Emerging Trends in the Satellite Industry

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B.S.
Babson College, 2004

SUBMITTED TO THE MIT SLOAN SCHOOL OF MANAGEMENT
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF

MASTER OF SCIENCE IN MANAGEMENT STUDIES
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2012

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Submitted to the MIT Sloan School of Management on May 11, 2012 in
partial fulfillment of the requirements for the degree of Master of
Science in Management

ABSTRACT

Risk aversion in the satellite industry has fostered long development cycles and low rates of innovation in the past. Emerging trends in propulsion technology development and spacecraft architecture design could lead to increased adoption of small satellites as well as more open, flexible and useful space systems. Two particular developments can be used to map the future of the industry. First, the development of MEMS thrusters for launch vehicles could enable dedicated launches for small satellites. This could substantially bring down the cost of satellite deployment. Second, the successful completion of the DARPA System F6 project could demonstrate the value of spacecraft fragmentation. This in turn could shift the focus of the industry from certain attributes that result in long development cycles, thereby opening the doors for open systems and greater innovation. Emerging trends in the satellite industry may result in paradigm shifts that would dramatically decrease satellite costs and increase innovation. This may ultimately result in a structural change in the satellite industry.

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Acknowledgements

I would like to thank many people at MIT: Dr. Utterback and Dr. Velásquez-García for being accessible during the past few months and for helping me develop this thesis. Danielle Wood, for taking the time to meet with me to explain her findings as well as basic concepts of aeronautics and astronautics. Alessandra Babuscia, of the Space System Laboratory, for explaining the way antennas work. Natalya Brikner for telling me about small rockets during Sidney Pacific open doors, and for being willing to explore the possibilities of new ventures. Gwen Gettliffe, of Course 16 for sharing information about space systems. James Draper for providing fascinating ideas in Kendall Square. Laura Guaglianone, for taking on the relatively simple, albeit frustrating task of editing this thesis. Tourists for blocking the entrance to building 5 with their cameras – in doing so they constantly reminded me that I had the privilege of attending a landmark institution: MIT.

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Table of Contents

2. Background Information

3. Problem Statement

4. Emerging Trends in Satellites

5. Possible Scenarios for the Future of the Satellite Industry

List of Tables and Figures

Tables

Figures

List of Abbreviations

ADCS	Attitude Determination and Control Systems
COTS	Commercial off the shelf
DARPA	Defense Advance Research Projects Agency
DBS	Direct Broadcast Satellite
DTH	Direct to Home
ELaNA	Educational Launch of Nanosatellites
ELF	Extremely Low Frequency
ELI	Elliptical
FAA	Federal Aviation Administration
FEEP	Field Emission Electric Propulsion
GEO	Geosynchronous
GLONASS	*Globalnaya Navigatsionnaya Sputnikovaya Sistema* – Global Navigation Satellite System
GPS	Global Positioning System
Isp	Specific Impulse
LEO	Low Earth Orbit
LISA	Laser Interferometer Space Antenna
MEMS	Microelectromechanical Systems
MEO	Medium Earth Orbit
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
PPT	Pulsed Plasma Thruster
USB	Universal Serial Bus

1. Introduction

Astronomy is older than history. For thousands of years, celestial objects have guided religion, mythology, agriculture, and navigation. Tablet 63 of the Enūma Anu Enlil (circa 1580 BC), a Babylonian record in cuneiform may be the oldest known text related to astronomy. The text is a record of observations of Venus [1]. The rest of the tablets, close to 70 in number, are mostly omens. The Enuma Anu Enlil is an example of the way stars are subjects of astrology and astronomy, of myth and science. Even today, some believe distant planets affect their destiny, while others want to colonize Mars. Even modern countries facing famine have space programs, investing scarce resources in the development of space-faring infrastructure and technology.

While it may seem difficult to compare the fiction and the reality of celestial objects in relation to mankind, in fact, fiction has often acted as precursor to reality in the aerospace industry. Fictional accounts of artificial satellites and their use in communications preceded their real-life development and adoption by as much as a century [2]. In 1945, science fiction writer Sir. Arthur C. Clarke proposed the use of Geo-stationary satellites for communications [3]. He may not have taken it seriously at the time, but twenty years later the first such satellite, Early Bird, was launched and successfully deployed. Today, there are more than 400 satellites in Geo-stationary, or *Clarke* orbit [4].

Economic, military, and scientific motivations encourage nations to invest in space. Spacecraft can take us beyond our world and teach us more about our own. Launching and deploying satellites can provide useful scientific information in the form of high-resolution images and remote sensing data. Satellites can provide close to real-time wireless communication anywhere in the world. Global Navigation Satellite Systems are being used at increasing rates by machines and devices all over the world. Some current satellite capabilities were unthinkable a few decades ago. Moreover, some futuristic small satellite applications may seem science fiction today, just like *Clarke* orbit a few decades ago. Understanding how markets, governments, and educational institutions are allocating resources in astronautic capabilities can help us envision the future.

This thesis intends to reconcile the current state of the space industry with a few emergent astronautical technologies and capabilities. The way those technologies and capabilities may affect the satellite industry going forward is compared, by analogy, to the way certain technologies and capabilities affected the computer industry more than thirty years ago. An explanation of the way emergent technologies may affect space trade is hereby offered, in the form of an industry analysis.

2.1 The Satellite Industry

Satellites are used in four broad function categories: Earth Observation & Remote Sensing, Space Science, Communication, and Global Navigation Satellite Systems. This last category includes GPS (American), GLONASS (Russian), Galileo (European), and Beidou (Chinese). According to the Satellite Industry Association, most operational satellites (57%) fall in the Communications category. Earth Observation (surveillance) and Remote Sensing comprise the second category with the most operational satellites (18%). Finally, 10% of operational satellites are used in Meteorological and Space Science and 8% in Navigation [5].

Table 1, Operational Satellites By Function, June 2011:

Operational Satellites By Function (June 2011)		
Commercial Communications	365	37%
Civil Communications	108	11%
Military Communications	84	9%
Military Surveilance and other	89	9%
Remote Sensing	92	9%
Navigation	75	8%
Space Science	59	6%
Meteorological	44	4%
Other	70	7%
Total	986	100%

Source: [5]

The close to one thousand satellites currently in operation fall into one of four types of orbits, according to the way they travel and how far from Earth they lie. Low Earth Orbit (LEO) encompasses the space between approximately 200 and 2000 kilometers above Earth's sea level (altitude). The second most popular is Geosynchronous Orbit (GEO), found at about 36,000 km of altitude. In the space between those two orbits, approximately one hundred satellites lie in either Medium Earth Orbit (MEO), or Elliptical Orbit (ELI). Table 2 breaks down the population of operational satellites by their orbit type.

Table 2, Operational Satellites By Orbit, June 2011:

Operational Satellites By Orbit (June 2011)		
LEO	480	49%
GEO	405	41%
MEO	66	7%
ELI	35	4%
Total	986	100%

Source: [5]

Launching Vehicles (Rockets) are used in the transportation and deployment of satellites in their corresponding orbits. In transportation, satellites are commonly referred to as "payloads". Those with mass of less than 2,500 kg are commonly classified as "small payloads." Launch vehicles, on the other hand, are also classified as either small or medium and heavy. Assuming that small launch vehicles cannot carry heavy payloads, Table 3 reveals that a good portion of Science and Engineering payloads must be small payloads, since most small launches are projected for science and engineering.

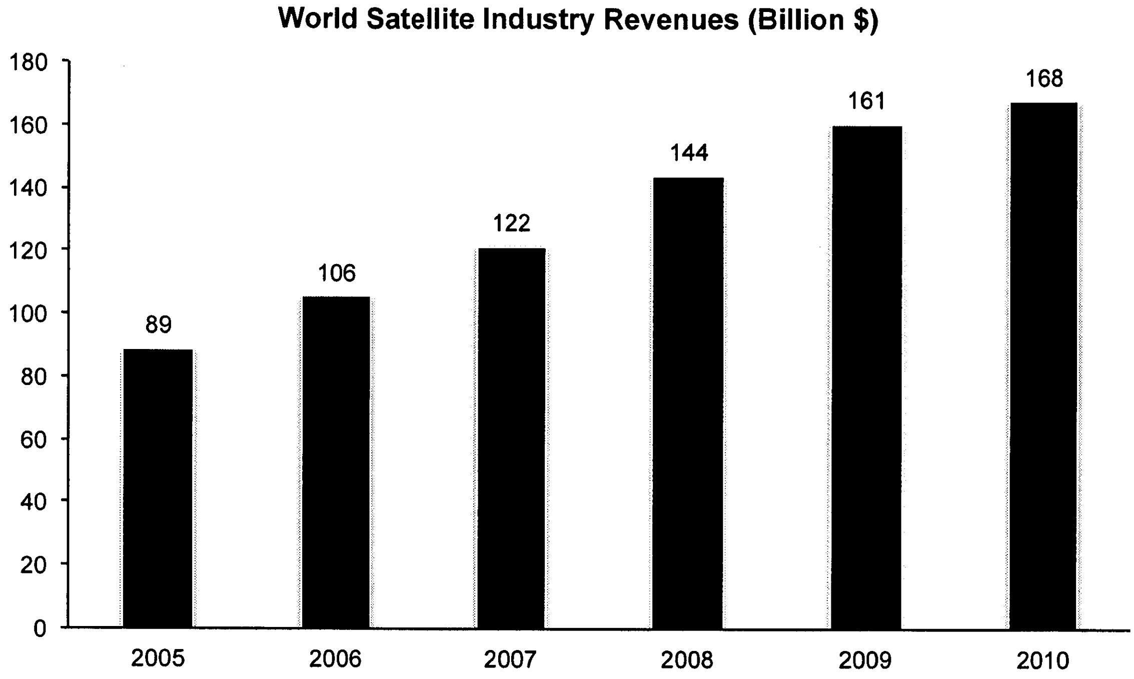
Table 3, Forecast of launch demand my mass classification, 2011 to 2020:

Forecast of launch demand (2011 - 2020)	Launch Demand by mass class		
	Small	Medium - to - Heavy	Total
Commercial Telecommunications	0	19	19
Commercial Remote Sensing	1	9	10
Science and Engineering	18	22	40
Commercial Cargo & Crew Transportation Services	0	60	60
Other Payloads Launched Commercially	0	1	1
Total	19	111	130

Source: [6]

In 2010, Space Industry revenues totaled $276.5 billion, of which 168.1 billion corresponded to the satellite industry [5]. From 2005 to 2010 the satellite industry posted an average annual growth of 11.2%, with a notorious slowdown between 2008 and 2010. Figure 1 displays the recent growth of the satellite industry.

Figure 1, Satellite Industry Revenues 2005 – 2010:



Source: [5]

Within the satellite industry, satellite-manufacturing revenues declined 20%, from $13.5 billion in 2009 to $10.8 billion in 2010, due to lower government activity and lower-priced spacecraft [5]. In the satellite services segment of the industry, (a $100 billion market, which accounts for 60% of the overall industry), consumer satellite television revenues represented a dominating 80% of revenues [5]. This suggests that the category offering the largest market for satellites is communications. Some services demanding high broadband capacity (throughput) have large projected growths. Direct Internet access is expected to grow at a 15.6% CAGR, and commercial mobility at 12.4% for the next five years [7]. Video and Internet backhaul, however, are expected to decline or show no growth. The substitution with optical fiber is especially evident in developed countries. The bulk of the revenues in the satellite industry come from communications including television and radio. Direct to home (DTH) and direct broadcast satellite (DBS) video transmission are expected to continue representing a large portion of the demand for satellite services with stable growth [7].

The satellite manufacturing and satellite services industries are highly consolidated, with a few players dominating the world market. Nevertheless, large corporations, such as EADS Astrium, BAE systems, Thales Alenia, Boeing, Lockheed Martin, and Northrop Grumman are slowly facing increased, although arguably presently insignificant competition from new players such as Space X, Orbital Sciences, Xcor

Aerospace and Virgin Galactic. Some of these new companies are focusing their development efforts in the space tourism and small launch vehicle markets. New micro-satellite manufacturers are also emerging. "The launch services sector of the space industry (supplier) has traditionally been more concentrated than the satellite operators and manufacturer sectors (buyer) of the industry, and it is reasonable to expect that suppliers of dedicated microsatellite launch services will remain more concentrated than buyers of that service [8]." Technology arguably constitutes a greater barrier to entry in the launch services industry than in the satellite manufacturing industry.

In addition to the new market entry of suppliers across the satellite industry, new customers are also growing in developing countries. According to Danielle Wood, PhD Candidate at MIT's Engineering Systems Division, three categories of satellites have significant potential impact on developing countries. Satellite remote sensing can improve urban planning, disaster management and food security. Satellite communication can meet needs in education, medical care, and government services. It can also increase economic efficiency by reducing information asymmetries that enable intermediaries to engage in arbitrage. Satellite navigation can empower aviation and wildlife tracking [9].

Although many satellite applications are facing substitution from competing technologies, there are still prospects for growth in the satellite industry. Moreover, greater rates of product and market development could yield new satellite applications and users. Table 4 summarizes highlights of select non-traditional Aerospace companies:

Table 4, Select Aerospace Companies' Highlights:

Company	Highlight
Space X	Falcon Rockets and Dragon Capsule scheduled to provide the first commercial cargo service to the International Space Station in May 2012
Orbital Sciences	Participating in DARPA F6
Xcor Aerospace	Developing suborbital vehicle Xerus for research, space tourism, and transporting microsatellites to low Earth orbit
Virgin Galactic	Suborbital Space Tourism Company
Pumpkin	Cubesat pioneer company
Nanoracks	Provides access to international space station for biomedical research and other scientific and educational purposes

Source: company websites

2.2 Trends in Small Satellites

The first satellite ever put in orbit by mankind was Sputnik 1, in 1957 [10]. Sputnik 1was a small satellite, with a mass of 84Kg. Since then, satellite mass has tended to increase due to augmented operational capacity and complexity. There is a recent trend, however, of increased small satellite adoption. Such spacecraft are especially useful today for in-orbit technology testing, earth imaging, and space science as well as atmospheric testing. Moreover, with the development of certain technologies, such as micro electromechanical systems (MEMS) thrusters and spacecraft fragmentation, a group of small satellites might be able to perform, in aggregate (homogeneous fragmentation) or in concert (heterogeneous fragmentation), the same functions as large satellites – with added benefits. This potential is discussed further in the section 4.2, while current and conventional uses of small satellites are discussed *infra*. The development of small satellites offers strong possibilities for the evolution of a more efficient space industry.

The proliferation of very small satellites (commonly termed "pico" and "nano" satellites) began early this century. Although The U.S. Department of Transportation has a specific mass classification system for satellites, Table 5 below, satellite sizes referenced herein will correspond to Table 6, which represents a classification commonly referenced in the trade by leading organizations.

Table 5, Payload mass classification by the U.S. Department of Transportation – Federal Aviation Administration (based on mass on the ground):

Classification	Min. Mass (Kg)	Max. Mass (Kg)
Pico		1
Nano	2	10
Mini	11	100
Micro	101	500
Small	501	2,500
Medium	2,501	4,500
Large	4,501	5,400
Heavy	5,401	

Source: [11]

Table 6, Common payload mass classification:

Classification	Min. Mass (Kg)	Max. Mass (Kg)
Pico		1
Nano	2	10
Mini	11	100
Micro	101	500
Small	501	2,500
Medium	2,501	4,500
Large	4,501	5,400
Heavy	5,401	

In recent years, the number of annual deployments has been about 12 for microsatellites, and around 9 for nanosatellites [8]. These figures are in loose agreement with Rachel Villain's (Director for Space at Euroconsult), estimation of an average of 23 satellites with mass up to 500 Kg. being deployed per year in the past decade [12]. Smallsats are typically built for $1 million to $10 million and there is no dedicated launcher available for less than $10 million [8]. Nevertheless, Microcosm Inc. identifies potential launch market-wide savings of more than $15 billion in a 12-year period, resulting from the development of low-cost responsive launch vehicles focused on the Smallsat Market [8]. In 2008 Futron Corporation identified 33 potential markets for low-cost microsatellites (100-200 kilograms, lifetime of 1-2 years, total cost of $5-10 million) in the military, commercial, and civil space sectors [13]. Table 7 provides specific yearly unit and dollar value estimates of particular markets in those sectors.

Table 7, Overall Potential Addressable Smallsat Markets in 2008:

	Satellites / Year		Revenue / Year ($MM)	
Market	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Military Science and Technology	10	20	75	150
Intelligence, Surveillance and Recon.	1	10	8	75
Remote Site Communications	10	15	75	113
Polling of Unattended Sensors	10	15	75	113
High-Resolution Earth Observation	5	10	38	75
Landsat-class Environmental Monitoring	3	6	23	45
Total	**39**	**76**	**293**	**570**

Source: Futron Corporation [13]

Jeff Foust, of Futron Corporation believes that "small satellites have the potential to be developed much more rapidly than larger spacecraft, as they are likely to be less complex than their bigger counterparts… (and) the ability to quickly develop and deploy smallsats can be a key competitive advantage for (them) versus other space or terrestrial systems [14]." Foust cites lack of affordable and timely access to orbit as the most prominent barrier to small satellite adoption, followed by lack of awareness by potential customers and the concern for orbital debris [14]. However, according to James R. Wertz, of Microcosm, "...satellites in these classes typically fly in lower orbits where debris does not accumulate due to drag." [8]. Assuming awareness to be a function of marketing promotion, which like any variable expense can be controlled by enterprises, only affordable and timely access to space remains a barrier to small satellite adoption. Therefore, it could easily be implied, that cost-effective developments in launching technologies would greatly increase the adoption of small satellites for the purposes they serve today.

There is significant potential demand for small satellites in the coming decade. According to Robert Meurer, of ATK spacecraft systems and services, speed from design to deployment is a key factor for the "tremendous growth potential projected over the next decade for earth imaging satellites on relatively small platforms of 200 to 300 kilograms [15]." This may be in part because "customers are procuring small satellites to do missions that in the past would have been the domain of large satellites [12]." Some of those new missions can be carried out with Cubesats.

A Cubesat is a picosatellite (1 Kg), the shape of a cube, of certain dimensions and characteristics. Early this century, Stanford and California Polytechnic University's Cubesat design specifications quickly established dominance, setting the standard for bus architecture in units of 10cm x 10cm x 10cm, (commonly termed 1U, or one unit). The relatively recent increase in the development of such spacecraft by educational and commercial institutions, coupled with lower launch costs and relaxed launch norms, resulted in 32 Cubesat launches, with 18 successful deployments into orbit by 2010, [16] with the cumulative number of launches doubling, and the number of Cubesats in orbit reaching 44 by July of 2011 [17]. The cost of such satellites can be as low as $7,500 without antennas or solar panels [18], and launch costs can be as low as $30,000 through NASA's Educational Launch of Nanosatellites program (ELaNA) [19], or 40,000 through piggyback launches [16]. Table 8 summarizes the costs of deploying one Cubesat (1U). The total cost of a Cubesat project can range from University of Hawaii's Mea Huaka'i (Voyager) $120,000 budget [16], to MIT's ExoPlanetSat $5,000,000 cost [20] and beyond.

Table 8, Cost of Cubesat deployment, select suppliers and methods:

	Cost / Cubesat (1U) Deployed
Nano Racks	50,000
Piggyback	40,000
NASA ELaNA	30,000

Sources: [22], [16], [19]

The uses for pico and nano satellites are as varied as their cost. For example, Stanford University's QuakeSat, a 3-Kg Cubesat, detects extremely low frequency (ELF) magnetic field signals, which correlate with earthquakes in both the weeks leading up to and the months following an earthquake [16]. AtmoCube, a 1-Kg Cubesat from Italy is building a precise map of the Earth's magnetic field and radiation [16]. Bio-Nano Satellite-1, a 10-Kg satellite from Stanford University and NASA Ames Research Center studies the growth rate of yeast cells in microgravity [16]. Nanosatellites have proven effective in atmospheric and spacecraft testing, biomedical research, and remote sensing, and their uses are not limited to educational experimentation.

The Pumpkin Corporation has been the pioneer in the commercial development of Cubesats. Founded by Andrew E. Kalman, of Stanford University, Pumpkin had sold 280 Cubesat kits by November of 2010 [21]. At that time, given the barriers to their deployment and short life at LEO, only 5 Cubesats were in Orbit [21]. Boasting simple, COTS parts [12], Pumpkin Cubesats are cheap and easy to assemble. According to Kalman, "(large satellite manufacturers) are not really interested in something that will earn them less than $10 million, (and) that's why there's always an opportunity for someone like (Pumpkin) to try to pull off something risky [21]." Another company at the forefront of new business development in space is Califorina-based Nanoracks LLC. The company provides access to the International Space Station in the form of Cubesat-like "cubelabs". This facilitates biomedical experimentation in microgravity environments. The price tag for Nanoracks services per 1U is $50,000 [22]. By December of 2011 Nanoracks had conducted a dozen missions, with a similar number of missions scheduled for 2012 [23]. Both Pumpkin and Nanoracks are evidence of the recent emergence of breakthrough products and services in aerospace.

It seems reasonable to expect an increased demand for small satellites in the near future, from Pico to Micro satellites, of mass classes ranging from 1 Kg. to 500Kg. will become useful in a broader range of activities as they replace larger spacecraft. Furthermore, if space science and technology testing users continue adopting nanosatellites, due to their low cost and ease-of use, the development of dedicated launches may enhance small satellites' value proposition via timely and low-cost access to space.

3.1 The Cost-Complexity Death Spiral

The rate of innovation in the space industry has been much slower than in the computer or mobile device industries. Most of the 995 artificial satellite spacecraft in orbit today have less processing power than most cell phones used by pedestrians on Earth [15]. Though less powerful, the artifacts up there are thousands of times more voluminous, tens of thousands of times more massive, and millions of times more expensive than the devices we keep in our pocket for everyday communication. This may not be a fair comparison for many reasons, but the discrepancy between satellite and mobile phone capabilities can shed light on the reinforcing loops that can come into play in industrial technological developments. Furthermore, a general understanding of the space industry's dynamics, including current market and technological trends, can help us formulate possible scenarios in which balancing forces may come into play within the space industry. This thesis intends to explain why the satellite industry has presented such a slow rate of innovation in the past, and what current trends and future events could bring about change.

During the four decades after the Second World War, country super-powers jockeyed for the establishment of a new world order as well as economic and political dominance. During the Cold War, the Union of Soviet Socialist Republics and the United States set forth ideals, propaganda and technological development with the goal of establishing economic and political supremacy. The space race is a nice example. Both countries allocated large resources to projects such as Sputnik 1 and the Apollo Program, even though there was arguably no immediate market need for such projects. They were, however, on top of national agendas for political reasons. This non-market approach towards spacefaring is still present today in vestiges of government subsidy, intervention, and bureaucracy. Moreover, space programs are very military–oriented and considered issues of national security.

Security as it relates to space is not defined exclusively by military actions. NASA tracks more than 16,000 incontrollable objects, each larger than ten centimeters, orbiting earth, [24] flying at speeds of about 28,000 Km/h, [25]. Thousands more of smaller dimensions also orbit the Earth. Both accidental and intentional events have dramatically increased the amount of space debris in recent years. In February of 2009, the dysfunctional Cosmos 2251 satellite, a Russian spacecraft, collided with an Iridium communication satellite of the U.S.A. [26]. Two years before, in January of 2007, The People's Republic of China destroyed its Fengyun-1C weather satellite in order to test an Anti-Satellite weapon [27]. The Cosmos 2251 collision and the Chinese government's target practice have generated more than 4,000 new orbiting projectiles, representing a 60% increase in the number of such items tracked by NASA [28]. This means that the debris that has accumulated in Low Earth Orbit since 1957, with the deployment of Sputnik, took only two years to increase by more than fifty percent (from 2007 to 2009). If the number of orbiting projectiles reaches a tipping point, according to the "Kessler syndrome" [29], the cascade effect of having projectiles create projectiles could severely hinder humanity's communication and scientific capabilities in Low Earth Orbit. If there are tens of thousands of projectiles orbiting earth, as small as the probability of collision with one of the 995 satellites currently in operation may be, the cascading effect can produce a truly astronomical amount of space debris in the future.

Looking forward, space will remain a field of military, scientific and commercial exploration. The extent to which aerospace, and the satellite industry in particular will remain a target of government intervention will be contingent upon the evolution of such industry towards an open, competitive industry. More efficient launch vehicle propulsion engines could provide a competitive advantage for small payload delivery, therefore enabling the reduction of costs in Low-Earth-Orbit Satellite deployment by orders of magnitude. There is clearly room for improvement. "According to the GAO, weapon systems development programs were overrunning 42% in development cost and 25% in production cost, and were reaching initial operating capability, on average, 22 months behind schedule in 2009 [30]." The delayed development of weapon systems in the space industry can be considered a symptom of inefficiency. Nevertheless, satellites remain relevant, facing increasing demand. 107 satellites were manufactured in 2011 [32], although the FAA had previously estimated only 60 launches [25]. Some of the increased demand comes from small satellites, which has yielded controversy around their proliferation and utility.

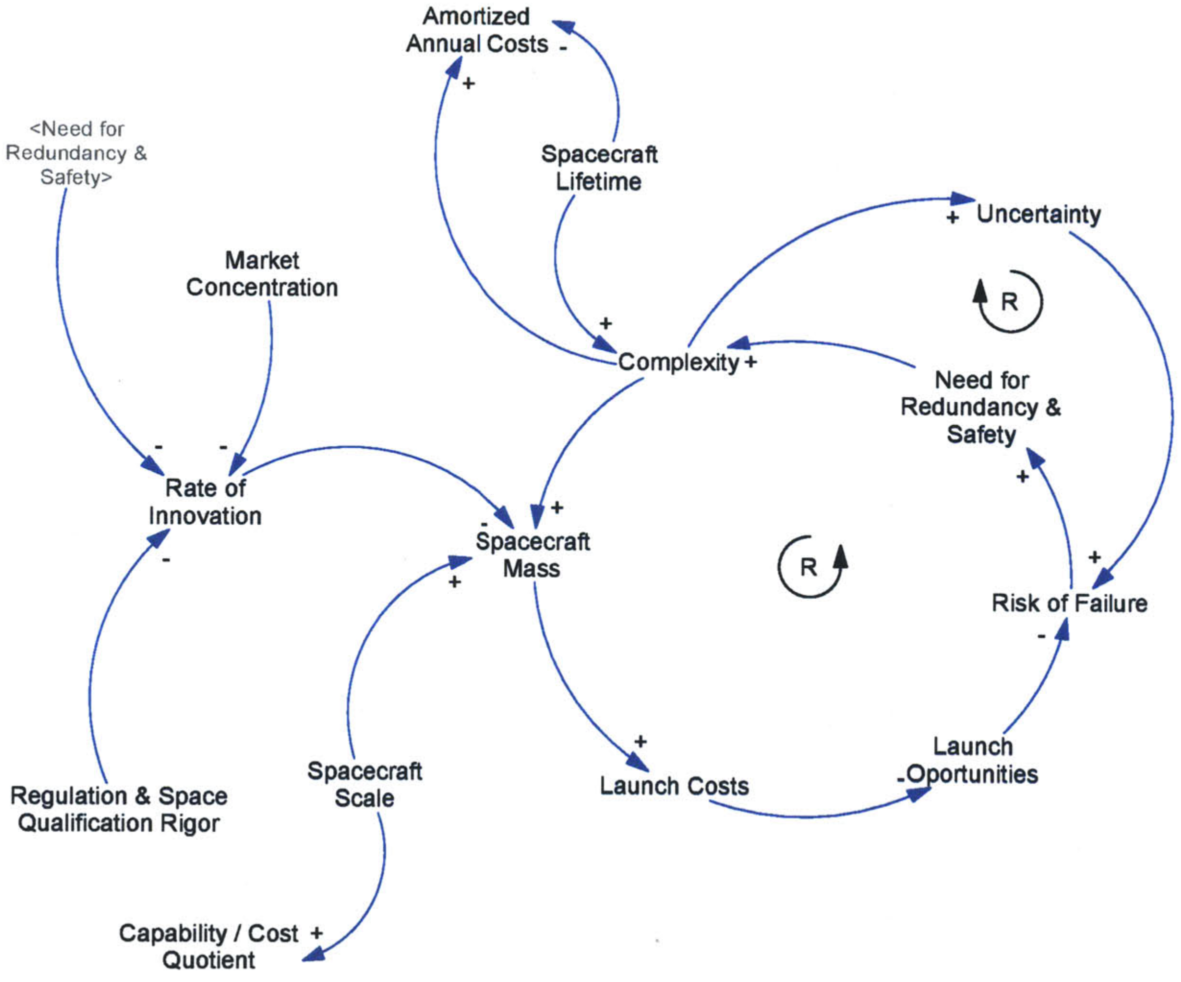
The satellite industry's emphasis on the wrong metrics may explain the current state of slow and costly spacecraft development. Owen Brown, of DARPA, and Paul Eremenko, of Booz Allen Hamilton define the relationship between uncertainty, complexity, and cost in spacecraft, as a cost-complexity death spiral:

"The array of uncertainties and failure modes itself grows with the system's complexity, and the mechanisms for addressing these potential failure modes add to it with the resultant effect of making overall system complexity grow exponentially. The system's cost follows suit. This is what we term the cost-complexity death spiral." [33]

"A focus on achieving capabilities embodied in requirements while minimizing cost has, under the influence of technical and programmatic uncertainty, led to ever more complex spacecraft with higher and higher cost, a cost-complexity death spiral. Decision makers respond to increased marginal cost by increasing the scale of spacecraft to maximize the overall capability/cost quotient, and increasing lifetime to minimize amortized annual costs. Both trends increase capability, which drives further increases in scale and lifetime." [31]

The causal loop diagram in Figure 2 attempts to show some of the dynamics and factors at play in the satellite industry, which relate to Brown and Eremenko's "cost-complexity death spiral." It is not an exhaustive analysis of the industry's dynamics, but rather an aid to their understanding in the construction of a mental model. Beyond this model, one might further consider the industry's genesis and its particular nature and relationship with government.

Figure 2, Causal loop diagram illustrating Brown and Eremenko's cost-complexity death spiral:



Source: Vagn Knudsen Salazar

The links between variables include mathematical symbols (+, -), which reflect the relationship between variables. They indicate when an increase in a particular variable yields an increase in a linked one (+), or a decrease (-). In other words, whether the movement of one variable in a number line affects the movement of another variable in a number line in the same direction. Reinforcing loops are marked with R, and intended to reveal reinforcing relations or virtuous and vicious cycles that normally tend towards some form of exponential growth. Some limiting factors, however, such as budgets and risk aversion, though not included in the diagram, might limit the growth of some variables, and interrupt the dynamic of a reinforcing loop.

As shown in Figure 2, there are various factors affecting the rate of innovation in the satellite industry. Market concentration (in a government intervention void), tends to discourage competition since industry players can obtain economic profit without an significant need for differentiation. In a less concentrated industry, the attainment of a competitive advantage serves as an incentive for innovation. The rigor of space qualification standards also discourages innovation by constraining experimentation and extending development cycles. In a similar way, the need for safety and redundancy, which derives directly from the risk aversion associated with having limited opportunities for exclusively large-scale rewards, deters innovation. The large scale of satellites, their high costs and complexity, as well as long development cycles and limited, expensive launching opportunities make satellite users highly risk-averse. This condition tends to slow the rate of innovation in the satellite industry. This is not to say that new generations of satellites are not more technologically advanced that the ones deployed in the past. However, the rate of innovation in the satellite industry has not been as high as in comparable high-tech industries such as consumer electronics and personal computers, where competition has been high and development cycles short. As products in those industries, dependent on more than just consumer preferences, existing satellites would be less massive and less clunky if the rate of innovation were higher.

Perhaps the most important conclusion from both the "cost-complexity death spiral" and Figure 2 above is the unintended consequence of having a cost-centric approach to project assessment in the space industry. It is strikingly similar to the unintended effect of fire prevention measures in the United States in the twentieth century, where regulatory policies produced unintended effects. Throughout most of the twentieth century, the Forest Service of the United States practically eradicated the occurrence of fires in the 1960's due to the organization's professionalism and technical expertise [34]. As a fire prevention measure small fires were put out quickly and efficiently, to avoid the occurrence of large fires. Ironically, this focus on fire prevention was precisely what caused the proliferation of very large fires in the year 2002. There was a delayed and unintended effect of putting out small fires, which usually consumed and cleared the brush. The level of the brush was so high in 2002 that small brush fires quickly caught on to the canopy of large trees, creating adult-size fires that spread faster and were difficult to control. As a result, the number of hectares consumed by fires in 2002 in the U.S.A. was abnormally high. This phenomenon can be related to fire prevention measures of the twentieth century, including the systematic focus on small fire control by the Forest Service. A key problem was the oversimplification and lack of understanding of the role that fires play in forests. Similar to the way that focusing on small fires in the twentieth century created greater fires in the twenty-first century, an unintended and delayed effect of having a cost-centric approach in satellite development may be contributing to the high costs of satellite manufacturing and deployment today. Although counter-intuitive, such unintended results were identified by Brown and Eremenko [31], and may be contributing to the reinforcing loop involving cost and complexity.

Like forest fire regulators of the past century, satellite developers and users tend to focus on two metrics in a cost-centric approach to project assessment; they focus on capability/cost and amortized annual costs. Efforts to affect the former include increased spacecraft capability in relation to cost. It is important to note here that this applies to capacity or capability per single, monolithic spacecraft. This follows strict economic rationale; given the high fixed costs associated with each satellite, including the high costs of launching the satellite, it is better to procure a large satellite and maximize its capabilities. For satellites of certain size, economies of scale are attainable. For example, if it takes a $50,000,000 rocket launch to transport a one-ton satellite to LEO, launch vehicle capabilities permitting, the marginal cost of sending a two-ton satellite might be low, with variance in fuel consumption. This focus on maximizing spacecraft scale and capabilities to maximize launch and spacecraft utility is denoted by Brown and Eremenko as a maximization of the capability/cost quotient. The unintended effect is an increase in spacecraft mass. Spacecraft lifetime is also maximized in an effort to dilute the investment in spacecraft equipment over a long period of time, therefore reducing the amortized annual costs. The unintended effect of this is increased spacecraft complexity. As an example one could think of a battery in a satellite. If the lifetime of the spacecraft is one year, a small, simple lithium battery might be fit. If, however, the lifetime requirement is of 15 years, technical complexities might arise out of having not only a larger battery, but perhaps one of more care-demanding compounds. There might even be a need for another power source altogether. There might be a counter-intuitive and counter productive effect of having a cost-centric approach focusing on cost per unit of capacity and cost per unit of time in the satellite industry. The unintended effect is an increase in costs derived from a cost-conscious approach, just like the unintended effect of having large forest fires due to brush fire prevention and eradication in the United States in the twentieth century.

Besides spacecraft lifetime maximization, the need for redundancy and safety is a source of complexity. Maximizing system reliability and minimizing the probability of operational failure implies redundancy and robustness, resulting in increased complexity. Having parallel and redundant systems is a way of assuring reliable functionality. If failure event occurrences follow a normal distribution, designing and developing spacecraft to hedge against a 99.7 percentile (three standard deviations above the mean) of occurrences, is disproportionately more complex and difficult than hedging against a 95 percentile (two standard deviations above the mean) of occurrences. Under this rationale, increasing reliability and safety of any given spacecraft has very high marginal complexity. Having various redundant and advanced systems in a monolithic spacecraft increases complexity. This condition derives from the satellite industry's evident risk-aversion and tendency towards perfecting systems and spacecraft.

A low rate of innovation, a race towards economies of scale with a cost-centric approach towards development, and heightened complexity all make spacecraft massive. This in turn drives spacecraft and launch costs up, reducing the opportunities for deployment and thereby eliminating the possibility of risk reduction via diversification. Design to deployment cycles are simply too long to allow for sequential launches under a single project. Satellite deployments therefore come in the form of large, one chance, win-all or lose-all gambles. The resulting high risk of failure puts pressure on reliability and the need for redundancy, which in turn increases complexity, closing the loop in the "cost-complexity death spiral." Within this spiral, engineers and decision makers strive for perfection, without considering that it "is attained not when there is nothing more to add, but when there is nothing more to take away [35]."

4.1 MEMS Thrusters

Leaving Earth is not easy, for a plethora of reasons. Neither is navigating space. Propulsion is arguably the main challenge. Transportation relies on Newton's third law of motion, where any force causes a reaction force of equal magnitude but opposite direction [36]. Land-bound transportation uses friction to achieve movement using the principle of action-reaction. For example, a car has an engine that spins its wheels; the wheels excert a force on the road, which pushes back on the wheels with a reaction force, which causes the vehicle to move as described by Newton's second law (force is equal to mass times acceleration). The principle of action-reaction can also be applied to space propulsion; however, friction cannot be used in space to propell objects because space is empty. Instead, the force is produced by ejecting mass at a certain speed. As a result, any maneuver in spacee requires mass, and spacecraft can run out of mass to hence become unable to continue maneuvering. Thrusters that produce thrust by expelling mass are called reaction engines; if they carry the mass they eject, the reaction engine is called a rocket.

The Earth's gravitational pull also challenges spaceflight. An object must achieve a certain speed (which depends on the object's location in terms of latitude and altitude) in order to escape the gravitational pull of the Earth. "Escape Velocity" is the term commonly associated with such condition. Rocket engines are used to depart earth because they carry the fuel and oxygen needed to produce thrust, unlike internal combustion engines and aircraft turbines that are "air breathing", that is, they use oxygen from their surroundings to burn the fuel. Oxygen is scarce at high altitudes, where propulsion is still needed in order to escape Earth's gravitational pull. Rocket engines are also the most powerful engines available for space flight since they can generate large amounts of thrust and eventually reach escape velocity.

Having a powerful thruster is important because it is directly correlated with the amount of mass that can be transported, or the "payload capacity". Rockets need to carry their own fuel and oxidizer, so propellant efficiency is extremely important (a high propellant efficiency yields a high capacity to transport other mass besides propellant). As mentioned before, spacecraft need to lose mass, in the form of accelerated burned fuel, to maneuver. Rockets typically have various "stages" of propulsion, dropping engines and fuel tanks as they go, in order to avoid carrying dead weight as fuel is consumed. Given the state of the art in rocket propulsion and launch vehicle technology, it is extremely costly, in terms of energy and economic resources, to place mass in space. In fact, orbiting payloads are typically 1% of total lift-off mass [37].

There are two broad types of propulsion engines suitable for spaceflight: chemical rockets and electric rockets. Chemical rockets rely on exotermic reactions to generate thrust, and can be monopropellant (decomposition of a substance using a catalyzer) or bipropellant (i.e., fuel fuel is burned using an oxidizer that is carried by the rocket). On the other hand, electric rockets use electromagnetic forces to generate thrust. Electric rockets include Arc-jets (electrically heated chemical rockets), Hall thrusters (magnetostatic rockets), Ion Engines (electrostatic engines), and colloid thrusters (electrostatic engines that ionize liquid propellant). Electric rockets offer the best mass efficiency because they can accelerate the propellant at very large speeds, but they deliver very low thrust compared to chemical rockets. Chemical rockets are currently the only technology capable to take off from Earth's surface, and electric engines are suitable for in-space navigation. The difference lies in fuel efficiency and thrust. The efficiency of a propellant is measured in terms of specific impulse (I_{sp}), or impulse per unit of propellant weight flow rate, which is measured in seconds (to first order, the speed of the jet that produces thrust is equal to the I_{sp} times Earth's gravity constant); however, each propulsive scheme has related a certain Isp range and thrust range; in practice, very mass-efficient rockets cannot deliver large forces and be used for takeoff because of physical limitations such as space charge and electrical breakdown. Table 9 provides a list of current chemical and electrical propulsion systems, with approximate average specific impulses (I_{sp}) obtainable from each type of propellant.

Table 9, Current Space Propulsion Systems:

Space Propulsion Systems

Category	Type	Propellant	Isp Aprox.
Chemical	Monopropellant	N2H2	230
Chemical	Solid Propellant	Aluminized HTPB/AP	290
Chemical	Bipropellant	Hydrazine or MMH plus N2O4	320
Electrical	Electrothermal	Heated hydrazine, H2 or waste gas	700
Electrical	Arcjets	Hydrazine	600
Electrical	Arcjets	Amonia	700
Electrical	Arcjets	H2	1000
Electrical	Pulsed Plasma Thrusters	Teflon	1100
Electrical	Hall Thrusters	Xenon	1750
Electrical	Ion Engines	Xe	3250
Electrical	Colloid Engine		1000
Electrical	Colloid Engine (ion emitting)		4000
Electrical	Field Emission Electric Propulsion (FEEP)		6000

Source: [38]

Different thrusters are appropriate for different types of missions. Below, Table 10 shows engine parameters for select electric thrusters.

Table 10, Different engine parameters for several electric thrusters:

Engine Parameters for Select Electric Thrusters

Parameter	Xe Hall	Xe ion	Cs FEEP	PPT	Electrospray
Isp (sec.)	1600	2800	6000	1000	250 - 8000
Efficiency (%)	50	65	80	7	77 - 90
Semi-angle (°)	40	<20	60	-	<18
Mission	Orbital raising (med. delta V)	Orbital t. (high delta V)	small orbital correction	small orbital correction	small orbital correction

Source: [39]

There are several Micro-electromechanical System (MEMS) technologies, either proven or under current development, that could be extremely valuable in miniaturized spacecraft development. MEMS thrusters, for example, can be batch fabricated with tight specs, bringing down costs due to economies of scale. MEMS thrusters developed thus far are very suitable for stationkeeping and attitude control, but not for lift-off or orbit changing since they cannot deliver high thrusts or achieve high accelerations. Some key MEMS thruster developments of the past decade are illustrated in **Appendix A**.

Electrospray thrusters, such as the colloid thrusters developed by Gassend & Velásquez [41], constitute some of the most advanced thrusters available for in-space satellite propulsion, and are the most appropriate for nanosatellites because they can efficiently span a wide range of I_{sp} and thrust. They also offer simple architecture. Electrospray refers to the technique of ionizing electrically conductive liquids using high electrostatic fields [41]. Electrospray thrusters are electrostatic accelerators of charged particles that use an electrically conductive liquid as propellant. These particles could be charged droplets, solvated ions, or a mix of them [40]. In 2004, Velásquez pioneered the field of MEMS multiplexed electrospray thrusters; he demonstrated both droplet emitting thrusters for low-I_{sp} maneuvers, and ion emitting thrusters for high-Isp maneuvers, using monolithic arrays of microfabricated emitters with as many as 1,000 emitters in 1 cm^2 [39], [40]. The Gassend & Velásquez engine was created using Pyrex and silicon substrates, as well as microfabrication techniques such as deep reactive ion etching, low-temperature fusion bonding, and anodic bonding [41]. There might be an increased demand for these types of thrusters if certain conditions are met, as anticipated by Protz in 2004:

"As satellite missions begin to require smaller satellites, launch systems and attitude control thrusters of reduced mass will be required. Micro-rocket engines could provide a low mass, high specific impulse, and modular answer to these needs. These small rocket engines would produce thrust of order of 10's of

Newtons at a thrust-to-weight of over 1000, over 10 times the thrust-to-weight of conventional chemical liquid bipropellant engines [42]."

Besides efficient satellite propulsion in space, MEMS thrusters constitute a latent solution to lift-off and vehicle launching on a small payload scale. Monopropellant rockets do not produce as much I_{sp} and thrust as bipropellant rockets because the chemical reactions they are based on are not as exothermic. Therefore, the development of miniaturized bipropellant rockets is particularly important for the development of low-cost launching technology. In his development and test of a microfabricated bipropellant rocket engine, London discusses how the use of pumps can help reduce thickness requirements and scale down thrusters to a size that "for a given thrust level implies (the) potential application of microfabricated rocket engines (for) small launch vehicles [42]." He explains that:

> *On traditional liquid-fueled launch vehicles, the engines themselves tend to weigh about twice as much as the payload being delivered to orbit. If they could produce this same thrust while weighing much less, this weight savings could be used to increase the size of the payload. There are two ways that the thrust-to-weight ratio can be increased for a given propellant combination... a higher chamber pressure will lead to a smaller engine for a given thrust level. Additionally, by simply making the engine smaller at a constant chamber pressure, the thrust to weight ratio will increase, everything else being equal* [42].

In 2010, building on London's findings, Brikner modeled the pumps that would allow scaled-down bipropellant micro-rockets. In the Brikner design, Giffard injectors are used to pressurize propellants in order to leverage favorable scaling effects encountered at micro scales [43]. Results show rocket performance comparable to turbo-pumped micro-rockets with specific impulse and thrust to weight values of 270 and 2000 s, respectively, and chamber pressures of up to 90atm [43]. This finding may result groundbreaking in the development of a MEMS Rocket engine for vehicle propulsion.

MEMS thrusters have the potential to revolutionize satellite and launch vehicle propulsion for low payload mass classes. Silicon, the base material for MEMS, has better strength-to weight ratio than any high-performance metal alloys. Chemical thrusters with pumps and no moving parts could theoretically power a small rocket to take off from Earth's surface. Electrospray ion thrusters could provide lightweight and efficient solutions for small satellite attitude control and station keeping. Micro solar thermal systems, although not yet developed, could enable orbit-changing missions for satellites in space. The technological feasibility of the downsizing of spacecraft has been proven, in parallel for satellites and launch vehicles. This opens the possibility of having dedicated launches of small payload capacity for the deployment of micro-satellites.

4.2 Fractionated Spacecraft Architecture and Plug & Play Functionality

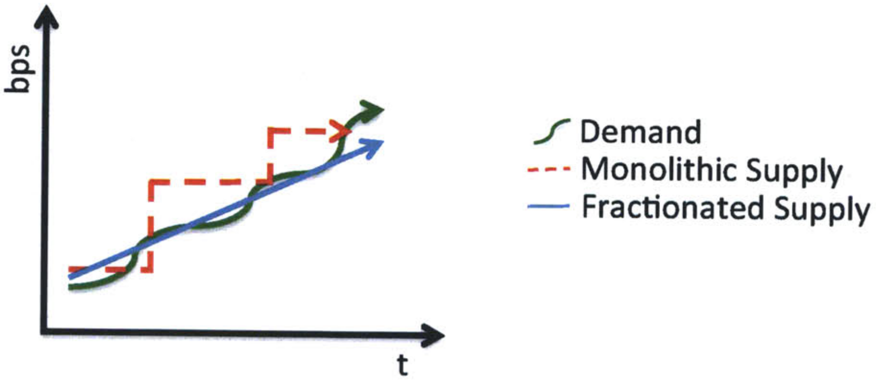
"*Fractionated spacecraft architectures consist of independent free flying modules forming a larger cooperative cluster through wireless communications networks. Such a cluster can replace a traditional monolithic spacecraft to potentially form a more responsive solution for implementing large space systems.*" [44]

Satellite operation is subject to risks and rewards like any other business. There is business cycle risk in the form of fluctuating demand, as well as financial risk in the form of variability of returns. Satellite manufacturers and users also face risk in the form of possible failure or delay in the development of mission-specific spacecraft. Finally, there is an operational risk, which derives from unforeseen events as well as error. Although all risks could be translated into and be measured in financial terms, they can be divided into four main types: Systematic business risk, and that of development, operation, and finance. A paradigm shift from monolithic spacecraft architecture to a fractionated one has the potential to reduce the four risks associated with launching and deploying satellites. The overall result of this kind of paradigm shift would be a dramatic decrease in satellite deployment risks and associated costs.

For satellite users, assessing demand might present a risk, given the high capital intensity associated with the deployment of large, high-capacity, monolithic spacecraft satellites. Be it transmission throughput in communications, number of subscriptions sold to end-users, number of images, or any measure of information as a product or service sold, commercial satellite users make their investment decisions assuming demand will be high enough for them to reach sales of a certain break-even quantity. Modular capacity additions could help smooth out the installed capacity curve (in this case, throughput is used as a proxy for capacity), from its current rigid increase step function as depicted below in Figure 3 for the case of commercial communications satellites.

Communication companies, for example, rely on satellite technology that can only add capacity in large increments, which increases the operational and financial risks inherent to their business. The operational risk derives from the potential failure of a single system, a large monolithic spacecraft. The financial risk derives from the high operational leverage, or the ratio of fixed costs to overall costs, associated with the financing of large, expensive satellites and their deployment. Long satellite development cycles and launch scheduling times force communications companies to forecast demand long into the future. Given large satellites' high throughput capacity, the addition or elimination of a single satellite greatly affects a communication company's installed capacity. Making a wrong decision can result in either overcapacity or the loss of market share due to unmet demand. The timely addition of capacity in small increments would help reduce the risk of forecasting demand in long anticipation, as well as the risk of adding capacity in large increments. In other words, the finer the supply, the more closely it could match demand.

Figure 3, Conceptual diagram of monolithic vs. fractionated supply increments *vis-à-vis* demand:



When capacity is added in large increments, as in the step function above, instances of large overcapacity may occur – overcapacity viewed as the excess supply with respect to demand at any given point in time. This happens in part because of the slow responsiveness of supply in the industry, which relates to the long development cycles and lead times to schedule vehicle launches. The time from satellite order to launch for a typical commercial GEO communications satellite is roughly 24 to 36 months [14]. With fractionated spacecraft, however, capacity could be added in small increments and more frequently, since spacecraft would be scaled down, and development cycles would tend to be shorter (as discussed infra). This would reduce a major part of the uncertainty associated with estimating demand or business cycle risk.

Modular designs would add flexibility and reduce both development risks and development cycles. The risks of failure and fragility of various systems are compounded when operating in one monolithic structure. This, in turn, increases the need for robustness, which usually requires redundancy and increased safety and reliability of systems in the monolithic structure. Making systems highly reliable, very safe, redundant and complex increases design and development costs. "The current approach – or lack thereof – to designing space systems for robustness and uncertainty is the key to the rapidly escalating costs and development timeliness facing the space industry [33]." Costs drive both the need for robustness as well as the cost of insurance. This creates a vicious cycle of robustness requiring complexity, with complexity driving costs. Insurance costs alone run "from 10% to 20% of the replacement cost of the payload, and on-orbit insurance (runs) in the range of 2% to 5% annually [33]."

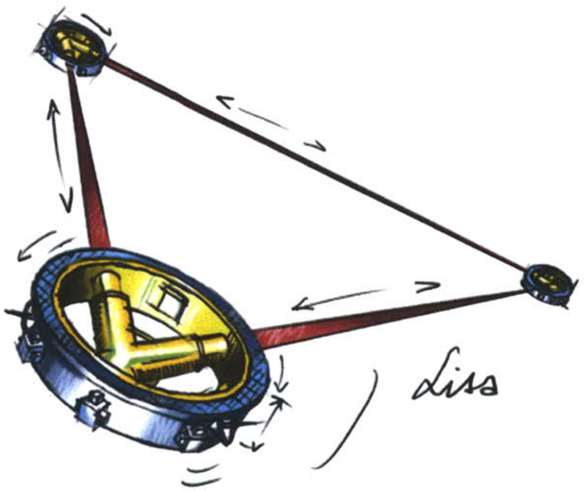
There is clearly a financial risk associated with the variance of realized returns. Such variance is driven by two uncertainties: The uncertainty and variability of operation while in orbit and the uncertainty of deployment success. Once in orbit, atmospheric conditions, equipment malfunction, and other factors may cause a range of performance outcomes that can translate to achieving zero financial returns, fewer financial returns than expected, or, though less likely, more financial returns than expected. In the case of success or failure in deployment, results can be considered binary: success yields financial returns, and failure invariably yields a loss.

Heterogeneous fragmentation can reduce the operational complexity of spacecraft, and homogeneous fragmentation may enable new technologies. By having attitude determination and control systems spread and applied to different modules, such systems can become less complex in most modules. "Pointing accuracy requirements can be relaxed for the non-payload modules. This can significantly simplify and shrink the attitude determination and control system (ADCS) for most of the spacecraft modules [33]." Just as heterogeneous fragmentation may open the possibility for simple modular designs, homogeneous fragmentation can enable new technologies:

> *"Certainly fractionated space systems enable a whole array of new missions unattainable with monolithic satellites. These include, for instance, distributed aperture sensing and observation, interferometry missions, and missions requiring satellites beyond the capacity of the largest single existing launch vehicle... fractionated architectures are an improved paradigm for the implementation of many, if not most, existing space missions* [45]."

As an example of fragmented architecture, Project LISA (Laser Interferometer Space Antenna), being developed by the European Space Agency, is intended to test Einstein's Theory of Gravity, observe galaxies far back in time, and explore black holes and their collision, among other things. LISA is conceived as an equilateral triangle formation consisting of three spacecraft located 5 million kilometers apart from each other and 50 million kilometers away from earth. With LISA, instead of building one very large antenna, the three-spacecraft formation will act like one very large antenna [46]. Figure 4 is an artistic representation of the LISA project.

Figure 4, Artistic representation of the LISA European Space Agency project:



Source: (60), Credits: ESA-C. Vijoux

The development risks associated with spacecraft can also be reduced via modular design and production. In monolithic satellites, parts and systems designs must be orchestrated into one massive and simultaneous effort, or, a sequence of interdependent developments. In such sequential development, the delay or design change of one system, lying in the critical path of the spacecraft's development, can significantly affect the execution of the project. With modular designs, in parallel, not a single module can significantly delay the overall project execution, simply because launch and deployment does not have to be delayed – modules can be added to orbiting spacecraft and clusters of spacecraft – in a plug-and-play fashion. Plug and Play: *A standard for the production of compatible computers, peripherals, and software that facilitates device installation and enables automatic configuration of a system.* [47]

Spacecraft fragmentation would enable plug-and-play functionality in satellites, thereby increasing flexibility and reducing operational complexity. Heterogeneous fragmentation would entail the decoupling of payloads from other support modules, which would give satellites a functional flexibility that would make them more versatile than ever before. An Earth observation satellite could switch to deep space observation, weather monitoring, or communications with the deployment of a new payload module. This is analogous to the way personal computers can add peripheral devices and switch among them with a USB interface. Versatility could be increased, and operational complexity (although arguably increased with the need for communication and coordination among different modules) could be reduced by different means. Pointing and location accuracy in satellites is driven by the payload, but "can be relaxed for the non-payload modules. This can significantly simplify and shrink the attitude determination and control system (ADCS) for most of the spacecraft modules [33]." In a similar way, navigation control can be concentrated in one module, (or more for redundancy and robustness), while other modules can simply navigate according to their position relative to the navigation control modules. Data exchange among modules can be performed with ultra-wideband technology, or low-power, omnidirectional, spread-spectrum links, making communication wireless. V-band and W-band radio frequency transmission could be used for power transmission, with higher frequencies allowing for smaller antenna sizes [33]. For transmission across large distances (kilometers), laser beams directed at photovoltaic cells might be viable [33]. The winning technologies to enable fragmented spacecraft architecture and cluster flying have yet to be determined, but may be established by ongoing government demonstration programs such as the U.S. Department of Defense's Advance Research Projects Agency (DARPA) System F6 Project. For a brief description of this project, from the agency's website, see **Appendix B**.

A paradigm shift from monolithic spacecraft architecture to a fractionated one, and the simplification of spacecraft development, as well as of design and operation, can have profound impacts in the satellite industry. The overall effect would be a move towards a more open and competitive industry. Table 11 summarizes some potential long-term effects of spacecraft fractionation on the aerospace industry:

Table 11, Industrial Base Effects of Fractionated Architectures:

INDUSTRIAL BASE EFFECTS OF FRACTIONATED ARCHITECTURES	
Term	Definition
Reduced barrier to entry	The splitting of a single large spacecraft into smaller pieces permits players outside of the large traditional primes to participate in development and fabrication
Increased number of competitive opportunities	With a standard open interface among modules, a spacecraft mission or program can be split up among multiple contractors raising today's very small number of competitive opportunitites
Volume for responsive spacelift	Launching fractionated spacecraft modules may be a significant market for small launch vehicle payloads
Improved operator NPV	If fractionated spacecraft really offer an enhanced value proposition over traditional monolithic ones, this will enhance the NPV and shareholder returns for commercial operators

Source: [18]

5.1 The Case for Disruption

There are three modes and four ways that technologies can interact, as identified by Pistorius & Utterback [48]. The three modes are: symbiosis, pure competition, and predator-prey. Technologies can complement each other and co-exist in symbiosis, or alternatively, compete with each other for survival and prevalence. Two technologies can also have conflicting effects on each other. An emerging technology can have a negative effect on an established technology, while being positively influenced by the established technology, and vice-versa. Figure 5 illustrates a multi-mode framework to assess the interaction among technologies.

Figure 5, Multi-mode Framework to Assess the Interaction Among Technologies:

		Effect of A on B's growth rate	
		Positive	Negative
Effect of B on A's growth rate	Positive	Symbiosis	Predator (A) - Prey (B)
	Negative	Predator (B) - Prey (A)	Pure Competition

Source: [48]

The nature of technological interaction can change over time. Currently, satellites in the pico to micro mass classes co-exist in symbiosis with large satellites. Pico satellites are often hosted payloads nested in large satellites. Micro satellites commonly "piggyback" on large satellite launches as secondary payloads. Similarly, MEMS thrusters, as station-keeping technology and used in satellite propulsion, currently complement the utility of large chemical rockets in launch vehicles. Perhaps the application of fractionated spacecraft architecture is yet to be proven as enabling technologies are just becoming available, but it remains fair to say that spacecraft fractionation does not necessarily entail spacecraft miniaturization, and that a change in architecture may bring about new ways to build and use spacecraft, not substitute them. In the two cases related to aerospace and identified in this thesis as emerging trends in satellites; MEMS thrusters, and fractionated spacecraft architecture, the adoption of those emerging technologies may initially increase the demand for the established technologies. This would represent a symbiotic interaction.

The case could be made that micro electro mechanical systems (MEMS) thrusters both for launch vehicle propulsion and satellite propulsion, as well as in other spacecraft functions such as antennas, inertial navigation, power supplies, sensors, etc. could enable radical innovations in satellites, especially due to their improved resistance to radiation (given the use of silicon as base material). In a similar way the use of small satellites and spacecraft fractionation have the potential to bring about important changes. Currently, small satellites serve very small markets in scientific research, while large satellites serve large communications markets. Under the predator-prey mode of interaction, "often the new technology enters a niche market rather than the main market of the mature technology, and as such it does not immediately threaten the mature technology… As the emerging technology matures, however, it will expand into other markets that will include the main markets of the mature technology as well as new markets that are not served by the mature technology [48]." If, for example clusters of small satellites could eventually enable data communications, they could come to compete with large monolithic satellites.

"*Light-weight (100 kg class and smaller) microsatellites, combined with miniaturized spacecraft components are a well-established technology proven to reduce the costs and enhance the capabilities of certain space missions. Though the capabilities of microsatellites are traditionally more limited than those of their larger counterparts, the relatively small mass of microsatellites could allow for drastically reduced launch costs; reduced development times for micro-satellites may also result in the use of more modern technology, which can enhance capabilities and mitigate some of the compromises made to reduce system mass.*" [49]

If small satellites and ancillary technologies such as MEMS thrusters and spacecraft fractionation come to compete with large monolithic satellites, their interaction will have followed the predator-prey mode.

An interesting analogy can be drawn between today's satellite industry and the computer industry of the Twentieth Century. In both cases, the nature of the interaction among established and emerging technologies warrants debate. The miniaturization of key components, the scaling-down of equipment, the shift from monolithic to fragmented architecture, and the buyer and supplier reinforcing focus on a set of product attributes, (and their ultimate shift towards a different set of attributes) is strikingly similar in aerospace today as in computers thirty years ago. At some point, both industries saw their main products, mainframe computers and satellites, grow in size and capabilities within monolithic structures. This can be attributed to suppliers focusing on attributes that customers valued, those that fueled re-enforcing loops: the capability/cost quotient & amortized annual costs, and the processing power in mainframe computers. However, with computers as with satellites, scaling down has entailed the miniaturization of key components – what happened with processing chips may happen with MEMS thrusters and other spacecraft parts; mass production may bring economies of scale in miniaturized technology. Current technology trends in satellites are comparable to technological trends that affected the computer industry of the 1980's. For reference to one company's evolution in the computer industry of the 1980's, see **Appendix C**, Mainframe Computers and IBM's Fortunes.

Both the computer industry of the 1980's and the satellite industry of the last decade, under a concentrated market structures, saw the emergence of new entrants honing emergent albeit underperforming technologies; DEC with minicomputers and "plug compatible" vendors such as Amdahl, Fujitsu, & Hitachi in the case of microcomputers, (39), and more recently, Space X & Orbital Sciences with small launch vehicles and perhaps Pumpkin with nanosatellites in the case of the satellite industry. In the computer industry, new entrants, focusing on technologies that underperformed in traditional attributes, but outperformed established products in new sets of attributes, leveraged open systems (plug-and-play modularity) in fragmented architectures (client-server) to deliver products and services to a new set of customers (small firms and non-government institutions).

A timid yet growing set of new satellite users in new markets, coupled with product architecture innovation, may ultimately increase satellite adoption and provide new game-changing uses for satellites. In the same way that large monolithic mainframe computers gave way to microcomputers in client-server architecture, large monolithic satellites may give way to microsatellites in fragmented spacecraft architecture. This may result in design modularity. In computers, "ultimately, the dynamic innovative industry that has grown up around (modularity) developed entirely new kinds of computer systems that have taken away most of the mainframe's market share... The fact that different companies (and different units of IBM) were working independently on modules enormously boosted the rate of innovation [51]." In the case of satellites, a move towards modularity and fragmented architecture could have similar effects in the satellite industry as it had in the mainframe computer industry, since according to Mathieu and Weigel:

"*The implementation of (modular) architecture and the development of an infrastructure of standardized modules could prompt sweeping changes to the space industrial base structure... the industry may gain new dynamics, become much more competitive, and much less stable and concentrated. The shorter cycles associated with fractionated architectures could set a faster pace and new opportunities could be created more frequently.*" [52]

To the extent that satellite users find value, just like computer users of the last century, in flexibility, replace-ability, small-increment capacity additions, and compatibility across systems and peripherals, microsatellites, MEMS thrusters, and fragmented spacecraft architecture could potentially disrupt the satellite industry.

5.2 Four Possible Scenarios for the Future of the Satellite Industry

A paradigm shift from monolithic spacecraft architecture to a fractionated one has the potential to reduce risks associated with capacity planning and demand forecasting, spacecraft development and operation, and overall financial risk. The diversification and therefore reduction of risks can be accomplished through the fragmentation of complex systems into various simple ones. To the extent that satellite users find value in flexibility, replace-ability, small-increment capacity additions, and compatibility across systems and peripherals they may shift to a value-centric approach to satellite procurement. This would entail perceiving value in a new set of attributes in satellites. The result would be an ultimate simplification of products and their development in the satellite industry, cutting down development cycles and costs.

Fractionated spacecraft architecture would facilitate a shift from a requirement-centric approach towards a value-centric approach in spacecraft development, which would ultimately break the "cost-complexity death spiral" as defined by Brown and Eremenko. Since not a single spacecraft would satisfy the requirements of a project or mission, and it is in terms of total lifetime-value that a system of fractionated spacecraft represents advantages, a different approach towards appraisal and evaluation of spacecraft and missions would be needed with fractionated spacecraft. With this new architecture, the lifetime value of satellite systems is larger, because lifetime is extended via simple modular replacement of payload and support spacecraft. When redundancy is achieved at the system level, via homogeneous fragmentation, no single modular component requires redundant systems that compound complexity. In other words, modularity adds flexibility by making it easier to replace modules and having various redundant modules instead of relying on one complex monolithic spacecraft. Therefore, the life and subsequently the lifetime value of a modular system will always be larger than the life and lifetime value of a single module. While individual modules in fractionated architecture may seem to underperform in cost / capability metrics typical of a requirement-centric approach in satellite procurement, the overall system they enable may provide better value over the system lifetime.

The modular flexibility of fractionated spacecraft architecture would allow satellite users and developers to move away from focusing on maximizing spacecraft lifetime (for the reduction of amortized annual costs) and the capability / cost quotient attributes in satellites. Therefore complexity and spacecraft scale (and mass) could be reduced according to the causal loop diagram illustrating Brown and Eremenko's cost-complexity death spiral (Figure 2).

The use of MEMS in spacecraft development will certainly catalyze great innovations going forward. MEMS thrusters in satellites alone have great potential. If applied to launch vehicle propulsion, MEMS thrusters may enable dedicated launches for small satellites with the use of small rockets. This breakthrough could potentially reduce launch costs in a very significant way, which would dramatically increase the number of launch opportunities. With reduced launch costs and increased launch opportunities, the risk of failure can be reduced (Figure 2).

MEMS thrusters and fractionated spacecraft architecture clearly complement each other, in a symbiotic relationship. Having ample launch opportunities and having dedicated launches would tremendously increase the utility of fractionated space systems, since modules would be easily and promptly replaced. By the same token, the replacement of modules creates demand for dedicated launches. Moreover, increased technological innovation in thrusters can improve the functionality of small satellites that rely on them for propulsion. Therefore, the simultaneous development of MEMS thrusters and fractionated spacecraft architecture would be more valuable than the aggregate value of each one's development in the absence of the other.

Two emerging trends in the satellite industry have been identified; the application of micro electro mechanical systems (MEMS) in spacecraft development, particularly thrusters, and the shift away from monolithic towards fractionated spacecraft architecture. There are two independent events or occurrences related to those two trends that could have important impacts on the future of the satellite industry. First, MEMS thrusters being able to deliver escape velocity for launch vehicles (rockets), and second, the successful completion of the DARPA F6 project. A conceptual map of the interaction between those two events yields the following four scenarios for the future, as illustrated in **Appendix D**.

Status Quo

If MEMS thrusters cannot be used in vehicle propulsion, but are limited to satellite propulsion, and the DARPA F6 project fails, limiting the shift towards fractionated spacecraft architecture, the existing state of affairs will dictate the future. The rate of innovation and level of competition will remain low, the industry highly consolidated, and spacecraft mostly massive. The "cost-complexity death spiral" will prevail.

Improved Space Infrastructure

Everything else held constant, if the DARPA F6 project succeeds, there could be an increased adoption of small satellites as hosted payloads. As explained above, spacecraft fractionation alone may break the "cost-complexity death spiral", allowing for greater rates of innovation and competition in the satellite industry. The result would be an open network and space infrastructure that would promote competition by making it easier for new entrants to gain access to space, as explained in **Appendix B**.

New Business Opportunities

Everything else held constant, if MEMS thrusters are able to provide escape velocity for launch vehicles, new business opportunities may arise. Low-cost access to space via dedicated launches for small satellites could increase their utility. Furthermore, reduced launch costs and increased launch opportunities would contribute to the easing of the "cost-complexity death spiral" by reducing the risk of failure, at least for small satellites.

Open Global Space Commons

With MEMS thrusters reaching escape velocity, enabling dedicated launches for small payloads, and DARPA F6 enabling spacecraft fractionation, the future of the satellite industry could be very different from the status quo. Spacecraft scale and therefore mass could be reduced, shorter spacecraft lifetime could reduce complexity, and low-cost access to space could reduce the risk of failure in the satellite industry. Ultimately, the possibility of dedicated launches for small satellites and fractionated spacecraft architecture would reduce the need for safety and increase the rate of innovation in the satellite industry. Under this scenario, the industry would be more competitive than it is today, with lower barriers to entry.

Four possible scenarios for the future of the satellite industry have been defined *supra*. Those scenarios are characterized by the outcomes of two independent events that have the potential to significantly impact the satellite inudstry. There are meaningful conclusions to be drawn from a quick assessment of the interaction between two emerging trends in an attempt to envision the future of the satellite industry. MEMS technology and fractionated architecture can change the dynamics of innovation and spacecraft development. Breakthroughs in both areas could eventually induce greater rates of innovation, and shift the development focus on certain product attributes such as amortized annual costs and the capability/cost quotient. This, coupled with the reduction of launch costs, would make satellites smaller, cheaper, shorter-lasting and more frequently deployed. Of all possible scenarios, the application of MEMS thrusters to launch vehicles and fractionated spacecraft architecture together would most likely yield a more open, innovative and competitive space industry than we know today.

6. Summary

Trends in propulsion technology and spacecraft architecture constitute potential game-changing developments in the satellite industry. The application of MEMS with silicon-based manufacturing in spacecraft development, particularly in satellites and potentially in launch vehicles, may constitute radical innovation. A shift from monolithic to fragmented spacecraft architecture may also bring about significant changes. Although events are yet to unfold, emerging trends in the satellite industry can very likely bring profound changes in product offerings, spacecraft applications and the overall exploitation of space commons in Low Earth Orbit and beyond.

Two particular developments related to current trends in satellites can be used to map the future of the industry. First, the development of MEMS thrusters for launch vehicles could enable dedicated launches for small satellites. This in turn could substantially bring down the cost of satellite deployment. Second, the successful completion of the DARPA System F6 project could enable spacecraft fragmentation. This in turn could shift the focus of the industry on certain attributes that reinforce long development cycles, opening the doors for open systems and greater innovation. The imminent results of this paradigm shift could be a dramatic decrease in satellite costs, a change towards a value-centric approach in satellite procurement, and ultimately a structural change in the industry.

Concurrent developments in propulsion technology and spacecraft architecture design could lead to increased adoption of small satellites as well as more open, flexible and useful space systems. MEMS technology and fractionated spacecraft architecture have the potential to increase competition in the satellite industry of the Twenty-first Century. As a result, artificial satellites could provide greater utility to humanity in the near future than they have in the past.

Appendix A:

Timeline of Important MEMS Thruster Developments

2000

London develops and tests a micro fabricated, bipropellant rocket engine.

2001

Hitt et al report the first MEMS monopropellant rocket (with significant thermal losses), using an array of Pt coated silicon columns as a catalyst bed.

2004

Velásquez develops the first MEMS multiplexed electrospray thrusters, introducing a technology that can satisfy a wide range of missions in miniaturized satellites. Droplet emitting thrusters for low-Isp maneuvers and ion emitting thrusters for high-Isp maneuvers are demonstrated.

2007

Gassend & Velásquez-García demonstrate a batch micro-fabricated MEMS planar array of electrospray ion thrusters with integrated extractor yielding high propulsive efficiency (~85%- 92%).

2009

Feras Eid et al demonstrate an efficient MEMS monopropellant rocket using a liquid catalyst; full thermal decomposition and minimum thermal losses are achieved. Krpoun et al demonstrate that the same electrospray architecture can produce low or high Isp by varying the hydraulic impedance of the electrospray emitters; opening the possibility of a more compact propulsion system.

Appendix B:

DARPA Future Fast Flexible Fractionated Free-Flying Spacecraft united by Information Exchange (F6) Project:

SYSTEM F6

System F6 seeks to demonstrate the feasibility and benefits of a satellite architecture wherein the functionality of a traditional "monolithic" spacecraft is delivered by a cluster of wirelessly-interconnected modules capable of sharing their resources and utilizing resources found elsewhere in the cluster. Such architecture enhances the adaptability and survivability of space systems, while shortening development timelines and reducing the barrier-to-entry for participation in the national security space industry.

The program is predicated on the development of open interface standards—from the physical wireless link layer through the network protocol stack, including the real-time resource sharing middleware and cluster flight logic—to enable the emergence of a space "global commons" which would enhance the mutual security posture of all participants through interdependence. A key program goal is the industry-wide promulgation of these open interface standards for the sustainment and development of future fractionated systems and low-cost commercial hardware for the sustained development of future fractionated systems beyond the System F6 demonstration.

The program will culminate with an on-orbit demonstration in 2015 of the key functional attributes of fractionated architectures. The technology objectives and program plan are driven by a small set of functional on-orbit demonstrations. Program success will be measured by the successful completion of these demonstrations, designed to prove the highest-risk elements of the architecture to potential transition partners and early adopters. The demonstrations will occur in low earth orbit (LEO), and will be approximately six months in duration. The functional demos are as follows:

- *Capability for semi-autonomous long-duration maintenance of a cluster and cluster network, and the addition and removal of spacecraft modules to/from the cluster and cluster network*
- *Capability to securely share resources across the cluster network with real time guarantees and among payloads or users in multiple security domains*
- *Capability to autonomously reconfigure the cluster to retain safety- and mission-critical functionality in the face of network degradation or component failures*

- *Capability to perform a semi-autonomous defensive cluster scatter and re-gather maneuver to rapidly evade a debris-like threat*

The general philosophy that underlies the technical approach and structure of the System F6 program is to arrive at the on-orbit functional demonstrations enumerated above through a disaggregated series of efforts.

Two key artifacts will be developed in the course of the program. The first is the F6 Developer's Kit (FDK), which is a set of open source interface standards, protocols, behaviors, and reference implementations thereof, necessary for any party, without any contractual relationship to any System F6 performer, to develop a new module that can fully participate in a fractionated cluster. The second is the F6 Technology Package (F6TP), which is a hardware instantiation of the wireless connectivity, packet-switched routing, and encryption capable of hosting the protocol stack and resource-sharing and cluster flight software needed to enable an existing spacecraft bus to fully participate in a fractionated cluster. In essence, the F6TP is a hardware instantiation of the FDK. [53]

Appendix C

Mainframe Computers and IBM's Fortunes

"In 1990 IBM was the second most profitable company in the world, with net income of $6 billion on sales of $69 billion [50]." In 1991, however, and for the first time in the company's history, IBM reported yearly losses. Amid an ensuing three-year loss streak totaling $16 billion, management planned for the corporation's breakup [50]. The emergence of new technologies, architectures, and nimble competitors forced IBM to revise its business model, product offerings and customer focus. Although changes started to brew with John Akers' management, the advent of deep changes brought about by Louis Gestner was instrumental for IBM's survival and restitution as a world-class leader in computer markets. In such a spectacular case of a turnaround, there is as much to learn from the actions taken by management to overcome adversity, as there is from the factors leading to the company's floundering.

IBM's dealings in the early nineties can be considered an example of the Innovator's Dilemma. "The innovator's dilemma is that doing the right things can lead to failure [54]." Thirty years ago, computer markets could be segmented into three product categories: Mainframes, Minicomputers, and Microcomputers (also known as Personal Computers, or PC's). The main differences across the three segments were stand-alone processing power and functionality. Mainframes were large in size and processing power. Microcomputers were at the opposite side of the size-processing power spectrum; individual PC's could not satisfy a large company's data-processing demands, and they were small. Working together though, in client-server architecture, microcomputers eventually offered a set of attributes and functionality that met customers' needs in a satisfactory way. This not only changed the name of the game in terms of products, but also rendered IBM's business model unfit for the emerging trends in the computer industry. Early on, IBM failed to see the emergence of minicomputers and microcomputers as business opportunities because the company was making sound economic decisions, and was focusing on delivering value to its most important clients in terms of the attributes they traditionally valued.

Early on, IBM did not invest in bringing minicomputer and microcomputer technologies under client-server architectures to market, because it did not want to cannibalize its mainframe sales or take a risk in a small or unproven market. "In technological terms, IBM was better positioned than any other company to participate in the client/server and Internet revolutions. As a practical matter, though, managers could not bring themselves to cannibalize mainframe sales by pushing replacement technologies [50]. IBM did not want to lose focus on its mainframe customers either, "they had no use for (minicomputer technology); it promised lower, not higher margins; and the market initially was significantly smaller [54]." Their main clients, and consequently IBM itself, were probably focusing on metrics such as processing capability/cost of acquisition, in a way that reinforced large-scale, monolithic computer development. Moreover, as single computers gained scale so did the size of each sale, and the concentration on fewer customers that could afford such purchases. This increased the buyers' bargaining power and IBM's dependence and focus on large-scale sales. The average sale price for mainframes dwarfed alternatives; "In 1990 a mainframe's price typically exceeded $500,000 while minicomputer prices were as low as $25,000, and microcomputers ranged from under $1,000 up to $25,000 [55]. Therefore, for some reasons, it made sense for IBM to hold fast to the mainframe architecture and avoid developing client-server solutions. Profitability only reinforced this belief.

However, as time went by, and newcomers in the computer industry gained terrain in the microcomputer market, the game started changing. "PC's, technical workstations, and networks of PCs and workstations began encroaching on markets previously reserved for minis and mainframes... Rather tan every computer company in the world designing and building its own proprietary parts, independent suppliers provided standard building blocks. As a consequence, a wide array of companies could build machines that performed across a broad spectrum of price and performance features [55].

The way that open, fragmented architecture of microcomputers and the client-server model drifted the market away from IBM's value proposition is clearly illustrated in the IBM Corporation Turnaround case. "With the introduction of the Personal Computer (PC), and for the first time, computational capability could be acquired in an incremental and decentralized manner. No longer were individual departments within a business completely dependent on monolithic data processing [50]."

When PCs were "networked" so that they could easily exchange information, it became possible to expand their uses beyond single-user systems. Groups of machines based on PC architectures operated together as "clients" – devices for interaction with users – and "servers" – more powerful back office machines that handled the bulk of processing duties. The popularly perceived superior economics and greater flexibility from the client / server model of computing led to reduced mainframe sales, which were the source of almost half of IBM's revenues and 70 – 80% of its profits. Where IBM's mainframes were based on proprietary technologies and typically produced gross margins in excess of 50%, client / server technologies were more "open" – more interoperable with the products of other vendors – and did not command such generous margins. Decentralized computing led customers to concentrate on personal productivity rather than on IBM's traditional forte, back office solutions. Customers purchasing decisions also became decentralized, moving away from the centralized (Management Information Systems) MIS organizations with whom IBM had long standing relationships [50]."

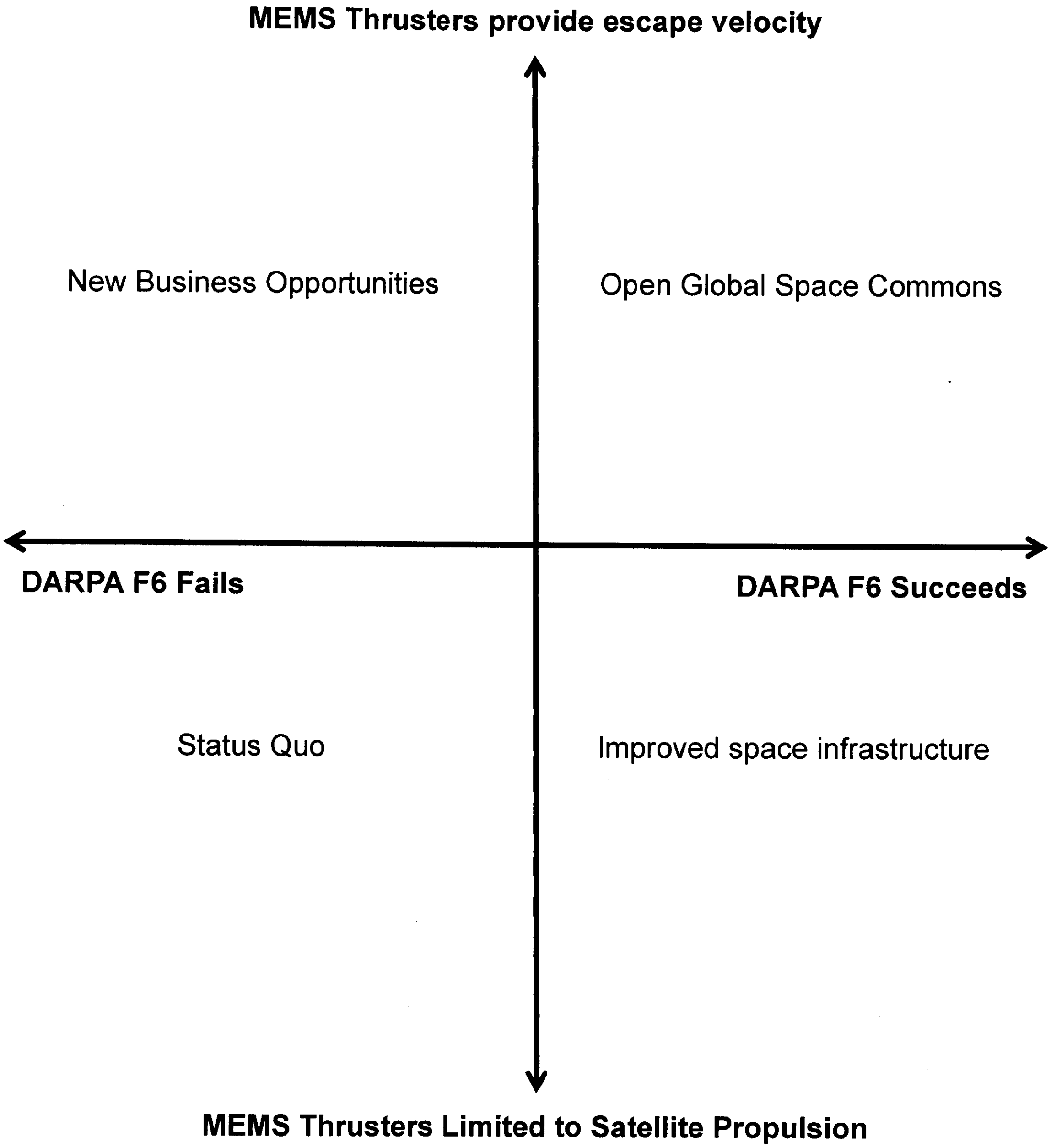
Despite IBM's successful turnaround, and the fact that PC's initially benefited from the existence of mainframe computers, in a symbiotic relationship, minicomputers and personal computers offered the innovator's dilemma for established players of the computer industry in the past century. "Their customers had no use for (minicomputers); it promised lower, not higher margins; and the market initially was significantly smaller [54]." Microcomputers were clearly less powerful, less sophisticated and less functional than mainframes. This condition, along with reduced attractiveness in terms of margins and market size are characteristics of disruptive technologies [56]. Another characteristic of disruptive technologies, as defined by Christensen, is established customers' lack of interest [56]. "IBM's large commercial, government, and industrial customers saw no immediate use for minicomputers [57]." Following the innovator's dilemma trap, "(IBM) listened to the customers, gave them the product performance they were looking for, and, in the end, (was) hurt by the very technologies the customers led them to ignore [57].

A key aspect of disruptive innovation is the offering of a "different package of performance attributes-ones that at least at the outset, are not valued by existing customers [57]." In the case of client-server architectures, which were enabled by microcomputers, the new attributes were openness, compatibility, connectivity and flexibility. Plug-and-play functionality was enabled. Capacity was added in smaller increments (workstations), and peripherals could come from diverse manufacturers. "The developers of the System 360 conceived of a family of computers that would include machines of different sizes suitable for different applications, all of which would use the same instruction set and could share peripherals. To achieve this compatibility they applied the principle of modularity in design [51]." Moreover, processing speed, storage capacity, and other attributes that were traditionally valued by established customers quickly improved in microcomputers, since "advances in semiconductor technology came so quickly that improvements in price/performance were expanding almost fourfold every three years in the 1980's [55]. This is why microcomputer products were able to invade established markets later on, which is another disruptive attribute recognized by Christensen, who argues that "the growth markets of the future will not be in today's monolithic one-size-fits-all product categories [56]."

The judgment of whether or not microcomputers and the emergence of client –server architectures were disruptive to IBM's mainframe business could be the subject of an interesting debate. IBM is a going concern and a profitable company. Today, there is clearly a market for mainframe computers as well as personal computers. Both live in symbiosis. Nevertheless, many characteristics of technological disruption can be identified in the emergence of the microcomputer and the client-server architecture *vis-a-vis* mainframe computers in the twentieth century.

Appendix D:

Possible Scenarios for the Future of the Satellite Industry



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