Development and Application of an Analysis Methodology for Satellite Broadband Network Architectures

by

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ABSTRACT

An analysis methodology for analyzing the technical and economic performance of a satellite network system has been developed and implemented. It was applied to a set of satellite broadband network system designs based on the five systems in Ku-band recently proposed to the Federal Communications Commission. The considered systems represent satellite constellations with low Earth orbits (LEO), medium Earth orbits (MEO), and highly elliptic orbits (HEO). The technical and economic performance of the systems was evaluated by the metric: cost per billable T1 minute required to achieve an internal rate of return of 30 % with key technical requirements satisfied. The robustness of the system with respect to the fluctuation in the market size was also examined. Various assumptions were made to allow a unified comparison and modeling of the systems. As a consequence, the analyzed system designs are only similar to the FCC filings. The computed results show that the preferred system differs for different levels of market demand. The MEO and HEO systems are better in low demand scenarios. The LEO systems can support very large number of customers and achieve low cost per subscription in high demand scenarios. In terms of robustness to the market fluctuations, the HEO system, which has the ability to deploy by sub-constellation, showed an improved metric by adapting the deployment schedule to the demand size. A computer tool has been developed to automate this methodology in order to efficiently evaluate the performance metric from a set of design variables.

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Biographical Note

Tatsuki Kashitani received a Bachelor of Science in engineering and applied science from California Institute of Technology in 1999. He has been studying as a candidate for the Master of Engineering degree at the MIT aeronautics and astronautics department since September 2000. After the expected graduation in June 2002, he plans to work at the Nagoya Propulsion and Guidance Works of Mitsubishi Heavy Industries Ltd. in Japan. He can be contacted by electronic mail at tatsuki@alumni.mit.edu.

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a_{SAT}	Semi-Major Axis of Satellite's Orbit
c_{labor}	Cost of Unit Labor
$C_{Insurance}$	Total Insurance Cost
C_{Labor_GS}	Total Ground Station Labor Cost
C_{Launch}	Total Launch Cost
C_{LV}	Cost of a Launch Vehicle
CPF	Cost per Minute of Subscription
C_{SAT}	Satellite Capacity (Number of Simultaneous Users Satellite Can Support)
$C_{Subscription\_2000}$	Charge for Subscription-Year in Constant 2000 Dollars
$C_{Subscription\_Nominal}$	Charge for Subscription-Year in Nominal Dollars
$C_{Subscription\_PV}$	Charge for Subscription-Year in 2000 Present Value
c_{TFU}	Theoretical First Unit Cost per Kilogram of Satellite Dry Mass
C_{Total_PV}	Total System Cost in 2000 Present Value
$d_{inclination}$	Degradation in LV Performance per Degree of Inclination Increase
$D_{LV\_fairing}$	Diameter of Launch Vehicle Fairing
D_{Market}	Distribution of Broadband Market
D_{SAT}	Diameter of Satellite Bus
$d_{Payload}$	Payload Power per Payload Mass
d_{SAT}	Satellite Density
D_{User}	User Terminal Antenna Aperture Diameter
e	Eccentricity of Satellite's Orbit
E_b / N_O	Signal-to-Noise Ratio Required for User Downlink
$f_{Downlink}$	User Downlink Frequency
$f_{User\_Downlink\_Power}$	Fraction of User Downlink Power in Payload Power
f_{Dry_Mass}	Fraction of Dry Mass in Wet Mass
$f_{Insurance}$	Insurance Rate
f_{NR_GS}	Non-Recurring Cost Factor of Ground Stations
f_{NR_SAT}	Non-Recurring Cost Factor of Satellites
$f_{Payload}$	Fraction of Payload Mass in Dry Mass
$f_{Satellite}$	Fraction of Satellite Market in Total Broadband Market
G_{PA}	Gain of Satellite's Phased Array Antenna for User Downlink
G_{User}	Gain of User Terminal Antenna
h	Altitude of Satellite's Orbit
$h_{LV\_fairing}$	Height of Launch Vehicle Fairing

i	Inclination of Satellite's Orbit
$i_{Inflation}$	Inflation Rate
i_{RR}	Internal Rate of Return
L_A	Atmospheric Loss
L_{GS}	Labor Required for a Ground Station
L_{LV}	Launch Site Latitude
$L_{Rain+Margin}$	Rain and Link Margins
L_S	Space Loss
l_{SAT}	Height of Satellite Bus
$M_{Broadband}$	Size of Total Broadband Network Market Demand
M_{Dry}	Satellite Dry Mass
m_{Grid}	Number of Potential Customers in Earth Grid
M_{LV}	Launch Vehicle Performance
m_{LV}	Launch Vehicle Margin
$M_{Payload}$	Mass of Satellite Payload
$M_{Satellite}$	Size of Satellite Broadband Network Market Demand
M_{Wet}	Satellite Wet Mass
N_{Grid}	Number of Earth Grids
N_{GS}	Number of Ground Stations
N_{Planes}	Number of Orbital Planes
NR_{SAT}	Non-Recurring Cost of Satellites
N_{SAT}	Number of Satellites
$n_{SAT\_per\_Plane}$	Number of Satellites per Orbital Plane
$N_{SAT\_Produced}$	Number of Satellites Produced
N_{Spare}	Number of Spare Satellites
$n_{Spare\_per\_Plane}$	Number of Spare Satellites per Orbital Plane
N_{SUB}	Number of Subscribers
n_{SUB}	Number of Subscribers in One Earth Grid
PC	Potential Customer Map
$P_{Min\_Coverage}$	Minimum Coverage Probability Required
$P_{Payload}$	Satellite Payload Power
$P_{User\_Dwonlink}$	Satellite's Power Used for User Downlink
$P_{User\_Downlink\_EIRP}$	Satellite's Effective Isotropic Radiated Power for User Downlink
$P_{User\_Downlink\_RF}$	Satellite's Radiated Power Used for User Downlink
R_{Earth}	Radius of the Earth

R_{GS}	Total Recurring Cost of Ground Stations
$r_{Max\_Allocation}$	Maximum Resource Allocatable to One Earth Grid Link
R_{PV}	System's Total Revenue in Present Value
R_{SAT}	Total Recurring Cost of Satellites
r_{SAT}	Satellite's Resource Available
R_{User}	Individual User Terminal Data Rate
R_{Total}	Total Downlink Data Rate
r_{Used}	Satellite's Resource Used for an Earth Grid Link
S	Transmission Pathlength from Satellite to Earth Grid
S_{SAT}	Radius of Satellite's Position with respect to the Center of the Earth
s_{SAT}	Learning Curve Slope for Satellite Production
s_{GS}	Learning Curve Slope for Ground Station Production
TFU_{SAT}	Theoretical First Unit Cost of Satellite
TFU_{GS}	Theoretical First Unit Cost of Ground Station
T_{User}	User Terminal System Noise Temperature
V_{SAT}	Satellite Bus Volume
y	Year
$\Delta\phi$	Relative Phasing between Satellites in Adjacent Orbital Planes
$\varepsilon_{Elevation}$	Elevation Angle of Satellite Seen by User
$\varepsilon_{Min\_Elevation}$	Minimum Elevation Angle Required
$\eta_{Amplifier}$	Amplifier Efficiency
η_{MA}	Efficiency of Multi-Access Scheme
η_{User}	User Terminal Antenna Illumination Efficiency
$\lambda_{Downlink}$	Downlink Wavelength
υ_{SAT}	True Anomaly of Satellite
Ω_{SAT}	Right Ascension of Ascending Node of Satellite's Orbit

List of Acronyms

CDMA	Code Division Multi-Access
CPF	Cost Per Function
DSL	Digital Subscriber Line
EIRP	Effective Isotropic Radiated Power
FCC	Federal Communications Commission
FDMA	Frequency Division Multi-Access
GEO	Geostationary Earth Orbit
GINA	Generalized Information Network Analysis
GNP	Gross National Product
HEO	Highly Elliptic Orbit
LEO	Low Earth Orbit
LV	Launch Vehicle
MDO	Multidisciplinary Design Optimization
MEO	Medium Earth Orbit
MIT	Massachusetts Institute of Technology
PPP	Purchasing Power Parity
PV	Present Value
QFD	Quality Function Deployment
QPSK	Quadrature Phase Shift Keying
TDMA	Time Division Multi-Access

1 Introduction

1.1 Satellite Broadband Networks

Data communication has become an important infrastructure in today's society. Personal, commercial, and government activities depend more and more on digital networks. As a consequence of this increase in broadband demand, many means of providing digital network connections compete for subscribers. The Federal Communications Commission (FCC) has been conducting a series of national surveys on the deployment of broadband networks to business and residential users since 1998. They define advanced communications capability as network connection with 200 kbps or greater data rate in both directions, and assess the availability in the United States. The three reports released so far indicate rapid deployment each year [FCC, 1999a; FCC, 2000; FCC, 2002a].

Over the past few decades, the world has seen the emergence and evolution of many technologies to provide digital network connection: modems that talk over analog phone lines, digital subscriber lines (DSL) that use a higher frequency band on phone lines, cable modems that use cable television lines, fiber optics that transmit signals through fiber optical cables, and satellite links that send signals on electro-magnetic waves back and forth to satellites.

With the successes of the Syncom satellite in 1963, technology became available to utilize the geostationary orbit. Since then the geostationary orbit has been the most common choice for communication applications, and other orbits have not been used as much [McLucas, 1991]. However, communication service using a constellation of satellites in lower altitude has been conceived and put into service today. For example, Globalstar and Iridium were deployed to provide global mobile phone service. These systems, however, experienced severe financial difficulties and filed for bankruptcy soon after service started.

In 1999, FCC received applications for non-geostationary data communication systems in the Ku-band from Boeing, Hughes (two applications), SkyBridge, and Virtual Geosatellite [FCC, 1999b; Boeing, 1999; Hughes, 1999a; Hughes, 1999b; SkyBridge, 1997; SkyBridge, 1999; Virtual Geosatellite, 1999]. These satellite systems aim to deliver broadband network connections to residential and business users. Their architectures represent LEO (low earth orbit), MEO (medium earth orbit), and HEO (highly elliptic orbit) constellations.

1.2 Thesis Objective

Given the financial difficulties that the two major satellite mobile phone ventures experienced in the late 1990's, the economic viability of satellite ventures should be assessed in the very early stages of design. However, such an assessment and unified comparison has not been carried out for the proposed broadband satellite systems highlighted above.

This thesis 1) describes a systems engineering methodology that has been developed and implemented to analyze the technical and economic performance of different broadband satellite networks and 2) provides some initial computed results for the point designs based on the proposed systems, and 3) suggests potential areas for future work.

1.3 Overview of Thesis

The next chapter provides background information on the proposed satellite network systems and their analysis. Chapter 3 explains the approach to the analysis problem, and Chapter 4 goes into the details of the developed models. The result is presented in Chapter 5. Chapter 6 concludes the thesis, and Chapter 7 suggests areas for further investigations. References and Appendices follow.

2 Background

2.1 Satellite Constellations

The idea of providing communication service by a constellation of satellites became a reality in the 1990's. It was thought that a constellation of small satellites at low altitude could provide wide coverage at competitive cost and schedule compared to other alternatives such as geostationary satellites and ground-based technologies. It was considered that the low-altitude reduces transmission delays, decreases satellite size and launch cost, and justifies multiple satellites and multiple launches.

In a typical satellite constellation, satellites are placed into coordinated orbital planes and orbits known as the Walker delta patterns. Three of the five studied systems are based on the Walker constellation (Boeing, SkyBridge, HughesNET). A Walker constellation consists of circular orbits of equal altitudes and inclinations. The orbital planes are evenly distributed around the equator, and the satellites are evenly distributed in the orbital planes. The number of orbital planes, the number of satellites per orbital plane, and the relative spacing between satellites in adjacent orbital planes characterize a Walker delta pattern. More recent constellations explore the utilization of elliptic orbits, mixed altitudes, and mixed inclinations. Hybrid constellations such as Ellipso use a mix of circular and elliptic orbits [Draim et al., 1992; Draim et al., 1997; Draim et al., 2000].

Two satellite constellations were deployed in the late 1990's to provide global mobile phone service. The Iridium system consists of 66 satellites in six near-polar orbital planes. The altitude of the orbit is 785 km. The satellites are capable of downlink, uplink, inter-satellite link, and routing calls. The functionality and capability pushed the Iridium satellites to be quite complicated and large. The Globalstar system, on the other hand, consists of 48 satellites at 1410 km altitude in eight orbital planes inclined at 52 degrees. The architecture of the Globalstar system emphasizes simplicity, and utilizes terrestrial infrastructure to a greater extent than the Iridium system [Gumbert, 1996].

Both the Iridium and the Globalstar ventures faced severe financial hardships once in operation. The number of subscribers did not grow as expected. The deployment of the Iridium system started in 1997, and service began in 1998. Nearly $5 billion was spent to build and maintain the system. However, Iridium was forced to file for a bankruptcy in August 1999 [Space News, 1999]. The Iridium satellites were once to be de-orbited for safe disposal, but a new company acquired the system to continue service. Iridium is now providing satellite communications services to the U.S. Government and commercial users [Space News, 2000]. Globalstar started service in 2000, but also filed bankruptcy in 2002 [Space News 2002]. The primary cause of these financial hardships was the uncertainty in the market with the high initial cost of the user terminals. Also, the terrestrial mobile phone service deployed faster at lower price. The satellite mobile phone became an expensive gadget for many people once their commonly visited areas were covered by terrestrial mobile phone service.

This implies that the robustness of the system architecture with respect to the fluctuation in economic circumstances is particularly important for success of these commercial satellite network ventures.

2.2 Overview of the Proposed Network Systems in Ku-Band

Upon receiving the first application from SkyBridge in 1997, the FCC called for others to file application for non-geostationary data communication systems in the Ku-band and established the cut-off date of January 8, 1999 [FCC, 1998]. This was done to allocate the spectrum to the most promising proposals. In 2002, FCC announced that these systems may advance their plans pending the creation of a frequency sharing and interference avoidance method so that they can operate simultaneously [FCC, 2002b; FCC, 2002c]. In this thesis, proposals from Boeing, Hughes (two applications), SkyBridge, and Virtual Geosatellite have been selected as representative candidates because they are relatively similar in system architecture and focus on providing digital network connection only. Pentriad was dropped from the study since it tries to provide broadcasting service with the same system. Table 2.1 summarizes the characteristics of the proposed systems. To standardize for comparison, it was assumed that the system development starts in the year 2001, and the network service is provided from 2006 to 2015. Other standardization will be discussed in later sections.

Table 2.1: Summary of Proposed Broadband Satellite Systems in Ku-Band.

Designator	Proposed System	Number of Satellites	Number of Orbital Planes	Number of Satellites Per Plane	Orbital Altitude (km)	Orbital Inclination (degrees)	Satellite Mass (kg)
LEO70	**HughesNET**	70	10	7	1490	54.5	2000
LEO80	**SkyBridge**	80	20	4	1569	53	1250
MEO20	**HughesLINK**	22	3	8/7*	15000	0/45*	2940
MEO22	**Boeing**	20	4	5	20182	57	3861
HEO	**Virgo**	15	3†	5	20281‡	63.4	3030

*One equatorial plane with eight satellites and two inclined planes with seven satellites each.
†Number of sub-constellations. ‡Semi-major axis.

2.2.1 Boeing

Boeing proposed a system with 20 satellites at 20182 km altitude in four orbital planes. The Boeing satellites are the largest of the five systems. The Boeing system is designed to provide "bandwidth on demand" communication services to corporate, institutional, governmental and large professional users. The provided data rate goes up to 240 Mbps [Boeing, 1999].

2.2.2 HughesLINK

HughesLINK is proposed by Hughes Communications. HughesLINK is a MEO constellation with 22 satellites at 15000 km altitude in three orbital planes. HughesLINK constellation uses a mix of the equatorial orbital plane and inclined orbital planes. The number of satellites per plane also differs for the equatorial and inclined planes. The system intends to provide broadband communications services at data rates from 1.54 Mbps to 155 Mbps [Hughes, 1999a].

2.2.3 HughesNET

HughesNET is a LEO constellation designed to work with the HughesLINK. It consists of 70 satellites in ten orbital planes at 1490 km altitude. HughesNET aims to provide broadband communications services to wide range of users worldwide at data rates from 512 kbps to 10 Mbps [Hughes, 1999b].

2.2.4 SkyBridge

The SkyBridge constellation has the largest number of satellites, but the satellites are the smallest of the five systems. The SkyBridge constellation consists of 80 satellites at 1569 km altitude in 20 orbital planes. The design of the architecture emphasizes simplicity. The satellites function in "bent pipe" fashion, just bouncing signals between user terminals and gateways [SkyBridge, 1997; SkyBridge, 1999]. However, this low complexity design of SkyBridge satellites could not be modeled since the simulation uses one generic satellite model, and cross-link capability is assumed.

2.2.5 Virgo

Virgo consists of three sub-constellations with five satellites each. Each sub-constellation consists of five elliptic orbits in different inertial orbital planes inclined at the critical inclination of 63.4 degrees. This inclination prevents the drifting of apogee caused by the non-spherical shape of the earth. The elliptic orbits have the semi-major axis of 20281 km and the eccentricity of 0.66. Satellites above a certain altitude are in "active arc" and turned on, while satellites below the active arc altitude are turned off. As a consequence, there are three active satellites in each sub-constellation at any moment. Since the satellites are active near the apogee, they appear to move relatively slowly in the user's field-of-view. The unique feature of Virgo system is that one sub-constellation alone can cover the northern or southern hemisphere continuously [Virtual Geosatellite, 1999]. Other systems require that their entire system be deployed to maintain coverage. The simulation captures this feature. Since Virgo has three sub-constellations, the deployment schedules of the second and third sub-constellations were allowed to adapt to the market size.

2.3 Past Studies on Satellite Constellation Performance

There have been several studies on the technical and economic feasibility of satellite network constellations. At MIT, several graduate theses investigated satellite network constellations with LEO, MEO, GEO, and elliptic orbits for mobile phone and data communication networks. The MITRE Corporation has conducted large detailed studies of mobile phone systems [Ciesluk et al., 1992; Gaffney et al., 1994]. This thesis builds upon and extends these studies. To model and simulate complex behavior of the satellite network systems, an analysis framework and simplifying assumptions were adopted from the past studies. To better understand the significance of market fluctuation on the cost per billable T1 minute metric and the survival of the system, the balance of model fidelity balance and computing expense were assessed. This made it possible to explore much larger market fluctuations.

2.3.1 Michael D. Violet & Cary C. Gumbert

Michael Violet and Cary Gumbert compared six mobile satellite phone systems using a cost per billable minute metric. The considered systems included two LEO systems, two MEO systems, one GEO system, and one hybrid system with circular and elliptic orbits. Using computer simulations, the cost of one billable minute of a phone call was estimated for each system assuming three different levels of market penetration. It was found that market penetration has the significant effect on the cost of the service. The studies also indicated that results could be very dependent on factors such as marketing strategy, which are difficult to incorporate in computer models [Violet, 1995; Gumbert, 1996; Gumbert et al., 1997].

2.3.2 Andjelka Kelic

Kelic carried out a similar analysis to Violet and Gumbert on broadband satellite systems using a cost per T1 minute metric. The investigated systems included four GEO systems and one LEO system. It was again shown that the cost per billable T1 minute metric was highly sensitive to market variations [Kelic, 1998].

2.3.3 Graeme B. Shaw

Shaw developed a systematic analysis methodology named Generalized Information Network Analysis (GINA) to assess the performance of distributed satellite systems. The GINA analysis looks at a satellite mission as an information process in which information is generated, gathered, transmitted, and exchanged. Then methods from information theory are applied to assess performance and satisfaction of requirements. Shaw applied this methodology to broadband satellite systems as one of the case studies [Shaw, 1999].

2.3.4 Melahn L. Parker

Parker analyzed satellite network architectures emphasizing the altitude and number of satellites in the constellation. He sampled many proposed systems and added ones he created from scratch. The cost per subscription was used as the metric to compare the different constellations and to study the design space trends [Parker, 2001].

3 Methodology

This chapter provides an overview of the approach that was taken to assess the technical and economic performance of different satellite broadband networks.

3.1 Requirements on Methodology

As a system engineering tool to be used in the conceptual design phase, the methodology itself is subject to requirements. The identified requirements are:

1) Since the satellite network system design is in its initial phase, only top-level information is available. The methodology must work with this limited information.
2) The intended use of the methodology is comparing design alternatives, exploring the design space, optimization, and sensitivity analysis. These usages require the methodology to return the computed result quickly so that it can be iterated.
3) These usages also require automation.
4) And last but not least, the methodology must be accurate.

3.2 Overview of Methodology

The problem being considered is a multidisciplinary problem since it involves many disciplines from orbital dynamics to economic analysis. The approach to this problem was adopted from the Multidisciplinary Design Optimization (MDO) theory. MDO is a framework for optimizing a system design that involves a number of disciplinary areas coupled to each other. MDO suggests the following step to approach problems [De Weck et al., 2002].

1) Define overall system requirements.
2) Define design vector, objective, and constraints.
3) System decomposition into modules.
4) Modeling of physics via governing equations at module level.
5) Model integration into an overall system simulation.
6) Benchmarking of model with respect to a known system from past experience.
7) Design space exploration to find sensitive and important design variables.

8) Formal optimization to find optimum.
9) Post-optimality analysis to explore sensitivity and tradeoffs.

Steps 1) to 6) were adopted and applied to the modeling and simulation of satellite broadband network systems in this thesis.

The proposed systems were compared by a single metric and the sensitivity of the metric to market demand fluctuations. The metric used is the cost per billable T1 minute achieving a 30 % internal rate of return. To enable the modeling and simulation, many simplifying assumptions were made. In simplifying the problem, the system goal was derived from the customer needs, and important technical parameters were identified by relevance to the system goal and customer needs. These parameters were incorporated in the models. The fidelity of the models is checked by benchmarking against the estimations in the FCC filings

The following sections explain how this approach was implemented.

3.2.1 System Goal

The unified goal of the satellite network systems must be clearly defined to meaningfully discuss and compare them. Although the stated goals of the five proposed systems differ in many aspects such as network data rate, target users, etc., they were altered to pursue an identical goal. The goal is to provide T1 data rate (1.54 Mbps) network connections to business and residential users while achieving a 30 % internal rate of return.

As a consequence, the systems that are compared in this thesis are not the exact representation of the proposed systems. Rather, they are the design space "point designs" based on the proposed systems. Only the variables in the design vector characterize and differentiate the architectures, although this takes pages of technical details in the FCC filings. The results presented later must be interpreted understanding that the findings are influenced by this simplification.

3.2.2 Customer Needs

In this study, it was decided to model the business and residential markets as potential customers, although satellite information networks are and will be used in many more applications given the expected rise in data rate and cost-effectiveness. For example, tele-medicine, tele-education, military, or mobile network connection on airplanes and ships, etc may become the "killer application." It is hard, however, to model these emerging applications. The size and distribution of such a market cannot be modeled with satisfactory confidence to extrapolate to the future. Because of this uncertainty it is important to assess the adaptability of the proposed systems to variability in market size.

The satellite network system must be aligned with the needs of customer for the system to be successful. Three major needs identified are availability, data rate and integrity of the connections. Availability is defined as the probability of establishing network connections when a customer wants it in the service area. Availability can further be decomposed into geographical and temporal availability. Data rate is the primary factor when consumers shop for network service providers. Thus, for a satellite network system to be successful in the market, the data rate must be competitive. Although integrity is not explicitly advertised or looked for in the consumer network service provider market, it is implicitly assumed that the provided connection has a certain quality.

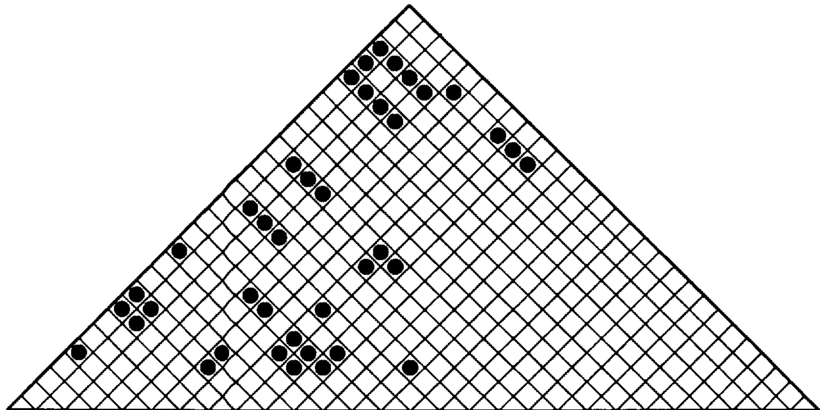
3.2.3 Find Key Parameters

Upon identifying the customer needs, the Quality Function Deployment technique was used to identify important technical requirements and important system parameters.

In modeling the satellite network systems, complete modeling and simulation of all of the involved physical and information processes is clearly impossible. Simplification is necessary. This must be done in a way that the simplified model still captures the trends and tradeoffs in the design space. The QFD technique helps identify important parameters by visually representing the relationships from user needs to technical requirements and from technical requirements to parameters in a traceable fashion. The relationship between each customer need and each technical requirement is ranked none, weak, medium, or strong (in this case by physical laws and engineering intuition). When the relationship matrix is populated with the strength of relationship, the technical variables can be ordered by the relevance to the customer needs [Clausing, 1993].

Figure 3.1 is the QFD requirements matrix, which relates customer needs to technical requirements. The matrix in the center is the relationship matrix filled with signs that indicate the strength of the relationship. To the left of the relationship matrix, customer needs are listed with the weighting. Above the relationship matrix, technical requirements and constraints are listed. The triangular matrix above the technical requirements contains the dots indicating the conflicts of requirements. Below the relationship matrix, the priorities of the technical requirements are listed. The upper row contains the absolute score which is the sum of the product of customer needs weight and relationship weight for each technical requirement. The lower row contains the normalized score between one and ten.

Data rate, geographical and temporal coverage, and bit error rate (BER) were chosen as the technical requirements that directly reflect the user needs discussed in the previous subsection. The results also indicated that the scalability and capability to operate with a partial constellation are important. Among the five systems compared, the HEO system has the ability to operate with partial constellation. It was decided that this feature should be reflected in the model and investigated.



Relationships
● Strong - 9
○ Moderate -3
△ Weak -1

		High Data Rate	Geographic Coverage	High Percent Temporal Coverage	Low Mean Response Time	Total System Capacity	Robust Satellite	Complement Exisiting Infrastructure	Fault Avoidance	Fault Tolerance	Functional Redundancy	Low Latency	Low BER	Low Satellite Complexity	High Scalability	Low Orbital Maintenance Effort	Operate w/ Parital Constellation	Allow Capacity Upgrade	Common Design	Fast Deployment	Provide Unique Service	Low Signal Attnuation		CONSTRAINTS	Operate within Allocated Spectrum	Comply w/ PFD Regulation	No Interference w/ Other Systems	Launch Vehicle Constraint	Disposal/Deorbit
Customer Requirements																													
Service Quality (=Terrestrial)																													
Speed	10	●				○			○	○	○				○							○							
Availability	8		●	●	●	●	○		●	●	●	△			○		○	○		△		○							
Data Integrity	5	○							○	○	○	●	●									○							
Cost (=Terrestrial)																													
Acquisition Cost	8		○	○	△	○	●					△	△	○		△	○		●	△									
Recurring Cost	10					●	○	○						●	●	○	○	○	●	○									
Industry Needs																													
Robust to Chaging Reqts	5	○	○	○	○	○		○				○	○		●		●	●											
High Usage Rate	10	○	●	●				●				○					○			○	●								
		150	201	201	95	231	126	129	117	117	117	106	68	114	189	38	153	99	162	76	90	69							
		6	9	9	4	10	5	6	5	5	5	5	3	5	8	2	7	4	7	3	4	3							
		T1=1.54 Mbps	Matched w/ Market	98 %	5 mins	Matched w/ Market							Less Than 10^-9							Less than 6 Years									

Figure 3.1: QFD Requirements Matrix Relating Customer Needs to Technical Requirements.

Figure 3.2 is the QFD design matrix, which relates the technical requirements to the system parameters. The matrix in the center is the relationship matrix filled with symbols that indicate the strength of the relationship. To the left of the relationship matrix, technical requirements are listed with the weighting found in the QFD requirements matrix. Above the relationship matrix, system parameters are listed. Below the relationship matrix, the priorities of the system parameters are listed.

From the QFD analysis, orbital parameters were found to be the most important. The next important group of parameters is related to the communication subsystems. This is consistent with the intuitive expectation.

These observations were used in choosing which parameters are incorporated in the simulation, and whether they go into the design vector or the constants vector. The design vector contains the design variables unique to the system, and the constants vector contains the parameters that are kept the same across the different systems.

Relationships
● Strong - 9
○ Moderate -3
△ Weak -1

		Altitude	# of Satellites	# of Satellite per Orbital Plane	# of Orbital Planes	Orbit Eccentricity	Inclination	Minimum Elevation Angle	Satellite Antenna FOV	Satellite Power	# of Ground Stations	Spot Beam Configuration	Crosslink Capability	# of Antennas	Frquency Reuse	SAT Uplink Antenna Gain	SAT Downlink Antenna Gain	UT Uplink Antenna Gain	UT Downlink Antenna Gain	UT Power	Data Access Path	Radiation Hardening	Debris Protection	Satellite Mass	Right Ascension of Ascending Node	Argument of Perigee	Time of Perigee Passage	ADACS Scheme	Propulsion Mehtod	Degree of New Technology	UT Tracking Capability	UT Antenna FOV	Operation Cycle	Allocated Spectrum	Thermal Control	Launch Vehicle	# of Spare Satellite on Orbit	Energy per Bit	SAT ponting Accuracy	Modulation & Coding	UT Pointing Accuracy	SAT Cross-sectional Area
High Data Rate	6	●						○		●		△			△	●	●	●	●	●	○										○			○	△			○	○	○	○	
Geographic Coverage	9	●	●	●	●	●	●	●	●	△	○	●	○	○	△	△	△	△	△	△					○	○	○					○		△								
High Temporal Coverage	9	●	●	●	●	●	●	●	●	△	○	●	○	○	△	△	△	△	△	△					○	○	○					○	○	△								
Low Mean Response Time	4	●	●	●	●	●	●	●	●	△	○	●	○	○	△	△	△	△	△	△					○	○	○				○	○		△								
Total System Capacity	10	○	●	○	○	○	△		△	●	●		○	△	●																			△								
Robust Satellite	5	○				○																●	●					●	●	△			○		○							△
Complement Exisiting Infrastructure	6										○										●																					
Fault Avoidance	5	●				○		○														●	●								○				○							
Falut Tolerance	5	○	●	●	○				△		○		○																	○					○		●					
Functional Redundancy	5												○	●																												
Low Latency	5	●	△	△	△						△		○								○										○											
Low BER	3	●						○		●						●	●	●	●	●	○										○							●	○	○	○	
Low Satellite Complexity	5	○	○	○	△	○			△	●			●	○		△	△					△	△	●				○	○	●					△				○			
High Scalability	8	●	●	●	●	●	●				●	○	○																							○	△					
Low Orbital Maintenance Effort	2	●				○	●																	●				●	●													●
Operate w/ Partial Constellation	7	●	●	●	●	●	●	●	●					○											○	○	○						○									
Allow Capacity Upgrade	4	●	●	●	●	○	○					○			○																			○								
Common Design	7		○	○	○						○			○																						△						
Fast Deployment	3	○	●	●	●	○	△																	●												●						
Provide Unique Service	4		○																											○												
Low Signal Attenuation	3	●	○			△					○					△	△	△	△		△														△							
		669	593	512	472	438	376	303	281	238	296	240	210	178	130	111	111	106	106	103	99	95	95	90	87	87	87	78	78	77	69	66	63	62	59	58	53	45	42	27	27	23
		10	9	8	7	7	6	5	4	4	4	4	3	3	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0

Figure 3.2: QFD Design Matrix Relating Technical Requirements to System Parameters.

3.2.4 Technical Requirements

From the QFD analysis described in the previous subsection, four technical requirements were identified as the direct transformations of the customer needs: temporal coverage, geographical coverage, data rate, bit error rate.

The required availability was set at 98 %. This probability is based on the stated values in the FCC filings. Geographical coverage may not necessarily be global. For example, a system may only cover parts of the Earth. The system could still be successful if it has enough subscribers to be profitable. Thus, the geographical coverage of the system must be matched with the distribution of potential customers on the Earth. Since the simulation takes into account the geographical distribution of the market, global coverage was not required. It was assumed that T1 data rate (1.54 Mbps) is necessary. There is not a crisp definition of broadband connection. Different groups use the term broadband with different definitions. The FCC reports refer to the connection with data rate higher than 200 kbps in both directions as advanced telecommunications technology, while they also use the term "high-speed" to refer to connection faster than 200 kbps at least in one direction [FCC, 1999a; FCC, 2000; FCC, 2002a]. The T1 data rate was chosen for compatibility with the Kelic's study [Kelic, 1998]. It was assumed that a bit error rate (BER) of 10^{-5} would characterize the required integrity for business and residential users. More critical applications such as the military require a BER of 10^{-9}, while more forgiving applications such as voice communication require a BER of 10^{-3}. As such, a BER of 10^{-5} was chosen as the requirement for a data communication network for residential and business users.

3.2.5 Performance Metric

The simulation must output one or more numbers that reflect the technical and economic performance of the satellite network system. Based on the GINA methodology, a cost per function (CPF) type metric was most appropriate [Shaw, 1999]. This analysis used the cost per minute of fully utilized T1 network connection achieving an internal rate of return of 30 % and satisfying the requirements defined above. This is a metric that it is neutral to system architecture and captures needs of customers, investors, and the service provider. This cost does not include the initial cost of the user terminal.

Other outputs include the number of subscriber-years over the operation period, total data throughput, mean number of satellites in view from users, etc.

3.2.6 System Model

Based on the above steps, the behavior of the satellite network system was modeled by a set of mathematical relationships. Several major models constitute the system simulation. The constellation & satellite model estimates various properties of the satellites. The system capacity model simulates the motion of the satellites over the Earth and estimates how many users can be supported. The cost model estimates the system's lifecycle cost. The market model represents the potential customers on the Earth who wish to subscribe to the satellite network system. These modules are further broken down into smaller components. The output of the integrated models is the performance metric of the system. Figure 3.3 shows the block diagram representation of the models.

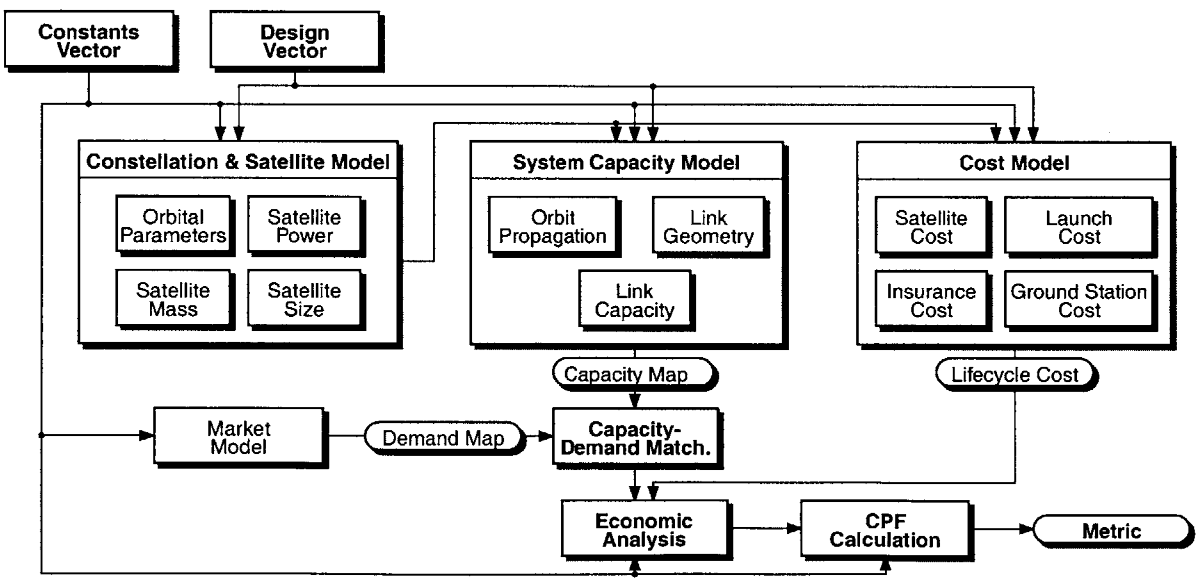


Figure 3.3: Decomposition of Computerized Analysis System Into Modules.

3.3 Implementation of Methodology

The system model and simulation were implemented in the Matlab environment. The orbit propagation data was pre-calculated using the Satellite Tool Kit. Appendix A shows the N^2

diagram, which shows the inputs and outputs to the modules. The table following the N^2 diagram lists the internal parameters.

4 System Model

This chapter explains the developed models. Each section describes the decomposed model shown in Figure 3.3: 1) constellation and satellite models, 2) system capacity model, 3) cost model, 4) capacity/demand matching, 5) market model, and 6) metric calculation.

4.1 System Model Overview

4.1.1 Design Vector

The design vector contains the design variables that characterize a broadband satellite system and differentiate it from others. The number of the design vector elements was kept low so that the results of the comparisons are traceable to design features. The low number of design vector elements also reduces the size of the design space when the developed tool is used for optimization.

As discussed in "Find Key Parameters" section, the Quality Function Deployment (QFD) analysis was used to identify the system design variables that are most relevant to the user needs. The design vector holds the constellation parameters sufficient to derive the orbital parameters of all satellites or the list of the orbital parameters for all satellites. The design vector also contains the payload power and the gain of user downlink satellites antenna. The Table 4.1 lists the elements of the design vector for the case in which constellation parameters are specified. Appendix B lists the numerical values of the design vectors of the studies systems.

Table 4.1: Elements of The Design Vector And Their Symbols.

Description	Symbol
Number of Orbital Planes	N_{Planes}
Number of Satellites per Orbital Plane	$n_{SAT\_per\_Plane}$
Altitude of Orbit	h
Inclination of Orbit	i
Relative Spacing between Satellites in Adjacent Orbital Planes	$\Delta\phi$
Power of Payload	$P_{Payload}$
User Downlink Satellite Antenna Gain	G_{PA}

4.1.2 Constants Vector

The parameters not included in the design vector are kept constant across different systems in order to make a meaningful comparison. These parameters constitute the constants vector. The table below lists the elements of the constants vector with the symbol, value, and unit.

Table 4.2: Elements of the Constant Vector with Their Symbols, Values, and Units.

Description	Symbol	Value	Unit
Total Broadband Market Size	$M_{Broadband}$	Figure 4.3	Subscription-Year
Market Distribution	D_{Market}	Figure 4.4	#
Fraction of Total Broadband Market Willing to Subscribe to Satellite Network	$f_{Satellite}$	0.0001~10	%
Power per Payload Mass	$d_{Payload}$	6	W/kg
Payload Mass Fraction in Dry Mass	$f_{Payload}$	33	%
Dry Mass Fraction in Wet Mass	f_{Dry_Mass}	83.1	%
Satellite Density	d_{SAT}	79	kg/m^3
User Downlink Power Fraction in Payload Power	$f_{Downlink\_Power}$	67	%
Amplifier Efficiency	$\eta_{Amplifier}$	20	%
Minimum Coverage Probability Required	$P_{Min\_Coverage}$	0.98	#
Minimum Elevation Angle Required	$\varepsilon_{Min\_Elevation}$	10	Degree
User Downlink Frequency	$f_{Downlink}$	12.2	GHz
Signal-to-Noise Ratio Required for User Downlink Frequency	E_b / N_O	4.4	dB
User Terminal Antenna Aperture Diameter	D_{User}	0.6	m
User Terminal Antenna Illumination Efficiency	η_{User}	0.6	#
User Terminal System Noise Temperature	T_{User}	135	K
Rain + Link Margin	$L_{Rain+Margin}$	6	dB
Individual User Terminal Data Rate	R_{User}	1.54×10^6	bps
Efficiency of Multi-Access Scheme	η_{MA}	90	%
Internal Rate of Return	i_{RR}	30	%
Inflation Rate	$i_{\inf lation}$	1.7	%
Theoretical First Unit Cost per Kilogram of Satellite Dry Mass	c_{TFU}	84,000	2000$/kg
Non-Recurring Cost Factor of Satellites	f_{NR_SAT}	3	#

Description	Symbol	Value	Unit
Insurance Rate	$f_{Insurance}$	20	%
Number of Ground Stations	N_{GS}	12	
TFU Cost of a Ground Station	TFU_{GS}	16000000	2000$/GS
Required Labor per Ground Station	l_{GS}	20	man-year/GS
Cost of Labor	c_{labor}	160000	2000$/man-year
Non-Recurring Cost Factor of Ground Stations	f_{NR_GS}	3	#
Number of Spare Satellites per Orbital Plane	$n_{Spare\_per\_Plane}$	1	#
Launch Vehicle Margin	m_{LV}	10	%
Height of Launch Vehicle Fairing	$h_{LV\_fairing}$	Table 4.4	m
Diameter of Launch Vehicle Fairing	$D_{LV\_fairing}$	Table 4.4	m
Cost of Launch Vehicle	C_{LV}	Table 4.4	2000$/LV
Launch Vehicle Performance	M_{LV}	Table 4.4	kg
Launch Site Latitude	L_{LV}	Table 4.4	degree
Degradation in Launch Vehicle Performance per Degree of Inclination Increase	$d_{inclination}$	40	kg/degree

4.2 Constellation and Satellite Model

The constellation and the satellites in it were modeled with a set of mathematical relationships that link the design vector and the constant vector to various parameters. Many of the relations are empirical. They are adopted from the previous works and from Space Mission Analysis and Design, 3rd Edition by Larson and Wertz [Violet, 1995; Gumbert, 1996, Larson et al., 1999].

4.2.1 Orbital Parameters

When the constellation parameters were specified instead of listing the orbital parameters for all satellites (Boeing, HughesNET, and SkyBridge), the orbital parameters were derived in the following way. The number of orbital planes N_{Planes} and the number of satellites per orbital plane $n_{SAT\_per\_Plane}$ determine the number of satellites in a constellation.

$$N_{SAT} = n_{SAT\_per\_Plane} \cdot N_{Planes} \qquad \text{(Equation 4.1)}$$

The semi-major axis a_{SAT} is simply the sum of the radius of the Earth (R_{Earth} = 6378137 m) and the altitude of the orbit h.

$$a_{SAT} = R_{Earth} + h \qquad \text{(Equation 4.2)}$$

When the complete list of satellites' Right Ascension of Ascending Node (RAAN) was not available in FCC flings, it was calculated based on the number of orbital planes. Because of the symmetry of the constellation, RAAN Ω_{SAT} of the n-th orbital plane can be calculated by spreading the orbital planes evenly around the Earth.

$$\Omega_{SAT} = (n-1)\frac{2\pi}{N_{Planes}} \qquad \text{(Equation 4.3)}$$

Similarly when not explicitly available in the FCC filing, true anomaly was estimated as follows. The true anomaly υ_{SAT} of the m-th satellite in the n-th orbital plane was calculated as,

$$\upsilon_{SAT} = (m-1)\frac{2\pi}{n_{SAT\_per\_Plane}} + (n-1)\cdot\Delta\phi, \qquad \text{(Equation 4.4)}$$

where $\Delta\phi$ is the relative phasing between satellites in adjacent orbital planes.

4.2.2 Spare Satellites

It was assumed that one spare satellite is needed for each orbital plane ($n_{Spare\_per\_Plane} = 1$). In the case of the Virgo's elliptic constellation, it was assumed that one spare satellite per each sub-constellation is needed. Thus, the number of spare satellites N_{Spare} is

$$N_{Spare} = n_{Spare\_per\_Plane} \cdot N_{Planes} \qquad \text{(Equation 4.5)}$$

4.2.3 Mass

The masses of various components were estimated from the payload power using empirical parametric relationships. First, the payload mass was estimated assuming the energy density $d_{Payload}$ of 6 watts per kilogram of payload mass [Violet, 1995; Gumbert, 1996].

$$M_{Payload} = \frac{P_{Payload}}{d_{Payload}} \qquad \text{(Equation 4.6)}$$

Second, the dry mass of the satellite was estimated assuming that the payload mass is 33 % of the spacecraft dry mass ($f_{Payload} = 0.33$) [Violet, 1995; Gumbert, 1996].

$$M_{Dry} = \frac{M_{Payload}}{f_{Payload}} \qquad \text{(Equation 4.7)}$$

Finally, the wet mass was estimated using the historical average of propellant mass fraction f_{Dry_Mass} of 83.1 % [Larson et al., 1999].

$$M_{Wet} = \frac{M_{Dry}}{f_{Dry\_Mass}} \qquad \text{(Equation 4.8)}$$

4.2.4 Dimension

The dimensions of the satellite must be estimated to verify fit in the launch vehicle fairings. The satellite bus volume V_{SAT} was first estimated from the wet mass M_{Wet} assuming the density d_{SAT} of 79 kg/m^3 for the overall satellite. This density is a historical average for communication satellites [Larson et al., 1999].

$$V_{SAT} = \frac{M_{Wet}}{d_{SAT}} \qquad \text{(Equation 4.9)}$$

The diameter of the satellite bus D_{SAT} was estimated from the satellite wet mass M_{Wet} using another parametric relationship [Larson et al., 1999].

$$D_{SAT} = 0.25 \cdot \sqrt[3]{M_{Wet}}$$ (Equation 4.10)

Finally, the height of the satellite bus l_{SAT} was calculated simply by dividing the volume by the base area.

$$l_{SAT} = \frac{V_{SAT}}{\pi \left(D_{SAT} / 2 \right)^2}$$ (Equation 4.11)

4.2.5 Power

Since there are multiple spot beams that are power-controlled, it is difficult to model the power consumptions for user downlink, user uplink, gateway downlink, and gateway uplink. Although complete description of the power consumption and management was not always present in the FCC applications, it was assumed that 2/3 of the payload power $P_{Payload}$ is available for the user downlink ($f_{Downlink\_Power} = 0.67$). The user downlink power $P_{User\_Dwonlink}$ is,

$$P_{User\_Downlink} = f_{User\_Downlink\_Power} \cdot P_{Payload}$$ (Equation 4.12)

The above power is input to the amplifier. Assuming an amplifier efficiency $\eta_{Amplifier}$ of 20 % the radio frequency power radiated is,

$$P_{User\_Downlink\_RF} = \eta_{Amplifier} \cdot P_{User\_Downlink}$$ (Equation 4.13)

Combining the radio frequency power $P_{User\_Downlink\_RF}$ and the phased array antenna gain G_{PA}, the Effective Isotropic Radiated Power (EIRP) for user downlink $P_{User\_Downlink\_EIRP}$ is

$$P_{User\_Downlink\_EIRP} = G_{PA} \cdot P_{User\_Downlink\_RF}$$ (Equation 4.14)

4.3 System Capacity Model

4.3.1 Overview of Capacity Simulation

The system capacity model simulates the motion of the satellites and estimates how many T1 lines the system can support. Using the orbit propagator, the link geometry between satellites and Earth grids is calculated. For the links that satisfy minimum elevation angle and minimum coverage probability required, a link budget calculation is done. The following subsections explain the details of this analysis. How this capacity estimate was matched with the market demand estimate will be explained later.

4.3.2 Assumptions on Capacity Simulation

In this study the capacity of the satellite network system was measured by the number of T1 connections supportable on user downlinks assuming that the user downlink is the bottleneck in the system. In reality, the capacity of a communication network is difficult to quantify. It depends on the origin and destination of the data sent and also on the bottlenecks in between. There are many links that can potentially be the bottleneck: gateway uplink, gateway downlink, user uplink, user downlink, satellite crosslink, and gateway to outside network. Moreover there are many causes of bottlenecks: power limit, bandwidth limit, energy flux regulation, interference regulation, etc. For example, if the Internet itself is clogged, the fast connection links between gateway and users are not very useful. Another consideration is that the user uplink may become the bottleneck because of multi-access scheme. Enabling a multi-access scheme for geographically separated users is complex and costly since users terminals must be synchronized and coordinated. The user downlink is restricted by the most severely limited resource, which is the payload power of the satellite. It is more feasible to increase gateway power or gateway antenna size than to increase satellite payload power or satellite antenna size. The user uplink can be similarly improved by enlarging and empowering user terminals. Or the user uplink data rate can be compromised as in consumer DSL services because many consumer applications require higher downlink data rate. Thus, assuming that gateway links and user uplink have enough data rate to route the network traffic, the capacity of the system was assumed to depend on the user downlink capacity.

The positions and links were calculated in 3-minute time steps over a 24-hour period. The surface of the Earth was divided into 15-degree latitude by 15-degree longitude grids. The 3-minute time step and 15-degree by 15-degree grid represents a compromise between computing expense and fidelity. The 15-degree by 15-degree grid size was chosen following Gumbert and Violet. The 3-minute time step was chosen since it is smaller than the time it takes for a LEO satellite's groundtrack to move 15 degrees latitude or 15 degrees longitude at the equator. The capacity simulation was done for one 24-hour period. The degradation of the satellite payload is not modeled.

4.3.3 Orbit Propagation

Satellite Tool Kit (STK) was used to propagate the orbits of the satellites. STK propagator takes into account up to the J2 and J4 effect from the non-spherical shape of the Earth. The propagator uses 60-second time steps, but the output was restructured to 3-minute time steps to reduce computational workload in later calculations. The position of the satellite was expressed in Cartesian coordinates fixed to the Earth for the convenience in later geometry calculations.

The orbits of the satellites are propagated for a 24-hour period. For this length of period, the propagator reproduces the constellation with a sufficient accuracy.

4.3.4 Link Geometry

The propagator provides the position of the satellite relative to the Earth. The radius of satellite's position S_{SAT} is the root of the sum of the squares of the three coordinates. The position of an Earth grid is known and constant. Thus, the transmission pathlength S from a satellite to the center of an Earth grid can be simply calculated by geometry. The elevation angle of the satellite seen from an Earth grid can be calculated using the cosine formula assuming that the Earth is spherical.

$$\varepsilon_{Elevation} = \cos^{-1}\left(\frac{S^2 + R_{Earth}{}^2 - S_{SAT}{}^2}{2 \cdot S \cdot R_{Earth}}\right) - \frac{\pi}{2} \qquad \text{(Equation 4.15)}$$

Figure 4.1 illustrates the link geometry between a satellite and an Earth Grid. This calculation is repeated for the link between each satellite and each Earth grid at each time step.

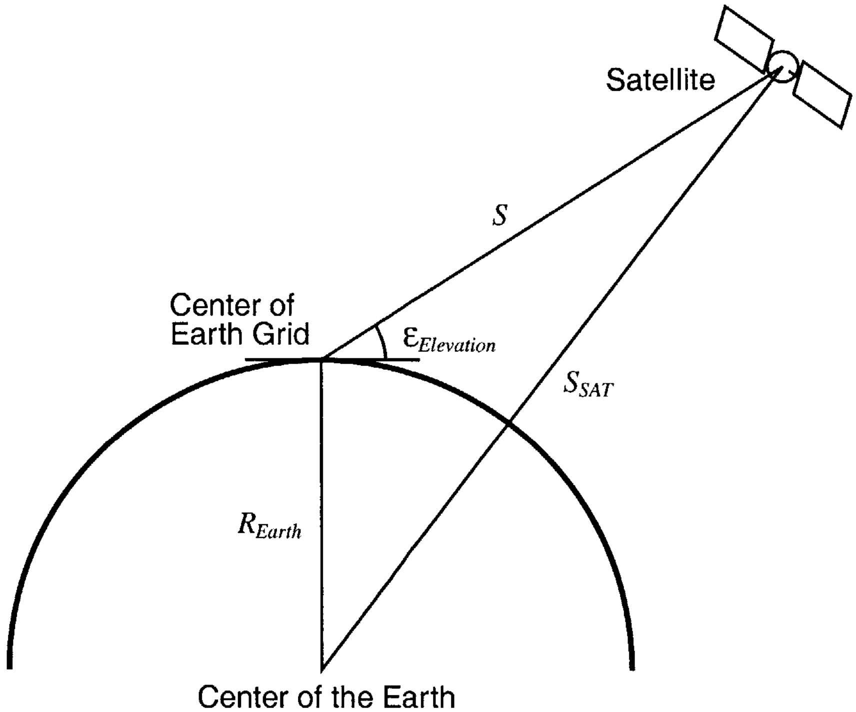


Figure 4.1: Link Geometry between Satellite and Earth Grid

After link geometry was calculated, elevation angle was checked to see if it satisfies the minimum required elevation angle of 10 degrees. Then the probability of coverage was computed by taking average over time steps. The Earth grids with probability of coverage greater than the required probability of 98 % form the service area for the system. Only the market within the service area was considered.

4.3.5 Assumptions on Link Calculation

Table 4.3 summarizes the assumptions made in the link calculations.

Table 4.3: Assumptions for Link Calculations.

Assumption	Value
Single User Downlink Data Rate	T1 = 1.544 Mbps
Downlink Frequency	12.2 GHz, center of 11.7 and 12.7 GHz
Required Bit Error Rate	10^{-5}
Modulation & Coding	QPSK + half rate Viterbi decoding
Required Signal-to-Noise Ratio	Eb/No = 4.4 dB
Rain Loss + Link Margin	6 dB
Multi-Access Scheme	Spot beams + FDMA, TDMA
Multi-Access Efficiency	90 %
Minimum Required Elevation Angle	10 degrees over horizon
User-Terminal Aperture Diameter	0.6 m
User-Terminal Illumination Efficiency	0.6
User-Terminal System Noise Temperature	135 K

A single user's data rate R_{User} was set at 1.54 Mbps. Frequency of downlink $f_{Downlink}$ was set at the center of the downlink band from 11.7 GHz to 12.7 GHz. Most systems plan to divide this band into channels, but for simplicity this frequency was used for all downlink calculations. Following the majority of the FCC applications, the combination of Quadrature Phase Shift Keying (QPSK) and half rate Viterbi decoding was chosen. For this modulation and coding, the signal-to-noise ratio E_b / N_O at the bit error rate of 10^{-5} is 4.4 dB [Larson et al., 1999].

Communication links are designed with some margin so that unpredictable losses do not frequently interrupt communication links. The predominant loss element in the Ku-band is rain and water in the atmosphere. Although it is possible to incorporate rain models such as the Crane model to predict the margin required to maintain certain availability at each Earth grid, one link margin was used for all links. After examining the rain attenuation sources, it was assumed that link margin $L_{Rain+Margin}$ of 6 dB is more than sufficient to maintain 98 % availability at Ku-band against rain and other loss sources [Elbert, 1999].

Satellites were assumed to use active phased array antennas with the capability to generate multiple spot beams and dynamically change the beam pattern to allocate more beams to the area with high demand. Specifying a dynamic beam pattern is difficult, and it is not done in the FCC filings. Thus, simplifying assumptions were made to still model the "intelligent" dynamically reconfiguring beam patterns without modeling individual spot beams. However the maximum frequency reuse ratio was not set. Inside spot beams, multi-access techniques are used to facilitate multiple users. Frequency Division Multi-Access (FDMA), Time Division Multi-Access (TDMA), and Code Division Multi-Access (CDMA) are commonly used. The multi-access scheme is simply modeled by multiplying single-access data rate by multi-access efficiency η_{MA}, which is the ratio of usable data rate to the total data rate. Assuming an efficient scheduler based multiple-access scheme, the multi-access efficiency was set at 90 % ($\eta_{MA} = 0.9$) [Bertsekas et al., 1992].

From a user's point of view, landscape, buildings, and the atmosphere limit the elevation angle at which a link can be established. The minimum elevation angle for user downlinks was set at 10 degrees following most of the FCC filings. The user's antenna was assumed to be a parabolic antenna with an aperture diameter D_{User} of 0.6 m and an illumination efficiency of 0.6. The system noise temperature T_{User} of the user terminal was assumed to be 135 K [Larson et al., 1999].

4.3.6 Link Capacity

The capacity of a link between one satellite and one Earth grid was measured by the number of users that can be supported. The attainable single-user data rate given the access geometry and link assumptions was calculated. Then, the number of users that can be supported with that data rate was calculated assuming the 10 % multi-access loss. In the calculation, it is assumed that full downlink power is available for the link being considered. The limitation due to a satellite's resource allocation is dealt with in the capacity/demand matching calculation.

The space loss L_S characterizes the weakening of the signal flux density due to the transmission pathlength S. The space loss also depends on the wavelength of the signal $\lambda_{Downlink}$. It can be calculated as,

$$L_S = \left(\frac{\lambda_{Downlink}}{4\pi S} \right)^2 \qquad \text{(Equation 4.16)}$$

The atmospheric loss L_A is the fading of the signal due to the absorption and scattering by the Earth's atmosphere. Because of the composition of the atmosphere, it depends strongly on the frequency of the signal. In the Ku-band, the atmospheric loss at the elevation angle of 90 degrees is 0.07 dB. At other elevation angles above 5 degrees, the atmospheric loss can be estimated by dividing the zenith attenuation by the sine of the elevation angle $\varepsilon_{Elevation}$ [Larson et al., 1999]. The atmospheric loss is,

$$L_A = 10^{\frac{-0.07}{\sin \varepsilon_{Elevation}}/10} \qquad \text{(Equation 4.17)}$$

The user's antenna collects and magnifies the signal. Given the antenna diameter, D_{User}, the wavelength of the signal, $\lambda_{Downlink}$, and the antenna illumination efficiency η_{User} of 0.6, the gain of user terminal antenna G_{User} can be calculated as

$$G_{User} = \eta_{User} \left(\frac{\pi \cdot D_{User}}{\lambda_{Downlink}} \right)^2 \qquad \text{(Equation 4.18)}$$

Given the parameters calculated above, the single-user downlink capacity of the satellite to the Earth grid (assuming full downlink power available) can be calculated as follows. The total data rate R_{Total} is determined by the downlink EIRP power $P_{User\_Downlink\_EIRP}$, various losses ($L_A, L_S, L_{Rain+Margin}$), gain of the receiving antenna G_{User}, its system noise temperature T_{User}, and the required SNR E_b / N_O.

$$R_{Total} = \frac{G_{User} \cdot L_S \cdot L_A \cdot L_{Rain+Margin} \cdot P_{User\_Downlink\_EIRP}}{(E_b / N_O) \cdot k_B \cdot T_{User}}, \qquad \text{(Equation 4.19)}$$

where k_B is the Boltzmann constant. Then, some fraction of this total data rate will be lost to facilitate multiple users. The capacity C_{SAT} or the number of T1 lines that can be put on this link is,

$$C_{SAT} = \frac{\eta_{MA} \cdot R_{Total}}{R_{User}},$$ (Equation 4.20)

where η_{MA} is the multi-access efficiency, and R_{User} is data rate of an individual user terminal.

4.4 Cost Model

Over its lifecycle, the service provider pays for various system costs. These costs were estimated with parametric cost estimation relationships assuming 1.7 % inflation rate.

4.4.1 Overview of Cost Estimating Methodology

The system cost was decomposed into satellite non-recurring cost, satellite recurring cost, launch cost, insurance cost, ground station non-recurring cost, ground station recurring cost, and ground station labor cost. Then the costs of the decomposed elements were estimated using parametric cost estimation relationships (CER) except for the launch cost. The launch cost was estimated by finding the combination of candidate launch vehicles that minimizes the total launch cost.

An annual inflation rate $r_{Inflation}$ of 1.7 % was assumed for the years from 2000 to 2015. The estimated costs are in the constant year 2000 dollars. The constant dollar was calculated by discounting the nominal dollar by the annual inflation rate for each year between the year 2000 and the year in which the cost occurs.

4.4.2 Satellite Production Costs

According to Violet and Gumbert, the theoretical first unit (TFU) cost of a satellite TFU_{SAT} can be estimated from its dry mass M_{Dry} [Gumbert, 1996; Violet, 1995]. Violet and Gumbert used the cost per dry mass of $70,000/kg in constant 1995 dollars. This number was converted to the TFU cost per dry mass c_{TFU} of $84,000/kg in constant 2000 dollars. The TFU cost of a satellite TFU_{SAT} is,

$$TFU_{SAT} = c_{TFU} \cdot M_{Dry}$$ (Equation 4.21)

When identical satellites are manufactured in some numbers, the cost per single satellite drops due to learning in manufacturing. The learning curve characterizes this effect. The learning curve slope s_{SAT}, which characterizes the strength of the learning effect, was chosen according to the number of manufactured satellites. The number of the manufactured satellites $N_{SAT\_Produced}$ is simply the sum of the number of satellites in the constellation N_{SAT} and the number of the spare satellites N_{Spare}.

$$N_{SAT\_Produced} = N_{SAT} + N_{Spare} \qquad \text{(Equation 4.22)}$$

If the number of manufactured satellites is less than 10, a learning curve slope of 0.95 was used. If the number of manufactured satellites is between 10 and 50, a learning slope curve of 0.9 was used. If the number of manufactured satellites is greater than or equal to 50, a learning curve slope of 0.85 was used. The total recurring cost R_{SAT} of satellites with learning effect taken into account is given by,

$$R_{SAT} = TFU_{SAT} \cdot N_{SAT\_Produced}^{\;1+\frac{\log s_{SAT}}{\log 2}} \qquad \text{(Equation 4.23)}$$

The satellite recurring cost was assumed to be paid in 2005. For HEO cases in which sub-constellation may start service after 2006, it was assumed that the satellite recurring cost is paid in the year prior to the start of the service.

4.4.3 Satellite Non-Recurring Costs

The non-recurring cost of the satellites NR_{SAT} includes research and development costs. This portion of the cost is independent of the number of satellites manufactured. The non-recurring cost was estimated based on the TFU cost of the satellite TFU_{SAT}. The TFU cost was multiplied by the non-recurring cost factor f_{NR_SAT} of 3. The non-recurring factor was kept constant over different systems.

$$NR_{SAT} = f_{NR\_SAT} \cdot TFU_{SAT} \qquad \text{(Equation 4.24)}$$

The non-recurring cost was spread over the five years from 2001 to 2005 before the start of service in 2006. The empirical cost spreading approximation developed by Wynholds and Skratt was used with 50 % expenditure at schedule midpoint [Larson et al., 1999]. Using this approximation, 5.8, 26.0, 36.5, 26.0, and 5.8 % of the non-recurring costs are spend in years from 2001 to 2005 respectively.

4.4.4 Launch Costs

The launch cost C_{Launch} was estimated by considering which and how many launch vehicles are needed to deploy the constellation. The FCC filings typically stated that their satellites would be designed so that they can be launched on several different launch vehicles, but the names of those launch vehicles were kept confidential. As such, Ariane V, Atlas V, Delta IV, and Proton M were chosen as the fleet of candidate launch vehicles.

The capacities of the candidate launch vehicles were adopted from International Reference Guide to Space Launch Systems, 3rd Edition. The following table summarizes the capacity and cost of different launch vehicles considered [Isakowitz, 1999].

Table 4.4: Characteristics of the Considered Launch Vehicles [Isakowitz, 1999].

Launch Vehicle	Cost (1998$)	Fairing Diameter (m)	Fairing Height (m)	Launch Site Latitude (degree)	Mass to 1,000 km Altitude (kg)	Mass to 15,000 Altitude (kg)	Mass to 35,000 Altitude (kg)
Ariane V	$150M	5.4	17.0	5.2	17856	13356	7756
Atlas V	$100M	5.0	20.7	28.5	13060	10060	6060
Delta IV	$90M	5.0	14.3	28.5	8060	6660	4860
Proton M	$80M	4.35	11.6	45.6	5174	4524	3624

The mass capacity was reduced by a launch vehicle degradation factor $d_{inclination}$ of 40 kg per a degree of inclination change from the orbital plane with inclination equal to the launch site latitude. The mass and dimension capacities were then decreased by launch vehicle margin m_{LV} of 10 %.

Based on the estimated mass and size of the satellites and the capacity of the candidate launch vehicles, the maximum number of satellites that can be launched on each launch vehicle was calculated. It was assumed that multiple satellites could be launched on a single launch vehicle if they fit in the fairing shroud and if they are in the same orbital plane. An exception was made for the HEO case where it was assumed that multiple satellites can be launched into orbits with different orbital planes by taking advantage of orbital regression.

From the number of orbital planes and the number of satellites per orbital plane, the combination of launch vehicles that minimizes the total launch cost was chosen [Munson et al., 2000].

The launch cost was assumed to be paid in 2005. For HEO cases in which sub-constellation may start service after 2006, it was assumed that the launch cost is paid in the year prior to the start of the service.

4.4.5 Insurance Costs

The insurance cost $C_{Insurance}$ was assumed to be the 20 % of the sum of the satellite production R_{SAT} costs and the launch cost of the entire constellation C_{Launch}.

$$C_{Insurance} = f_{Insurance} \cdot \left(R_{SAT} + C_{Launch}\right), \qquad \text{(Equation 4.25)}$$

where $f_{Insurance}$ is the insurance rate. The 20 % insurance is a commonly used figure for estimating the insurance cost.

The insurance cost was assumed to be paid in 2005. For HEO cases in which sub-constellation may start service after 2006, it was assumed that the insurance cost is paid in the year prior to the start of the service.

4.4.6 Ground Station Costs

It was assumed the twelve ground stations are built ($N_{GS} = 12$). This makes it necessary to make another assumption that the satellites have inter-satellite link capability since some satellite will have no ground station in their field-of-view. Like satellite costs, the recurring and non-recurring costs of ground stations were calculated with the TFU cost TFU_{GS} of $16 million and the learning slope s_{GS} of 0.9 [Larson et al., 1999].

$$R_{GS} = TFU_{GS} \cdot N_{GS}^{1+\frac{\log s_{GS}}{\log 2}}, \qquad \text{(Equation 4.26)}$$

where N_{GS} is the number of ground stations. The non-recurring cost NR_{GS} of the ground station was calculated with the non-recurring cost factor f_{NR_GS} of 3.

$$NR_{GS} = f_{NR\_GS} \cdot TFU_{GS} \qquad \text{(Equation 4.27)}$$

The non-recurring cost was spread over the years from 2001 to 2005 using the same schedule used for the satellite non-recurring cost.

Each ground station was assumed to require 20 man-years of labor ($L_{GS} = 20$). The labor cost c_{Labor} of $160,000 per man-year was assumed [Larson et al., 1999]. The total annual cost of ground station labor C_{Labor_GS} is,

$$C_{Labor\_GS} = N_{GS} \cdot c_{Labor} \cdot L_{GS} \qquad \text{(Equation 4.28)}$$

The ground station labor cost was assumed to be paid each year from 2006 to 2015.

4.4.7 Cost Model Results

Figure 4.2 is the plot of the decomposition of the total system costs for the systems.

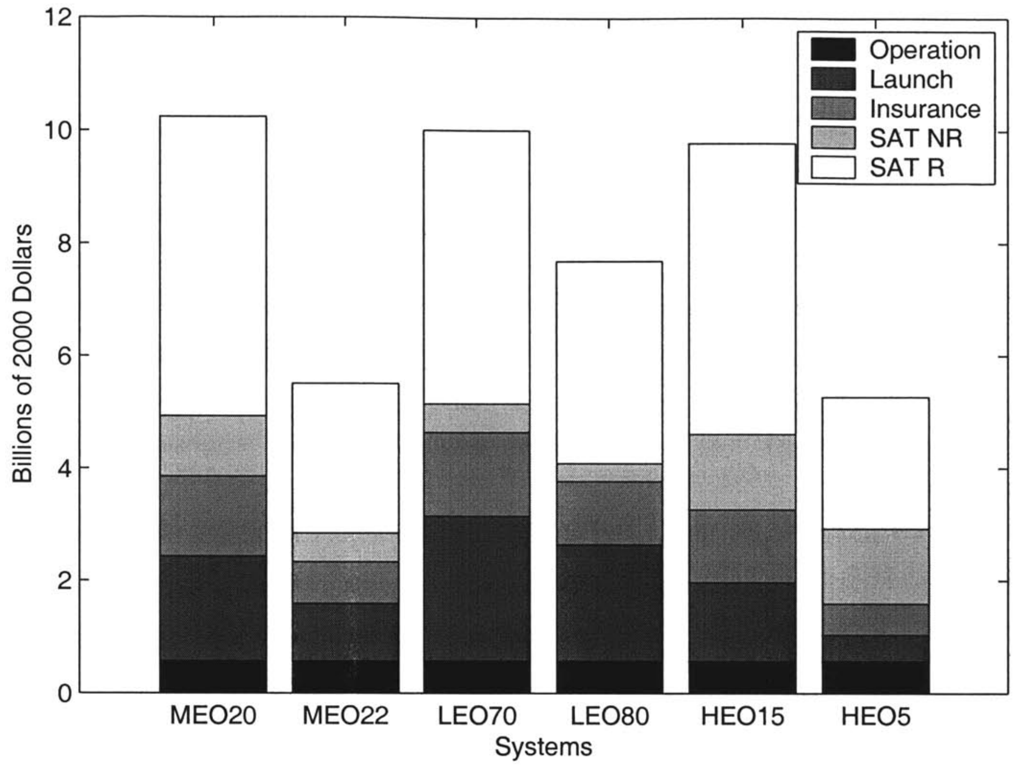


Figure 4.2: Break Down of System Costs Estimated by the Cost Model

4.5 Market Model

The market model generates a map of the potential customers who are willing to subscribe to the satellite broadband network. This will be combined with the system's capacity map generated by the system capacity model to estimate the number of subscribers. It was assumed that the potential customers buy the service and become subscribers if the system has enough capacity to support them.

The total size of the market and the distribution of the potential customers are estimated based on the projected broadband market size, global population distribution, and national income of countries.

4.5.1 Market Size

The size of the broadband market was modeled based on a market size projection. The market size projection is adopted from the broadband market report published in 1998 by Pioneer Consulting [Pioneer Consulting, 1998]. The estimate was fitted with a power function to extrapolate into the future. The total broadband market size for year "y" is estimated by the equation below.

$$M_{Broadband}(y) = (6.141\times10^{5})\cdot(y-1997)^{2.346} \quad \text{(Equation 4.29)}$$

Since this estimate is for all broadband technology, it was assumed that some fraction $f_{Satellite}$ of this market is willing to subscribe to a satellite network system. So, the market size of the satellite broadband market $M_{Satellite}$ is

$$M_{Satellite}(y) = f_{Satellite}\cdot M_{Broadband}(y) \quad \text{(Equation 4.30)}$$

This fraction $f_{Satellite}$ was kept as a scenario variable to study the effect of market fluctuations, and it was varied over five orders-of-magnitude from 0.0001 % to 10 %.

Figure 4.3 shows the market size projection and the curve fit used.

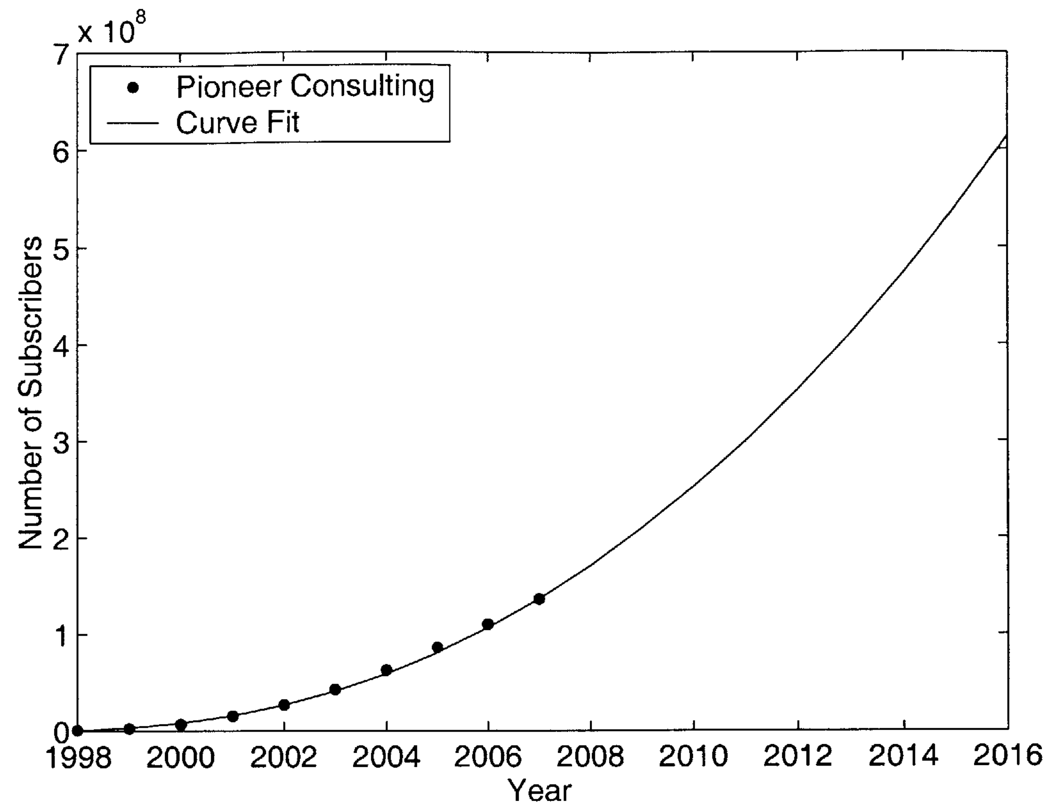


Figure 4.3: Estimate of Broadband Subscriber Growth and Curve Fit.

4.5.2 Market Geographic Distribution

The population is not uniformly distributed over the Earth. All satellite constellations are designed with the understanding of this fact. The scarce population near the poles allows inclination angle to be low. The Virgo constellation locates the apogees of its elliptic orbits over North America, Europe, and East Asia. As a result, the Virgo satellites spend more time over the areas with high concentration of wealth and population. Thus, it is important that the non-uniform distribution of the market is modeled.

The distribution of the demand is based on national income and global population distribution. The total market was first distributed to countries according to their national income, and inside each country the market was distributed according to the population distribution. The distribution map is normalized so that the sum of all elements is one.

The income data was obtained from World Development Indicators published by the World Bank [World Bank, 2000]. It contains a list of Gross National Product adjusted with Purchasing Power Parity (GNP PPP) for most countries in 1998. GNP is the sum of value added by all resident producers. GNP PPP is gross national product converted to international dollars using purchasing power parity rates. An international dollar has the same purchasing power as the U.S. dollar in the United States [World Bank, 2000]. For countries whose GNP PPP was not available from World Development Indicators, estimates were obtained from the World Factbook published by the Central Intelligence Agency [CIA, 2000].

The global population distribution is available from the Center for International Earth Science Information. The Gridded Population of the World Version 2 is a digitized population map with 20-minute longitude by 20-minute latitude resolution [CIESIN, 2000].

Combining the two maps, the market distribution map D_{Market} was constructed. The resolution of the map was reduced to 15 degrees latitude by 15 degrees longitude to reduce the computational efforts in the simulation. The grids south of S75 latitude were omitted because of the very scarce population there. The resulting distribution map has 240 grids ($N_{Grids} = 240$), and it is normalized so that the sum of all elements is one.

$$\sum_{Grid=1}^{240} D_{Market}(Grid) = 1 \qquad \text{(Equation 4.31)}$$

Figure 4.4 shows the GNP PPP and population distribution maps along with the resulting market distribution map.

The product of the satellite market size $M_{Satellite}$ and the market distribution D_{Market} is the potential customer map PC, which has the number of potential customers in each Earth Grid in each Year.

$$PC(y, Grid) = M_{Satellite}(y) \cdot D_{Market}(Grid) \qquad \text{(Equation 4.32)}$$

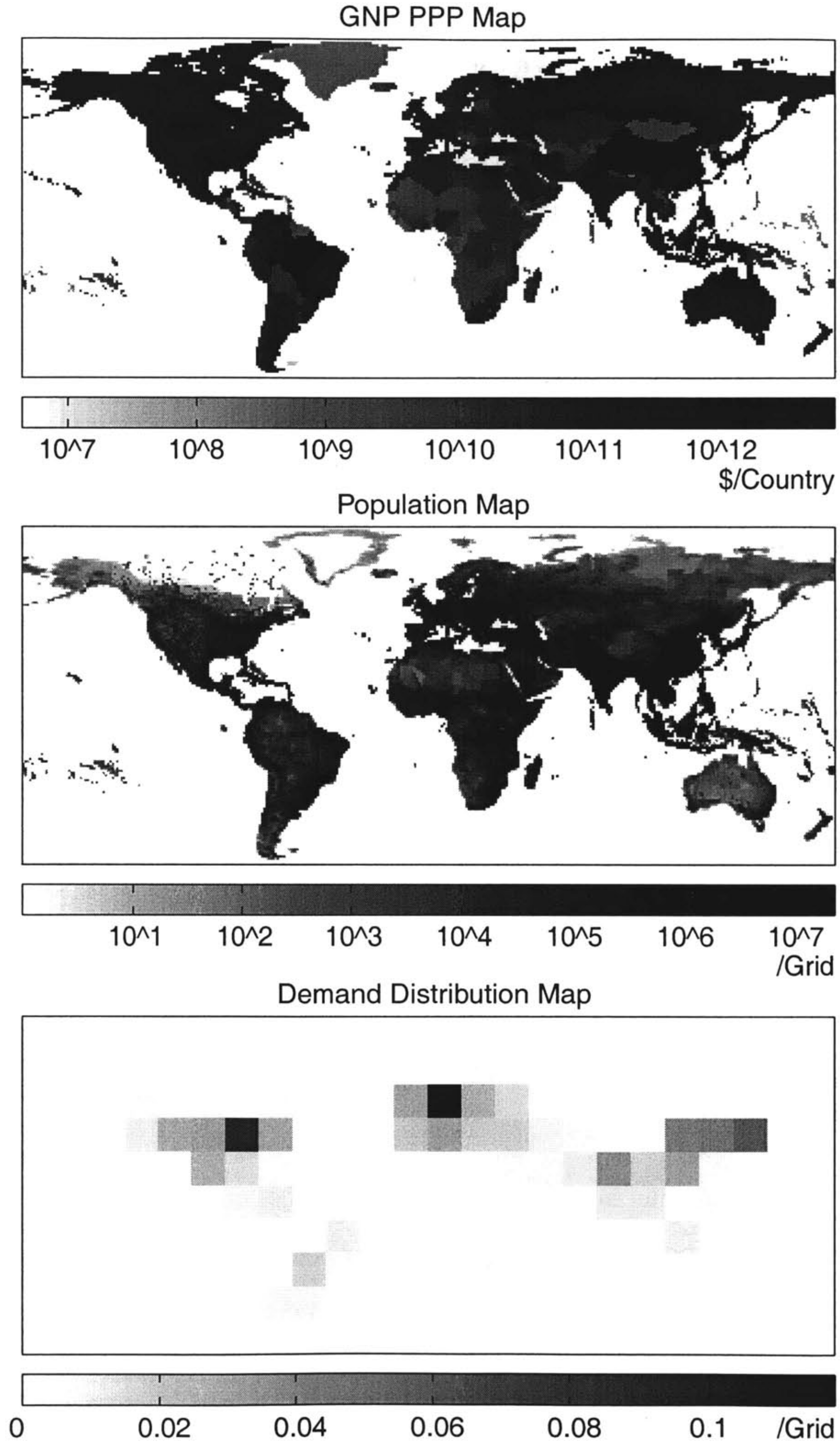


Figure 4.4: Global Distribution Maps of GNP PPP, Population, and Estimated Market Demand.

4.6 Capacity-Demand Matching

4.6.1 Assumptions on Capacity-Demand Matching

The output of the capacity model is the system capacity map. Combining this with the market demand map, the subscriber map was generated. Due to the limited amount of information on the transmission scheme and the available programming and computing resources, the following assumptions were made to enable the simplified approach.

As stated in the previous section, it was assumed that the satellites use phased array antennas to dynamically reconfigure spot beam patterns to adapt to the demand distribution. Since the capacity of each satellite was calculated as the maximum number of subscribers between each satellite and each Earth grid given the full satellite resources, the capacity must be adjusted based on the satellite's resources allocation to the Earth grids the satellite is seeing. "Resources" refer to the payload power available for user downlink. To emulate the "intelligent" satellite, a satellite's resources were allocated starting from the grid with largest capacity to the least capacity until the satellite's resources run out or there are no potential customers in the satellite's field-of-view. This approach is based on the following assumptions: 1) the demand distribution is known; 2) given finite payload power, it is sensible to allocate more resources to the Earth grid links with the largest capacity. However, to provide geographical coverage, not all resources should be concentrated to a single or to a few grids. As a consequence, the maximum resources that can be allocated to one Earth grid were limited.

4.6.2 Capacity-Demand Matching Algorithm

Based on the above assumptions, the following algorithm was used to combine the system capacity map with the market demand map to generate the subscriber map.

Depending on the number of satellites, the maximum resources $r_{Max\_Allocation}$ that can be allocated to one Earth grid link is calculated as,

$$r_{Max\_Allocation} = 2\frac{N_{SAT}}{N_{Grid}}, \qquad \text{(Equation 4.33)}$$

where N_{SAT} is the number of satellites in the constellation, and N_{Grid} is the number of Earth grids (=240). The factor of two is there to model some flexibility in resource allocation. The allocatable resource of one means that all of satellite's power for user downlink can be used for the communication with one grid. Starting from the grid with the best link capacity, the allocation of a satellite's resources to that grid is calculated as follows. The amount of resources required to support the entire grid demand given the link geometry is calculated. This amount of resources is compared to the maximum resources allocatable to one grid calculated before and the resources the satellite has r_{SAT}. The smallest of the three is used as the resources used for that grid r_{Used}.

$$r_{Used} = \min\left(\frac{m_{Grid}}{C_{SAT}}, r_{SAT}, r_{Max\_Allocation}\right), \qquad \text{(Equation 4.34)}$$

where m_{Grid} is the demand grid obtained from the potential customer map generated by the market model. The number of subscribers in that grid n_{SUB} is,

$$n_{SUB} = r_{Used} \cdot C_{SAT} \qquad \text{(Equation 4.35)}$$

These calculations were repeated for all Earth grids in the satellite's field-of-view until the satellite's resources are used up or there are no potential customers in the field-of-view. This is repeated for all time steps in the simulation. When the calculation for one satellite is finished, the potential customer map is passed on to the next satellite for the same calculation. The calculation is repeated for all active satellites in the constellation.

Once the subscriber map is generated, the total number of subscribers can be estimated by taking the time average of the number of subscribers in each grid and then summing the average number of subscribers over all grids.

$$N_{SUB} = \sum_{Grid}\left(\frac{\sum_{Time} n_{SUB}}{N_{Time\_Steps}}\right), \qquad \text{(Equation 4.36)}$$

where N_{Time_Steps} is the number of time steps (=481). This algorithm was repeatedly applied ten times to the ten years of the operational life of the system because the potential customers increase over the 10-year period. The system capacity map was reused assuming that system capacity is constant.

4.7 Metric

Based on the results from the previous models, the metric model calculates the performance metric: the cost per billable T1 minute while achieving the internal rate of return of 30 %.

4.7.1 Assumptions on Metric Calculation

It was assumed that the charge for the network service in year 2000 constant dollars $C_{Subscription\_2000}$ is constant during the operation period. Thus, the charge in nominal dollars $C_{Subscription\_Nominal}$ increases with the inflation rate $i_{Inflation}$.

$$C_{Subscription\_Nominal}(y) = C_{Subscription\_2000} \cdot (1 + i_{Inflation})^{y-2000}, \qquad \text{(Equation 4.37)}$$

where y is the year in the operational period from 2006 to 2015. The charge in present value $C_{Subscription\_PV}$ can be calculated by discounting the nominal charge by the internal rate of return i_{RR} each year.

$$C_{Subscription\_PV}(y) = C_{Subscription\_Nominal} / (1 + i_{RR})^{y-2000} \qquad \text{(Equation 4.38)}$$

Combining the two equations, the charge in present value can be expressed as,

$$C_{Subscription\_PV}(y) = C_{Subscription\_2000} \cdot \left(\frac{1 + i_{Inflation}}{1 + i_{RR}} \right)^{y-2000} \qquad \text{(Equation 4.39)}$$

4.7.2 Metric Calculation

Combining the results from the cost estimations, the life-cycle cost of the system was calculated in 2000 present value (C_{Total_PV}). Then the charge for a year of subscription was adjusted so that the net present value of the system will be equal to zero. Because the net present value is calculated with a 30 % rate of return, zero net present value means that the system returns exactly 30 % on investments.

The revenue is solely from the subscription fees. Thus, the total revenue in present value R_{PV} is the product of the charge in present value $C_{Subscription\_PV}$ and the number of subscribers $N_{Subscribers}$, summed over the operation period.

$$R_{PV} = \sum_{y=2006}^{2015} C_{Subscription\_PV}(y) \cdot N_{Subscribers}(y) \qquad \text{(Equation 4.40)}$$

Substituting the expression for $C_{Subscription\_PV}$, R_{PV} can be written as,

$$R_{PV} = C_{Subscription\_2000}\left[\sum_{y=2006}^{2015}\left(\frac{1+i_{Inflation}}{1+i_{RR}}\right)^{y-2000} \cdot N_{Subscribers}(y)\right] \qquad \text{(Equation 4.41)}$$

Since the system is required to have zero net present value, the revenue in present value R_{PV} is equal to the total system cost in present value C_{Total_PV}. Substituting R_{PV} by C_{Total_PV} and solving for $C_{Subscription\_2000}$, the charge per subscription-year in 2000 constant dollars is,

$$C_{Subscription\_2000} = \frac{C_{Total\_PV}}{\sum_{y=2006}^{2015}\left(\frac{1+i_{Inflation}}{1+i_{RR}}\right)^{y-2000} \cdot N_{Subscribers}(y)} \qquad \text{(Equation 4.42)}$$

The charge per billable T1 minute is the annual subscription cost divided by the number of minutes in a year. The cost of subscription is this charge per subscription.

$$CPF = \frac{C_{Subscription\_2000}}{60 \times 24 \times 365} \qquad \text{(Equation 4.43)}$$

In the FCC filing, Virtual Geosatellite describes its plan to deploy the three sub-constellations sequentially. This is possible because Virgo's sub-constellation can provide continuous coverage over a hemisphere independent of other sub-constellations. Thus, for HEO cases, the deployment schedule of two sub-constellations for the northern hemisphere and one for the southern hemisphere was optimized so that the cost per T1 minute metric is minimized. The first sub-constellation was assumed to start the service in 2006, and the start year for the other two were adjusted from 2006 to 2015 or not deployed at all. This optimized HEO constellation is referred to as HEO system. As references, the HEO system with only one sub-constellation for the northern hemisphere operating from 2006 and the HEO system with all three sub-constellations operating from 2006 were constructed. These two reference cases are referred to as HEO5 and HEO15 systems respectively.

4.8 Benchmarking against Estimations of the FCC Filings

The fidelity of the models must be examined by comparing their output to the external results. This process of benchmarking anchors the simulation models to reality. It would be best to compare it to existing systems. However, since similar systems have not been deployed, the models are compared to the estimations in the FCC filings.

4.8.1 Satellite Mass Benchmarking

The model's prediction of the satellite wet mass was compared to the estimation in the FCC filings. Figure 4.5 shows the plot of the benchmarking result. The model prediction matches the estimates in the FCC filings quite well except for the HEO15/Virgo case. This discrepancy may be because of different satellite technology levels that the Virgo estimate assumes for its elliptic orbits. However, since the cost estimation details are not present in the FCC filing, this explanation for the discrepancy could not be verified.

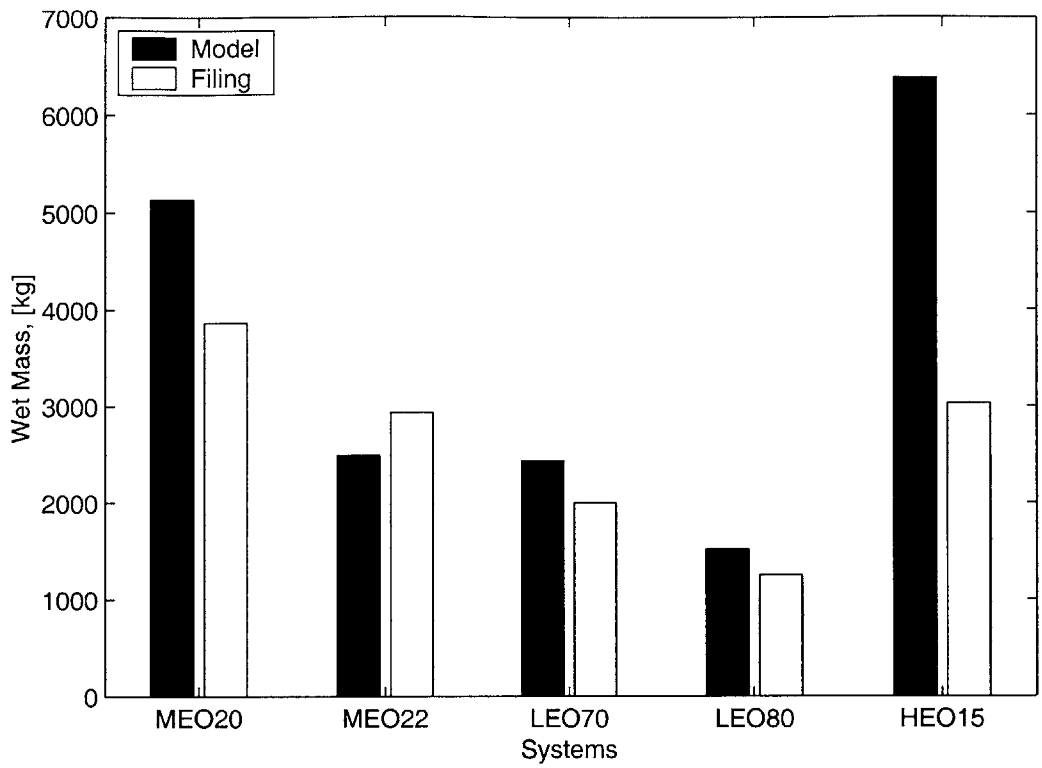


Figure 4.5: Benchmarking by Satellite Wet Mass.

4.8.2 System Costs Benchmarking

System cost up to the first year of operation was compared between the model and the estimates in the FCC filings. Figure 4.6 shows the plot of the benchmarking result. The system cost estimate for SkyBridge is not present since it could not be located. The model predicts higher cost. This inconsistency comes mostly from satellite costs. For example, although Virgo's satellites were as massive as Boeing's as shown in Table 1, their estimated cost was almost half of Boeing's. Since the satellite cost model is based on the dry mass, this trend could not be reproduced with the cost model.

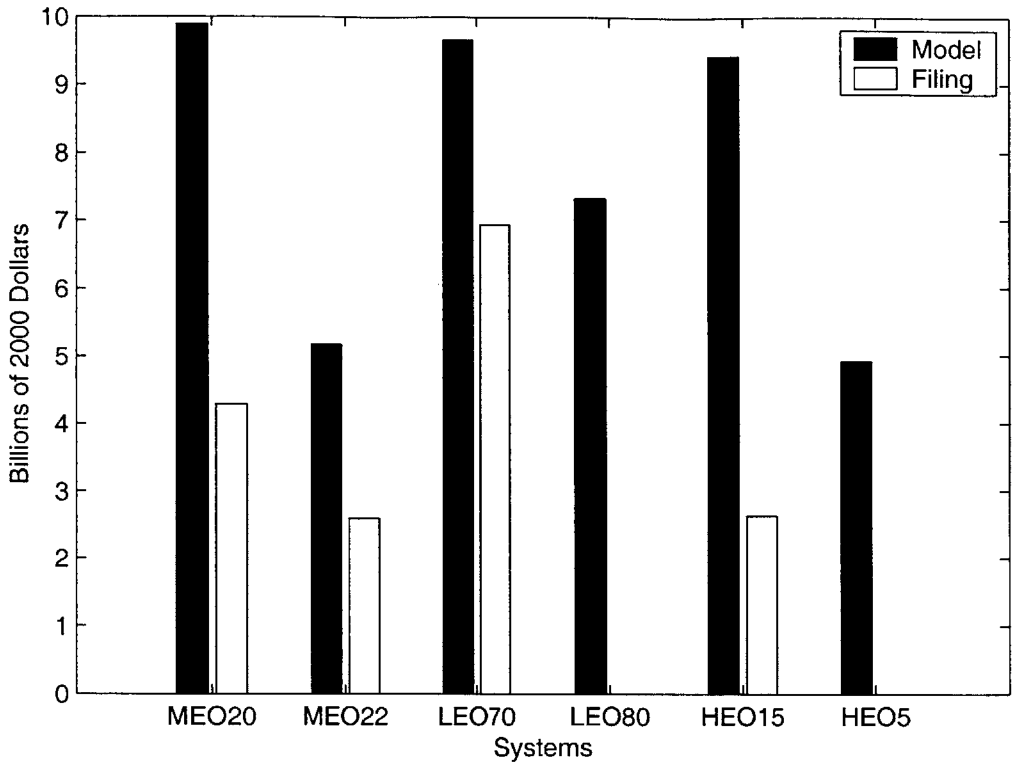


Figure 4.6: Benchmarking by Systems Cost up to the First Year of Operation.

5 Results

5.1 Market Capture

Figure 5.1 shows how each system captures market demand from 2006 to 2015 at different market demand sizes. Different lines correspond to different satellite market fractions from 0.0001 % to 10 %. The market size is the broadband market forecast in Figure 4.3 multiplied by the market fraction. Since the HEO system's deployment schedule was optimized in each scenario, the curves show a sudden rise when an additional sub-constellation comes into service.

As seen in the plots, in the low demand scenarios all systems have enough capacity to meet the demands. The number of subscribers is determined by the market demand. So the shape of the curves resembles the shape of the market size plot (Figure 4.3). In very high demand scenarios, MEO and HEO systems show saturation. The number of subscribers is determined by the system's capacity. LEO systems still show growth in very high demand cases. The link calculation shows that the LEO systems have much greater capacity because of the inverse square law for signal strength and path length. However, in reality, factors that were not accounted for in the developed models probably will limit the capacity of the LEO systems. For example, power flux density regulations limit the power that satellites can emit onto the ground. Interference with other sources also limits the power emitted. Finite available frequency bandwidth is another limitation. Satellites can utilize the allocated frequency bandwidth more efficiently by having a larger number of more pointed spot beams. However, since spot beams were not modeled in the capacity simulation, this limit does not exist in the simulation.

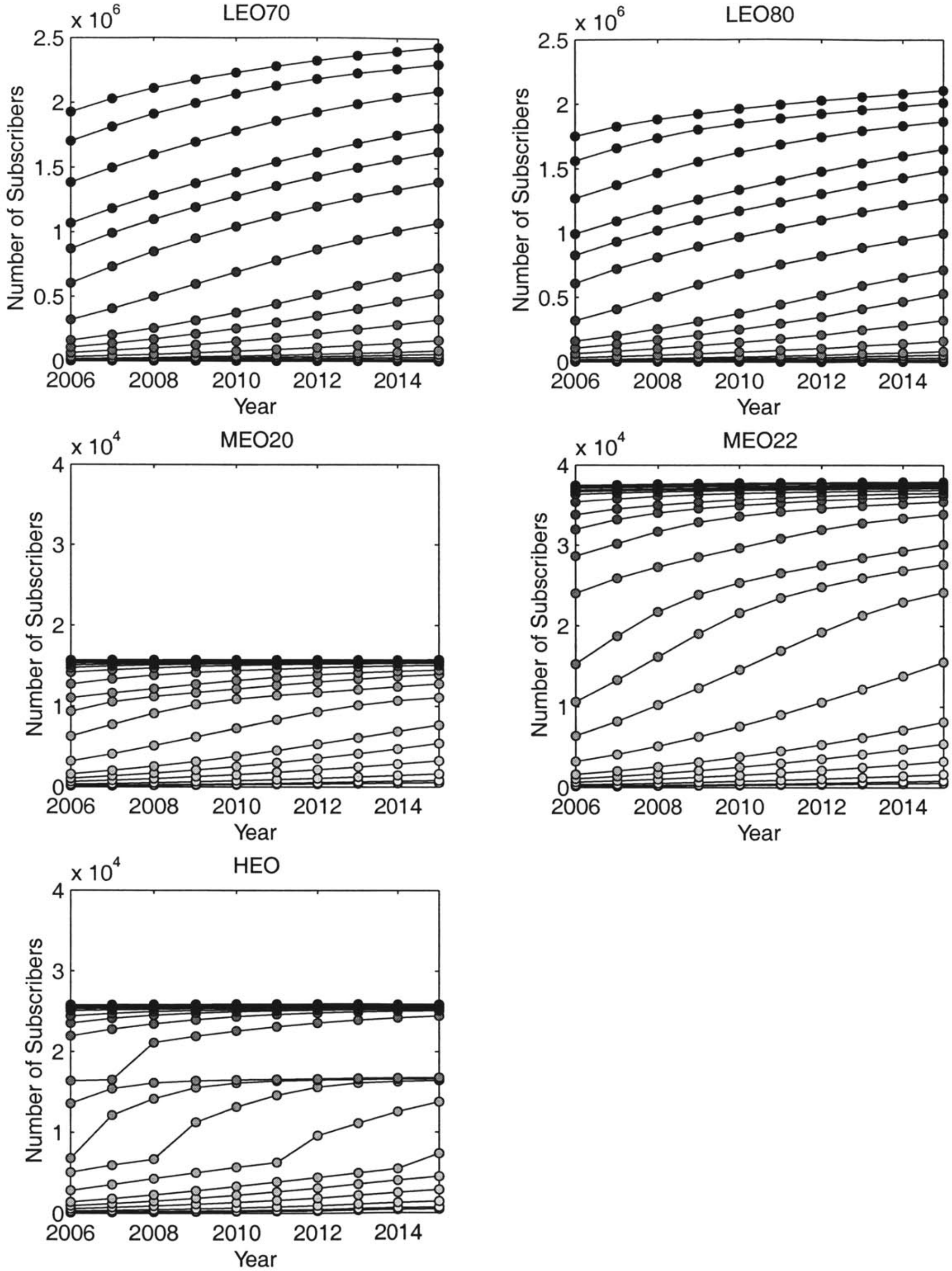


Figure 5.1: Market Capture of the LEO70, LEO80, MEO20, MEO22, and HEO Systems.

5.2 Cost per T1 Minute Metric

The metric was calculated for different scenarios. Figure 5.2 and Figure 5.3 show how the metric responds to the market fraction changes. In the low demand scenarios, the metric asymptotes to the reciprocal of the market size since the number of subscribers is determined by the market demand while the lifecycle cost is nearly fixed. In very high demand scenarios, the metric asymptotes to a constant. This is because the number of subscribers saturates at the system's capacity limit.

The plot shows the HEO5 and HEO15, which are HEO systems with one and three sub-constellations respectively, along with the HEO system with optimized deployment schedule for the lowest cost per subscription. It can be seen that the optimized HEO system moves from the HEO5 to HEO15 as the demand becomes larger. Without scaling, HEO15 is the second most expensive system in the low demand scenarios, but by adjusting the number of sub-constellations, it is the second best system. And by scaling, the HEO system can accommodate three times more subscribers than HEO5 system in higher demand scenarios.

The numerical values of the metric strongly depend on the assumptions made. For example marketing and charging schemes would be strong factors in determining the actual prices for the service. It is also possible to allow more subscribers than the capacity by speculating not all subscribers will need the full bandwidth at the same moment.

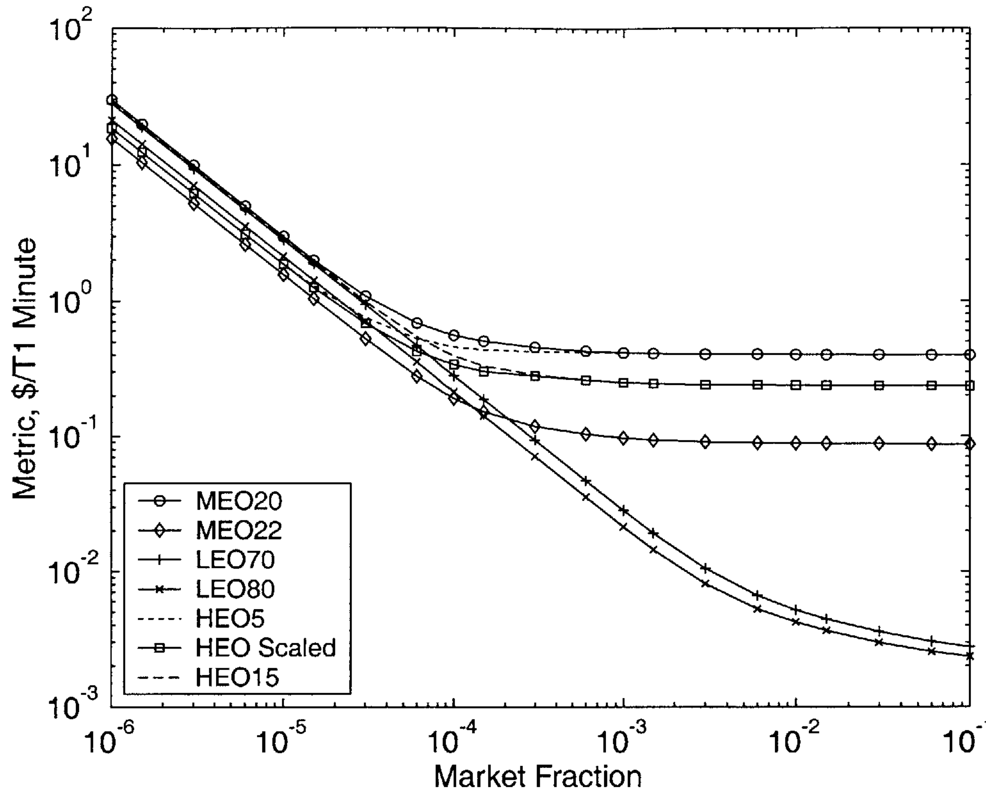


Figure 5.2: Cost per T1 Minute Metric at Different Market Demand Levels.

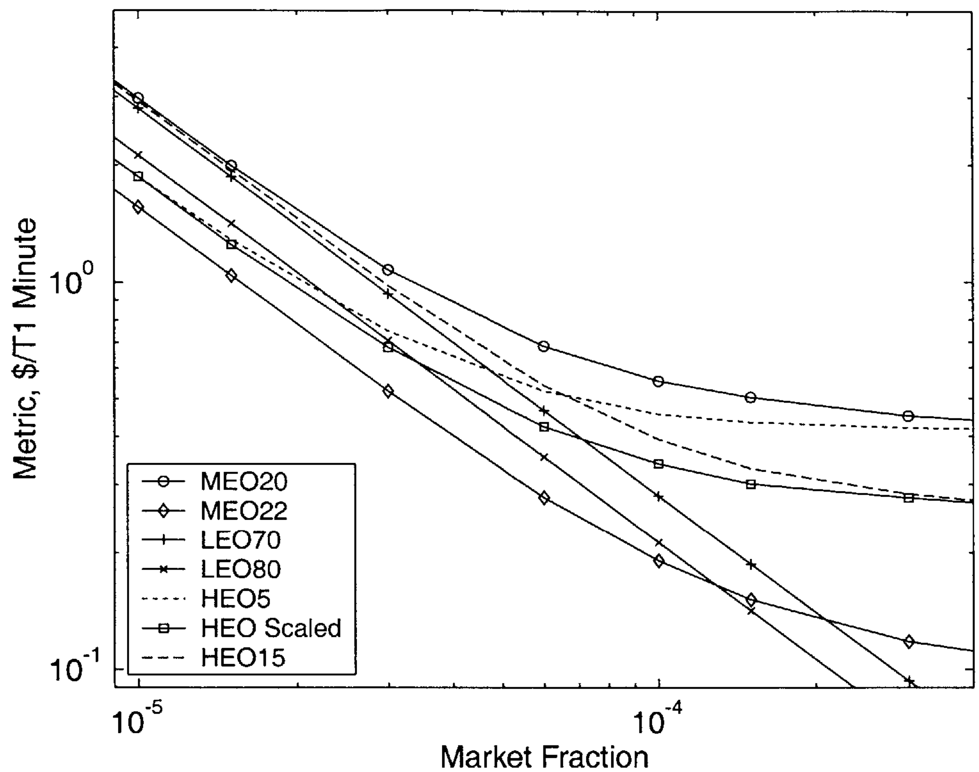


Figure 5.3: Cost Per T1 Minute Metric Plot Magnified.

6 Conclusion

With the soaring demand for network communications service, satellite broadband network systems have been proposed to FCC. On the other hand, the difficult financial experiences of the Iridium and Globalstar systems calls for an economic assessment of satellite ventures in the very early stage of design. In this study, an analysis methodology has been developed and implemented for satellite networks systems. It was applied to a set of satellite broadband network systems based on the five systems recently proposed to the FCC. The considered systems represent satellite constellations with LEO, MEO, and elliptic orbits. The technical and economic performance of the systems was evaluated by the metric: cost per billable T1 minute required to achieve an internal rate of return of 30 % with key technical requirements satisfied. Various assumptions were made to allow a unified comparison and modeling of the systems. As a consequence, the analyzed systems are not exact representations of the proposed systems.

The computed results show that the preferred system differs for different levels of market demand. The MEO systems are better in low demand scenarios. The LEO systems can support very large number of customers and low cost per subscription in high demand scenarios. In terms of robustness to the market fluctuations, the HEO system, which has the ability to deploy by sub-constellation, showed an improved metric by adapting the deployment schedule.

A computer tool has been developed to automate this methodology in order to efficiently evaluate the performance metric from a set of design variables. It was implemented so that it can be reused for design space exploration, optimization, or sensitivity analysis. In fact, it was used by Cyrus Jilla in one of his case studies of distributed satellite system optimization [Jilla, 2002].

7 Future Work

7.1 Model Fidelity

The fidelity of all simulation modules can be enhanced given more data and relationships. However, this may sacrifice the computing expense and automation, and thus the usefulness in robustness evaluation and optimization.

Many properties of the satellites are derived from two design vector elements; payload power and antenna gain. The fidelity of the satellite model can be heightened by increasing the number of design vector elements and/or using more detailed estimation relationships.

The cost model can also be made more precise by increasing the number of design vector elements and/or using more detailed estimation relationships.

The method used for link calculation was adopted for various reasons. The compared systems must be standardized for comparison. Not all information necessary to carry out detailed modeling of the communication process was available. The computing expense was kept low so that the developed tool has a quick return time, and thus is useful in sensitivity analysis, design space exploration, and optimization. Removing these limitations would enable the use of a more sophisticated link calculation method.

7.2 Market Model

This study used the market model based on a particular market forecast. If other market scenarios are of interest and available, they should be used. The modeling of the market is one of the most difficult tasks. In this thesis, it was decided to vary the potential market size over a very wide range instead of picking a few market sizes. This approach enabled the investigation of robustness of the systems to the market fluctuation. This approach also made the market forecast error less significant. Since the ratio of satellite market with respect to the total broadband market is varied over a very wide range, the small error in the market size forecast does not have a significant effect on the calculated trend. The market forecast used in this study is from 1998, when the prospect for network communications services and economy in general was optimistic. However, this can be corrected simply by looking at scenarios with smaller market fractions.

As discussed in the market model section, residential and business users are not the only potential customers. Other applications may turn out to be the "killer application" for satellite network systems. Incorporating other applications into the market model could address this scenario.

In the simulation, the interaction of the system with other satellite network systems or any other network service is not modeled. Since there is always a competition in the market, modeling more than one system simultaneously would be useful.

7.3 Phased Deployment Granularity

The scalability of satellite constellations is worth further investigation. In this thesis, only HEO systems had the ability to adjust the deployment schedule of the second and third sub-constellations. Elliptic constellation concepts that allow many sub-constellations have been designed (e.g. COBRA, Teardrop) [Draim et al., 2001a; Draim et al., 2001b]. Increasing the granularity of partial deployment is expected to further increase the scalability and maximum capacity. However, increasing the number of satellites poses such problems as interference and hand-over. Thus, both positive and negative effects must be investigated to evaluate the net effect.

7.4 User Terminal Initial Cost

As mentioned in the Performance Metric section, the user's initial cost of installing and introducing the user terminal is not accounted for in this study. The amount of required initial investment is as important as the recurring cost when potential customers shop for network services. The slow market penetration of satellite mobile phones is partially due to the price of the handset. The complexity of user terminals is influenced by many factors, such as the amount of tracking effort, power, and signal processing.

Bibliography

[Bertsekas et al., 1992] Bertsekas, Dimitri and Gallager, Robert, Data Networks, 2nd Edition, Princeton-Hall, Englewood Cliffs, New Jersey, 1992.

[Boeing, 1999] The Boeing Company, "Application for Authority to Launch and Operate a Non-Geostationary Medium Earth Orbit Satellite System in the Fixed Satellite Service," Seattle, Washington, 1999.

[CIA, 2000] Central Intelligence Agency, The World Factbook, Washington, D.C., 2000.

[CIESIN, 2000] Center for International Earth Science Information Network, Columbia University; International Food Policy Research Institute; and World Resources Institute, "Gridded Population of the World, Version 2," Palisades, New York, 2000, http://sedac.ciesin.columbia.edu/plue/gpw.2000

[Ciesluk, 1992] Ciesluk, W. J., Gaffney, L.M., Hulkower, N.D., Klein, L., Oliver, P.A., Pavloff, M.S., Pomponi, R. A., and Welch, W. A., "An Evaluation of Selected Mobile Satellite Communications Systems and Their Environment," MITRE Corporation, MTR 92B0000060, Bedford, Massachusetts, April 1992.

[Clausing, 1993] Clausing, Don, Total Quality Development, ASME Press, New York, NY, 1993.

[De Weck, 2002] De Weck, Olivier, Willcox, Karen, Classnotes for 16.888/ESD.77J Multidisciplinary System Design Optimization, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Massachusetts, 2002.

[Draim et al., 1992] Draim, John E., Kacena Thomas J., "Populating the Abyss--Investigating More Efficient Orbits," Proceedings of the 6th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, Sept 21-24, 1992.

[Draim et al., 1997] Draim, J., Helman, G., Castiel, D., "The Ellipso™ Mobile Personal Communications System; Its Development History and Current Status," Paper IAF-97-M.3.03 presented at the 48th International Astronautical Federation Congress, Turin, Italy, October 6-10, 1997.

[Draim et al., 2000] Draim, John E., Cefola, Paul J., Castiel, David, "Elliptical Orbit Constellations--A New Paradigm for Higher Efficiency in Space Systems?" 0-7803-5846-5/00, 2000, IEEE.

[Draim et al., 2001a] Draim, John E., Cefola Paul J., Inciardi, Richard, Carter David, Proulx Ron, Laarsen Duane E., "Beyond GEO–Using Elliptical Orbit Constellations to Multiply the Space Real Estate," Paper IAF-01-A.1.03 Presented at the 52nd International Astronautics Federation Congress, Toulouse, France, October 1-5, 2001.

[Draim et al., 2001b] Draim, John E., Inciardi Richard, Cefola, Paul, Proulx, Ron, Carter, David, "Demonstration of the COBRA Teardrop Concept Using Two Smallsats in 8-Hour Elliptic Orbits," Paper SSC01-II-3 Presented at the 15th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August 13-16, 2001.

[Elbert, 1999] Elbert, B. R., Introduction to Satellite Communication, Artech House, Boston, Massachusetts, 1999.

[FCC, 1998] Federal Communications Commission, "Cut-off Established for Additional Applications and Letters of Intent in the 12.75-13.25 GHz, 13.75-14.5 GHz, 17.3-17.8 GHz and 10.7-12.7 GHz Frequency Bands," Report No. SPB-141, Washington, D.C., November 2, 1998, http://www.fcc.gov/Bureaus/International/Public_Notices/1998/pnin8260.wp

[FCC, 1999a] Federal Communications Commission, "Inquiry Concerning the Deployment of Advanced Telecommunications Capability to All Americans in a Reasonable and Timely Fashion, and Possible Steps to Accelerate Such Deployment Pursuant to Section 706 of the Telecommunications Act of 1996," CC Docket No. 98-146, Washington, D.C., February 2, 1999,
http://www.fcc.gov/Bureaus/Common_Carrier/Reports/fcc99005.txt
http://www.fcc.gov/Bureaus/Common_Carrier/Reports/fcc99005.wp
http://www.fcc.gov/Bureaus/Common_Carrier/News_Releases/1999/nrcc9004.html)

[FCC, 1999b] Federal Communications Commission, "Satellite Applications Accepted For Filing in the 12.75-13.25 GHz, 13.75-14.5 GHz, 17.3-17.8 GHz and 10.7-12.7 GHz Frequency Bands," Report No. SAT-00013, Washington, D.C., March 23, 1999,
http://www.fcc.gov/Bureaus/International/Public_Notices/1999/pnin9060.pdf

[FCC, 2000] Federal Communications Commission, "Inquiry Concerning the Deployment of Advanced Telecommunications Capability to All Americans in a Reasonable and Timely Fashion, and Possible Steps to Accelerate Such Deployment Pursuant to Section 706 of the Telecommunications Act of 1996," CC Docket No. 98-146, Washington, D.C., August 21, 2000,
http://www.fcc.gov/Bureaus/Common_Carrier/Orders/2000/fcc00290.pdf
http://www.fcc.gov/Bureaus/Common_Carrier/News_Releases/2000/nrcc0040.html

[FCC, 2002a] Federal Communications Commission, "Inquiry Concerning the Deployment of Advanced Telecommunications Capability to All Americans in a Reasonable and Timely Fashion, and Possible Steps to Accelerate Such Deployment Pursuant to Section 706 of the Telecommunications Act of 1996," CC Docket 98-146, Washington, D.C., February 6, 2002,
http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-02-33A1.txt
http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-02-33A1.pdf
http://www.fcc.gov/Bureaus/Common_Carrier/News_Releases/2002/nrcc0201.html

[FCC, 2002b] Federal Communications Commission, "Ku-Band Satellite Service Moves Forward," IB Docket No. 01-96, Washington, D.C., April 18, 2002,
http://www.fcc.gov/Bureaus/International/News_Releases/2002/nrin0205.txt
http://www.fcc.gov/Bureaus/International/News_Releases/2002/nrin0205.pdf
http://www.fcc.gov/Bureaus/International/News_Releases/2002/nrin0205.html

[FCC, 2002c] Federal Communications Commission, "The Establishment of Policies and Service Rules for the Non-Geostationary Satellite Orbit, Fixed Satellite Service in the Ku-Band," IB Docket No. 01-96,Washington, D.C., April 18, 2002,
http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-02-123A1.txt
http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-02-123A1.doc
http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-02-123A1.pdf

[Gaffney, 1994] Gaffney, L.M., Hulkower, N. D., Klein L., and Lam, D. N., "A Reevaluation of Selected Mobile Satellite Communication Systems: Ellipso, Globalstar, IRIDIUM, and Odyssey," MITRE Corporation, MTR 93B0000157, Bedford, Massachusetts, May 1994.

[Gordon et al., 1993] Gary D. Gordon and Walter L. Morgan, Principles of Communications Satellites, John Wiley & Sons, New York, New York, 1993.

[Gumbert, 1996] Gumbert, Cary Craig, "Assessing Future Growth Potential of Mobile Satellite Systems Using a Cost Per Billable Minute Metric," Master's Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1996.

[Gumbert et al., 1997] Gumbert, Cary C., Violet, Michael D. et al., "Cost per Billable Minute Metric for Comparing Satellite Systems," Journal of Spacecraft and Rockets, Vo.34, No.6, November-December 1997.

[Hughes, 1999a] Hughes Communications, Inc, "Application of Hughes Communications, Inc. for Authority to Launch and Operate HughesLINK, a Global Ku Band Broadband Satellite System," Washington, D.C., 1999.

[Hughes, 1999b] Hughes Communications, Inc, "Application of Hughes Communications, Inc. for Authority to Launch and Operate HughesNET, a Global Ku Band Broadband Satellite System," Washington, D.C., 1999.

[Isakowitz, 1999] Isakowitz, S.J., International Reference Guide to Space Launch Systems, 3rd Edition, American Institute of Aeronautics and Astronautics, Reston, Virginia, 1999.

[Jilla, 2002] Jilla, Cyrus, D., "A Multiobjective, Multidisciplinary Design Optimization Methodology for the Conceptual Design of Distributed Satellite Systems," Doctoral Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, June 2002.

[Kelic, 1998] Kelic, Andjelka, "Assessing the Technical and Financial Viability of Broadband Satellite Systems Using a Cost Per T1 Minute Metric," Master's Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1998.

[Larson et al., 1999] Larson, Wiley J., Wertz, James R., Space Mission Analysis and Design, Third Edition, Microcosm, Torrance, California, 1999.

[McLucas, 1991] McLucas, John L., Space Commerce, Harvard University Press, Cambridge, Massachusetts, 1991.

[Munson et al., 2000] Munson, J.E., and Jilla, C.D., "An Optimization Approach to the Launch Vehicle Selection Process for Satellite Constellations," Proceedings of the 18th AIAA International Communications Satellite Systems Conference, Oakland, California, April 2000.

[Parker, 2001] Parker, Melahn L., "Broadband Satellite Constellation Design & Evaluation," Master's Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, June, 2001.

[Pioneer Consulting, 1998] Pioneer Consulting, LLC, "Global Broadband Access Markets: xDSL and Cable Modems Threatened by Broadband Satellite, Wireless and All-Optical Solutions," Cambridge, Massachusetts, October 1998 (Executive summary publicly available), http://www.pioneerconsulting.com

[Shaw, 1999] Shaw, Graeme B., "The Generalized Information Network Analysis Methodology for Distributed Satellite Systems," Doctor's Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1999.

[SkyBridge, 1997] SkyBridge, LLC, "Application of SkyBridge L.L.C. for Authority to Launch and Operate the SkyBridge System, a Global Network of Low Earth Orbit Communications Satellites Providing Broadband Services in the Fixed Satellite Service," Washington, D.C., 1997.

[SkyBridge, 1999] SkyBridge, LLC, "Amendment to Application of SkyBridge L.L.C. for Authority to Launch and Operate the SkyBridge System," Washington, D.C., 1999.

[Space News, 1999] Space News International, "Iridium Files for Bankruptcy Protection," Springfield, Virginia, 13 August, 1999, http://www.space.com/businesstechnology/business/iridium_chapt11.html

[Space News, 2000] Space News International, "U.S. to Pay $84 Million For Use of Iridium Satellites," Springfield, Virginia, 6 December, 2000, http://www.space.com/businesstechnology/business/iridium_dod_001206.html

[Space News, 2002] Space News International, "Globalstar Files for Chapter 11 Bankruptcy Protection," Springfield, Virginia, 15 February, 2002, http://www.space.com/spacenews/marketmonitor/globalstar_021502.html

[Violet, 1995] Violet, Michael David, "The Development and Application of A Cost Per Minute Metric for The Evaluation of Mobile Satellite Systems in a Limited-Growth Voice Communications Market," Master's Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1995.

[Virtual Geosatellite, 1999] Virtual Geosatellite, LLC, "Application of Virtual Geosatellite, LLC for Authority to Launch and Operate Virgo, a Global Fixed-Satellite Service System Employing Nongeostationary Satellites in Sub-Geosynchronous Elliptical Orbits," Washington, D.C., 1999.

[World Bank, 2000] Development Data Group, The World Bank, World Development Indicators, Washington, D.C., 2000.

Appendix A: N^2 Diagram

Design Vector		2-5,11,12	1-10				2-5		
	Constants Vector	21-27,30,48	16-20,29,30	28	30-37	13-15	48-54	40-47	15,38,39
		Derived Vector	55	55	64	55	59,61,62	55,56,58	55
			Access Enumerate	65	65				65
				Coverage Filter		66			
					System Capacity	67			
						System Subscribers			68
							Launch Cost	72	
								System Cost	81
									Performance

Input
Module → Output

ID	M-File	Description	Unit	Structure
1	DesignVector	Name of the Constellation		
2	DesignVector	Number of Orbital Planes	#	
3	DesignVector	Number of Satellites in One Orbital Plane	#	
4	DesignVector	Altitude of the Satellites	m	
5	DesignVector	Inclination of Satellite Orbits	rad	
6	DesignVector	Satellite Phasing between Adjacent Planes	rad	
7	DesignVector	Right Ascension of Ascending Node	deg	1xN_SAT
8	DesignVector	True Anomaly	deg	1xN_SAT
9	DesignVector	Argument of Perigee	deg	1xN_SAT
10	DesignVector	Eccentricity	#	
11	DesignVector	Satellite Payload Power	W	
12	DesignVector	Satellite User Downlink Antenna Gain		
13	ConstantsVector	Total Broadband Market Size		1x10
14	ConstantsVector	Fraction of Total Broadband Market Willing to Subscribe to Satellite Network		
15	ConstantsVector	Distribution of Total Broadband Market		1x240
16	ConstantsVector	Ephemeris Epoch Date & Time		
17	ConstantsVector	Date and Time of Start of Simulation		
18	ConstantsVector	Date and Time of End of Simulation		
19	ConstantsVector	Latitude at the Center of Grid		1x240
20	ConstantsVector	Longitude at the Center of Grid		1x240
21	ConstantsVector	Payload Power per Unit Payload Mass	W/kg	
22	ConstantsVector	Mass Fraction of Payload wrt. Dry Mass		
23	ConstantsVector	Fraction of Dry Mass in Wet Mass		
24	ConstantsVector	Density of Satellite	kg/m^3	
25	ConstantsVector	Power Fraction of User Downlink in Payload Power		
26	ConstantsVector	Efficiency of Amplifier		
27	ConstantsVector	Efficiency of Phased Array Antenna		
28	ConstantsVector	Minimum Coverage Probability Required		
29	ConstantsVector	Minimum Elevation Angle for User Terminal Downlink	rad	
30	ConstantsVector	Downlink Frequency	Hz	
31	ConstantsVector	Signal-to-Noise Ratio (Eb/No) Required for User Terminal Downlink		
32	ConstantsVector	User Terminal Aperture Diameter	m	
33	ConstantsVector	User Terminal Illumination Efficiency		
34	ConstantsVector	User Terminal System Noise Temperature	K	
35	ConstantsVector	Rain Loss + Link Margin		
36	ConstantsVector	Data Rate of Individual User Terminal	bps	
37	ConstantsVector	Efficiency of Multi-Access Scheme		
38	ConstantsVector	Discount Rate for Present Value Calculation		

ID	M-File	Description	Unit	Structure
39	ConstantsVector	Inflation Rate for Constant Dollar Calculation		
40	ConstantsVector	Theoretical First Unit Cost per Kilogram of Satellite Dry Mass	2000$/kg	
41	ConstantsVector	Satellite Non-Recurring Cost Factor		
42	ConstantsVector	Insurance Rate		
43	ConstantsVector	Number of Ground Stations		
44	ConstantsVector	TFU Cost of Ground Station	2000$	
45	ConstantsVector	Amount of Labor Required for Each Ground Station	Man-Year	
46	ConstantsVector	Cost of Labor	$2000/Man-Year	
47	ConstantsVector	Non-Recurring Cost Factor for Ground Stations		
48	ConstantsVector	Number of Spare Satellite Per Plane		
49	ConstantsVector	Launch Vehicle Performance and Payload Margin		
50	ConstantsVector	Launch Vehicle Names		1x4
51	ConstantsVector	Launch Vehicle Cost & Payload Fairing Diameter & Height Matrix	2000$, m, m	4x3
52	ConstantsVector	Launch Vehicle Performance Matrix (to Given Altitude at Launch Site Inclination)	kg	4x8
53	ConstantsVector	Launch Site Latitude Vector	degree	1x4
54	ConstantsVector	Decrease in Launch Vehicle Performance for Each Degree of Inclination Change	kg/degree	
55	DerivedVector	Number of Satellites in the Constellation		
56	DerivedVector	Number of Spare Satellites		
57	DerivedVector	Payload Mass	kg	
58	DerivedVector	Satellite Dry Mass	kg	
59	DerivedVector	Satellite Wet Mass	kg	
60	DerivedVector	Satellite Bus Volume	m^3	
61	DerivedVector	Satellite Bus Diameter	m	
62	DerivedVector	Satellite Bus Height	m	
63	DerivedVector	Total RF Power for User Terminal Downlink per Satellite	W	
64	DerivedVector	Total EIRP for User Terminal Downlink per Satellite	W	
65	AccessEnumerate	Matrix of Space Loss + Atmospheric Loss between Satellite & Earth Grid (0 if no access)		N_SATx 481x240
66	CoverageFilter	Map of grids with acceptable coverage		1x240
67	SystemCapacity	Number of users that can be supported		N_SATx 481x240
68	SystemSubscribers	Number of Subscriber-Years for Each Year of Service		1x10

ID	M-File	Description	Unit	Structure
69	LaunchCost	Max. # of Satellites each LV Can Deploy		
70	LaunchCost	Launch Vehicle Suite for One Plane		
71	LaunchCost	Launch Vehicle Suite Required for Constellation Initial Deployment		
72	LaunchCost	Initial Deployment Launch Cost	2000$	
73	SystemCost	Cost of Space Segment	2000$	
74	SystemCost	Cost of Deployment	2000$	
75	SystemCost	Cost of Ground Segment	2000$	
76	SystemCost	Cost of Insurance	2000$	
77	SystemCost	Cost History in Nominal Dollars	$	
78	SystemCost	Cost History in 2000 Constant Dollars	2000$	
79	SystemCost	Cost History in 2000 Present Value	2000$	
80	SystemCost	Total System Cost in 2000 Constant Dollars	2000 PV	
81	SystemCost	Total System Cost in 2000 Present Value	2000 PV	
82	Performance	Number of Grids with Probability of Coverage > required		
83	Performance	Number of Grids with Positive Populations & Probability of Coverage > required		
84	Performance	Number of Satellites in View Averaged over Populated Grids		
85	Performance	Number of Satellites in View Averaged over Covered and Populated Grids		
86	Performance	Probability of Coverage Averaged over Populated Grids		
87	Performance	Probability of Coverage Averaged over Covered and Populated Grids		
88	Performance	Total number of subscriber over 10 years	Man-Year	
89	Performance	Total throughput over 10 years	Bit	
90	Performance	Break even annual charge per T1 line	2000$/T1-year	
91	Performance	Break even per-minute charge per T1 line	2000$/T1-minute	

Appendix B: Design Vector

LEO70

Number of Orbital Planes: 10

Number of Satellites Per Orbital Plane: 7

Inclination: 54.5 degrees

Phasing between Satellites in Adjacent Orbital Planes: 30.857 degrees

Payload Power: 4000 W

User Downlink Phased Antenna Gain: 28.7 dB

Satellite	Semi-Major Axis (km)	Inclination (degree)	Eccentricity	Perigee Argument (degree)	RAAN (degree)	True Anomaly (degree)
1	7868.1	54.5	0	0	0	0.0
2	7868.1	54.5	0	0	0	51.4
3	7868.1	54.5	0	0	0	102.9
4	7868.1	54.5	0	0	0	154.3
5	7868.1	54.5	0	0	0	205.7
6	7868.1	54.5	0	0	0	257.1
7	7868.1	54.5	0	0	0	308.6
8	7868.1	54.5	0	0	36	30.9
9	7868.1	54.5	0	0	36	82.3
10	7868.1	54.5	0	0	36	133.7
11	7868.1	54.5	0	0	36	185.1
12	7868.1	54.5	0	0	36	236.6
13	7868.1	54.5	0	0	36	288.0
14	7868.1	54.5	0	0	36	339.4
15	7868.1	54.5	0	0	72	61.7
16	7868.1	54.5	0	0	72	113.1
17	7868.1	54.5	0	0	72	164.6
18	7868.1	54.5	0	0	72	216.0
19	7868.1	54.5	0	0	72	267.4
20	7868.1	54.5	0	0	72	318.9
21	7868.1	54.5	0	0	72	10.3

Satellite	Semi-Major Axis (km)	Inclination (degree)	Eccentricity	Perigee Argument (degree)	RAAN (degree)	True Anomaly (degree)
22	7868.1	54.5	0	0	108	92.6
23	7868.1	54.5	0	0	108	144.0
24	7868.1	54.5	0	0	108	195.4
25	7868.1	54.5	0	0	108	246.9
26	7868.1	54.5	0	0	108	298.3
27	7868.1	54.5	0	0	108	349.7
28	7868.1	54.5	0	0	108	41.1
29	7868.1	54.5	0	0	144	123.4
30	7868.1	54.5	0	0	144	174.9
31	7868.1	54.5	0	0	144	226.3
32	7868.1	54.5	0	0	144	277.7
33	7868.1	54.5	0	0	144	329.1
34	7868.1	54.5	0	0	144	20.6
35	7868.1	54.5	0	0	144	72.0
36	7868.1	54.5	0	0	180	154.3
37	7868.1	54.5	0	0	180	205.7
38	7868.1	54.5	0	0	180	257.1
39	7868.1	54.5	0	0	180	308.6
40	7868.1	54.5	0	0	180	360.0
41	7868.1	54.5	0	0	180	51.4
42	7868.1	54.5	0	0	180	102.9
43	7868.1	54.5	0	0	216	185.1
44	7868.1	54.5	0	0	216	236.6
45	7868.1	54.5	0	0	216	288.0
46	7868.1	54.5	0	0	216	339.4
47	7868.1	54.5	0	0	216	30.9
48	7868.1	54.5	0	0	216	82.3
49	7868.1	54.5	0	0	216	133.7
50	7868.1	54.5	0	0	252	216.0
51	7868.1	54.5	0	0	252	267.4
52	7868.1	54.5	0	0	252	318.9
53	7868.1	54.5	0	0	252	10.3
54	7868.1	54.5	0	0	252	61.7
55	7868.1	54.5	0	0	252	113.1
56	7868.1	54.5	0	0	252	164.6
57	7868.1	54.5	0	0	288	246.9
58	7868.1	54.5	0	0	288	298.3
59	7868.1	54.5	0	0	288	349.7

Satellite	Semi-Major Axis (km)	Inclination (degree)	Eccentricity	Perigee Argument (degree)	RAAN (degree)	True Anomaly (degree)
60	7868.1	54.5	0	0	288	41.1
61	7868.1	54.5	0	0	288	92.6
62	7868.1	54.5	0	0	288	144.0
63	7868.1	54.5	0	0	288	195.4
64	7868.1	54.5	0	0	324	277.7
65	7868.1	54.5	0	0	324	329.1
66	7868.1	54.5	0	0	324	20.6
67	7868.1	54.5	0	0	324	72.0
68	7868.1	54.5	0	0	324	123.4
69	7868.1	54.5	0	0	324	174.9
70	7868.1	54.5	0	0	324	226.3

LEO80

Number of Orbital Planes: 20

Number of Satellites Per Orbital Plane: 4

Inclination: 53 degrees

Phasing between Satellites in Adjacent Orbital Planes: 67.5 degrees

Payload Power: 2500 W

User Downlink Phased Antenna Gain: 29.2 dB

Satellite	Semi-Major Axis (km)	Inclination (degree)	Eccentricity	Perigee Argument (degree)	RAAN (degree)	True Anomaly (degree)
1	7847.4	53	0	0	0	0.0
2	7847.4	53	0	0	0	90.0
3	7847.4	53	0	0	0	180.0
4	7847.4	53	0	0	0	270.0
5	7847.4	53	0	0	18	67.5
6	7847.4	53	0	0	18	157.5
7	7847.4	53	0	0	18	247.5
8	7847.4	53	0	0	18	337.5
9	7847.4	53	0	0	36	135.0
10	7847.4	53	0	0	36	225.0
11	7847.4	53	0	0	36	315.0
12	7847.4	53	0	0	36	45.0
13	7847.4	53	0	0	54	202.5
14	7847.4	53	0	0	54	292.5
15	7847.4	53	0	0	54	22.5
16	7847.4	53	0	0	54	112.5
17	7847.4	53	0	0	72	270.0
18	7847.4	53	0	0	72	0.0
19	7847.4	53	0	0	72	90.0
20	7847.4	53	0	0	72	180.0
21	7847.4	53	0	0	90	337.5
22	7847.4	53	0	0	90	67.5
23	7847.4	53	0	0	90	157.5
24	7847.4	53	0	0	90	247.5

Satellite	Semi-Major Axis (km)	Inclination (degree)	Eccentricity	Perigee Argument (degree)	RAAN (degree)	True Anomaly (degree)
25	7847.4	53	0	0	108	45.0
26	7847.4	53	0	0	108	135.0
27	7847.4	53	0	0	108	225.0
28	7847.4	53	0	0	108	315.0
29	7847.4	53	0	0	126	112.5
30	7847.4	53	0	0	126	202.5
31	7847.4	53	0	0	126	292.5
32	7847.4	53	0	0	126	22.5
33	7847.4	53	0	0	144	180.0
34	7847.4	53	0	0	144	270.0
35	7847.4	53	0	0	144	0.0
36	7847.4	53	0	0	144	90.0
37	7847.4	53	0	0	162	247.5
38	7847.4	53	0	0	162	337.5
39	7847.4	53	0	0	162	67.5
40	7847.4	53	0	0	162	157.5
41	7847.4	53	0	0	180	315.0
42	7847.4	53	0	0	180	45.0
43	7847.4	53	0	0	180	135.0
44	7847.4	53	0	0	180	225.0
45	7847.4	53	0	0	198	22.5
46	7847.4	53	0	0	198	112.5
47	7847.4	53	0	0	198	202.5
48	7847.4	53	0	0	198	292.5
49	7847.4	53	0	0	216	90.0
50	7847.4	53	0	0	216	180.0
51	7847.4	53	0	0	216	270.0
52	7847.4	53	0	0	216	0.0
53	7847.4	53	0	0	234	157.5
54	7847.4	53	0	0	234	247.5
55	7847.4	53	0	0	234	337.5
56	7847.4	53	0	0	234	67.5
57	7847.4	53	0	0	252	225.0
58	7847.4	53	0	0	252	315.0
59	7847.4	53	0	0	252	45.0
60	7847.4	53	0	0	252	135.0
61	7847.4	53	0	0	270	292.5
62	7847.4	53	0	0	270	22.5

Satellite	Semi-Major Axis (km)	Inclination (degree)	Eccentricity	Perigee Argument (degree)	RAAN (degree)	True Anomaly (degree)
63	7847.4	53	0	0	270	112.5
64	7847.4	53	0	0	270	202.5
65	7847.4	53	0	0	288	0.0
66	7847.4	53	0	0	288	90.0
67	7847.4	53	0	0	288	180.0
68	7847.4	53	0	0	288	270.0
69	7847.4	53	0	0	306	67.5
70	7847.4	53	0	0	306	157.5
71	7847.4	53	0	0	306	247.5
72	7847.4	53	0	0	306	337.5
73	7847.4	53	0	0	324	135.0
74	7847.4	53	0	0	324	225.0
75	7847.4	53	0	0	324	315.0
76	7847.4	53	0	0	324	45.0
77	7847.4	53	0	0	342	202.5
78	7847.4	53	0	0	342	292.5
79	7847.4	53	0	0	342	22.5
80	7847.4	53	0	0	342	112.5

MEO20

Number of Orbital Planes: 4

Number of Satellites Per Orbital Plane: 5

Inclination: 57 degrees

Phasing between Satellites in Adjacent Orbital Planes: 36 degrees

Payload Power: 8444 W

User Downlink Phased Antenna Gain: 28.9 dB

Satellite	Semi-Major Axis (km)	Inclination (degree)	Eccentricity	Perigee Argument (degree)	RAAN (degree)	True Anomaly (degree)
1	26560	57	0	0	0	0
2	26560	57	0	0	0	72
3	26560	57	0	0	0	144
4	26560	57	0	0	0	216
5	26560	57	0	0	0	288
6	26560	57	0	0	90	36
7	26560	57	0	0	90	108
8	26560	57	0	0	90	180
9	26560	57	0	0	90	252
10	26560	57	0	0	90	324
11	26560	57	0	0	180	72
12	26560	57	0	0	180	144
13	26560	57	0	0	180	216
14	26560	57	0	0	180	288
15	26560	57	0	0	180	0
16	26560	57	0	0	270	108
17	26560	57	0	0	270	180
18	26560	57	0	0	270	252
19	26560	57	0	0	270	324
20	26560	57	0	0	270	36

MEO22

Payload Power: 4100 W

User Downlink Phased Antenna Gain: 32.9 dB

Satellite	Semi-Major Axis (km)	Inclination (degree)	Eccentricity	Perigee Argument (degree)	RAAN (degree)	True Anomaly (degree)
1	21378	0	0	0	0	0
2	21378	0	0	0	0	45
3	21378	0	0	0	0	90
4	21378	0	0	0	0	135
5	21378	0	0	0	0	180
6	21378	0	0	0	0	225
7	21378	0	0	0	0	270
8	21378	0	0	0	0	315
9	21378	45	0	0	0	0
10	21378	45	0	0	0	51.4
11	21378	45	0	0	0	102.9
12	21378	45	0	0	0	154.3
13	21378	45	0	0	0	205.7
14	21378	45	0	0	0	257.1
15	21378	45	0	0	0	308.6
16	21378	45	0	0	180	0
17	21378	45	0	0	180	51.4
18	21378	45	0	0	180	102.9
19	21378	45	0	0	180	154.3
20	21378	45	0	0	180	205.7
21	21378	45	0	0	180	257.1
22	21378	45	0	0	180	308.6

HEO

Payload Power: 10500 W

User Downlink Phased Antenna Gain: 35 dB

Satellite	Semi-Major Axis (km)	Inclination (degree)	Eccentricity	Perigee Argument (degree)	RAAN (degree)	True Anomaly (degree)
1	20281	63.435	0.66	270	341.5	0
2	20281	63.435	0.66	270	53.5	170.0
3	20281	63.435	0.66	270	125.5	216.4
4	20281	63.435	0.66	270	197.5	143.6
5	20281	63.435	0.66	270	269.5	190.0
6	20281	63.435	0.66	270	255.3	158.7
7	20281	63.435	0.66	270	327.3	201.4
8	20281	63.435	0.66	270	39.3	116.4
9	20281	63.435	0.66	270	111.3	180.6
10	20281	63.435	0.66	270	183.3	244.1
11	20281	63.435	0.66	90	52.2	0
12	20281	63.435	0.66	90	124.5	170.0
13	20281	63.435	0.66	90	196.5	216.4
14	20281	63.435	0.66	90	268.5	143.6
15	20281	63.435	0.66	90	340.5	190.0

Satellites 1~5: Sub-Constellation for the Northern Hemisphere

Satellites 6~10: Sub-Constellation for the Northern Hemisphere

Satellite 11~15: Sub-Constellation for the Southern Hemisphere