satellite i.
$\langle OC \rangle_{global}$	=	Global overcapacity of satellite transponders.
$r(t)$	=	Range of load factors (min-max values difference) at time t.

r_0 = Initial range or dispersion of load factors.

$R_{Tx}(t)$ = Number of retired transponders during year t.

S_{Tx_global} = Global supply of transponders.

T_{obs} = Time to obsolescence.

α = Exponential coefficient in the range model.

$\Delta D_{Tx}(t)$ = Incremental demand for transponders during year t.

$\Delta S_{Tx}(t)$ = Incremental supply of transponders during year t. $\Delta S_{Tx}(t) = A_{Tx}(t) - R_{Tx}(t)$.

$\sigma(t)$ = Standard deviation of $L(t, i)$.

τ = Exponential fill time constant.

6.1. Introduction and problem statement

On October 4, 1957, a small beeping satellite, Sputnik, heralded the beginning of the Space Age. From this humble start, the space industry grew into an impressive $100 billion industry four decades later. Space technology today pervades many aspects of our daily lives with services ranging from video distribution for TV and cable networks, to telephony and data communications, and to Earth monitoring and meteorological services (not to mention the less publicly visible military applications of reconnaissance of electronic surveillance). The commercial space industry unfortunately hit turbulence around the year 2000; its growth potential and financial attractiveness were revised downwards, especially after the collapse of the Low Earth Orbit (LEO) communications systems, which led many companies and investors to revise their commitment to this industry. In 2002 for example, only six communications satellites were ordered, thus severely straining the satellite manufacturers operations. The number of satellites ordered per year has increased since then, and is expected to range between eight and fifteen for the rest of the decade[1]. Satellites have been rightfully described as the lifeblood of the entire space industry (satellite manufacturers, launch system providers, satellite operators, equipment providers and space insurance), and the number of satellites ordered per year is to a large extent the defining metric of the industry's level of activity, at least upstream of the space industry value chain (e.g., for the satellite manufacturers and equipment providers).

Another equally important and defining metric downstream in the space industry value chain (e.g., for the satellite operators) is the utilization rate, or load factor, of a satellite or a fleet of satellites. Simply put, a high utilization rate suggests that the demand for on-orbit capacity may not yet be fully satisfied, and the market can absorb additional capacity (hence new satellites will be ordered). Conversely, a low utilization rate suggests that there might be over-capacity in the market, and investment in additional capacity is better put on hold until the market conditions are carefully investigated (or the satellite operator fully loads its on-orbit assets before investing in new ones).

In this study, we set out to explore the loading dynamics of GEO communications satellites. This paper is organized as follows. Section 2 presents different average load factors of communications satellites, and discusses them as measures of supply and demand (im)balance of on-orbit transponders. Three average load factors are considered: first, the global average load factor of the entire fleet of GEO satellites, $\langle L \rangle_{global}$; second, the regional load factor of GEO satellites serving specific geographic regions, $\langle L \rangle_{region}$, for example North America, Western Europe, or Asia Pacific; and third, the average load factor of specific satellite operators $\langle L \rangle_{operator}$. The discussions in this second section of this paper were supported by data that is either available publicly or reported in the specialized press. Following the "static" analyses of load factors in Section 2, we turn our attention in the third and fourth sections of this paper to the loading dynamics–not averages but evolution over time of the load factor–of a satellite after it has been launched. We identified a sample of twenty-one communications satellites over North America, launched between 1980 and 1997, and collected their yearly load factor from the time of their launch until their retirement. To the best knowledge of the authors, this is the first time such time series data of satellite load factors has been collected, analyzed, and presented to the technical community. The data we collected allowed us to answer three questions. First, how fast does a satellite get "filled up" after it has been launched? Second, does a satellite load factor reach a steady-state level? Third, if a steady-state load factor is reached, does it remain at that level or does it decline (when and how fast if so) as the satellite ages? We found some interesting loading patterns that we report and analyze in Section 4. Finally, Section 5 concludes with the summary and implications of this work.

6.2. Satellite load factor and fleet average load factors

The load factor of a communications satellite, also known as its utilization rate or fill rate, is defined as the ratio of the number of transponders active or leased at a given time to the total number of transponders on-board the spacecraft. For a given spacecraft i, its load factor at time t is given by Eq. 1:

$$L(t, i) = \frac{n_{Tx\_active}(t, i)}{N_{Tx\_total}(i)} \qquad (1)$$

Equation 1 represents the "instantaneous" load factor of one specific satellite. This measure of the utilization of a satellite payload is rarely available publicly. Instead, the specialized press often reports "average" load factors, for example the "average" load factor for the entire GEO fleet of communications satellites every year. Figure 1 illustrates this global average, $\langle L \rangle_{global}$. There are however different ways of averaging load factors. For example, an average can be calculated for all the satellites serving a given geographical region, e.g., North America or Western Europe, $\langle L \rangle_{region}$ as seen in Fig. 5.2. Another average load factor can be calculated for the entire fleet of satellites of a given satellite operator, $\langle L \rangle_{operator}$ as seen in Figure 3. It is important to note the difference between these average load factors and the "instantaneous" load factor for one specific satellite given in Eq. 1, the analysis of the latter being the novel contribution in this paper.

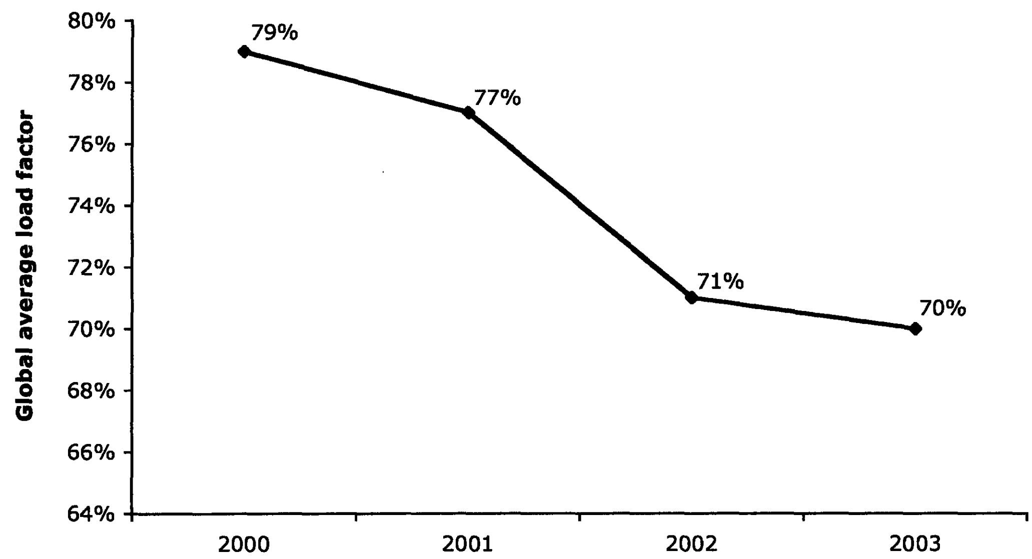


Figure 6.1: Average load factor of the entire fleet of GEO communications satellites, $\langle L \rangle_{global}$. Adapted from Ref. 2.

Average load factors are important metrics in the commercial satellite communications world. They represent a measure of the supply/demand imbalance of on-orbit transponders, globally or regionally, and reflect to some extent how well satellite operators are managing their on-orbit assets, as we will discuss shortly.

Global load factor: Figure 6.1 shows a steady decline in the average load factor of the entire GEO fleet of communications satellites, $\langle L \rangle_{global}$, from 79% in 2000 to 70% in 2003. In 2003, there was globally a total of 7,585 transponders available on-orbit[2]. We refer to this as the global supply of transponders, S_{Tx_global}. An average global load factor of 70% (69.85%) indicates that out of the 7,585 transponders available, there were in effect 5,299 transponders in use in 2003. We refer to this number as the global demand for transponders in 2003, D_{Tx_global}. The number of unused transponders in 2003 was therefore 2,286. This represents a significant unused on-orbit capacity. Equation 2 relates the global supply and demand of transponders to the global average load factor:

$$\langle L \rangle_{global} = \frac{D_{Tx\_global}}{S_{Tx\_global}} \qquad (2)$$

Figure 6.1 also shows a significant drop in global load factor, $\langle L \rangle_{global}$, between 2001 and 2002 from 77% to 71%. This is due to three colluding factors: 1) a significant number of new transponders were launched in 2002 (over 1,000 transponders), 2) few were retired resulting in a net add of 745 transponders in 2002 (compared to 103 net add in 2001), and 3) the demand for additional transponders in 2002 grew at a very slow rate of 2.9%.[2] More generally, we can relate the global load factor from one year to another by considering the incremental demand for transponders during that year $\Delta D_{Tx}(t)$, and the added and retired transponders during that year $A_{Tx}(t) - R_{Tx}(t)$, as shown in Eq. 3 (the subscript *global* is omitted from Eq. 3 for readability purposes but should be assumed for all the variables):

$$\langle L(t+1) \rangle = \frac{D_{Tx}(t+1)}{S_{Tx}(t+1)} = \frac{D_{Tx}(t) + \Delta D_{Tx}(t)}{S_{Tx}(t) + \left[A_{Tx}(t) - R_{Tx}(t)\right]} \approx \langle L(t) \rangle \times \left[1 + \frac{\Delta D_{Tx}(t)}{D_{Tx}(t)} - \frac{\Delta S_{Tx}(t)}{S_{Tx}(t)}\right] \qquad (3)$$

We define the global overcapacity, $\langle OC \rangle_{global}$, as the percentage of unused transponders from the global supply of on-orbit transponders (Eq. 4):

$$\langle OC \rangle_{global} = \frac{S_{Tx\_global} - D_{Tx\_global}}{S_{Tx\_global}} = 1 - \langle L \rangle_{global} \qquad (4)$$

It should be noted that some industry observers consider 20% or less of unused transponders a useful margin to have for reliability purposes (e.g., back-up), and to accommodate occasional leases of satellite capacity for unplanned events[2]. While this distinction between unused transponders and overcapacity is pertinent, it can be argued that 20% unused transponders when the global supply is over 7,000 transponders (instead of say a few hundred transponders) is excessive and does constitute "overcapacity". Changes in global transponder supply, demand, overcapacity, and load factors between 2000 and 2003 are summarized in Table 6.1.

Table 6.1: Global supply, demand, and overcapacity in satellite transponders (Data source: Euroconsult[2]).

	2000	2003
Global supply of Tx, S_{Tx_global}	6,409	7,585
Global demand for Tx, D_{Tx_global}	5,072	5,299
Global load factor, $\langle L \rangle_{global}$	79%	70%
Un-used Tx	1,337	2,286
Overcapacity, $\langle OC \rangle_{global}$	21%	30%

Regional load factor: Communications satellites are launched into specific orbital slots and designed to serve specific geographical regions. Regions in turn have different supply/demand characteristics that are not reflected in the global average load factor $\langle L \rangle_{global}$. This finer level of detail is instead captured in the regional load factor, calculated for all satellites serving a given geographical region $\langle L \rangle_{region}$. Figure 6.2 represents this metric for North America, Western Europe, Central and East Europe, and the Asia Pacific region. We see for example that the supply/demand imbalance is significantly higher in Central Europe with a load factor of 56% (or conversely an overcapacity of 44%[*]) than in Northern America where the average load factor is 76% (or 24% overcapacity). Increased overcapacity, along with industry structure and competitive intensity, translates into increased downward pressure on transponders lease prices. For example, the average lease price of a transponder in North America in 2003 averaged $1.2 million/year, whereas in Central and Eastern Europe, transponder lease price averaged $0.9 million/year[2].

[*] Or 44% – 20% = 24% based on the definition of overcapacity used in Ref. 2.

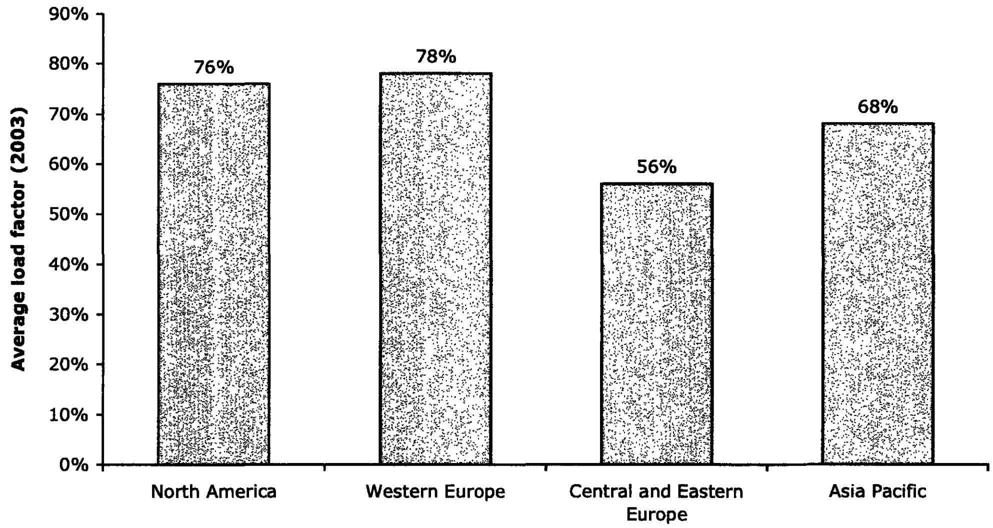


Figure 6.2: Average load factor in 2003 by region (Data source: Euroconsult[2]).

Operator load factor: A third "average" load factor can be calculated for the fleet of satellites of a given satellite operator, $\langle L \rangle_{operator}$. This metric reflects to some extent how well a particular satellite operator is managing its on-orbit assets. Figure 6.3 shows the load factors of four major satellite operators. Eutelsat for example had 77% of its on-orbit capacity leased in 2003, whereas Intelsat had only 61% of its on-orbit capacity utilized during that year (from a total of 1,845 transponders)[2]. This low utilization rate represents a sizeable opportunity loss for Intelsat: a simple calculation shows that, at an average lease price of $1.4 million/year, should Intelast improve its management and operation of its on-orbit assets to the level of Eutelsat (77%), it could generate an additional $400 million per year. This is a significant revenue increase for a company that generates approximately a billion dollars a year. Figure 6.3 also shows the contributions of Video and Voice and Data services to the utilization of satellite fleet of each of the four satellite operators we considered. Video is clearly seen as a major contributor to satellite utilization (approximately 50% for three major satellite operators) except for Intelsat, which for historical reasons, being an Inter-Governmental Organization until 2001, had limited strategic flexibility in deciding its service mix of voice and video.

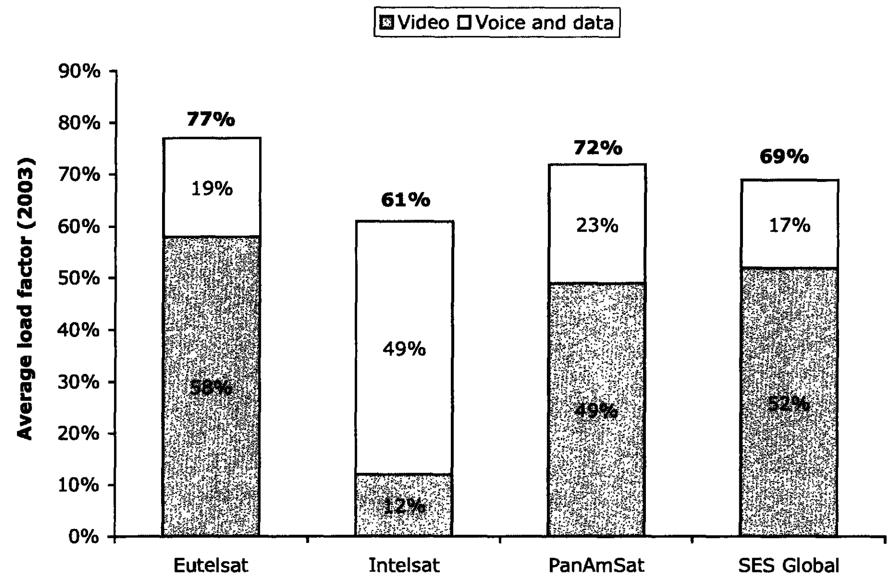
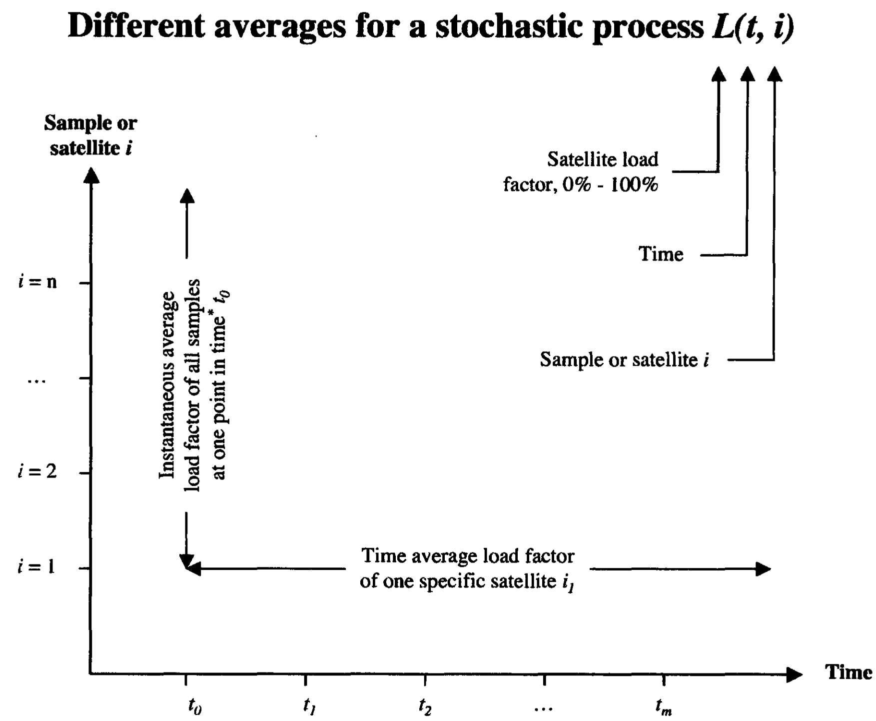


Figure 6.3: Average load factor of four major satellite operators, and contributions of Video and Voice and Data services to the utilization of their satellite fleet (Data source: Euroconsult[2]).

6.3. Satellite loading dynamics following launch: data collection and methodology

In the previous section, we discussed different average load factors for communications satellites, $\langle L \rangle_{global}$, $\langle L \rangle_{region}$, $\langle L \rangle_{operator}$, from data that is either available publicly or reported in the specialized press. In this section, we are interested in gaining insights into the loading dynamics–not averages but evolution over time of the load factor–of a single satellite i, after it has been launched, $L(t, i)$. A satellite load factor, $L(t, i)$, can be modeled as a stochastic process or a random function of time. A stochastic process is simply an indexed family of random variables in which the index corresponds to time[3] (in other words, for every specific time t_0, $L(t_0, i)$ is a random variable). We therefore posit that $L(t, i)$ follows some random probability distribution and can be analyzed statistically. The reader may be familiar with "time series": when the time index of a stochastic process takes only discrete values, the stochastic process is called a time series. Figure 6.4 shows the different averages that can be computed for a stochastic process.



* Sometimes referred to as *expectations* or *ensemble average*

Figure 6.4: Modeling satellite load factor as a stochastic process *L(t, i)*.

In order to conduct our statistical analysis of *L(t, i)*, we first needed to obtain load factor data of a number of satellites from the time of their launch until their retirement. This information is understandably proprietary and satellite operators are not necessarily eager to publicly share such data, which can be used to target marketing or sales efforts.

To circumvent this difficulty, we teamed with Communications Center, a company that has been tracking and measuring North American transponder usage and supply using their own earth stations of spectrum analyzers in conjunction with a variety of video and audio receivers. The reader is referred to Ref. 4 for a thorough discussion of the data collection methodology. We identified a sample of twenty-one communications satellites over North America, launched between 1980 and 1997, and collected their yearly load factor from the time of their launch until their retirement. To the best knowledge of the authors, this is the first time such time series data of satellite load factor is collected, analyzed, and presented to the technical community.

An initial display of the raw data collected did not reveal any interesting pattern. However, when we segmented our sample into three categories defined by the launch period of the satellite: early 1980s, late 1980s, and mid 1990s, and initialized the time axis to the year of launch, we found some very interesting patterns in the load factor time series *L(t, i)*. These are discussed in the following section.

6.4. Statistical analyses of satellite load factor

Of the twenty-one satellites for which we tracked the transponder usage throughout their design lifetime, eight were launched in the early 1980s, seven were launched in the late 1980s, and six were launched in the mid 1990s.

6.4.1. Load factors of satellites launched in the learly 1980s

Figure 6.5 shows the load factor raw data for the first group of satellites launched in the early 1980s. The time axis for all the satellites was initialized to the year of launch.

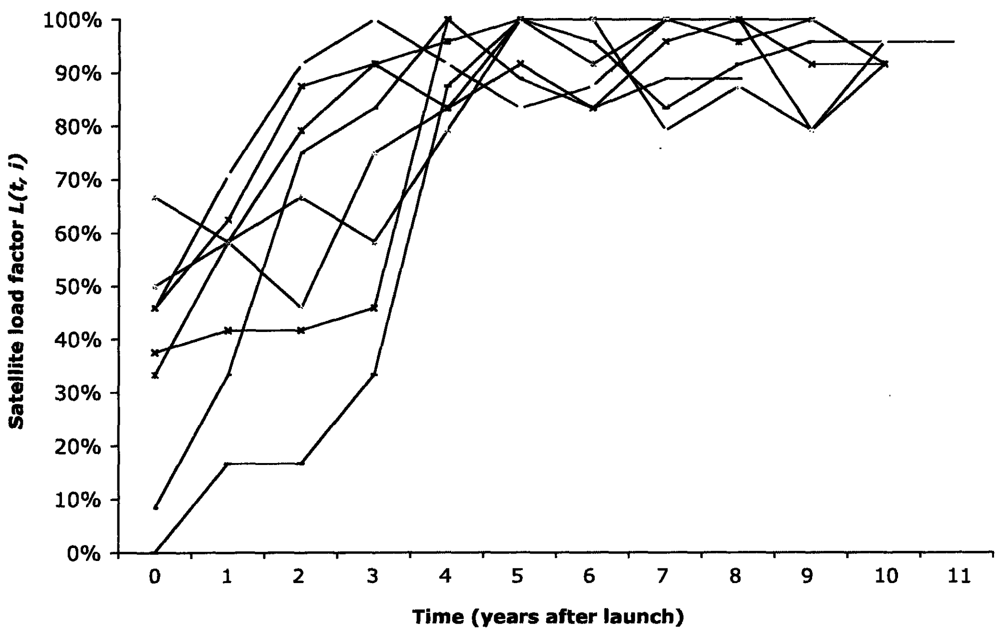


Figure 6.5: Load factor raw data for 8 satellites in our sample that were launched in the early 1980s

The data shows that a satellite load factor increases after it has been launched, as new customers are acquired and additional transponders are leased. The load factor ramp-up reaches steady state within three to five years. Interestingly, we find that some capacity on-board a satellite is already pre-booked (before the satellite is launched) and the initial average load factor is not 0% (it is in fact 35% for the sample in Fig. 6.5). This observation makes business sense and operators ideally should strive to book the entire satellite capacity as soon as or before the spacecraft reaches orbit; failure to do so can be interpreted as an opportunity loss for the operator of the satellite (i.e., an asset or the communications payload in our case is available to generate revenue but it is not put to work).

The "instantaneous" average load factor (see Fig. 6.4) is the average at every time step of all the satellite load factors in our sample. It is calculated as follows:

$$\overline{L}(t) = \frac{1}{n}\sum_{i=1}^{n} L(t, i) \qquad (5)$$

Based on the previous observations, we propose to model the instantaneous average load factor of a communications satellite $\overline{L}(t)$ as a function of time with three parameters or degrees of freedom: an initial beginning-of-life average load factor $\overline{L}_{BOL}$ at $t = 0$, a steady-state end-of-life average load factor, $\overline{L}_{EOL}$, and an exponential fill process with a time constant τ. Equation 6 represents our model structure. Results of the regression analysis using this model are given in Table 6.2.

$$\overline{L}(t) = \overline{L}_{BOL} + \left(\overline{L}_{EOL} - \overline{L}_{BOL}\right) \times \left(1 - e^{-\frac{t}{\tau}}\right) \qquad (6)$$

Table 6.2: Average load factor model parameters for satellites launched in the early 1980s

Model parameter	Value
Beginning-of-life average load factor, $\overline{L}_{BOL}$	35%
End-of-life average load factor, $\overline{L}_{EOL}$	95%
Exponential fill time constant τ	2.5 years
R^2	0.95

In addition to the instantaneous average load factor, $\overline{L}(t)$, the data collected allows us to model the envelope or range within which the satellites load factors fall for every time step after launch, as we discuss below. Figure 6.6 shows: 1) the envelope (minimum and maximum values) of the load factor for the satellites in our sample, 2) the observed instantaneous average load factor, and 3) the modeled instantaneous average load factor as given by Eq. 6 and Table 6.2.

We observe for example on Fig. 6.6 an initial large dispersion of load factors right after launch ($\overline{L}_{BOL}$ varies from 0% to 67%, and has an average of 35%). This may reflect how aggressive a satellite operator has been in pre-booking capacity on-board its satellite before launch: a satellite with an initial load factor of 0% suggests the satellite operator has either delayed or not been successful in its sales and marketing effort before its on-orbit asset was launched and became operational. On the other hand, a communications satellite with a high initial load factor suggests either that the operator has been aggressive and successful in its sales efforts prior to the launch of the spacecraft, or that the spacecraft is in fact a "replacement satellite" taking over capacity from another satellite that has reached the end of its service life. This latter hypothesis will be further discussed later.

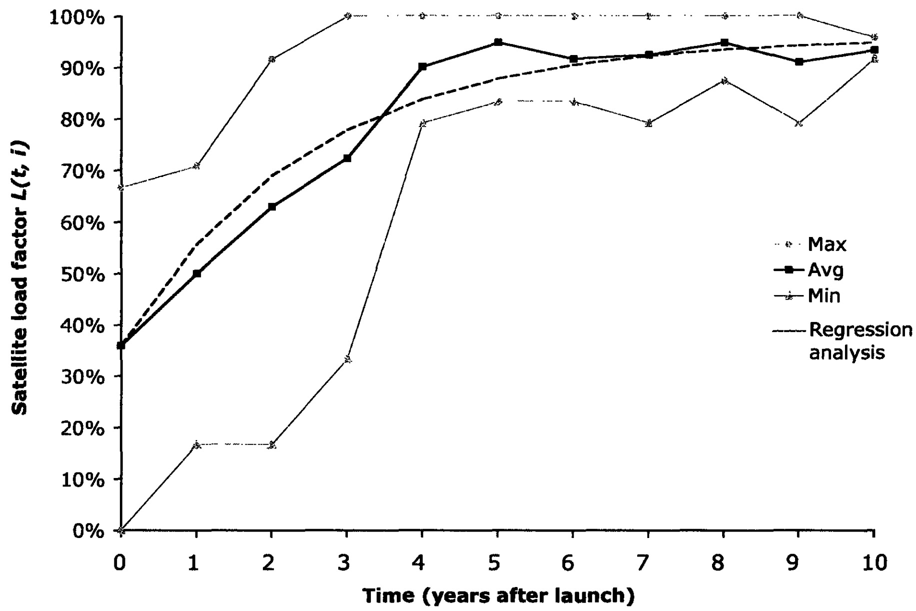


Figure 6.6: Load factor (average, min-max, and regression analysis) for 8 satellites in our sample that were launched in the early 1980s

We also observe on Fig. 6.6 that the dispersion of the load factor at every time step narrows down with time and reaches almost a steady state within four years. The range, or difference between the minimum and maximum values, in the load factors for satellites launched in the early 1980s is represented in Fig. 6.7.

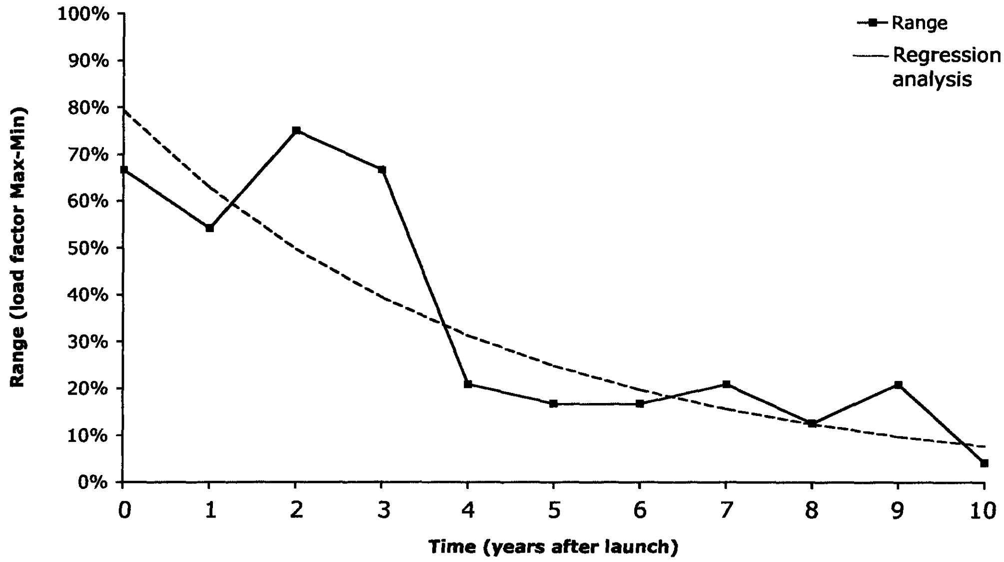


Figure 6.7: Dispersion or range of load factors (min-max difference) for satellites launched in the early 1980s.

We propose to model this range *r(t)* with a decreasing exponential function of time. Equation 7 represents our model structure (also shown in Fig. 6.7).

$$r(t) = r_0 \times e^{-\alpha \times t} \qquad (7)$$

Results of the regression analysis using this model are given in Table 6.3.

Table 6.3: Model parameters for the range of load factors (Eq. 7) for satellites launched in the early 1980s.

Model parameter	Value
Initial range, r_0	79%
Exponential coefficient, α	0.23
R^2	0.71

For simplification, we assume that the range is symmetrical with respect to the sample mean. By doing so, we make an average error of 18% on the minimum and maximum values of the load factors at each time step for the satellites in our sample (alternatively we could provide a parametric model for the minimum or maximum values of the load factor).

Finally, although the data we collected is insufficient to confirm the following (our sample space is too small to prove the following statistical inference), we **hypothesize** that the load factor *L(t, i)* is normally distributed, i.e., it has a Gaussian probability density function at each time step, and that the dispersion of load factors we observed in Fig. 6.6 and 6.7 represent 95% of all possible measurements. In other words, we assume that the range *r(t)* represents four standard deviations[#], $\sigma(t)$, of our assumed random vector *L(t, i)*. The Gaussian distribution we consider for *L(t, i)* is truncated and confined to the values of *L* between 0% and 100%. We translate this hypothesis mathematically as follows (the values of the parameters are summarized in Table 6.4):

$$\begin{cases} f[L(t)] = \dfrac{1}{\sigma(t) \times \sqrt{2\pi}} \times Exp\left\{ -\dfrac{\left[L(t) - \overline{L}(t)\right]^2}{2[\sigma(t)]^2} \right\} & \text{for } 0\% \le L \le 100\% \\ \overline{L}(t) = \overline{L}_{BOL} + \left(\overline{L}_{EOL} - \overline{L}_{BOL}\right) \times \left(1 - e^{-\frac{t}{\tau}}\right) & (8) \\ \sigma(t) = \dfrac{r(t)}{4} = \dfrac{r_0}{4} \times e^{-\alpha \times t} \end{cases}$$

Table 6.4: Summary of the model parameters for the load factor (Eq. 8)

Model parameter	Value
Beginning-of-life average load factor, $\overline{L}_{BOL}$	35%
End-of-life average load factor, $\overline{L}_{EOL}$	95%
Exponential fill time constant τ	2.5 years
Initial range, r_0	79%
Exponential coefficient, α	0.23 years^{-1}

[#] For a normally distributed random variable x, 95.4% of all measurements fall within the mean plus or minus two standard deviations ($\mu_x \pm 2\sigma_x$)

6.4.2. Load factors of satellites launched in the late 1980s

We now turn to our attention to the second group of satellites in our sample. These satellites were launched in the late 1980s. As mentioned previously, we tracked transponder usage of twenty-one satellites throughout their design lifetime: eight of these were launched in the early 1980s, seven were launched in the late 1980s, and six were launched in the mid 1990s.

Figure 6.8 shows: 1) the envelope (minimum and maximum values) of the load factor for the satellites in this second group of our sample, 2) the observed instantaneous average load factor, and 3) the modeled instantaneous average load factor as given by Eq. 9.

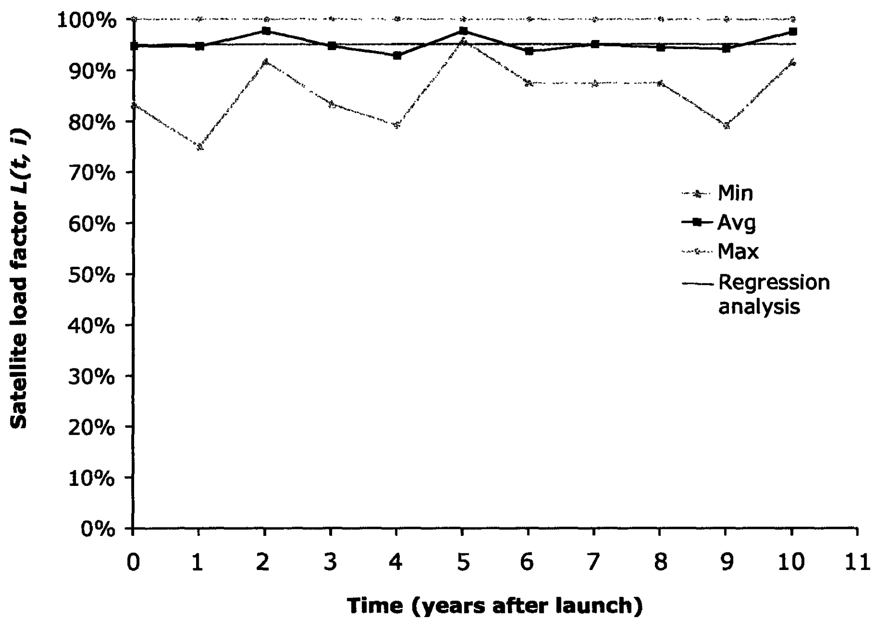


Figure 6.8: Load factor (average, min-max, and regression analysis) for 7 satellites in our sample that were launched in the late 1980s

The fundamental difference in the loading dynamics between the satellites in our sample that were launched in the early 1980s (previous subsection) and those launched in the late 1980s is the absence of a ramp-up phase in the latter, as seen in comparing Fig 6.6 and Fig 6.8. In other words, the sampled satellites that were launched in the late 1980s start with an initially high load factor ($\overline{L}_{BOL} = 95\%$) and their load factor remains relatively constant through their design lifetime ($\overline{L}_{BOL} = \overline{L}_{EOL}$); whereas the sampled satellites that were launched in the early 1980s start with a lower load factor ($\overline{L}_{BOL} = 35\%$), then exhibit a fill process and take between three to five years before their load factor reaches a steady-state (Fig. 6.6).

Two reasons can explain this difference in the loading dynamics between these two groups of satellites in our sample: 1) by the late 1980s, satellite operators had determined from their past experience how to aggressively pre-book capacity on-board their satellites before launch and realized the quantifiable financial advantages of doing so, or 2) most satellites launched in the late 1980s are simply "replacement satellites" taking over capacity from other satellites that are considerably loaded but have reached the end of their service life. If the retiring and replacement satellites have identical capacity, then the beginning-of-life load factor of the replacement satellite will be equal to the end-of-life load factor of the retiring satellite. Otherwise, if the two satellites' capacities differ, we will observe a discontinuity in the L_{EOL} of the retiring satellite and the L_{BOL} of the replacement satellite.

We propose to model the instantaneous average load factor of the satellites in our sample that were launched in the late 1980s (Fig. 6.8) as a constant. Also, for simplification, we assume that the range or dispersion of $L(t, i)$ around the mean $\overline{L}$, is symmetrical with respect to the sample mean. By doing so, we make an average error of 8% on the minimum values of the load factors at each time step for this second group of satellites our sample. Mathematically, we write this trivial model as follows:

$$\begin{cases} \overline{L}(t) = \overline{L}_{BOL} = 95\% \\ r(t) = r_0 = 5\% \end{cases} \qquad (9)$$

6.4.3. Load factors of satellites launched in the mid 1990s

We now turn our attention to the third and last group of satellites in our sample. This group consists of six satellites launched in the mid 1990s. Figure 6.9 shows: 1) the envelope (minimum and maximum values) of the load factor for the satellites in this third group of our sample, 2) the observed instantaneous average load factor, and 3) the modeled instantaneous average load factor as given by Eq. 10.

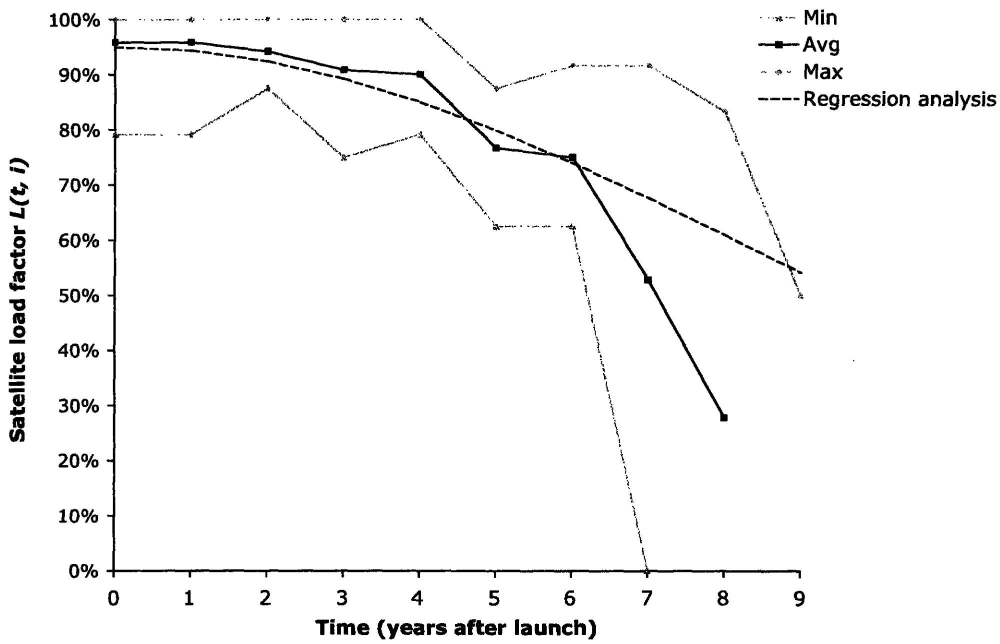


Figure 6.9: Load factor (average, min-max, and regression analysis) for 7 satellites in our sample that were launched in the mid 1990s

We first observe on Fig. 6.9 that satellites launched in the mid 1990s in our sample start with an initially high load factor ($\bar{L}_{BOL} = 95\%$), just as we saw previously on Fig. 6.8 for the satellites launched in the late 1980s. The same previous interpretation or explanation applies, namely that this reflects either the fact that these satellites are replacement satellites, or that satellite operators are now routinely pre-booking most of the capacity on-board their satellites before their launch.

Figure 6.9 shows however one striking difference with all previous load factor dynamics, namely that satellites exhibit a decrease in their load factor after five to seven years of operations. This observation will be of significant importance if it is a common loading pattern to all communications satellites launched over the last decade. We discuss the implications of this observation in the Conclusion. Unfortunately, given the small size of our sample and some of the problems with the data that we have (for example one satellite in our sample failed after 7 years of operations, which we can see on Fig. 6.9, and thus significantly distorted the averages), we cannot confirm this loading pattern. We can instead hypothesize that if this loading pattern is confirmed, it may correspond to end-users of satellite capacity turning away from "aging" transponders and switching towards newer more powerful and reliable units. This hypothesis is plausible given that there has recently been an increasing over-supply of transponders (on-orbit capacity is becoming increasingly commoditized), and end-users have significantly more choice and market power than in the past to "shop around" for newer, better, and cheaper transponders.

We propose to model the instantaneous average load factor of the satellites in our sample that were launched in the mid 1990s (Fig. 6.9) as a decreasing function of time with two parameters or degrees of freedom: an initial beginning-of-life average load factor $\overline{L}_{BOL}$, and a Time to obsolescence, T_{obs}, as shown in our model structure in Eq. 10.

$$\overline{L}(t) = \overline{L}_{BOL} \times e^{-\left(\frac{t}{T_{obs}}\right)^2} \qquad (10)$$

Such model structure is often used to model the sales of a component as it goes through its life-cycle phases of maturity, saturation, then decline and phase-out. The reader is referred to Ref. 5 and 6 for a more elaborate discussion of this model's rationale and assumptions. Parameters of the regression analysis using this model are given in Table 6.5.

Table 6.5: Model parameters for the average load factor (Eq. 10) of satellites launched in the mid 1990s.

Model parameter	**Value**
Beginning-of-life average load factor, $\overline{L}_{BOL}$	95%
Time to obsolescence, T_{obs}	12 years
R^2	0.84

The range of the data we collected for the load factors of satellites launched in the mid 1990s (before the one satellite failure occurred as seen on Fig. 6.9) falls within plus or minus 15% of instantaneous average load factor model given in Eq. 10 and Table 6.5. Unfortunately, the quality of the data for this group of satellites does not warrant that we further model this range as we did with the two previous groups of satellites in our sample.

6.4.4. Summary of satellite loading dynamics: four archetypes

Based on our previous discussion and data analyses, we propose four archetypes for satellite loading dynamics. These archetypes are classified based on two dimensions: the type of capacity launched, whether it's a new or replacement satellite; and the market conditions, whether the market is supply-constrained (i.e., the demand can absorb any capacity that is provided) or whether there is over-capacity in the market. These four archetypes are represented in Fig. 6.10.

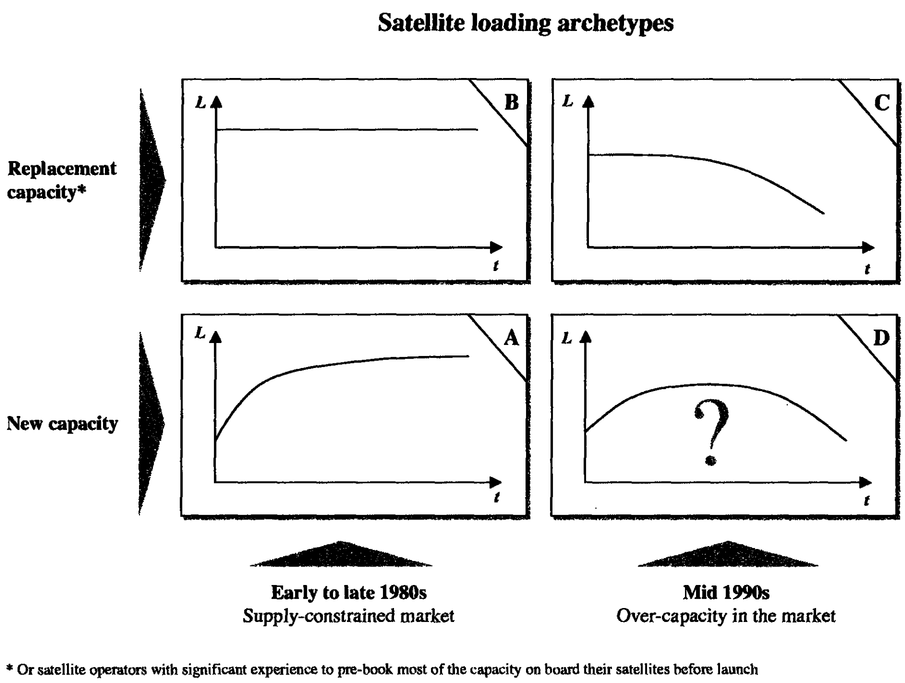


Figure 6.10: Satellite loading dynamics: four archetypes classified across two dimensions, type of capacity launched, and supply/demand (im)balance in the market.

Archetype A: This archetype or satellite loading pattern corresponds to what we observed with the first group of satellites in our sample (Fig. 6.5 and 6.6), namely an initial ramp-up phase of the load factor followed by a steady-state phase that remains throughout the operational life of the satellite. The satellite load factor increases after launch as new customers are acquired an additional transponders are leased. The steady-state phase is maintained throughout the operational life of the satellite, as the demand for on-orbit capacity remains unmet (supply-constrained market).

Archetype B: This archetype corresponds to what we observed with the second group of satellites in our sample (Fig. 6.8), namely a relatively constant load factor throughout the operational life of the satellite (absence of a ramp-up phase). Satellites that exhibit such loading dynamics are replacement satellites taking over capacity from other satellites that are considerably booked but have reached the end of their service life.

Archetype C: This archetype corresponds to what we observed with the third group of satellites in our sample (Fig. 6.9), namely a steady-state phase with a relatively high beginning-of-life load factor (again with an absence of a ramp-up phase as with archetype B), followed by a decline phase or a decrease in the load after several years of operations. This loading pattern is proposed for replacement satellites that are launched to serve a market that is over-supplied with on-orbit capacity, and customers can turn away from "aging" transponders and switch towards newer more powerful and reliable units.

Archetype D: Although we did not observe this loading pattern in our data, we can hypothesize the existence of such loading dynamics for a "new" satellite (i.e., not a replacement satellite) that is launched to serve a market over-supplied with on-orbit capacity. This archetype therefore has an initial ramp-up phase, a steady-state phase, and a decline phase.

6.5. Conclusion

In this paper, we set out to explore the loading dynamics of GEO communications satellites. We began by presenting different average load factors of communications satellites, and considered them as measures of supply and demand (im)balance of on-orbit transponders. We first discussed the global average load factor of the entire fleet of GEO satellites, $\langle L \rangle_{global}$; second, since different regions have different supply/demand characteristics of on-orbit capacity (that are not reflected in the global average load factor), we discussed average load factors for satellites serving specific regions, $\langle L \rangle_{region}$, for example North America, Western Europe, or Asia Pacific; and third, we discussed satellite operator load factors, $\langle L \rangle_{operator}$, and suggested that this measure reflects to some extent how well these operators are managing their on-orbit assets. These discussions were supported by data that is either available publicly or reported in the specialized press.

Following these "static" analyses of load factors, we turned our attention to the loading dynamics–not averages but evolution over time of the load factor–of a satellite after it has been launched. We identified a sample of twenty-one communications satellites over North America, launched between 1980 and 1997, and collected their yearly load factor from the time of their launch until their retirement. To the best knowledge of the authors, this is the first time such time series data of satellite load factor has been collected, analyzed, and presented to the technical community. The data we collected allowed us to answer three questions. First, how fast does a satellite get "filled up" after it has been launched? Second, does a satellite load factor reach a steady-state level? Third, if a steady-state load factor is reached, does it remain at that level or does it decline (when and how fast if so) as the satellite ages? We found and modeled three different loading patterns that are consistent within groups of satellites launched in the early 1980s, in the late 1980s, and in the mid 1990s (load factor ramp-up in three to four years; a steady-state load factor between 80% and 100%; and a decline in load factor after five to seven years on-orbit for satellites launched in the mid 1990s). Based on these findings, we proposed four archetypes or loading dynamics patterns that we classified based on two dimensions: the type of capacity launched, whether it is a new or replacement satellite (the load factor of a replacement satellite exhibits no initial ramp-up phase); and the market conditions, whether the market is supply-constrained or whether there is over-capacity in the market (the loading dynamics of a satellite in a market with over-capacity exhibit a decline phase or a decrease in the load after several years of operations). This loading pattern with a decline phase is proposed for satellites that are launched to serve a market that is over-supplied with on-orbit capacity, and customers can turn away from "aging" transponders and switch towards newer more powerful, reliable, and cheaper units.

References – Chapter 6

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Chapter 7

Conclusions and Recommendations for Future Work

7.1. Summary and Contributions

This thesis revolves in general around engineering, economics, and policy issues in the satellite services industry. In particular, this work analyzes the dual character (competing/complementary) of space-based communications versus terrestrial networks, as well as the current policy and regulatory environments of the industry. In addition, economics and engineering analyses are blended in a holistic approach providing valuable insights into the industry's performance and the impact that technical parameters (such as a spacecraft design lifetime) might have on the whole industry value-chain.

This work is divided in two parts. The first part begins by discussing the background of the communications satellite industry, its value-chain, service applications, history and evolution, and then explores two questions of significant importance to the survival and sustained growth of this industry: 1) are satellite communications solutions competing or complementary alternatives to terrestrial networks–in what context and for what service applications? And 2) what are the characteristics of the regulatory and policy environments and how do they affect the satellite communications industry?

Establishing a sound framework and setting coherent definitions constitutes a significant contribution. Chapter 2 started by summarizing the evolution of the satellite communications industry and introduced the key definitions of satellite services used by the International Telecommunication Union (ITU). Then, a snapshot of the current financial state of the satellite services industry was presented. The first contribution of this thesis was the identification and classification of the different types of service applications delivered by communication satellites (transmission of voice, data, and video). Finally, the key facts and figures of some of the most important satellite operators were presented at the end of the chapter.

The central question of the first part of this thesis was addressed in Chapter 3: Are terrestrial networks a competing or a complementary alternative to satellite solutions, in what context and for what service applications? The chapter started with what is one of the conceptual contributions of this thesis: the development of a framework designed to analyze the tradeoffs associated with satellite and terrestrial telecommunication technologies. This framework was structured around three axes: type of solution (satellite versus terrestrial networks), service application (voice and data, and video), and geographic market (urban versus rural areas, and emerging versus developed regions). The most important advantages of satellite technologies over terrestrial networks were explored: coverage, multiple access, distribution and flexibility. The current challenges and opportunities for satellite operators in urban and rural areas were also investigated. In conclusion, the case was made that: a) Satellite solutions have important competitive advantages when it comes to transmit voice and data in rural markets as well as in urban areas in emerging countries (where terrestrial networks have not been deployed and their deployment would be less financially and technically attractive than employing space-based solutions) b) Amongst the video service applications, the DTH TV represents the most dynamic market with the highest potential of growth for satellite operators. Other video service applications such as contribution and feed of cable TV head-ends should prove to be a stable market for satellite service providers. On the other hand, the author of this thesis believes that satellite operators should forge partnerships with some of their competing telecommunication services providers (i.e., DSL and cable operators), in order to exploit the dual character (competing/complementary) of telecommunication technologies. Lastly, Chapter 3 finished with an overview of what could be a disruptive technology: the WiMAX, which might considerably impact the satellite services industry in the near future.

Chapter 4 provided an overview of the regulatory environment for satellite operators. Two of the most important regulatory issues for satellite operators were discussed, namely spectrum/orbit allocation and space environmental pollution. As new satellite service applications (such as DTH TV) have been developed, regulatory bodies have allocated high radio frequencies (Ka-band) to be used by DBS operators (different than those frequencies allocated to FSS operators). In practice, however, with continual behind-the scenes maneuvering by both terrestrial and satellite services providers as well as by other stakeholders in the industry, frequency allocations are not always respected. Chapter 4 also identified a need of global regulations about spacecraft disposal in a way such that operators have to propel unused satellites to orbits far from the geostationary orbit. This is likely to have negative financial implications for satellite operators. An important claim of Chapter 4 is that there is a critical need to enforce space debris regulations. The geostationary orbit must be recognized as a precious real-state resource that is likely to become useless should a spacecraft collision occur in the GEO ring. Such an incident might have extremely negative consequences for the development of telecommunication services on Earth. Chapter 4 also described the space communications policy of the United States and Europe. In the United States, as a result of the deregulation of the industry started in 1972 with the "Open Skies" policy, the regulatory environment for satellite operators is probably one of the most flexible in the world. Different policies (such as the "orbital spacing" decision) have been implemented to promote competition and the development of the industry with minimal regulations. On the other hand, in regard to space-based communications policy, the European Union (EU) is only an emerging system, and there is still no European organization serving as one common authority over space-based communications issues. In addition, analysts suggest the necessity to further ease the current regulatory environment in order to promote competition among satellite operators. From a broader perspective, the EU has implemented a strategy to expand the European share in fast-growing markets where space-based services are fundamental. However, more international cooperation is desirable. Cooperation in regulatory issues should result in a more sound and healthy satellite communications industry, as well as in a more beneficial U.S. – Europe relationship in general. It was argued that in fact, the evolving nature of the U.S. – EU aerospace-related interactions has become part of the set of major factors that influence the geopolitical dynamics and the structure of international relations.

While market and policy issues play a central role in shaping the structure of the satellite services industry, economic and engineering considerations can provide decisive insights that might significantly alter the dynamics of the sector. The second part of this thesis focuses on the lifeblood of the satellite industry: the satellite itself (as opposed to the industry-context explored in Part I). In particular, part II explores issues associated with satellite design lifetime.

Chapter 5 explored the engineering and economic issues at stake for reducing or extending a complex system's design lifetime, using spacecraft as example. Firstly, it was argued that the interests of the different stakeholders that are involved are not necessarily aligned. Secondly, the qualitative implications associated with reducing versus extending a product's durability (or a system's design lifetime) were discussed. Following the qualitative discussion, quantitative analyses was presented in order to determine whether an optimal design lifetime for complex engineering systems (from the customer's perspective) exists. In order to answer this question, two new concepts were introduced: the need on the one hand to view in a system the flow of service (or utility) that it will provide over its design lifetime, and on the other hand, to introduce metrics per unit time such as cost, utility and value as functions of time. Optimality presupposes a metric that is minimized or maximized; a metric was therefore proposed in order to capture the present value of a system as a function of its design lifetime. It was then shown that, under certain assumptions, satellites do have optimal design lifetimes that maximize a value metric. Theses results disprove the traditional implicit assumption that satellite operators are always better off acquiring spacecrafts designed for the maximum technically achievable lifetime. The results demonstrate the importance of undertaking the engineering, market, and financial analyses described in this chapter. Finally, a provocative question was raised: are satellites manufacturers driving themselves out of business by designing for increasingly longer lifetime? It was shown that design lifetime might be a powerful lever that can significantly impact the market size for commercial communications satellites as well as the financials of the key players in the space sector. The main claim of this chapter is that a) issues pertaining to the specification of a system's design lifetime are much more complex than those related to a simple product's durability; and that b) these issues require much more attention than what they have received so far in the literature, as the impact of a system's design lifetime can ripple throughout an entire industry value chain.

Chapter 6 analyzed the loading dynamics of GEO communications satellites. Different average load factors of communications satellites were presented, and considered them as measures of supply and demand (im)balance of on-orbit transponders. Specifically, three types of average load factors were discussed: global average load factor of the entire fleet of GEO satellites, average load factors for satellites serving specific regions, and satellite operator load factors. The attention was then turned to the loading dynamics–not averages but evolution over time of the load factor–of a satellite after it has been launched. A sample of twenty-one communications satellites over North America (launched between 1980 and 1997) was identified. Yearly load factor data, from the time of their launch until their retirement, was collected. To the best knowledge of the author, this is the first time such time series data of satellite load factor has been collected, analyzed, and presented to the technical community. The collected data provided insights on three questions:

1) How fast does a satellite get "filled up" after it has been launched? 2) Does a satellite load factor reach a steady-state level? 3) If a steady-state load factor is reached, does it remain at that level or does it decline as the satellite ages? Three different loading patterns were founded and modeled: load factor ramp-up in three to four years; a steady-state load factor between 80% and 100%; and a decline in load factor after five to seven years on-orbit. These patterns are consistent within groups of satellites launched in the early 1980s, in the late 1980s, and in the mid 1990s, respectively. Based on these findings, four archetypes or loading dynamics patterns were proposed, that can be classified using two dimensions: a) the type of capacity launched (whether it is a new or replacement satellite); and b) the market conditions (whether the market is supply-constrained or whether there is over-capacity in the market).

In sum, the main findings of this thesis are: 1) in Chapter 3, a conceptual contribution was the development of a framework designed to analyze the tradeoffs associated with satellite and terrestrial telecommunication technologies, specifically, this framework should prove useful to organize the discussion on the dual character of satellite and terrestrial networks (complementary versus competing technologies); 2) the case was made that: a) satellite solutions have important competitive advantages when it comes to transmit voice and data in rural markets as well as in urban areas in emerging countries, and that b) amongst the video service applications, the DTH TV represents the most dynamic market with the highest potential of growth for satellite operators; 3) in Chapter 4, a critical need to enforce space debris regulations was identified; and 4) the case was made that more international cooperation in regulatory issues is desirable; 5) in Chapter 5, the case was made that: a) issues pertaining to the specification of a system's design lifetime are much more complex than those related to a simple product's durability; and that b) these issues require much more attention than what they have received so far in the literature; 6) it was shown that under certain assumptions, satellites do have optimal design lifetimes that maximize a value metric, disproving the traditional implicit assumption that satellite operators are always better off with spacecrafts designed for the maximum technically achievable lifetime; 7) it was shown that design lifetime might be a powerful lever whose lifetime can ripple throughout an entire industry value chain; 8) in Chapter 6, time series data of satellite load factor were collected, analyzed, and presented to the technical community.

Asides from the specific contributions per chapter, a fundamental contribution of this thesis is the broad perspective that it introduces. In the academic and business literature, one can find various reports and studies on different topics related to the satellite communications industry. However, to the best knowledge of the author, this is the first time that the members of the commercial space sector are presented with a comprehensive analysis of the structure and the dynamics of the satellite operators industry, including the market outlook, the policy and regulatory environments, engineering considerations, and economic issues faced by major stakeholders in the sector. The second major contribution of this thesis is the multidisciplinary approach that is proposes. It is divided in two parts combining engineering, economics, industry analysis and policy in a way that identifies insights beyond the reach of any one isolated discipline.

7.2. Recommendations for future work

One of my mentors once said that a good thesis raises more questions than it answers. I have chosen not to break with tradition, and I have identified two major questions (one for each part of the thesis) that would be interesting to address in future work.

7.2.1. On market issues:

In future work for part one, on market issues, it should prove useful to the satellite services industry to explore the structure that could be used by satellite operators to partner with competitors (i.e., terrestrial telecommunication services providers) in order to meet customer demands and to deliver complete solutions to the customers (instead of only providing transmission services). As a result of the increasing complexity of customer needs and demands, new partnerships models among telecommunication service providers have emerged since 2004. Satellite operators should, in the opinion of the author, become *solution* providers, not *services* providers. They need a strategy that clearly identifies where a *satellite solution provider* wants to add value across the value chain. One solution could be to integrate products and services while conserving and increasing consumer loyalty. The development of a strategy to forge these partnerships in order to provide complete solutions to customers, while preserving the distinctiveness of the satellite services and the advantages of space-based communications, should prove to be an interesting challenge. The author proposes a three-axis framework as a starting point to explore the different possible partnership schemes, the consequences and the dynamics that these partnerships would create in the telecommunications industry, as well as the trade-offs associated to this proposal. The first axis would include the type of technologies available for delivering telecommunication services. The second axis would consider the type of service provider, and finally the third element would evaluate the different types of services to be delivered. Figure 7.1 shows a graphic representation of this framework.

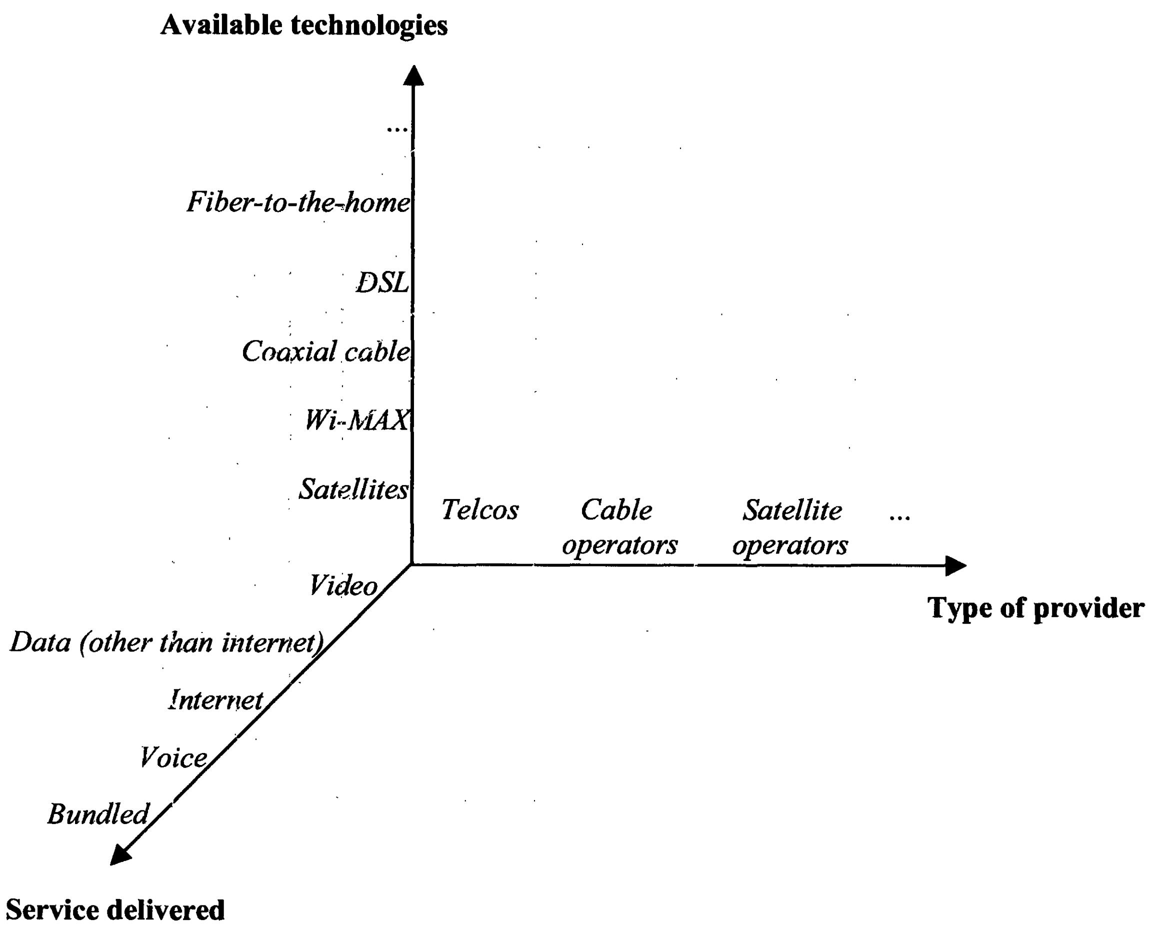

Figure 7.1: Graphic representation of the framework proposed to analyze the possible partnership structures amongst telecommunication service providers.

7.2.2. On economic and engineering issues:

For part two, on economic issues related to the analysis of utilization rates of GEO communication satellites, it would be interesting to integrate transponder lease price with the loading dynamics models that were developed in this chapter, in order to develop satellite revenue or utility models. While satellite cost models are pervasive throughout the aerospace industry, revenue models or utility models for satellites are quasi-inexistent. The absence of quantitative revenue models (in the case of commercial systems) or utility models (in the case of scientific or military systems) makes it difficult to build the case for such systems to policy-makers or decision-makers, especially in the light of their exorbitant costs. Furthermore, the specification and selection of a system design lifetime, or of a system life extension (e.g., Hubble Space Telescope) will always have weak arguments fraught with subjectivity in the absence of quantitative revenue or utility models.

Appendix A

Global trends in communication satellites capacity

This appendix presents a brief description of recent trends in communication satellites capacity.

Important changes in the types of capacity and services implemented in the satellite services industry have recently taken place in the United States. These transformations have been observed mainly in three areas:[1]

- The proportion of FSS versus broadcast capacity and services;
- The proportion of capacity in different frequency bands available and in use; and
- The transition of video transmissions from analog to digital.

These trends became apparent in 2004. They are:

⇒ From a 15 percent of total capacity in the United States in 2002, direct broadcast services capacity represented over 30 percent in 2004, and some forecast analyses by Futron Corporation[2] suggest that it will represent nearly 60 percent in 2010.

⇒ In 2002 C-band and Ku-band capacity was split almost evenly (50% each); Ka-band capacity in 2004 accounted for 20%, and the same previously mentioned forecast analyses[3] suggest that the C- and Ku-bands together will represent less than fifty percent of overall capacity by 2010.

⇒ In 2002, 52% of the FSS video capacity over the United States was occupied by analog television broadcasts. In 2004 this number decreased to 40%, and if this trend continues, the proportion of satellite capacity carrying digital channels will be around 90% by 2010.

Satellites have continued to grow in size, in terms of bandwidth launched, over the last fifteen years.[4] The general trend has been around one 36 MHz transponder equivalent per year. In 2003 and 2004, however, a significant decline in this trend was observed. The excess supply of on-orbit capacity experiences in recent years, which lead to declines in transponder lease prices, may explain the lack of orders of high-capacity satellites. It is more economical for satellite operators to reconfigure the excess capacity they have on orbit in order to satisfy current demand than to launch more satellites.

While this may explain some short-term drivers for the decline in satellite size, other drivers could affect the longer-term trend. The satellites expected to be launched in 2006 include several DBS satellites with fewer and smaller transponders, but much higher-powered.

References – Appendix A

[1] Anon., "The Transformation of the Satellite Services Industry". Futron Corporation, Bethesda, MD, January 2005.

[2] Anon., "The Transformation of the Satellite Services Industry". Futron Corporation, Bethesda, MD, January 2005.

[3] Anon., "The Transformation of the Satellite Services Industry". Futron Corporation, Bethesda, MD, January 2005.

[4] Anon., "Is bigger better?". Futron Corporation, Bethesda, MD, 2004.