



**THE FINANCIAL IMPACT OF COMMERCIAL SMALL SATELLITE AND
SMALL LAUNCH PROVIDERS ON THE DEPARTMENT OF DEFENSE**

THESIS

Peter A. DeBois, Captain, USAF

AFIT-ENV-MS-17-M-183

**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY**

AIR FORCE INSTITUTE OF TECHNOLOGY

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Peter A. DeBois, MS

Captain, USAF

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Peter A. DeBois, MS

Captain, USAF

Committee Membership:

Clay Koschnick, Lt Col, USAF, PhD
Chair

R. David Fass, PhD, Lt Col, USAF (Ret.)
Member

Mr. Roy Bryson
Member

Abstract

Investment in the commercial space industry has grown significantly over the past decade. This investment has led to a tremendous leap in capability for small satellite systems and a greater demand for small launch vehicles. At the same time, space system affordability is a point of emphasis within the Department of Defense (DoD) which raises the question: Can the DoD lower space access costs through the exploitation of the growing small satellite and small launch marketplace? We perform a financial analysis of newly developed small launch vehicles delivering a small satellite constellation to low earth orbit (LEO) to perform wideband communication. The results are then compared against the historical costs of the DoD's Wideband Global SATCOM (WGS) constellation.

We conclude small communication satellites delivered to LEO by newly developed small launch vehicles produce potential cost savings ranging from 10% to 22% versus WGS. Small satellite and small launch vehicle systems must evolve to meet the capability and performance of the DoD's current wideband communication system, but the potential financial savings found in our research gives the DoD flexibility in procuring future space capabilities for U.S. defense.

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Peter A. DeBois

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I. Introduction

In the constrained budget environment of the Department of Defense (DoD), acquisition programs are under constant scrutiny; the space realm is no exception. The DoD has an ever-growing need to develop and procure affordable weapon systems. Greater competition in the defense market may provide the opportunity for programs to become more affordable. As defense programs and systems become more affordable, the DoD may be able to provide greater war fighting capabilities for the nation and the service members who fight its wars. Defense program affordability ties directly with the marketplace economics of the defense industry.

Economists inform us that the monopolization of a marketplace deters the opportunity of consumer price differentiation (Perloff, 2008, pp. 443–444); the Department of Defense (DoD) has, over many years, expressed its agreement with this economic theory through directives from top acquisition leadership. The DoD’s former lead acquisition officer, Frank Kendall, has issued guiding principles for Department acquisition specifically highlighting the importance of a full and open competitive environment stating: “Competition is the most effective tool we have to control cost” (F. Kendall, 2015b). To enact these guidelines, the DoD acquisition community must make every attempt to search out and analyze the impacts of new private sector investment and technological development. The marketplace of space exploration has become a newly competitive market for the DoD.

The space environment presents a constantly changing risk profile for DoD assets. Due to the increasing numbers of spacefaring nations, the DoD is constantly attempting

to limit risk and improve the resiliency of satellite constellations. *Disaggregation* is one possible avenue to improve resilience in the space environment. *Disaggregation* is defined by Air Force Space Command as: “the dispersion of space-based missions, functions or sensors across multiple systems spanning one or more orbital plane, platform, host or domain” (*Resiliency and Disaggregated Space Architectures: White Paper*, 2013). Former Commander of Air Force Space Command, General John Hyten commented on disaggregation that “taking big satellites, breaking them up into small pieces and putting them into smaller satellites is one aspect and one technique to get resilience out of your capabilities” (Hyten, 2015). The concept of disaggregation poses the opportunity to improve resilience while also reducing costs within the DoD space construct. Disaggregation may allow for less complex satellites, shorter development timelines, and lower launch costs--potentially making access to space more affordable.

Background/Purpose

The DoD currently relies on two launch providers for National Security Space (NSS) missions: United Launch Alliance (ULA) and Space Exploration Technologies Corp. (SpaceX). ULA has been the only launch service provider to the DoD until the recent certification of SpaceX to compete for future NSS launches (“Air Force’s Space and Missile Systems Center Certifies SpaceX for National Security Space Missions,” 2015). In fact, SpaceX’s first contract award to launch a NSS mission occurred in April 2016 for approximately \$83M (“Air Force Awards GPS III Launch Services Contract,” 2016). The current DoD launch services framework provides few industry options which is contrary to the goals expressed by the Department to create an open and competitive

environment. Although the cost of the new contract awarded to SpaceX was described as 40% lower than previous government estimates (Klotz, 2016), the total mission cost continues a trend of high-cost space access for the DoD. The latest DoD contract for a block buy of launch services costs approximately \$5.9 billion (*Selected Acquisition Report Evolved Expendable Launch Vehicle*, 2016). Previous studies have demonstrated a need for low-cost launch vehicles to take advantage of improvements in small satellite technology (Grosselin III, 2011; Pawlikowski, Loverro, & Cristler, 2012). Those low-cost launch vehicles are now being developed.

The reason for increasing interest in low-cost launch vehicles is a product of the burgeoning small satellite marketplace and its demand for cheaper space access. Private industry investment into low-cost space launch platforms is booming with companies such as Firefly, Vulcan Aerospace, Rocket Labs, and Virgin Galactic recently entering the marketplace (Stallmer, 2016). The technology revolution happening with smaller satellites has presented the DoD with copious numbers of new satellite developers in the marketplace as well. Over the last five years, an average of eight new space firms have joined the marketplace annually (*Start-Up Space: Rising Investment in Commercial Space Ventures*, 2016). This influx may provide additional options to disaggregate satellite constellations in a more competitive way for the DoD. A 2013 study by the Air Force Scientific Advisory Board stated that: “microsatellites have significant near-term (2-5 years) mission capability” (Gustafson & Zolper, 2013). Wegner, Adang, and Rhemann (2014) state that low-cost commercial satellites may be able to satisfy 80% of disaggregated satellite architecture by 2025.

Research Question

Can the DoD lower space access costs through the exploitation of the growing small satellite and small launch marketplace? The DoD has emphasized repeatedly that acquisition costs must decrease and a competitive marketplace of suppliers may assist with this endeavor. The small satellite and small launch commercial market has now reached a tipping point of new providers. With the emergence of these providers comes the opportunity to examine whether or not they can provide a net positive financial impact for the DoD while ushering in the envisioned future disaggregated architecture. Until now, there has been no quantification of the financial impact the small launch market may have upon the DoD space mission.

Assumptions/Methodology

A financial analysis is only as credible as the assumptions and framework from which it stems. The analysis forthcoming will be a product of studies, models, and publicly available information regarding the capability of small satellite technology which may begin to fill the void of some space defense requirements. In an effort to paint a picture for a resilient disaggregated architecture, this financial analysis focuses on the use of small communication satellites to assume or augment the communication role of the United States Air Force's Wideband Global SATCOM (WGS) constellation. We focus solely on small satellite architecture costs and the costs of launching said architecture. Future ground systems are not a focus of our analysis. All architectural frameworks are obtained from publicly available information, published studies and literature, and subject matter experts.

Our analysis compares the new small launch vehicle capability pricing now present in the marketplace against the historical cost of using current DoD launch providers. It is widely understood that government programs do not simply absorb commercial pricing due to government-specific requirements. To accommodate for these additional costs, a government cost factor is applied to form a more reasonable analysis. Additionally, Monte-Carlo simulation is used to properly bound the cost uncertainty surrounding the analysis.

Furthermore, our analysis is based on a small satellite constellation with the ability to provide nominally similar communication capabilities as the existing WGS system. Small communication satellite pricing is developed using cost-estimating relationships (CERs) predicated on historical small satellite costs. Again, Monte-Carlo simulation is utilized to bound the cost uncertainty. Finally, we conduct a comparative cost analysis between a hypothetical commercial, small satellite communication constellation and the DoD's organic WGS system.

Chapter Summary

The DoD has been continually working toward establishing a competitive environment for DoD acquisition; today, that competitive environment is revealing itself in the realm of space. This research analyzes the costs associated with the DoD space vision of utilizing both small launch and small satellite providers to fill the role of military communications similar to the Wideband Global Satellite constellation. The upcoming chapters in this thesis detail the prior literature on this topic, present the assumptions and methodology utilized in this analysis, provide the results of the analysis,

answer the research question, and recommend future research areas to examine.

II. Literature Review

Since the launch of Sputnik by the Soviet Union in the 1950s and President Kennedy's call to send an American to the moon by the end of the 1960s, the final frontier of space has become exponentially more valued by governments, militaries, and now private industries. This newly contested environment has placed a premium on timely and efficient access to space and on the development and implementation of cutting edge technology for the DoD. The following chapter presents an overview of previous research, literature, and key events related to DoD space market competition, DoD space launch, disaggregated satellite constellations, and small satellite capability. This information laid the foundation for answering the thesis question: "Can the DoD lower space access costs through the exploitation of the growing small satellite and small launch marketplace?"

DoD Space Market Competition

A monopoly is established when there is only one supplier of a good for which there is no close substitute; an oligopoly is established when there are few suppliers of a good with considerable barriers to market entry (Perloff, 2008, pp. 443–444). In both economic structures, the supplier is a price setter rather than a price taker (Perloff, 2008, pp. 443–444). DoD acquisition has steadily emphasized a move away from monopolistic and oligopolistic markets to take advantage of the benefits of free market competition for weapon system programs. The DoD's former acquisition chief, Frank Kendall, has issued support for "full and open competition" through two consecutive initiatives known as Better Buying Power (BBP) 2.0 (2012) and Better Buying Power 3.0 (2015). In Better

Buying Power 2.0, Mr. Kendall stressed creating and maintaining competitive environments for DoD acquisition programs. Additionally, he made clear the importance of increasing opportunity for small businesses in the defense industry (Kendall, 2012). BBP 3.0 continued the DoD's competition push by outlining improved outreach to the small business community, global allies, and friends to take advantage of market efficiencies (F. Kendall, 2015a).

Increasing competition among DoD suppliers reduces the threat of monopolistic environments and decreases the likelihood of the government being a "price taker." The Institute for Defense Analyses (IDA) studied "The Mechanisms and Value of Competition for Major Weapon Systems" within the DoD (Dominy et al., 2011). The researchers did not find statistical evidence concluding that competition had brought "price to cost" but did conclude that competition in the defense market "had an important role in driving innovation in defense systems and in making prime contractors more responsive to DoD" (Dominy et al., 2011). While these findings support the DoD's push for competition in order to increase capability, they do not provide significant evidence for cost savings through increased competition.

The space realm, once dominated by military and other government agency investment, has increasingly become the next frontier for private industry. According to the Tauri Group, a consulting firm specializing in space and technology, 2015 was a record-setting year for investment in space ventures by private industry--totaling \$2.7B. On average, the commercial space market has seen eight new companies join the commercial market each year over the last five years. This represents a five firm annual increase versus the early 2000s (*Start-Up Space: Rising Investment in Commercial Space*

Ventures, 2016). Silicon Valley and the investment community as a whole are steadily increasing their technological investment beyond the confines of the Earth--50 venture capital firms are investing in space-based companies (*Start-Up Space: Rising Investment in Commercial Space Ventures*, 2016).

The Commercial Spaceflight Federation (CSF) is an organization comprised of commercial spaceflight developers, operators, spaceports, suppliers, and service providers whose goal is “to preserve American leadership in aerospace through technology innovation, and inspiring young people to pursue careers in science and engineering” (“About - Commercial Spaceflight Federation,” n.d.). The President of CSF, in testimony before the U.S. House Committee on Science, Space, & Technology, detailed three ways in which the U.S. launch service market is dealing with the burgeoning small satellite demand for space access: 1) investment into the development of a new class of small launch vehicle systems, 2) bundled satellite deals on dedicated medium lift rockets, and 3) secondary payload opportunities on launch missions with excess capacity. Note, as small launch vehicle systems have not been fully developed, many small satellites fly as secondary payloads. The CSF believes the market will be much better served once all options for space access are on the table for small satellite developers (Stallmer, 2016).

DoD Space Launch Historical Evolution and Analysis

The DoD’s Evolved Expendable Launch Vehicle (EELV) program was founded in response to President Bill Clinton’s 1994 National Space Transportation Policy (NSTP). The NSTP provided for the continued use of expendable launch vehicles while

significant research and development funding would be invested into reusable launch vehicles (Greaves, 1997; “Statement on National Space Transportation Policy,” 1994). The President’s policy can be partly attributed to the Space Shuttle Challenger explosion in January 1986 which grounded Space Shuttle flights (reusable launch vehicle) and caused a greater reliance on expendable launch vehicles (Greaves, 1997).

The EELV program continued to develop and eventually culminated with the creation of a sole supplier of expendable launch vehicles in 2006. The sole supplier was a result of a merger of the owners of EELV’s prominent launch systems, the Atlas V (Lockheed Martin) and Delta IV (Boeing) rockets, creating the United Launch Alliance (ULA) (“FTC gives clearance to United Launch Alliance,” 2006; R. Kendall, 2003). United Launch Alliance has been the singular launch service provider for DoD National Security Space (NSS) missions until 2015, when Space Exploration Technologies Corp. (SpaceX) was certified to launch NSS missions (“Air Force’s Space and Missile Systems Center Certifies SpaceX for National Security Space Missions,” 2015).

The most recently contracted Air Force “block buy” (buying rocket launch services in bulk) of EELV systems was estimated to cost approximately \$5.9B for 26 rocket launches (*Selected Acquisition Report Evolved Expendable Launch Vehicle*, 2016). Although the Air Force believes the contract saved the Department close to \$4B (Gruss, 2014), it demonstrated the extraordinarily high costs of achieving DoD space access. The addition of SpaceX into the DoD launch market was expected to bring down costs--and has initially appeared to do so--as evidenced by SpaceX’s contract award of a GPS III satellite launch of \$83M in 2016 (“Air Force Awards GPS III Launch Services Contract,” 2016). While the GPS mission has not yet flown and the final cost of the SpaceX

contract award is undetermined, the contract award is 40% below original government cost estimates (Klotz, 2016).

Due to the large satellite missions currently required by the DoD, the current infrastructure of launch providers maintains the capability to lift well beyond the small satellite requirements stemming from the commercial market. The lightest launch vehicle configurations from ULA are cited to lift payloads weighing between 9,100 kilograms (kg) to 9,800 kg to Low Earth Orbit (LEO) (“Atlas V and Delta IV Technical Summary,” 2013). SpaceX claims a lift capability of 22,800 kg (“SpaceX Capabilities & Services,” n.d.) to LEO. Low Earth Orbit is the predominant orbit utilized by the commercial small satellite market so the lift capability required for small satellites is well below the maximum capability that can be provided by either ULA or SpaceX. This creates an expensive fixed cost floor for small satellite missions.

Small satellite launch has been a concern of the DoD to one degree or another for the past 20 years. Post-Desert Storm, the Operational Responsive Space (ORS) organization was created. Operationally Responsive Space was intended to facilitate responsive space-lift for the nation; although it did not gather momentum in the early 2000s, the DoD and Congress renewed its efforts in 2007 with the goal of “investigating many potential and emerging responsive space options” (Steele, 2009). Operational Responsive Space has been a part of lifting small experimental satellites to space for the DoD utilizing rockets such as Orbital ATK’s Minotaur 4 rocket (which is built around excess ballistic missile motors). Orbital ATK has been awarded a contract priced at \$23.6M to launch an ORS satellite in 2017 (Gruss, 2015b). With the emergence of new

small launch vehicles in the marketplace, the vision of ORS may be thrust further into the spotlight.

The burgeoning market of new launch vehicle development has not always been seen as economically viable. A 2005 study by the Space Policy Institute at George Washington University investigated the economic factors surrounding the costs of launch vehicles. Hertzfeld, Williamson, and Peter (2005) identified several problems that prevent a dramatic drop in prices for launch vehicles from a government perspective:

- The cost of a launch is not the same as the price paid to a company for a launch.
- Government R&D is valued in the national economic accounts as a sunk cost—one that is not expected to be recovered and is not factored into marginal costs. In the private sector, R&D is expected to be recovered during the life cycle of a product.
- Production and operating efficiencies cannot reduce the cost or price by an order of magnitude or more.
- Prices charged will be as much above average costs as the market will bear. New entrants are likely to set prices just below existing competitors and those prices certainly will not equal minimum average production costs.

The study was extremely bearish on the likelihood of a viable private market for space launch. Since the main customers for launch vehicles are governments with only a few commercial customers, the study posited costs would remain high:

As long as existing launch vehicles are able to have a dual pricing/costing environment, the cost of launches will remain high. Dual pricing occurs when companies can charge according to market conditions for commercial launches but have different arrangements for some customers; for example, the government. (Hertzfeld, Williamson, & Peter, 2005)

This study did not envision the large amount of investment pouring into the commercial market for space but deftly pointed out: “Private investments in future systems occur only when identifiable markets are clearly evident” (Hertzfeld et al., 2005). The economic

analysis of historical launch costs determined that as the price of space access for lighter lift vehicles declined, more customers would appear; conversely, the equivalent price decrease for heavier lift vehicles would not see an equivalent increase in customers (Hertzfeld et al., 2005). The analysis was done from the perspective of the launch vehicle supplier. Though the market is now displaying increased efforts towards cheaper, lighter lift vehicles, it has been spurred on due to the immense demand of small satellites.

In 2011, RAND produced a study analyzing the research question: “Would a more risk-tolerant launch posture improve U.S. Air Force small satellite launch capabilities?” (Grosselin III, 2011). The analysis detailed the risk of launch success for the available launch systems compared to launch vehicle costs. The launch vehicles examined ranged from high-cost, highly reliable launch vehicles to low-cost, low reliable launch vehicles (LCLR LV). This research presented insight into whether utilizing less reliable, small launch vehicles would benefit the Air Force when attempting to launch small satellites. Although a low-cost, low reliability launch vehicle was not present at the time of the study, the analysis determined that “the development of a LCLR LV would provide significant cost savings while reducing financial risk” (Grosselin III, 2011). This study laid the foundation for examining the small launch providers invading the marketplace today. Additionally, the study determined that medium launch vehicles would be the most cost effective for small satellite launch. Finally, although launch cost per small satellite would decrease with multiple satellites launching on one large launch vehicle, the researcher determined that the risk to those satellites on board would also increase as one failure could wipe out multiple small satellites (Grosselin III, 2011).

Disaggregation of Satellite Constellations & Small Satellite Capability

Air Force Space Command (AFSPC) is the lead organization for the majority of DoD space operations. As space-based capabilities continue to evolve, the strategy of Air Force Space Command does as well. Then AFSPC Commander, General John Hyten, presented his Space Enterprise Vision from his headquarters at Peterson Air Force Base, Colorado:

In the recent past, the United States enjoyed unchallenged freedom of action in the space domain...Most U.S. military space systems were not designed with threats in mind, and were built for long-term functionality and efficiency, with systems operating for decades in some cases. Without the need to factor in threats, longevity and cost were the critical factors to design and these factors were applied in a mission stovepipe. This is no longer an adequate methodology to equip space forces...Going forward, we will rigorously focus on a clear definition of warfighter requirements with programs acquired using greater horizontal integration across the space enterprise. We will also move toward shorter program life cycles and decreased time between constellation updates, which improves the availability of new technology on-orbit. (Air Force Space Command Public Affairs, 2016)

One avenue being investigated to meet General Hyten's vision is disaggregated satellite constellations. As stated in the introduction, disaggregation is defined as "the dispersion of space-based missions, functions or sensors across multiple systems spanning one or more orbital plane, platform, host or domain" (*Resiliency and Disaggregated Space Architectures: White Paper*, 2013). Disaggregation is not a new concept; in fact, it has been studied extensively by some of the DoD's top space leadership. A 2012 study, "Disruptive Challenges, New Opportunities, and New Strategies," outlined the following disruptive challenges facing DoD in space and the methods of adequately responding to these challenges (Pawlikowski et al., 2012). Table 1 lists these challenges and responses.

Table 1: Disruptive Challenges and Responses to Challenges

Disruptive challenges	Responses to challenges
Aggregated, concentrated architectures	More, smaller, less-complex satellites
Systems vulnerable, little/no ability to deter/withstand attack	Mixed constellations
Integrated, closed-ground architectures	Increase constellation size
High cost of launch	Distribute capability
Export controls limiting competition/partnering	Encourage low-cost medium launch
Space acquisition culture and processes biased toward top-down redesign and re-optimization for all new requirements	Change export controls

The study expressed the benefits of disaggregated satellite constellations from a resiliency standpoint and stressed the need for low-cost launch vehicles to support such a construct.

At the 2015 Small Satellite Conference in Utah, General Hyten detailed his awareness of the impact small satellites can have on the DoD space mission (Hyten, 2015). He specifically discussed the possibilities of small satellites taking on some of the capability currently provided by military satellite communications; he explained the impressive feat of the space company, Dynetics, and its ability to produce a 250-pound satellite producing 1.2 gigabytes of throughput. In contrast, the Air Force Wideband Global SATCOM (WGS) weighs in at over 13,000 pounds and yields a throughput of 2 gigabytes (Hyten, 2015). Dynetics states that their small satellite mission life may range up to seven years (“TerraSense TM small satellite platform,” 2014).

The Boeing Corporation produces WGS for the DoD and describes its role as “to provide broadband communications connectivity for U.S. and allied warfighters around the world. Wideband Global SATCOM is the highest-capacity military communications system in the U.S. Department of Defense arsenal providing a quantum leap in communications capability for the U.S. military” (“Wideband Global SATCOM,” n.d.). Ten satellites may ultimately make up the WGS constellation for the DoD; eight satellites are currently in geosynchronous orbit (Ray, 2016).

Wideband Global SATCOM is a part of the broader military satellite communication construct for the DoD. The Center for Strategic and Budgetary Assessments (CSBA) presented an analysis for “The Future of MILSATCOM” in 2013; they outlined six recommendations to combat the threats facing military satellite communication such as WGS (Harrison, 2013)--see Table 2.

Table 2: Six Recommendations to Combat MILSATCOM Threats

Recommendation	Detail
Three-tier satellite architecture	Strategic protected level, tactical level, and non-essential communications level
Pivot to the Pacific	Invite regional allies to be a part of middle tier to reduce cost and improve interoperability and complicate an adversary’s likelihood of attack
Avoid strategic cost traps	Do not attempt to out build enemies anti-satellite (ASAT) weapons, focus on ability to attack ASAT capabilities
Leverage current programs to build and evolve new capabilities	Reduce program office staffing to limit the number of personnel thinking of ways to change requirements

Use competition more appropriately	Sole source contract award where it may cost government less and allow competition to take place where natural market forces are at play
Consolidate MILSATCOM programs under one service	Create better alignment of authorities and budgets, reduce redundancy and overhead costs across services

A study from the Space Defense Journal documented a future construct of satellite constellations for the DoD similar to the recommendations of CSBA. The construct called for three layers of satellite assets for the DoD: a strategic layer, a tactical layer, and a commercial layer (Figure 1). The study designed a space construct that decreases the size of the satellites used by DoD. The construct relies on commercial small satellites to take on the more basic technology used for national security while maintaining strategic and tactical-level satellites to handle sensitive national security capabilities (Wegner, Adang, & Rhemann, 2014).

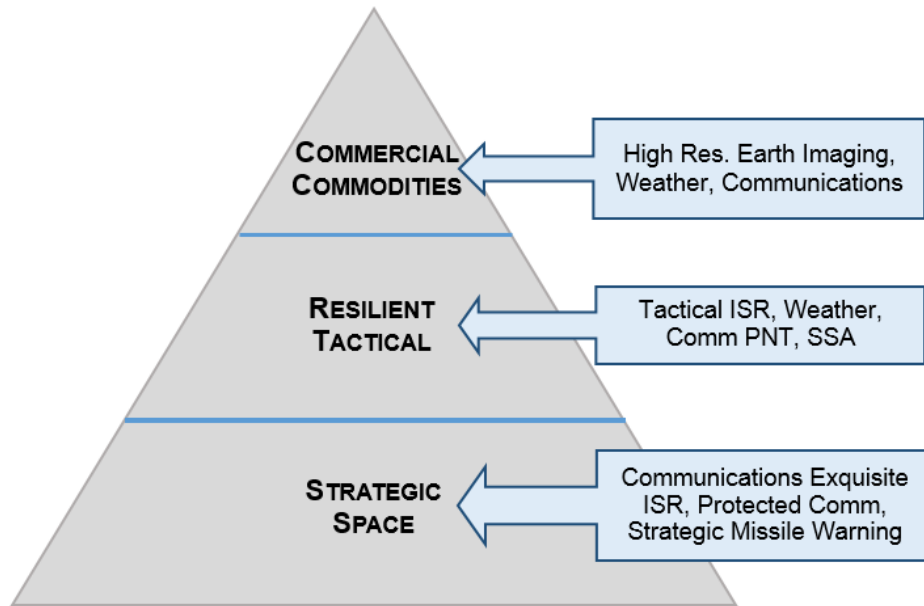


Figure 1: Three-Layer Space Architecture (Wegner et al., 2014)

The Space Defense Journal study continued the trend of subject matter expert opinion that small satellites can provide the DoD required capability in a small satellite, disaggregated type of architecture.

The Air Force Scientific Advisory Board (AF SAB) studied the mission utility of microsatellites in 2013. The microsatellites studied were all less than 300 kilograms and were measured by their utility in five categories: complete mission capability, disaggregated requirements, augmentation of current capabilities, fractionation of satellites, or reconstitution of capability. The study found that, as of 2013, microsatellites have significant near-term capability to augment weather and space situational awareness requirements. Surveillance, navigation, missile warning, and communication capabilities will be possible in the mid-to far-term. The SAB determined that the current launch and ground architecture within the Air Force were not adequate to completely support

microsatellite missions. Ultimately, the SAB recommended four actions to better serve microsatellite missions (Gustafson & Zolper, 2013):

Table 3: SAB Recommendations to Better Serve Microsatellite Missions

Recommendation	Detail
Undertake Pathfinder Microsat Program	Further develop the near-term mission sets within a dedicated program utilizing best practices from other microsatellite programs
Adapt and mature launch architecture for microsatellite use	Establish a launch office dedicated to microsatellites, improve EELV rideshare program, and develop small launch vehicle industrial base
Implement a microsat command ground architecture	Leverage common ground architecture used at Naval Research Laboratory and Kirtland Air Force Base to ensure scalability for increased microsatellite mission use
Invest in Science and Technology to create lasting employment of microsatellites	Advances in microsatellite technology will continue reduction in size of microsatellites and optimize performance for AF missions

The SAB's recommendations again lay out the critical need for the low-cost launch vehicles being developed in the marketplace today.

Chapter Summary

Chapter Two provided an overview of previous research, literature, and key

events pertaining to DoD space market competition, DoD space launch, disaggregated satellite constellations, and small satellite capability. The literature review reinforced the need for a current financial analysis demonstrating the impact that small launch and small satellite markets can have on the DoD. The emphasis on competition in the DoD and explosion of investment into small space launch and small satellites has coincided at a critical time. Although previous analysis claimed private industry is unlikely to join the space market, the flood of companies entering the market today appears to contradict that argument. The DoD space launch infrastructure in its current state is not producing low-cost outcomes; meanwhile, the certified launch vehicle's lightest configurations are well beyond the requirements of small satellites. The threats facing the DoD in space are constant and evolving. Current large DoD satellite configurations may eventually be replaced in a disaggregated architecture. The literature review lends support for low-cost, small launch vehicles to enable the small satellite evolution. The next chapter will outline the methodology utilized in our financial analysis to answer the research question.

III. Methodology

Chapter 3 defines the methodology used in our research to include the data sources, small launch vehicle cost analysis, small satellite cost analysis, and comparative analysis against current DoD space costs. Our methodology followed the basic framework to perform a proper cost and uncertainty analysis as outlined in the Joint Agency Cost Schedule Risk and Uncertainty Handbook (JCSRUH). The basic steps of this framework are:

1. Develop the point estimate
2. Specify the uncertainty around the point estimate
3. Apply correlation when appropriate
4. Run the simulation
5. Analyze the results (*Joint Agency Cost Schedule Risk and Uncertainty Handbook*, 2014)

We apply this framework to demonstrate the potential cost impact of commercial small launch vehicles and small satellites on the DoD.

As stated in the literature review, small satellites are becoming capable of taking on many different DoD mission sets. Our research approach focuses on basic wideband communications. The WGS constellation currently provides wideband communications for the DoD. Wideband Global SATCOM has eight satellites in geosynchronous orbit (22,300 miles above the earth). This orbit allows the constellation to limit the number of satellites used to maintain constant communication over particular regions of the globe. The higher the orbit of a satellite constellation, the greater power required from the space vehicle to perform its required mission. The growth in small satellites has resided within

low earth orbit (LEO) which requires more satellites to cover the same area as satellites in geosynchronous orbit (GEO). The advantage of LEO is less power is required for both the satellite and launch vehicle to complete the mission. As explained in Chapter 2, small satellite capability and environmental resilience (via disaggregated architecture) are critical reasons why a small satellite communication reference architecture was chosen for our research.

Data Sources

The primary data sources for this thesis are listed below. Note: all cost figures have been adjusted into base year 2016 dollars utilizing the Office of the Secretary of Defense (OSD) inflation rates:

- The NASA Venture Class Launch Services (VCLS) contract award (Wall, 2015)
- Satellite cost estimating relationships (CERs) from the Unmanned Space Vehicle Cost Model (USCM10) database (“Unmanned Space Vehicle Cost Model,” 2014)
- Aerospace Small Satellite Cost Model (SSCM14) (“Small Satellite Cost Model,” 2015)
- EELV and WGS Selected Acquisition Reports (SAR) (*Selected Acquisition Report Evolved Expendable Launch Vehicle*, 2016, *Selected Acquisition Report Wideband Global SATCOM*, 2016)
- Defense Automated Cost Information Management System (DACIMS)

The NASA VCLS contract award designates three small launch vehicle developers: Firefly Space Systems, Rocket Lab, and Virgin Galactic will each launch a 60 Kilogram (kg) payload to Low Earth Orbit on behalf of NASA by April 2018 (Table 4) (Ramsey, 2015; Wall, 2015).

Table 4: NASA Venture Class Launch Services Contract Award

Launch Vehicle	Alpha (Firefly)	Electron (Rocket Lab)	LauncherOne (Virgin Galactic)
Satellite Weight (Kg)	60	60	60
Contract Cost \$M	\$5.5	\$6.9	\$4.7

A small communication satellite platform is used as the reference architecture in order to perform the financial analysis. Table 5 outlines the basic reference architecture utilized and how the architecture compares to WGS (*Selected Acquisition Report Wideband Global SATCOM*, 2016).

Table 5: Small Comm Satellite Reference Architecture vs WGS

Category	Small Comm Satellite	WGS (Objective/Threshold)
Space Vehicle Weight	180 Kg	~5,900 Kg
Throughput	1.2 Gbps	3.6 Gbps/1.2 Gbps
Mission Life	7 Years	14 Years

Wideband Global SATCOM provides greater processing throughput and longer mission life. Conversely, the reference architecture is 97% smaller than WGS and has the equivalent throughput as the threshold requirement of WGS. Additionally, WGS provides 39 channels and X-band communication, which is not currently available from new small communication satellites (Hyten, 2015; *Selected Acquisition Report Wideband*

Global SATCOM, 2016). The mission-life difference requires that this analysis include an orbital refresh of the small satellite constellation to conduct a proper comparison of satellite systems. Wideband Global SATCOM is a more sophisticated satellite system than the theoretical reference architecture, but both systems can provide wideband communication capability for the DoD. Any procurement of small communication satellites will be developed to meet DoD requirements.

The Unmanned Space Vehicle Cost Model (USCM) database contains space vehicle cost and technical data for military, NASA, and commercial space programs. The database contains 103 space programs from over 45 years of satellite development and production; it is a primary database for estimating costs of satellite programs at the Space and Missile Systems Center (SMC) at Los Angeles Air Force Base, California. The database also contains a multitude of cost-estimating relationships (CERs) based on the 103 programs and provides the communication satellite payload CERs we use in our financial analysis (“Unmanned Space Vehicle Cost Model,” 2014).

The Aerospace Corporation’s Small Satellite Cost Model (SSCM14) database contains space vehicle data for 79 small satellite programs from over 20 years of small satellite data collection. The database breaks down CERs to the subsystem level to estimate the costs of small satellites. The model’s CERs are proprietary and may only be obtained by request through the Aerospace Corporation (“Small Satellite Cost Model,” 2015). Contractor profit and Cost Data Summary Reports (CSDR) are derived from the Defense Automated Cost Information Management System (DACIMS).

Selected Acquisition Reports (SARs) provided annually to the United States Congress provide the launch vehicle and satellite costs and performance (Table 5) used

for the comparative analysis. Specifically, the 2015 SARs are used to determine the costs of the WGS constellation and EELV program. Selected Acquisition Reports were obtained from the Office of the Secretary of Defense and Joint Staff Freedom of Information Act Reading Room.

Small Communication Satellite Constellation

Our small satellite mission is composed of a 66-satellite launch campaign to Low Earth Orbit (LEO) for which we considered two different procurement strategies: Single block procurement and three-block procurement. A single block procurement strategy enables the contracted supplier to produce all units (satellites and launch vehicles) on a constant production line (66 satellites). The second procurement strategy is a three-block procurement, which disrupts the contracted supplier's production line between blocks causing a non-constant production line (22 satellites per block). We estimate the former procurement to demonstrate the costs of a smooth production process in which learning is constant and factors that may typically disrupt government procurement and supplier production do not arise. We estimate the latter procurement schedule to align more closely with WGS' satellite multi-block procurement and with a more typical government procurement construct where the supplier's production line is not perfectly stable and learning may be lost from one block to the next.

To maintain constant communication at Low Earth Orbit, many satellites must be utilized. A single satellite at LEO has less earth coverage than satellites at higher orbits (i.e. Geosynchronous Orbit). A 66 small-satellite constellation is equivalent to the commercially-active Iridium communication satellite constellation, which currently

provides “coverage of the entire earth, including oceans, airways and Polar Regions” (“The Global Network: Satellite Constellation,” 2012). The Iridium constellation has been analyzed and determined to be capable of meeting real-time communication requirements with several non-operational satellites (Fossa Jr., 1998).

A 66 small-satellite constellation allows the financial analysis to be bounded conservatively versus a more aggressive constellation approach mirroring smaller satellite constellations, such as Globalstar, which employed a 40+ satellite constellation at LEO (de Selding, 2006). As stated previously, the small satellite reference architecture has a mission life of approximately seven years; each WGS has a mission life of 14 years. The small communication satellite’s lower-mission life will require an earlier refresh of the constellation.

Small Launch Vehicle Cost Methodology

The VCLS contract award of small launch vehicles is used as an analogy to perform the cost analysis of small launch vehicles for DoD space missions. This estimating methodology is utilized when limited program information is available (*Air Force Cost Analysis Handbook-Chapter 10 Estimating with Analogies and Build Up Methods*, 2008). Satellite weight will be the primary cost driver to estimate the costs of small launch vehicles.

The analogy equation below (Eq. 1) depicts the formula utilized to determine the initial launch cost (*Air Force Cost Analysis Handbook-Chapter 10 Estimating with Analogies and Build Up Methods*, 2008):

$$\frac{H}{PH} = \frac{X}{PX} \quad (1)$$

where H is the known cost of the analogous item (VCLS launch cost), X is the cost to be estimated for the new item (small launch vehicle cost), PH is the known value of a specified property of the analogous item (VCLS space vehicle weight), and PX is the known or estimated value of the specified property of the new item (small satellite vehicle weight).

The launch of National Security Space (NSS) missions has been held to a stricter level of scrutiny since the launch failures of the 1990s; this greater level of scrutiny, referred to as “Mission Assurance,” increased costs to launch DoD space assets (Pawlikowski et al., 2012). Due to this increased scrutiny for NSS missions, an additional cost factor is applied to the launch vehicle costs to account for DoD’s mission assurance requirement. This DoD cost factor was developed in two primary ways: 1) from the ratio of launching a commercial Falcon 9 rocket versus launching a Falcon 9 for the DoD, and 2) from a historical analysis of costs attributed to NSS missions.

According to SpaceX, the Falcon 9 rocket costs commercial customers \$62M (“SpaceX Capabilities & Services,” n.d.). The most recent contract award to launch a GPS satellite for the U.S. Air Force was \$82.7M (Klotz, 2016). This cost difference between commercial and DoD customers amounts to a 33% cost increase. We use this cost factor as a proxy for the mission-assurance requirement and apply it to the small launch vehicles in this analysis. The 33% cost factor is supported by analyzing historical costs attributed to NSS missions based on recommendations of the Space Launch Broad

Area Review (BAR), Joint Assessment Team (JAT) and Independent Review Team (IRT) (contact the corresponding author for additional information).

A 10,000 trial Monte Carlo simulation, with Latin Hypercube sampling, is performed using a triangular probability distribution to adequately bound the uncertainty of the estimate for launch vehicle costs. Simulation is performed using the *Risk Solver Platform* software add-in for Microsoft Excel®. Monte Carlo simulation provides “the process of generating random values for uncertain inputs in a model, computing the output variables of interest, and repeating this process for many trials in order to understand the distribution of the output results” (Evans, 2013, p. 331). Latin Hypercube sampling is the recommended sampling method “because it draws random numbers more evenly and it will generally require fewer iterations to obtain the same level of accuracy” (*Joint Agency Cost Schedule Risk and Uncertainty Handbook*, 2014).

A triangular probability distribution is the recommended subjective uncertainty distribution of the U.S. Air Force when utilizing analogy and/or factor estimates. Triangular distributions are established with three inputs: a low, a “most likely”, and a high. The low input represents the 15th percentile of the triangular distribution and the high input represents the 85th percentile of the triangular distribution. The output of the analogy equation is equal to the “most likely” input of the triangular distribution. Cost estimating uncertainty “deals with the fact that our estimating methods, data, and tools are neither totally precise nor totally accurate” (*Joint Agency Cost Schedule Risk and Uncertainty Handbook*, 2014). Developing the point estimate of the launch vehicle cost and applying uncertainty allows the analysis to determine an appropriate theoretical first unit cost (T1) of a small launch vehicle. See Appendix A for the guidelines for applying

subjective distributions (*Joint Agency Cost Schedule Risk and Uncertainty Handbook*, 2014).

Due to the large number of small launch vehicles required to satisfy DoD's requirement for full-earth coverage (similar to the WGS satellite constellation), it is appropriate to implement a learning curve to the launch vehicles' production. The concept of the learning curve "states that as production quantities double, the associated labor (time) needed to build those items falls at a constant percentage rate" (*Air Force Cost Analysis Handbook-Chapter 8 The Cost Improvement Curve*, 2007).

Uncertainty is applied to the learning curve slope--similar to the theoretical first unit (T1) launch cost. This is because the data driving both inputs (launch cost and learning slope) arrive from different sources and no historical data is perfectly representative of producing small launch vehicles. This procedure follows the instruction of the Joint Agency Cost Schedule Risk Uncertainty Handbook (JCSRUH) (*Joint Agency Cost Schedule Risk and Uncertainty Handbook*, 2014). The International Cost Estimating and Analysis Association (ICEAA) has published learning curve rates for various military platforms. ICEAA detailed an 85.4% learning curve slope for the Titan III C launch vehicle (ICEAA, n.d.). The Titan III C is a historical launch system that provides a credible lower bound for the production learning curve slope; therefore, the 85.4% learning curve is applied as the low input of a triangular probability distribution for the learning curve slope.

The "most likely" input of the probability distribution is 91.6%. This slope is derived from a database of launch vehicle historical actuals at the subsystem level. System level learning is then calculated through review of Cost Data Summary Reports

(CSDR) to ensure proper subsystem allocation to the system level (contact the corresponding author for more information). The “high” input of the triangular distribution is 95% to ensure a conservative bound is applied to the distribution while still maintaining some learning during the production process. The probability distribution of the learning curve is truncated on the high side at 100% (no learning) as recommended within the JCSRUH (*Joint Agency Cost Schedule Risk and Uncertainty Handbook*, 2014).

As previously stated, the small launch vehicle cost analysis will include estimates for both a single block procurement, enabling a constant production line (1 block of 66 satellites) and a three-block buy procurement, triggering a non-constant production line (3 blocks of 22 satellites each). Although 66 launch vehicles are procured within the three-block scenario, the three blocks emulate a break in launch vehicle production for the contracted supplier. We consider two different methods for implementing a multi-block buy procurement causing a break in production from one block to the next: 1) the first launch vehicle produced in blocks two and three begin at the equivalent midpoint unit cost of the previous block. This limits learning from one block to the next due to a break in production. 2) The first launch vehicle in blocks two and three begin at the equivalent unit cost of the T1 of the first block. This demonstrates a total loss in learning achieved from one block to the next due to a break in production. Equation 2 shows the learning curve formula:

$$Y = T1 * X^b \quad (2)$$

where Y is the cost of the Xth unit, T1 is the theoretical cost of the first unit, X is the unit number, and b is the learning curve slope.

Small Satellite Cost Methodology

The small satellite estimate is broken into three pieces: communication payload, space vehicle, and contract award fee. The CERs for communication satellites within the USCM10 database are used to estimate the cost of the small satellite communication payload. The CERs are derived using Minimum Unbiased Percentage Error (MUPE) regression. Costs are commonly broken into two categories: Non-recurring and recurring. Non-recurring costs are costs attributed to initial development and design (“Non-Recurring Costs (NRC),” n.d.). Equation 3 shows the CER for non-recurring costs associated with the communication payload where X_1 is equal to the payload weight in pounds (“Unmanned Space Vehicle Cost Model,” 2014):

$$Y = 2061 * X_1^{0.695} \quad (3)$$

Recurring costs are costs incurred during every production unit (“Recurring Cost,” n.d.). Equation 4 shows the CER for recurring costs associated with the communication payload, where X_1 is equal to the payload weight in pounds, and X_2 is equal to 1--if the payload has a high-level of protected communication technology (“Unmanned Space Vehicle Cost Model,” 2014).

$$Y = 399.3 * X_1^{0.7161} * 2.759^{X_2} \quad (4)$$

The space vehicle portion of the small satellite is estimated at the subsystem level using the Aerospace cost model: Power, Structure, ADCS, Propulsion, TT&C, C&DH, Thermal, IA&T, SEPM, and LOOS (“Small Satellite Cost Model,” 2015). Lastly, the contract award fee is derived as an analogy to historical WGS profit from Cost Data Summary Reports (contact the corresponding author for more information). The overall satellite cost analysis breakdown and reference databases are provided in Table 6.

Table 6: Space Vehicle Breakdown and Reference Database

Space Vehicle Breakdown	Reference Database
1.0 Space Vehicle	
1.1 Integration, Assembly, and Test	SSCM14
1.2 Systems Engineering, Program Management	SSCM14
1.3 Space Vehicle Bus	SSCM14
1.3.1 Power Subsystem	
1.3.2 Structure Subsystem	
1.3.3 ADCS Subsystem	
1.3.4 Propulsion Subsystem	
1.3.5 TT&C subsystem	
1.3.6 C&DH subsystem	
1.3.7 Thermal Subsystem	
1.4 Communication Payload	USCM10
1.5 Launch Operations	SSCM14
1.6 Contract Award Fee	DACIMS

Similar to the launch vehicle analysis, a 10,000 trial Monte Carlo simulation, with Latin Hypercube sampling, was performed using the appropriate probability distributions (as specified from the satellite databases) to adequately represent the uncertainty of the estimate for small communication satellite costs. We applied a normal probability distribution for the small satellite payload costs derived from USCM10. To realistically model the payload costs using a normal distribution, the distribution is truncated at zero as a negative payload cost is not a reasonable estimate. Truncating the distribution to a positive minimum was not used as truncating at zero already limits the variance of the selected distribution (*Joint Agency Cost Schedule Risk and Uncertainty Handbook*,

2014). The simulation was performed using the *Risk Solver Platform* software add-in for Microsoft Excel®.

The small satellite constellation is composed of 66 individual satellites; therefore, their production is assumed to follow a learning curve similar to the launch vehicle analysis. According to the Defense Manufacturing Management Guide for Program Managers, the learning curve standard within the aerospace industry is an 85% slope (“Defense Manufacturing Management Guide for Program Managers,” 2012). The historical learning curve derived from the USCM database produces a slope of 95%. USCM maintains historical data of mostly large satellite systems that are not produced in large quantities (“SMC Cost Improvement Paper,” 2016). With these data points and the Risk Handbook’s recommendation to use individual uncertainty distributions for T1 and the learning curve slope, 85% and 95% were used as the low and high parameters respectively, for a triangular probability distribution; the midpoint, 90%, represents the most likely slope of the small satellite production. The probability distribution of the learning curve is truncated on the high side at 100% (no learning), as recommended within the JCSRUH (*Joint Agency Cost Schedule Risk and Uncertainty Handbook*, 2014).

The small satellite analysis emulates the two procurement strategies used for the small launch vehicles: buy all at once (which allows for a constant production line) and a three-block buy procurement. For the three-block buy procurement, we consider the same two non-constant production line scenarios that were evaluated in the launch vehicle analysis. Recall, the first non-constant production line scenario reverts back to the midpoint unit cost from the previous block; the second non-constant production line scenario reverts back to the first block’s T1 cost at the beginning of blocks two and three.

Comparative Analysis

The final component of the research is a comparative analysis. The costs of the small launch vehicles will be compared to the current costs of DoD launches. The December 2015 Selected Acquisition Report (SAR) for EELV identified the procurement costs of the EELV Block Buy contract from 2013 to 2017. This contract acquired 36 rocket cores ranging from ULA's smallest launch vehicles (Atlas V 401 and Delta IV M+ 4,0) to its largest launch vehicle (Delta IV Heavy). WGS has been lifted to orbit six of the last eight missions by the Delta IV M+ 5,4 launch vehicle ("Delta IV to launch WGS-8," 2016). The Delta 5,4 falls near the midpoint of ULA launch vehicle lift capabilities ("Atlas V and Delta IV Technical Summary," 2013); therefore, the average procurement costs over the course of the block buy is utilized for the comparative analysis versus the small launch vehicle costs (Appendix B).

The small communication satellite costs are compared to the costs of the current WGS constellation. The December 2015 SAR identified the historical development and procurement costs of the WGS constellation (Appendix C). Lastly, the small mission set (small launch vehicle cost plus small satellite cost) is compared to the total cost of procuring and launching the WGS satellite constellation (WGS plus EELV).

Chapter Summary

This chapter outlined the methodology used to answer the thesis research question through an explanation of the data sources, the cost-estimating methods for the small launch vehicles and small satellites, and the comparative analysis. This methodology

brought together data from a vast number of databases to form a reasonable analysis.

Similar to other comparative analyses, the assumptions are vast for this research, and the results may fluctuate with further detailed assumptions of communication satellite and launch vehicle architectures. Our research will detail the results of the financial analysis in Chapter 4. The results will help determine the potential financial impact of the growing small launch vehicle and small satellite marketplace on the DoD.

IV. Analysis and Results

Chapter 4 explores the results of the financial analysis methodology outlined in Chapter 3. Specifically, this chapter provides the small launch vehicle and small satellite cost estimates as well as the comparative analysis of costs between the small satellite mission and the WGS satellite constellation. Most importantly, the results of this chapter answer the research question, “Can the DoD lower space access costs through the exploitation of the growing small satellite and small launch marketplace?”

Small Launch Vehicle Cost Results

Beginning with the launch vehicle cost results, the following cumulative density function (CDF) provides a graphical representation of the total cost of the first procurement strategy of 66 small launch vehicles procured in a single block from a constant production line (Figure 2).

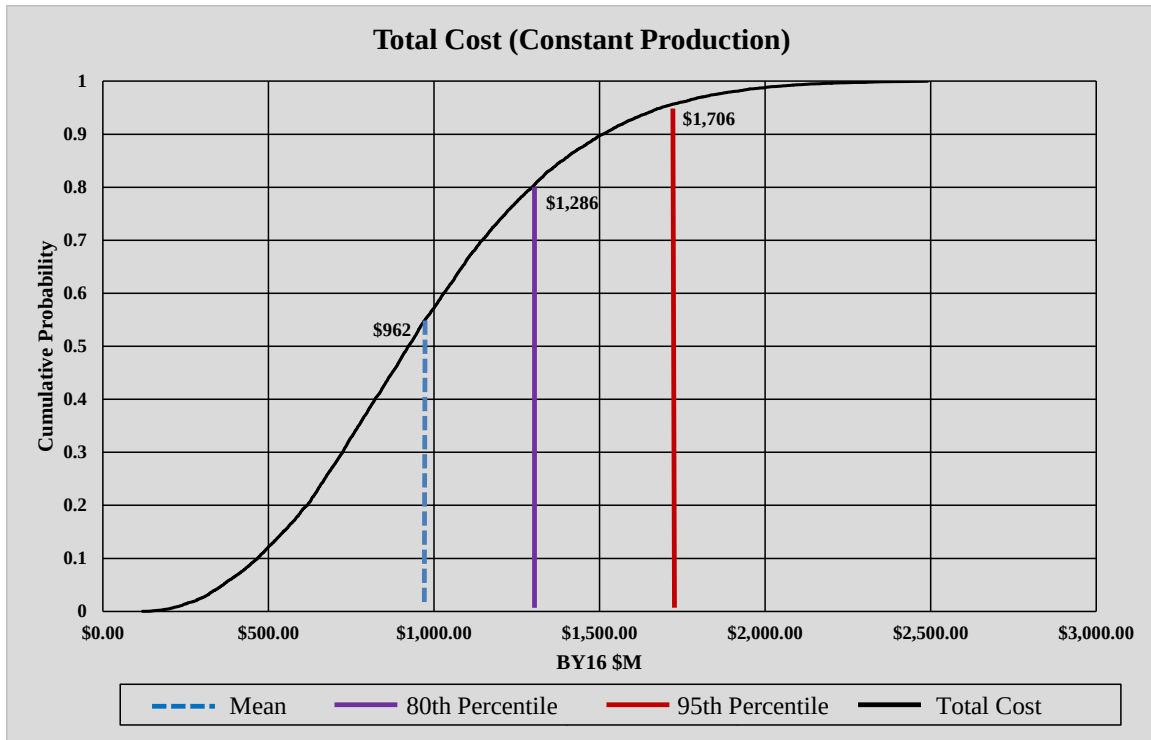


Figure 2: Launch Vehicle Constant Production CDF

Based on Figure 2, it appears that the procurement costs for the small launch vehicles using a constant production line is unlikely to exceed \$2B (~1.2% probability). The single block procurement is a bold assumption regarding the possibility of flawless execution from the contracted launch vehicle providers. The cumulative density function demonstrates the wide range of outcomes for a 10,000-trial simulation, but it is useful in understanding the probability of incurred costs to the DoD. There is a greater than 50% probability that 66 launch vehicles can be procured for under \$1B. In the DoD space domain, where the dollar value of billions is common for a single satellite program, the ability to procure 66 launch opportunities for less than \$1B is an unusual feat. In this scenario, as well as those to come, the truncation of the learning curve slope at 100% ensures that production will become less costly as more units are produced; in general,

truncation of the distribution on its upper tail forces costs down in the aggregate.

Therefore, without truncation, the total cost of constant production would likely be greater in the aggregate; however, when truncation was excluded the increase was minimal (less than \$1M).

The next CDF provides a graphical representation of the total cost of procuring 66 small launch vehicles in three blocks; this strategy assumes a non-constant production line with a learning curve slope restart equivalent to the midpoint unit cost of the previous block (Figure 3). Appendix D provides a sample trial of launch vehicle unit costs and demonstrates subsequent blocks beginning at the midpoint of the previous block.

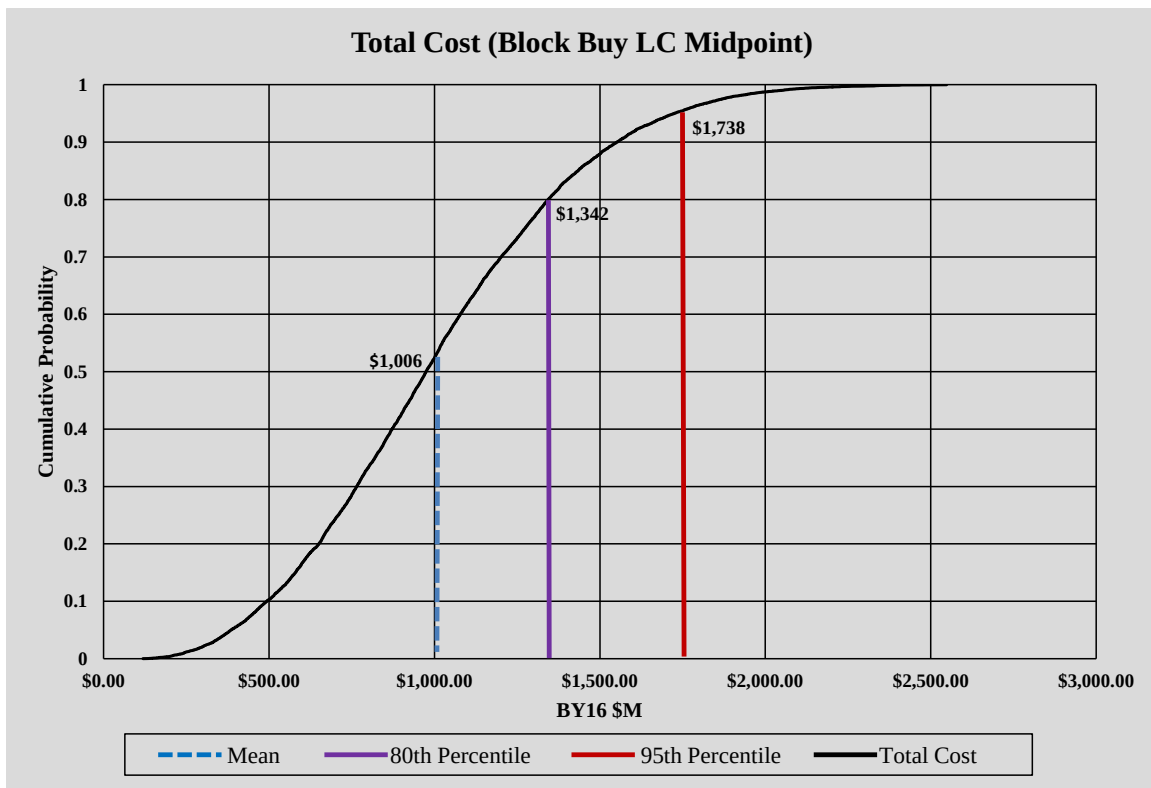


Figure 3: Launch Vehicle Block Buy LC Midpoint CDF

This procurement strategy is more consistent with DoD acquisition and does not demonstrate immense cost growth from the single block procurement. The ability to retain half of the learning from the previous block still allows the launch vehicle costs to decrease at a significant rate (similar to constant production) as evidenced by the only \$44M increase in total cost from single block procurement to this multi-block buy scenario (at the mean). The minimal unit costs of small launch vehicles ensures smaller variation between slightly differing learning curve slopes. Note, the CDF slope becomes flatter since the likelihood of higher costs increases due to lower learning curve effects. The cumulative probability of obtaining 66 launch vehicles for \$1B or less falls by 10% versus a constant production line.

The final launch vehicle CDF provides a graphical representation of the total costs of procuring 66 small launch vehicles again through a multi-block buy; in this instance though, each subsequent block reverts to the theoretical first unit cost (Figure 4).

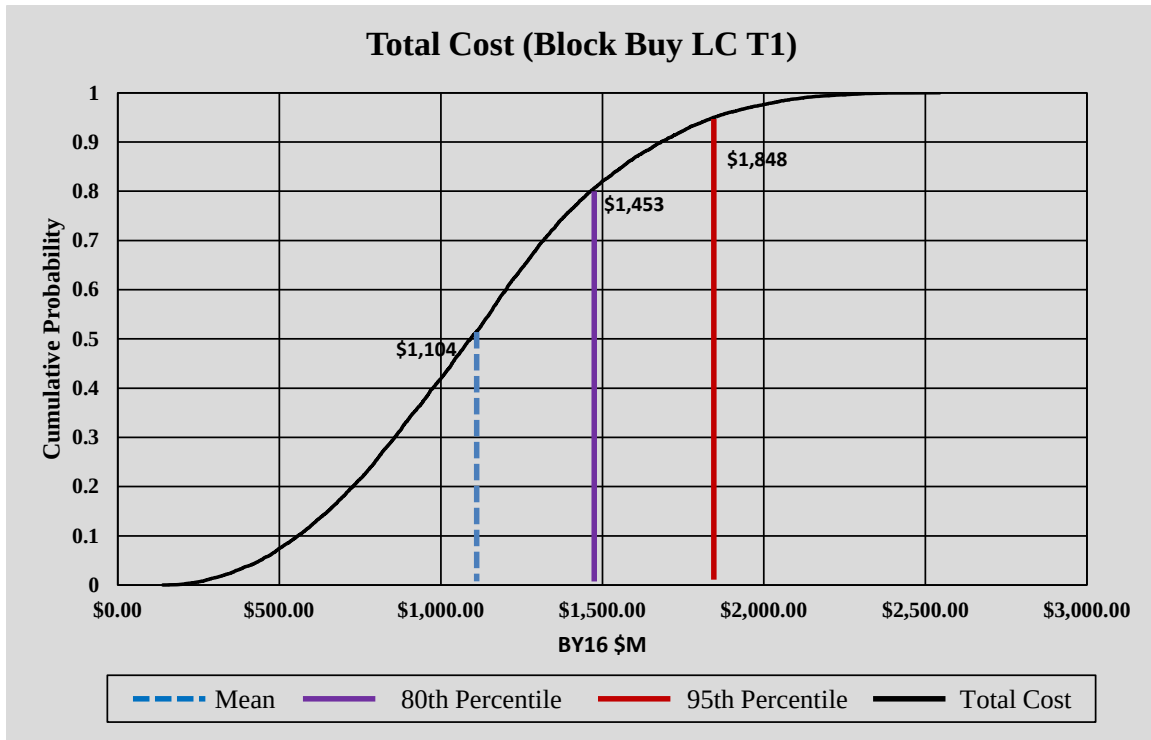


Figure 4: Launch Vehicle Block Buy LC T1 CDF

The final method for procuring launch vehicles demonstrates an even more conservative approach than the previous multi-block buy scenario. Restarting the production line learning curve to the T1 for each subsequent block increases the likelihood of higher costs to the DoD compared to the other scenarios. The slope of the CDF continues to flatten as no learning is retained from block to block. The cumulative probability of obtaining 66 launch vehicles for \$1B or less falls by 20% versus the first scenario of a constant production line. This final block buy scenario may represent the following case: with the expansion of many new small launch vehicle providers, a new launch vehicle provider is selected for each block. The different scenario results demonstrate that procuring 66 launch vehicles on average will cost the DoD from \$960M to \$1.1B. See Appendix D for sample output of individual launch vehicle costs.

Small Satellite Cost Results

The following are results of the small satellite analysis. The total cost of 66 small communication satellites procured from a single block on a constant production line are shown in Table 7.

Table 7: Constant Production Acquisition Results

Constant Production Acquisition			
BY16 \$M	Small Satellite (Mean)	Small Satellite (80%)	Small Satellite (95%)
Non-Recurring Sat Constellation Costs	\$ 85	\$ 108	\$ 130
Recurring Sat Constellation Costs	\$ 1,551	\$ 1,932	\$ 2,452
Total	\$ 1,636	\$ 2,040	\$ 2,582

The non-recurring costs of the small satellite constellation are approximately 5% of the total cost and remain the same (nominally) throughout the different procurement scenarios as they are not affected by learning due to their non-recurring nature. The recurring costs drive the majority of total procurement costs for the DoD. The following cumulative density function (CDF) provides a graphical representation of the total recurring costs of procuring 66 small satellites in a single block (Figure 5).

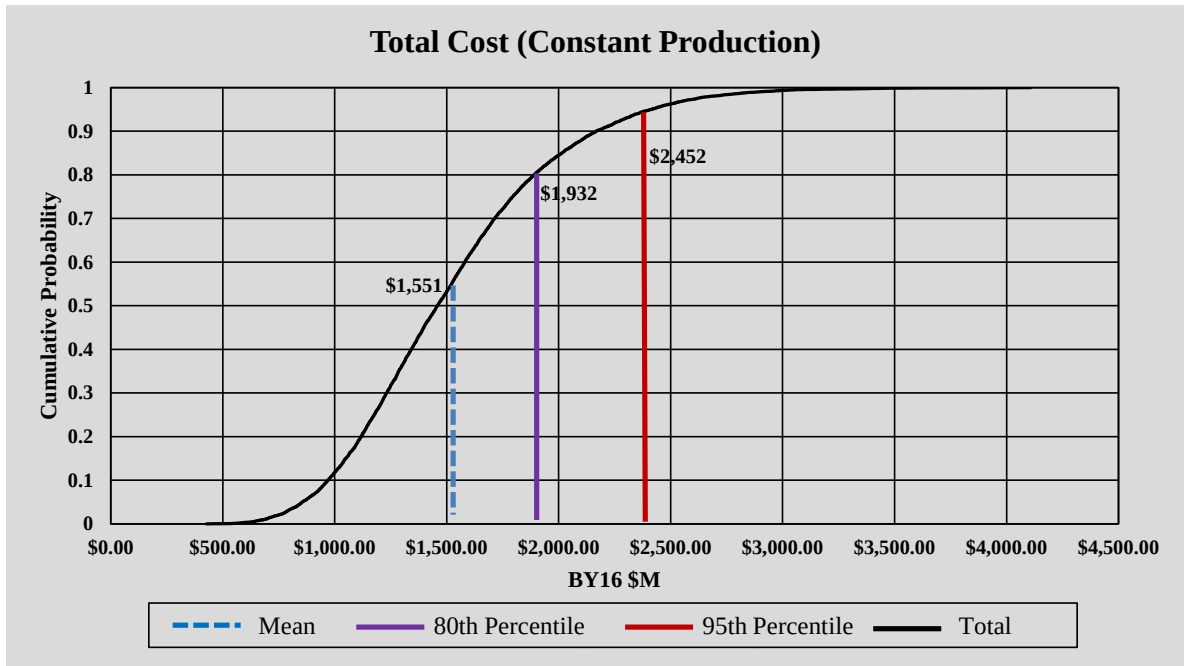


Figure 5: Small Satellite Constant Production CDF

Similar to the launch vehicle analysis, the bold assumption of a constant production line assumes no interruption to the production of the small communication satellites. The small satellites are estimated to cost more on an individual basis than their launch vehicle counterparts do (similar to DoD satellite and launch programs today). Under these assumptions, the single block procurement cost is unlikely to exceed \$2.5B (~3.8% probability). The truncated probability distributions (at zero) applied to the small satellites creates a cost floor and causes a slight rightward shift of the total recurring costs in each procurement scenario.

Table 8 demonstrates the total cost of procuring 66 small communication satellites in three blocks. The first satellite of blocks two and three begin at the midpoint unit cost of the previous block; this represents a partial loss in learning from one block to the next.

Table 8: Three Block Buy LC Midpoint Acquisition Results

Three Block Buy LC Midpoint Acquisition			
BY16 \$M	Small Satellite (Mean)	Small Satellite (80%)	Small Satellite (95%)
Non-Recurring Sat Constellation Costs	\$ 85	\$ 108	\$ 130
Recurring Sat Constellation Costs	\$ 1,623	\$ 2,003	\$ 2,516
Total	\$ 1,708	\$ 2,111	\$ 2,646

Due to the increased recurring costs, the non-recurring costs account for less of the total than during the single block procurement (~4.98%). The following cumulative density function (CDF) provides a graphical representation of the total recurring cost of procuring 66 small satellites in three blocks from a non-constant production line; in this case, the learning curve slope restarts equivalent to the midpoint unit cost of the previous block (Figure 6).

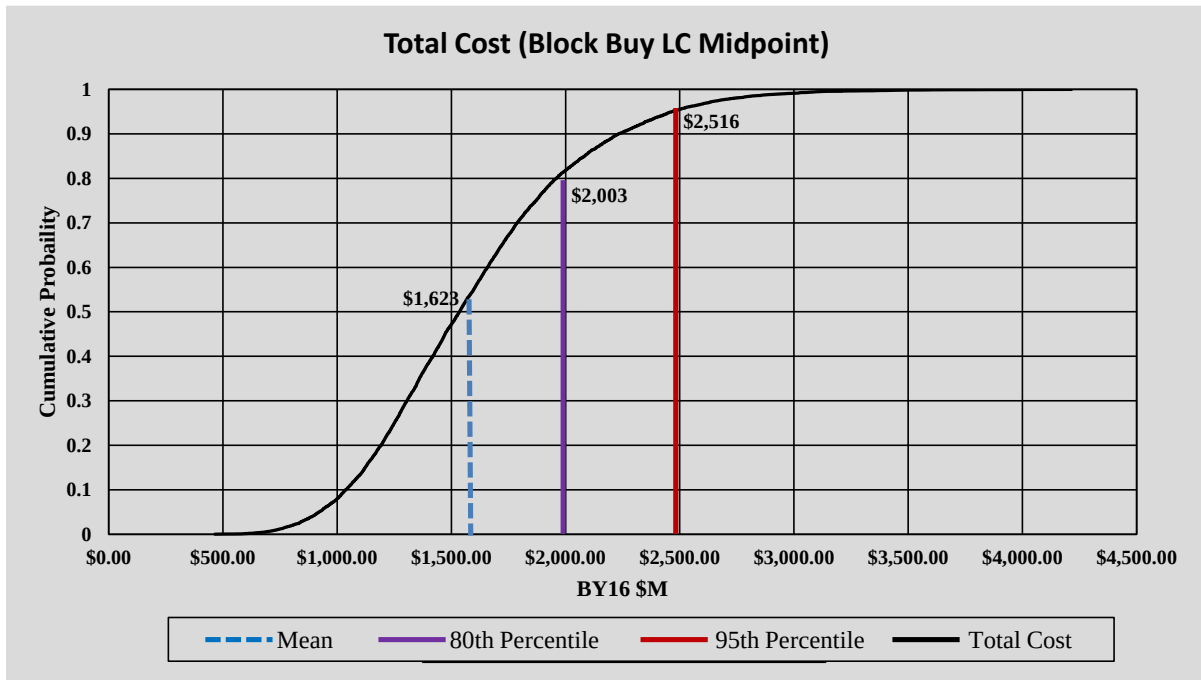


Figure 6: Small Satellite Block Buy LC Midpoint CDF

Similar to the launch vehicle analysis, the first method of applying learning to small communication satellites in a multi-block buy construct increases the total cost of

acquisition. The increase in total cost from a single block procurement to a three-block buy procurement is greater than the launch vehicle analysis due to the higher unit costs of the satellites; therefore, any difference in learning applied to the supplier's production process has a greater impact scenario to scenario.

Table 9 illustrates the total cost of 66 small communication satellites also procured in three blocks. In this instance, the first satellite of blocks two and three are equivalent to the T1 unit cost of block one; this represents a complete loss in learning from one block's production to the next.

Table 9: Three Block Buy LC T1 Acquisition Results

Three Block Buy LC T1 Acquisition			
BY16 \$M	Small Satellite (Mean)	Small Satellite (80%)	Small Satellite (95%)
Non-Recurring Sat Constellation Costs	\$ 85	\$ 108	\$ 130
Recurring Sat Constellation Costs	\$ 1,792	\$ 2,173	\$ 2,663
Total	\$ 1,877	\$ 2,281	\$ 2,793

The non-recurring costs account for a smaller percentage of the total costs (~4.5%) due to the higher recurring costs of this block buy assumption versus previous scenarios. The following cumulative density function (CDF) provides a graphical representation of the total recurring cost of procuring 66 small satellites in three blocks again assuming a non-constant production line; here, the learning curve slope restarts equivalent to the theoretical first unit cost (Figure 7).

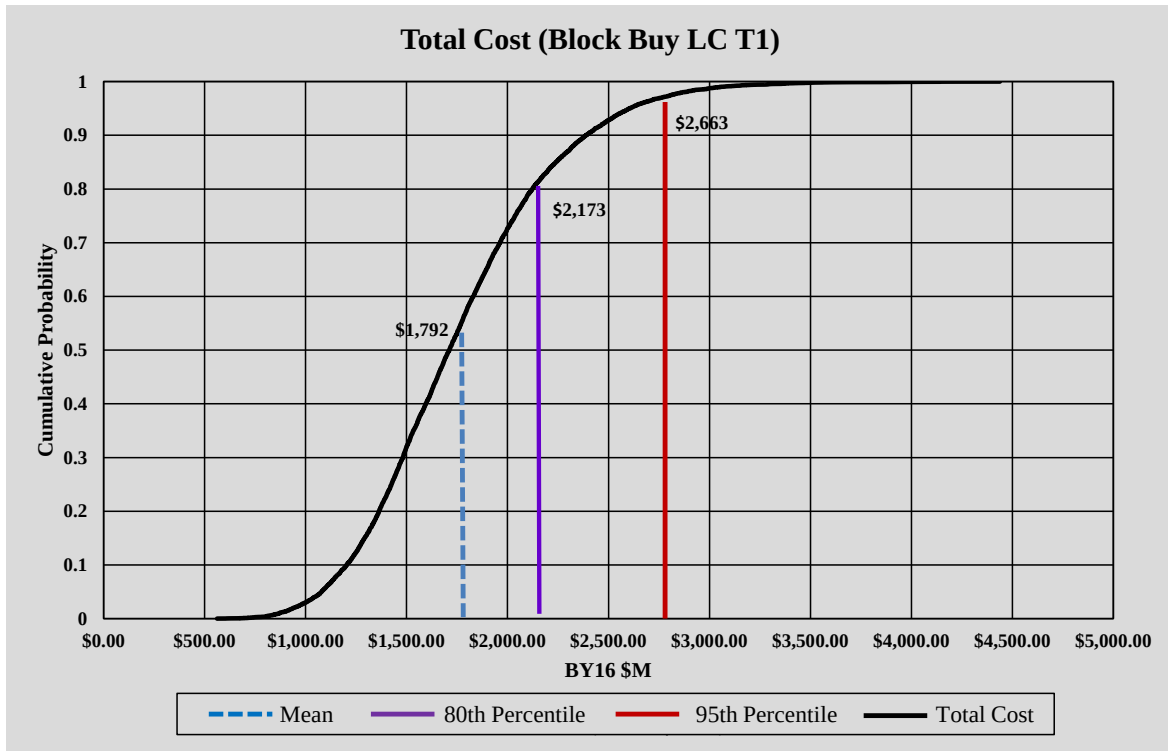


Figure 7: Small Satellite Block Buy LC T1 CDF

The final scenario demonstrates the highest DoD procurement cost of small communication satellites. The slope of the CDF is flatter than all previous scenarios, and the cumulative probability of costs exceeding \$2.5B has increased (~7.2% probability). The varying procurement scenarios alter the production learning slopes and provide a sensitivity analysis to the research; they demonstrate that, on average with conservative assumptions, the costs of procuring 66 small communication satellites for the DoD will fall below \$1.8B. The comparative analysis will address how these costs compare to WGS.

Comparative Analysis Results

As stated in the methodology section, the reference satellite architecture only

achieves half of the current mission life for the WGS constellation; therefore, the WGS constellation is compared to the small satellite constellation with one refresh of the entire small satellite constellation. Figure 8 demonstrates the cost difference between the WGS mission versus the small satellite constellation acquired in a single block with an orbital refresh.

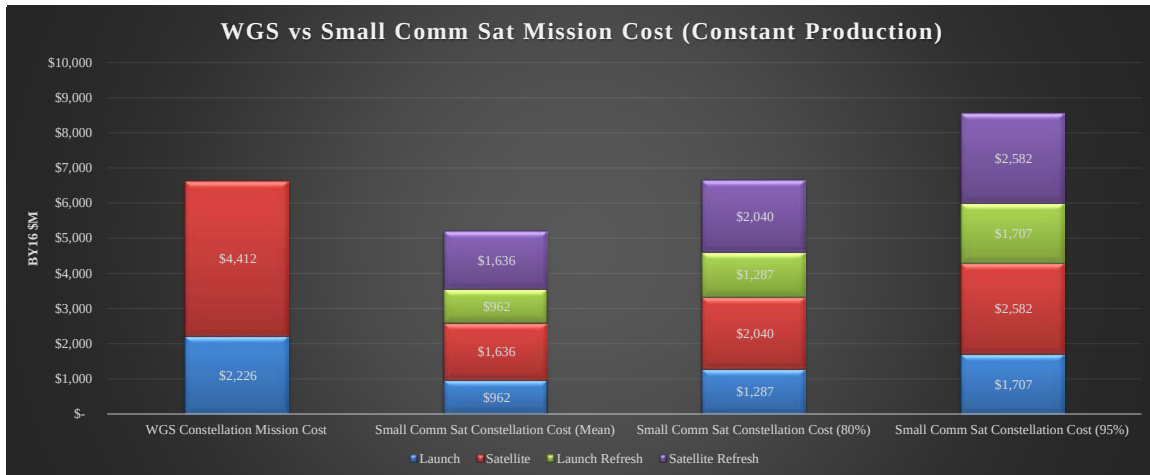


Figure 8: WGS vs Small Comm Sat Mission Cost (Constant Production)

Under constant production, the small communication satellite mission cost falls well below that of WGS (at the mean)—even with an orbital refresh of the entire constellation. At the upper-percentile tails of the simulation, cost savings become much less likely. The WGS mission cost includes both development and production costs. Wideband Global SATCOM development costs account for approximately 12% of the total satellite program costs. Although this percentage is higher than the estimated costs of development for the small communication satellite (~5%), it remains a small percentage of the overall WGS historical costs. Additionally, Figure 8 demonstrates a similar cost ratio between the satellite and launch vehicle for WGS and the small satellite

constellation. Table 11 summarizes the cost savings (nominally and as a percentage) of the small satellite constellation with a constant production line versus the WGS system.

Table 10: Constant Production vs WGS Cost Comparison

<u>Procurement w/Refresh</u>	<u>Cost Savings</u>	<u>Cost Savings Percentage</u>
Constant Production (Mean)	\$ 1,442	21.7%
Constant Production (80%)	\$ (15)	-0.2%
Constant Production (95%)	\$ (1,939)	-29.2%

Under constant production, the small satellite constellation mission produces substantial cost savings versus the WGS mission cost at the mean. The cost savings versus WGS may be high under single block procurement and a constant production line, but this procurement strategy is not consistent with the multi-block buy strategy used for WGS. Nevertheless, under perfect production conditions (constant learning and zero breaks), it is probable that a small satellite constellation would produce cost savings for the DoD on a constant production line versus WGS historical costs. As an aside, it is important to note the cost savings of the small satellite mission would double under a scenario in which satellite mission duration was equal to WGS.

Figure 9 shows the cost difference between the WGS system versus the small satellite constellation procured in three blocks, with a production learning curve slope reverting to the midpoint unit cost of the previous block, and an orbital refresh.

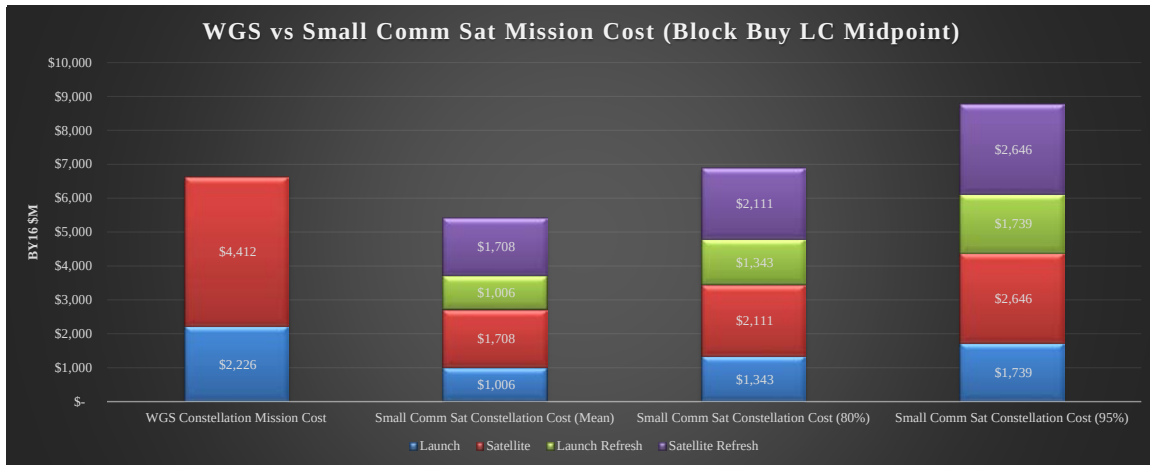


Figure 9: WGS vs Small Comm Sat Mission Cost (Block Buy LC Midpoint)

In this scenario, the cost delta between WGS and the small satellite constellation shrinks versus the single block scenario (constant production) while still maintaining savings at the mean. Table 11 lists the cost savings versus WGS.

Table 11: Block Buy LC Midpoint vs WGS Cost Comparison

<u>Procurement w/Refresh</u>	<u>Cost Savings</u>	<u>Cost Savings Percentage</u>
Block Buy LC Midpoint (Mean)	\$ 1,210	18.2%
Block Buy LC Midpoint (80%)	\$ (269)	-4.1%
Block Buy LC Midpoint (95%)	\$ (2,131)	-32.1%

Under multi-block buy procurement with block's two and three reverting to the midpoint unit cost of the previous block, the mean continues to produce substantial cost savings versus the WGS system. As expected, when applying a more direct comparison--as it pertains to multi-block buy procurement of satellite systems--the cost delta decreases between WGS and the small satellite mission. On average, the small satellite mission would produce cost savings versus WGS under this multi-block buy scenario. This scenario represents less than perfect production but still maintains a level of learning between subsequent blocks.

Figure 10 illustrates the cost difference between the WGS mission versus the small satellite constellation procured in three blocks, with the production learning curve slope reverting to the theoretical first unit cost, and an orbital refresh.

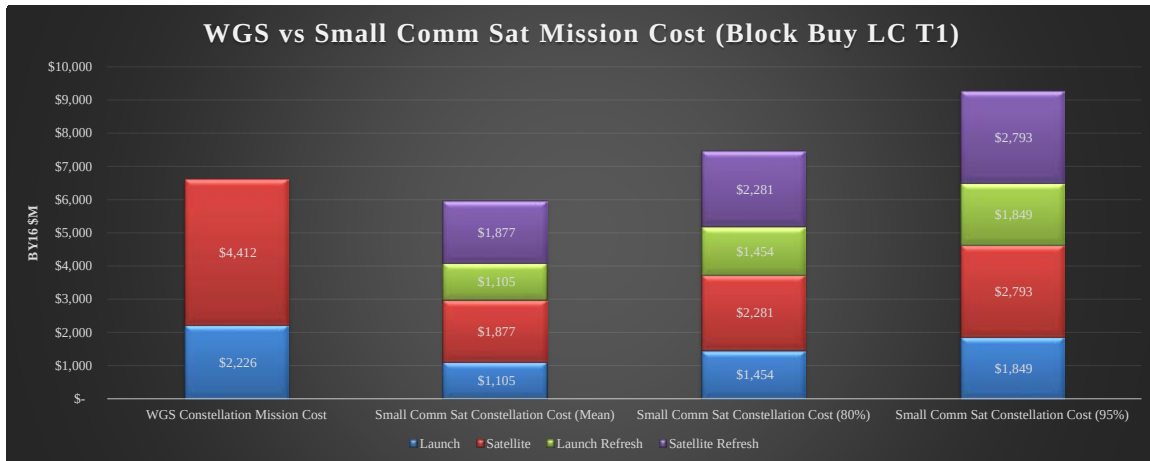


Figure 10: WGS vs Small Comm Sat Mission Cost (Block Buy LC T1)

In the most conservative scenario, the small satellite mission achieves much less cost savings at the mean with a full orbital refresh of the constellation. Table 12 shows the cost savings versus WGS.

Table 12: Block Buy LC T1 vs WGS Cost Comparison

Procurement w/Refresh	Cost Savings	Cost Savings Percentage
Block Buy LC T1 (Mean)	\$ 675	10.2%
Block Buy LC T1 (80%)	\$ (832)	-12.5%
Block Buy LC T1 (95%)	\$ (2,645)	-39.8%

Under multi-block buy procurement with the learning curve slope reverting to T1 in subsequent blocks, cost savings versus the WGS system are less (at the mean) than any of the previous scenarios. The upper tails of the cumulative probability represent a significant lack of savings versus WGS. The final scenario demonstrates a drop in savings of 11.5% versus single block procurement and 8% versus the previous multi-

block buy scenario (at the mean).

The cost savings associated with each procurement scenario may not represent a one-for-one replacement for the WGS constellation. They do present the DoD with an opportunity to bring down the size and complexity of communication satellite systems as a critical wideband capability is being provided by a more cost-efficient reference architecture. At the mean, the reference architecture will provide at least \$675M in cost savings for the DoD. These savings may allow the DoD to bolster other space assets while obtaining a more resilient construct of many small satellites versus a vulnerable, very few.

Chapter Summary

Chapter 4 detailed the results of the small launch vehicle and small communication satellite analysis and the comparative financial analysis versus the WGS constellation. Cost savings were demonstrated to be achievable in all production scenarios of the small satellite mission. Without the need for an orbital refresh, the savings would double for the DoD. Chapter 5 will analyze the results as they pertain to the original research question, document the limitations of the financial analysis, and provide recommendations for future research.

V. Conclusions and Recommendations

Chapter 5 presents concluding remarks regarding the thesis research question. Additionally, this chapter will detail the limitations of the financial analysis. Lastly, this chapter will summarize the research and provide recommended areas of future research.

Research Question

We set out to determine “can the DoD lower space access costs through the exploitation of the growing small satellite and small launch marketplace?” Simply stated, the answer is “yes.” We determined that the small satellite architecture can provide full-earth communication coverage at cost savings ranging from 10% to 22% versus the current WGS constellation (at the mean). Cost savings were not found in all trials as demonstrated in the upper-percentile tails of the simulations; however, on average, whether produced on a constant or non-constant production line, the small satellite architecture offers savings when compared to the current WGS constellation. As stated previously, the small communication satellite reference architecture does not completely replicate the capacity or capability of WGS. Therefore, for logical DoD investment, the savings percentage found within the analysis must exceed the performance difference of the small satellite architecture versus the WGS constellation.

At the foundational level of providing satellite communications, the DoD can obtain lower-space access costs through the exploitation of the growing small satellite and small launch marketplace. The emergence of greater competition in the marketplace grants the DoD the ability to reduce costs for the space mission and embrace the likely disaggregated future of space capabilities. The potential savings provide the DoD with

the ability to expand capacity and capability of future satellite systems.

Additionally, the small communication satellite's mission life is estimated at seven years, which is half the expected mission life of WGS. DoD-operated satellite systems have been operational longer than anticipated across multiple platforms including missions related to global positioning, communication, and weather. The fluctuations in mission life, both positive and negative, will greatly influence the cost difference presented within this analysis. If the small communication satellite constellation can obtain greater mission life as the technology matures, this may be viewed as a financial boon for the DoD--the constellation refresh limits the expected cost savings by a factor of two. Moreover, as discussed in Chapter 2, General Hyten's vision for future satellite constellations embraces "decreased time between constellation updates" (Air Force Space Command Public Affairs, 2016). If the future relies on satellite systems to be updated at a higher frequency, the results of this analysis take on even greater meaning for the DoD space financial portfolio. Finally, the choice of a 66-satellite constellation for the reference architecture was conservative. The ability to satisfy communication requirements with fewer than 66 satellites and launches will dramatically decrease costs of the small communication satellite mission and allow the DoD greater financial flexibility in accomplishing its goals. See Appendix E for example launch campaign sensitivity analysis.

Limitations

This thesis made specific assumptions in order to perform the most reasonable and applicable analysis. These assumptions establish the following limitations on the

analysis conducted:

WGS versus small communication satellite constellation. Our research provided a comparative analysis of two satellite systems that are not identical in capability or performance. WGS is a mature, powerful, and continuously improving communication constellation which cannot be rivaled by today's small communication satellites. The DoD has the contractual opportunity to extend the WGS constellation to 10 total satellites with the eighth satellite having been launched on 7 Dec 2016 (Ray, 2016). The remaining WGS satellites will not be launched until 2019 (Swarts, 2016) which creates the opportunity for full development of the new small launch vehicle capabilities and a maturing commercial production line. The overwhelming growth in private funding, small satellite capability, and renewed governmental interest provide a bright outlook for the capability of small satellites into the future. With a time horizon of several years due to the existing WGS system, the capability gap can be expected to decrease.

Ground system exclusion rationale. The ground system for the potential small satellite constellation was excluded from this financial analysis due to the great, unknown future of Air Force space ground systems. General Hyten has expressed concern for the abundance of separate Air Force ground systems for different satellite constellations. The Air Force has begun to study a uniform enterprise-level ground infrastructure for their space missions. Air Force personnel have gone as far as pondering how to outsource the satellite operations of WGS and GPS so uniformed military personnel can focus on battle management operations (Gruss, 2015a). According to subject matter experts, WGS ground development costs are minimal and only reside within the early

stages of WGS RDT&E funding. Currently, the Command and Control System-Consolidated (CCS-C) program provides ground system capability for WGS and other Military SATCOM (“Command and Control System Consolidated,” 2013).

Space market growth. Our analysis assumes the continued growth and development of the small satellite and small launch vehicle marketplace. If the industry falls on economic hardships, the ability to produce and launch a 66-satellite constellation may not be possible. A disruption in the development of small launch vehicles would nullify the financial assumptions and conclusions made in this research. These economic concerns are critical for emerging technology, but they apply to the established large satellite manufacturers and launch vehicle providers within the market as well. Additionally, with the entrance of extremely wealthy entrepreneurs (Jeff Bezos, Paul Allen, Richard Branson, etc.), the next decade will demonstrate whether a positive return on investment is truly possible in space with some of the deepest pockets supporting separate ventures.

Mission Failures. Launch and/or satellite failure is always a concern regarding space missions. Whether it is the Challenger Space Shuttle tragedy of 1986 or the most recent Falcon 9 launch failure, these events create real concern for producers and consumers of the “final frontier.” Our research did not factor into its launch campaign any specific mission failures. The non-constant production line methods may account for some possible loss of learning costs due to a failure, but are not explicitly accounted for in our research.

Other analysis limitations. Non-recurring software development costs are not included within our analysis for the small satellite reference architecture. Non-recurring

costs are an extremely small percentage of our analysis, but without a more thoroughly developed reference architecture, system software costs could not be adequately measured. The addition of software development costs would reduce the small satellite mission savings versus WGS, albeit minimally. WGS non-recurring costs account for only 12% of total satellite costs and the small satellite non-recurring costs account for approximately 5% of total satellite costs. Additionally, the satellite payload non-recurring CER falls very minimally out of the CER range (payload weight). Although this damages the validity of using the payload CER, it still provides the best available method of estimating the payload non-recurring costs at the time of this research.

Recommended Future Research

Our financial analysis explores the DoD's ability to launch small satellites via small, dedicated launch vehicles to complete DoD missions with the potential to obtain significant financial savings. The findings of our analysis opens the door for future research as the small launch vehicle market expands and begins to complete launches.

Will the assumptions of this analysis hold up as more launches are awarded and completed? The baseline of small launch costs are predicated on NASA's VCLS contract. As more contracts are awarded, researchers should update and refine small launch vehicle costs for the DoD.

Can the demand for small-dedicated launch vehicles be sustained as large launch vehicle companies drive down costs through reusable first stages and engines? SpaceX and ULA are both pursuing reusable technology that, if successful, will drive down launch costs. As these costs begin to decrease, will cost effectiveness outweigh the risks

to load-up large launch vehicles with many small satellites versus the dedicated small launch vehicles analyzed in our research?

Another future research opportunity is to incorporate the risk of failure into launch vehicle and satellite system analysis. A launch or on-orbit failure is of great expense to the companies, agencies, and users involved in a given mission. Are new launch or satellite systems systematically more vulnerable to failure? Have the launch failures of SpaceX over the past few years proved that paying more for an established launch provider is worth the cost increases to the DoD?

Lastly, the capability growth of small satellites over time is another possible research area. Small satellite capability has clearly been growing as evidenced throughout our research, but can small satellite growth be quantified over time? Does satellite capability follow a technological growth function similar to Moore's law concerning circuits?

Last Words

Our research quantifies the cost of a disaggregated satellite architecture and demonstrates that small communication satellites can potentially be built and delivered to space cheaper than existing systems. The space realm has been on a tremendous innovative trajectory. With the investment into the space market by pioneering entrepreneurs, it is possible that advancements in the miniaturization of technology has arrived in the final frontier of space exploration.

The DoD has the opportunity to leverage this technological advancement while maintaining an acceptable financial profile for its space mission. Space is a constantly

evolving domain that becomes more congested by the year as countries around the world begin to see the value in space assets—both economically and militarily. As the space domain evolves and presents new opportunities, the DoD must evolve to ensure not only technical superiority in space but also fiscal responsibility by obtaining the greatest technology at the most affordable price. There remain few ways more cost effective than exploiting the advancements of the burgeoning private sector for national defense.

Appendix A: Joint Agency Cost Risk Schedule Uncertainty Handbook Subjective

Distributions

Distribution	Point Estimate Position	Point Estimate and Probability	Mean*	CV*	15%	85%
Lognormal Low	Median	1.0 (50%)	1.0113	0.1509	0.8560	1.1682
Lognormal Med	Median	1.0 (50%)	1.0318	0.2541	0.7718	1.2958
Lognormal High	Median	1.0 (50%)	1.0632	0.3613	0.6957	1.4373
Lognormal EHigh**	Median	1.0 (50%)	1.1067	0.4743	0.6273	1.5943
Normal Low	Mean	1.0 (50%)	1.0000	0.1501	0.8445	1.1555
Normal Med	Mean	1.0 (50%)	1.0000	0.2501	0.7409	1.2591
Normal High	Mean	1.0 (50%)	1.0024	0.3458	0.6400	1.3632
Normal EHigh	Mean	1.0 (50%)	1.0154	0.4258	0.5547	1.4703
Weibull Low	Mode	1.0 (25%)	1.1581	0.1794	0.9564	1.3695
Weibull Med	Mode	1.0 (20%)	1.3932	0.3324	0.9563	1.8547
Weibull High	Mode	1.0 (15%)	2.1037	0.5723	1.0000	3.2766
Triangle Low Left	Mode	1.0 (75%)	0.8775	0.1779	0.6953	1.0414
Triangle Low	Mode	1.0 (50%)	1.0000	0.1500	0.8338	1.1662
Triangle Low Right	Mode	1.0 (25%)	1.1225	0.1391	0.9586	1.3046
Triangle Med Left	Mode	1.0 (75%)	0.7959	0.3270	0.4923	1.0690
Triangle Med	Mode	1.0 (50%)	1.0000	0.2500	0.7230	1.2769
Triangle Med Right	Mode	1.0 (25%)	1.2041	0.2161	0.9310	1.5078
Triangle High Left*	Mode	1.0 (75%)	0.7454	0.4479	0.3467	1.1028
Triangle High	Mode	1.0 (50%)	1.0000	0.3501	0.6122	1.3878
Triangle High Right	Mode	1.0 (25%)	1.2858	0.2834	0.9034	1.7109
Triangle EHigh Left*	Mode	1.0 (75%)	0.7454	0.4960	0.3004	1.1501
Triangle EHigh	Mode	1.0 (50%)	1.0045	0.4439	0.5088	1.4998
Triangle EHigh Right	Mode	1.0 (25%)	1.3674	0.3426	0.8758	1.9140
Uniform Low Left	Mode	1.0 (75%)	0.8701	0.1724	0.6882	1.0520
Uniform Low	Mode	1.0 (50%)	1.0000	0.1500	0.8181	1.1819
Uniform Low Right	Mode	1.0 (25%)	1.1299	0.1328	0.9480	1.3118
Uniform Med Left	Mode	1.0 (75%)	0.7835	0.3191	0.4804	1.0866
Uniform Med	Mode	1.0 (50%)	1.0000	0.2500	0.6969	1.3031
Uniform Med Right	Mode	1.0 (25%)	1.2165	0.2055	0.9134	1.5196
Uniform High Left	Mode	1.0 (75%)	0.6969	0.5023	0.2726	1.1213
Uniform High	Mode	1.0 (50%)	1.0000	0.3500	0.5757	1.4243
Uniform High Right	Mode	1.0 (25%)	1.3031	0.2686	0.8788	1.7275
Uniform EHigh Left	Mode	1.0 (75%)	0.6949	0.5774	0.2085	1.1813
Uniform EHigh	Mode	1.0 (50%)	1.0000	0.4500	0.4544	1.5456
Uniform EHigh Right	Mode	1.0 (25%)	1.3897	0.3238	0.8441	1.9353
Beta Low Left	Mode	1.0 (61%)	0.9393	0.1600	0.7750	1.0986
Beta Low	Mode	1.0 (50%)	1.0000	0.1502	0.8375	1.1625
Beta Low Right	Mode	1.0 (39%)	1.0607	0.1417	0.9014	1.2249
Beta Med Left	Mode	1.0 (63%)	0.8833	0.2827	0.6046	1.1517
Beta Med	Mode	1.0 (50%)	1.0000	0.2502	0.7255	1.2745
Beta Med Right	Mode	1.0 (37%)	1.1170	0.2240	0.8483	1.3957
Beta High Left	Mode	1.0 (66%)	0.8085	0.4191	0.4117	1.1862
Beta High	Mode	1.0 (50%)	1.0000	0.3501	0.6046	1.3955
Beta High Right	Mode	1.0 (33%)	1.2021	0.2912	0.8157	1.6061

** EHigh = Extreme High

* To match these paramaters, tools must be set to truncate the distribution at zero.

Note: High triangle used to apply subjective distribution to launch vehicle analysis.

Appendix B: EELV SAR funding

Fiscal Year BY 2016 \$M	Quantity	3020/21 Procurement	Avg Launch Cost
2000	1	110.31	110.31
2001	5	815.90	163.18
2002		0.00	
2003	1	301.21	301.21
2004	7	1579.26	225.61
2005	4	914.85	228.71
2006	1	2107.72	2107.72
2007	3	2438.51	812.84
2008	5	1832.32	366.46
2009	6	2315.27	385.88
2010	5	1652.79	330.56
2011	8	2290.60	286.32
2012	9	3019.03	335.45
2013	7	2207.08	315.30
2014	6	1041.75	173.63
2015	8	1234.13	154.27
2016	7	2589.40	369.91
2017	7	2646.76	378.11
			278.2 *Avg Block Buy Pricing
			2225.94 8 Launches

Note: Highlighted years represent Air Force block-buy and all costs are in base-year 2016 dollars.

Appendix C: WGS SAR funding

Fiscal Year	Quantity	3600 RDT&E BY16 \$M	3020 Procurement (Missile Procurement, AF) BY16 \$M
1999		1.1	0.0
2000		7.1	0.0
2001		118.7	0.0
2002	2	118.4	826.9
2003	1	0.0	381.8
2004		0.0	0.0
2005		42.1	0.0
2006		98.2	0.0
2007	1	33.8	578.8
2008	1	0.0	488.0
2009		10.8	0.0
2010		46.0	0.0
2011	1	59.1	581.7
2012	2	0.0	694.2
Total	8	\$ 535.42	\$ 3,551.45

Fiscal Year	3021 Procurement (Space Procurement, AF) BY16 \$M	3080 Procurement (Other, AF) BY16 \$M
1999	0.0	0.0
2000	0.0	0.0
2001	0.0	0.0
2002	0.0	0.0
2003	0.0	22.2
2004	0.0	15.2
2005	0.0	0.0
2006	0.0	0.0
2007	0.0	0.0
2008	0.0	0.0
2009	0.0	0.0
2010	0.0	1.8
2011	0.0	1.7
2012	284.4	0.0
Total	\$ 284.38	\$ 40.85

Note: WGS cost and funding are in base year 2016 dollars (RDT&E and Procurement)

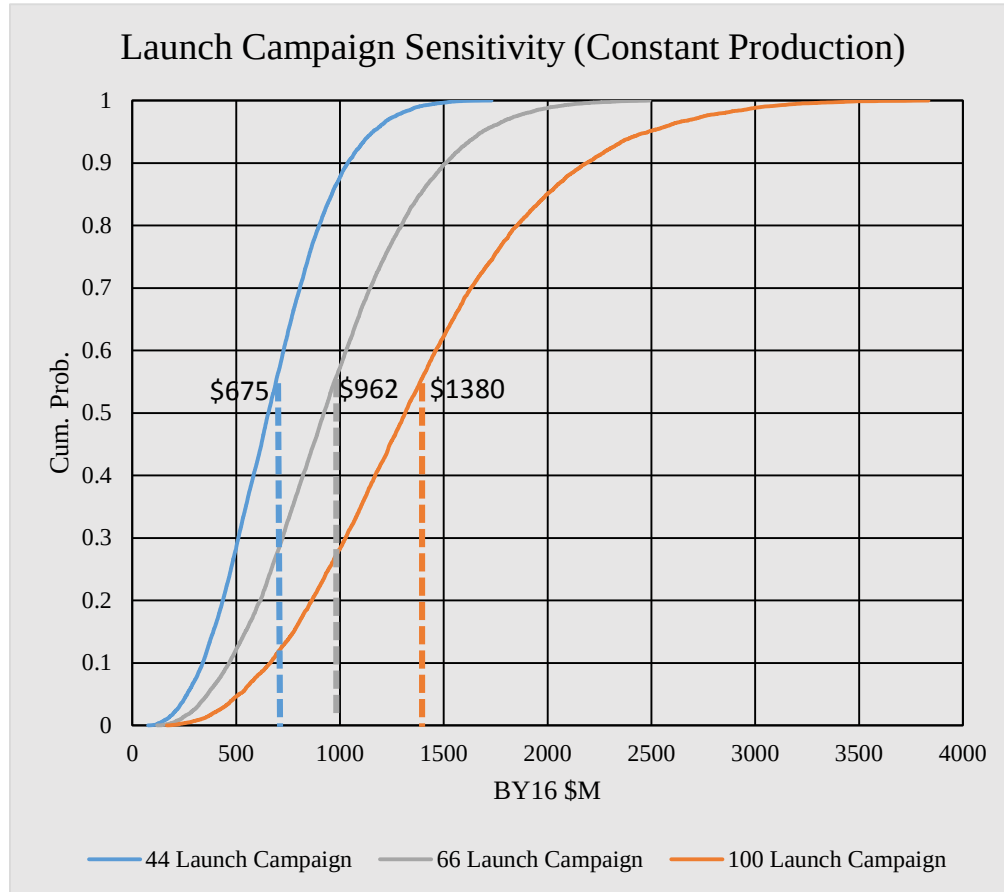
Appendix D: Sample Unit Launch Vehicle Costs

Launch #	Constant Production (BY16 \$M) ¹	Block Buy LC Midpoint (BY16 \$M) ²	Block Buy LC T1 (BY16 \$M) ³
1	\$ 19.86	\$ 19.86	\$ 19.86
2	\$ 17.50	\$ 17.50	\$ 17.50
3	\$ 16.25	\$ 16.25	\$ 16.25
4	\$ 15.42	\$ 15.42	\$ 15.42
5	\$ 14.80	\$ 14.80	\$ 14.80
6	\$ 14.32	\$ 14.32	\$ 14.32
7	\$ 13.92	\$ 13.92	\$ 13.92
8	\$ 13.59	\$ 13.59	\$ 13.59
9	\$ 13.30	\$ 13.30	\$ 13.30
10	\$ 13.04	\$ 13.04	\$ 13.04
11	\$ 12.82	\$ 12.82	\$ 12.82
23	\$ 11.20	\$ 12.82	\$ 19.86
24	\$ 11.12	\$ 12.62	\$ 17.50
25	\$ 11.03	\$ 12.43	\$ 16.25
26	\$ 10.96	\$ 12.27	\$ 15.42
27	\$ 10.88	\$ 12.11	\$ 14.80
28	\$ 10.81	\$ 11.97	\$ 14.32
29	\$ 10.74	\$ 11.84	\$ 13.92
30	\$ 10.67	\$ 11.72	\$ 13.59
31	\$ 10.61	\$ 11.60	\$ 13.30
32	\$ 10.55	\$ 11.49	\$ 13.04
33	\$ 10.49	\$ 11.39	\$ 12.82
45	\$ 9.91	\$ 11.39	\$ 19.86
46	\$ 9.87	\$ 11.29	\$ 17.50
47	\$ 9.83	\$ 11.20	\$ 16.25
48	\$ 9.80	\$ 11.12	\$ 15.42
49	\$ 9.76	\$ 11.03	\$ 14.80
50	\$ 9.72	\$ 10.96	\$ 14.32
51	\$ 9.69	\$ 10.88	\$ 13.92
52	\$ 9.65	\$ 10.81	\$ 13.59
53	\$ 9.62	\$ 10.74	\$ 13.30
54	\$ 9.59	\$ 10.67	\$ 13.04
66	\$ 9.24	\$ 10.04	\$ 11.29

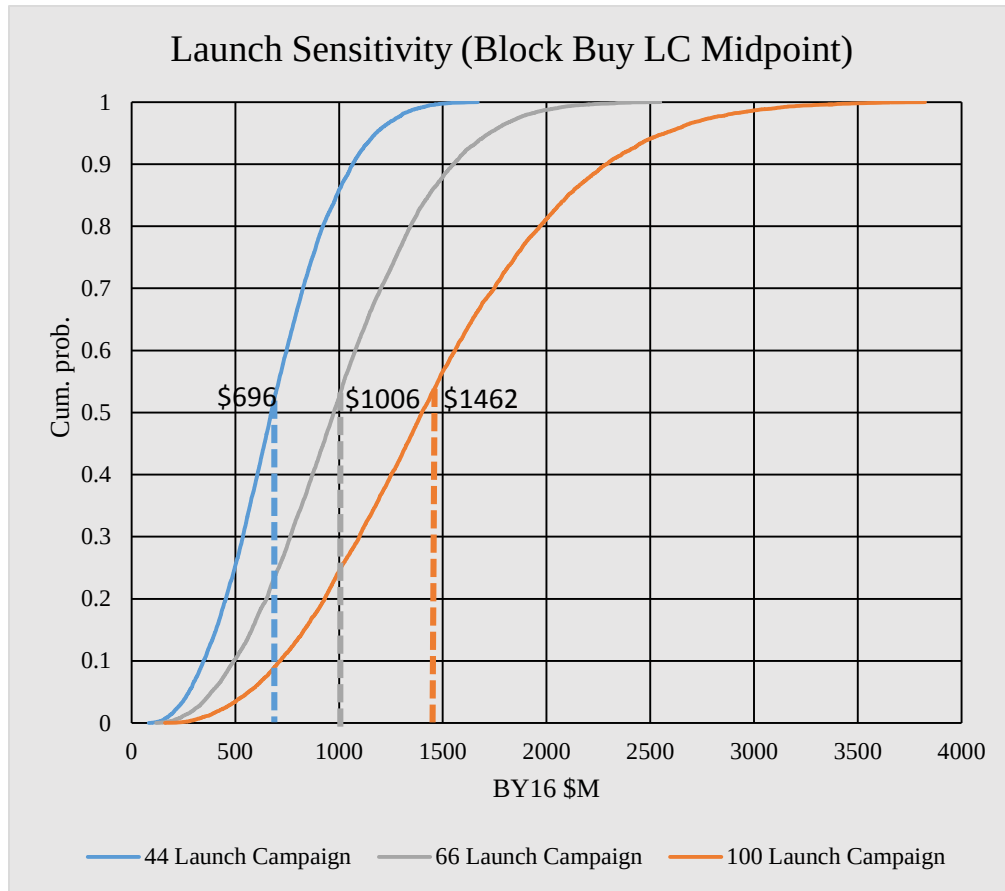
Note:

- 1 Constant production maintains constant learning through all 66 launch vehicles
- 2 Block buy LC Midpoint restarts learning at midpoint of previous block
- 3 Block buy LC T1 restarts learning at T1 cost of block 1
- 4 Small satellite unit costs follow similar format

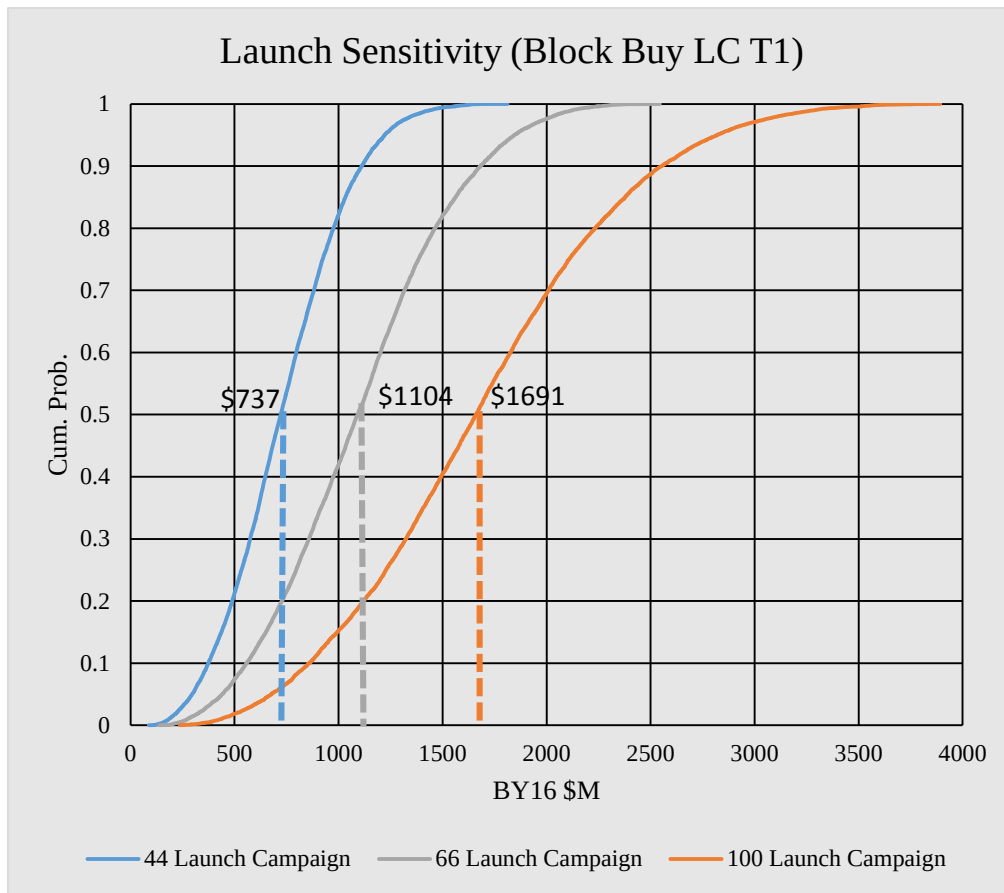
Appendix E: Launch Campaign Sensitivity Analysis



Note: Single block procurement, constant production line sensitivity analysis of launch costs under various launch campaigns. Similar cost disparity found in small satellite campaign.



Note: Block buy, non-constant production line, with a learning curve restart of the midpoint of the previous block sensitivity analysis of launch costs under various launch campaigns.



Note: Block buy, non-constant production line, with a learning curve restart at the T1
sensitivity analysis of launch costs under various launch campaigns

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Vita

Captain Peter A. DeBois completed his undergraduate studies at the United States Air Force Academy, where he was awarded a degree in Economics. Following the completion of his undergraduate degree, he was commissioned as an officer in the U.S. Air Force.

During his Air Force Career, Captain DeBois gained a variety of experience ranging from Acquisition Cost Analyst, Executive Officer, and Afghan Biometrics Advisor. Upon graduation from the Air Force Institute of Technology, he will be assigned to the Air Force Cost Analysis Agency, Andrews Air Force Base, Maryland.

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14. ABSTRACT Investment in the commercial space industry has grown significantly over the past decade. This investment has led to a tremendous leap in capability for small satellite systems and a greater demand for small launch vehicles. At the same time, space system affordability is a point of emphasis within the Department of Defense (DoD) which raises the question: Can the DoD lower space access costs through the exploitation of the growing small satellite and small launch marketplace? We perform a financial analysis of newly developed small launch vehicles delivering a small satellite constellation to low earth orbit (LEO) to perform wideband communication. The results are then compared against the historical costs of the DoD's Wideband Global SATCOM (WGS) constellation. We conclude small communication satellites delivered to LEO by newly developed small launch vehicles produce potential cost savings ranging from 10% to 22% versus WGS. Small satellite and small launch vehicle systems must evolve to meet the capability and performance of the DoD's current wideband communication system, but the potential financial savings found in our research gives the DoD flexibility in procuring future space capabilities for U.S. defense.					
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